Potential Late-Holocene Disjunction of *Sequoia sempervirens* on the Central Oregon Coast

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Source: Northwest Science, 87(2):81-94. 2013.
Published By: Northwest Scientific Association
DOI: http://dx.doi.org/10.3955/046.087.0201
URL: http://www.bioone.org/doi/full/10.3955/046.087.0201

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Abstract

A large (> 200-cm diameter) coast redwood (*Sequoia sempervirens*) stump occurring upright on an Oregon beach, 257 km from the northern limit of its native distribution, may be a remnant of an extinct disjunct population or it may be the result of vertical emplacement of a drift log. Holocene tree stumps *in situ* in paleosols commonly emerge on the shore platform as a result of a complex history of dune activity, subsidence, and erosion. An historical account reported organic soils associated with the stump during the late 1800s; such soils are normally removed quickly by wave action after exposure. We used several methods to corroborate this account. The stump's *in situ* origin is supported by 1) a radiocarbon age indicating a death date between 1820 and 1720 years ago, coeval with other paleosols and *in situ* stumps; 2) its height and upright position, which are only matched by other *in situ* stumps; and 3) a photograph from 1912 showing uneroded wood inconsistent with a sea-drift history. Other evidence failed to support the *in situ* origin: 1) ground-penetrating radar did not reveal an associated paleosol, 2) the age of a nearby paleosols and stumps within 3 km were younger than the stump, and 3) three paleosols did not yield redwood pollen or wood. The only support for a sea-drift origin is that its age slightly predates a known tsunami that may have emplaced the stump. The balance of evidence suggests that the redwood stump is a remnant of an extinct late-Holocene disjunct population.

Keywords: coast redwood, driftwood, ground penetrating radar, paleosol, subduction zone earthquakes

Introduction

Big Stump is a large coast redwood (*Sequoia sempervirens*) stump located on the shore platform, close to the mean high–tide elevation, near Waldport, OR, 257 km north of the native range limit of this species (Figures 1 and 2). Whereas redwood drift logs are common on Oregon beaches, Big Stump is oriented in a nearly vertical upright (apparent growth) position, in contrast to the majority of large drift logs (often with attached rootwads) normally in a horizontal position. Elsewhere on Oregon beaches, upright tree stumps rooted *in situ* in paleosols may appear on the beach platform after winter storms remove sand. Such *in situ* stumps originated when trees and soils were buried in Holocene beach sand and dunes and later exposed by beach erosion (Hart and Peterson 2007). In this study, we examine the age and setting of Big Stump with the aim to distinguish its provenance either as sea drift or *in situ*, and in doing so to assess the possibility of a recent extinction of a northern disjunct redwood population.

The possibility of a major extinct disjunction of redwood has great biogeographical significance. The low freezing tolerance of redwood is the likely control of its northern limit near the Chetco River in southwestern Oregon. Redwood at that site, and at the mouth of the Smith River, are perched on terraces above the river and the cold-air drainages that form under winter high-pressure systems (MacGinitie 1933). However, during recent decades, redwood have been widely planted in tree farms throughout the central Oregon Coast Range and to a lesser extent closer to Portland, where it grows faster than Douglas-fir (*Pseudotsuga menziesii*), even in competitive

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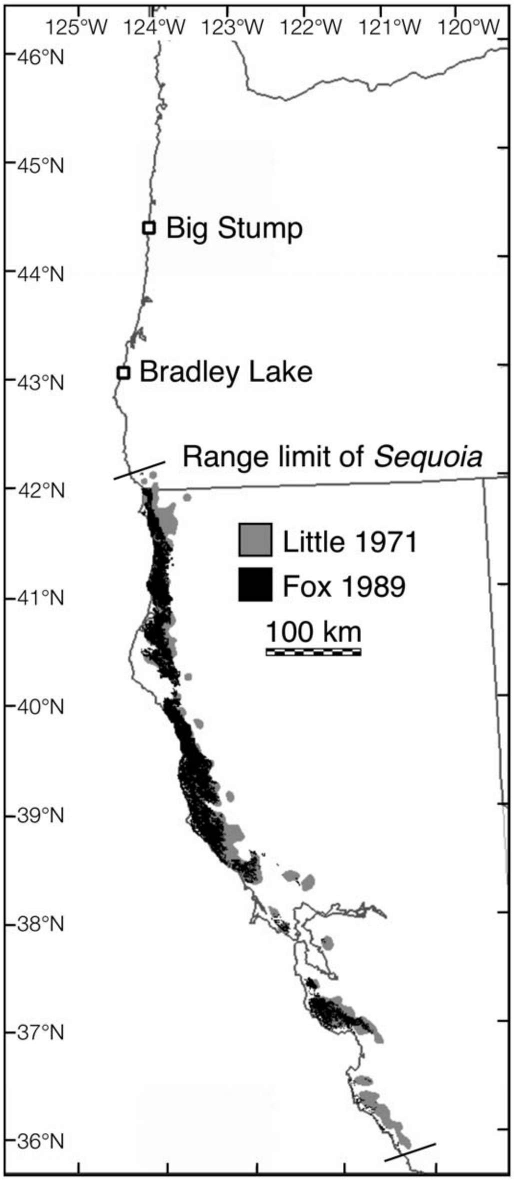

Figure 1. Geographic range of *Sequoia sempervirens*. Gray shading is from Little (1971) and black shading is from a more spatially precise inventory (Fox 1989).

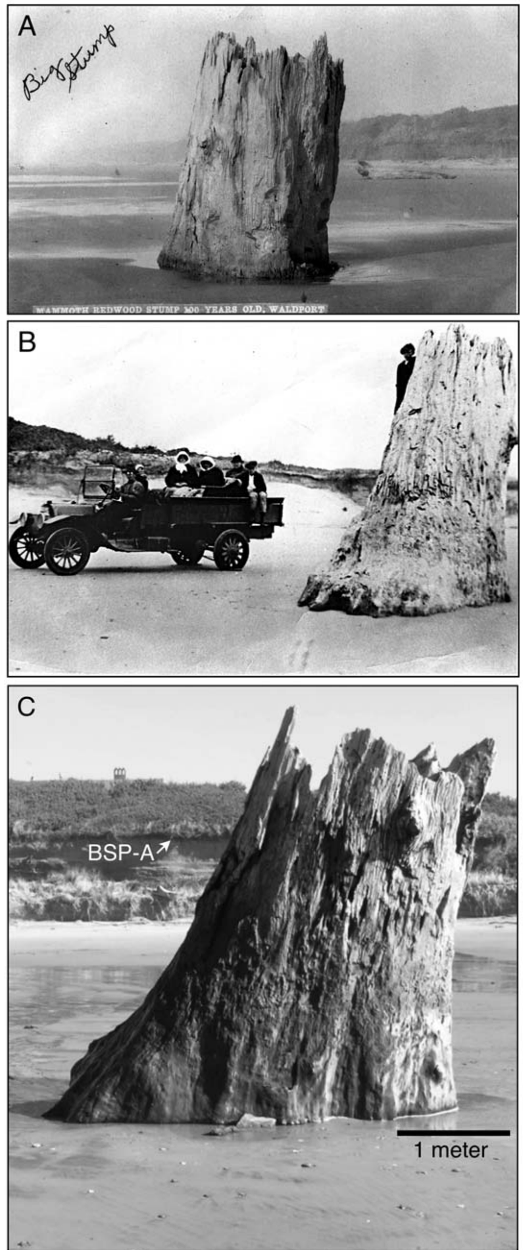

Figure 2. (A) Big Stump in 1912 viewed facing north. Caption reads “Mammoth redwood stump 100 years old, Waldport.” Photo courtesy of Waldport Heritage Museum, 320 NE Grant, Waldport, 97394. (B) Big Stump in ca. 1920 viewed facing southeast. Photo courtesy of Cape Cod Cottages, 4150 SW Pacific Coast Hwy, Waldport, OR 97394. (C) Big Stump in February 2008 viewed facing east. Scale bar is 1 m. The BSP-A paleosol, a 30-cm sandy A-horizon in a beach cliff 65 m ESE of Big Stump, is labeled. Photo by Daniel Gavin.

growing conditions (Dietz 2009). The climatic controls on the northern limit of the species, therefore, may be sufficiently weak and diffuse over such a broad region that it is reasonable to expect naturally occurring disjunctions under past conditions. MacGinitie (1933) speculated that because seedlings are more sensitive to frost damage, dispersal limitation and the regeneration niche of redwood might result in its current distribution. Others have speculated that, because redwood may persist clonally for generations, it may tolerate unfavorable climate in place; but it also may adapt slowly to a changing climate and have low vagility (Douhovnikoff and Dodd 2010). Whereas dynamic range limits are expected from established theory regarding relations between the fundamental niche and geographic distribution (Pulliam 2000, Beckage et al. 2012), the discovery of a recent extinction of such a long distance disjunct population could indicate a much more dynamic biogeographic history of redwood than previously understood.

Current understanding of recent changes of redwood distribution is sparse, but in general supports the possibility of northern range extension during the Holocene. The most recent fossil evidence of redwood north of its current range, at a site on the Columbia River, dates to a much warmer period during the early Pliocene (Chaney 1944, Sawyer et al. 1999). During the colder climate of the last glacial maximum 21,000 years ago, redwood may have contracted southward into central and southern California, though off-shore pollen records suggests it generally remained within its current distribution albeit at low densities (Heusser 1998). During the middle Holocene (7000 to 3000 years ago), increased summer insolation and an intensified and northward-shifted Pacific Subtropical High pressure system resulted in an enhancement of the California Current (Barron 2003, Thompson et al. 2003). This reduced seasonal climatic extremes in coastal northern California as reflected by vegetation change near the California coast (Briles et al. 2008) and by a large increase of redwood in pollen records from this time (Heusser 1998, Sawyer et al. 1999). The effect of the California Current on upwelling and the increased onshore flow may have increased fog and favored redwood (Pisias et al. 2001). In addition, a strong coast-to-interior pressure gradient during the middle Holocene contributed to onshore flow and caused extensive dune accretion along the Oregon coast (Peterson et al. 2007). It is possible the same pattern reduced the number of freezing events and ameliorated the climatic constraints on the northern limit of redwood. Unfortunately, few paleoecological studies have addressed the impact of Holocene climate changes on Oregon's coastal forests.

We undertook an interdisciplinary study of the age and provenance of Big Stump. As evidence supporting an *in situ* (rooted) or *ex situ* (sea drift) origin may be elusive, we constructed a set of potential lines of evidence (Table 1). Our rationale is that we could provide very strong support for a local or *in situ* origin if we discover associated organic soils of the same age as the stump. In addition, a northern redwood disjunction would be strongly supported by discovery of additional fossil evidence, namely redwood pollen or wood in paleosols. Based on the potential for false interpretation (Table 1), we consider weaker support for a local or *in situ* origin from correlating the age of Big Stump with other dated *in situ* stumps. In contrast, a comparison of the age of Big Stump with coastal processes, especially earthquakes and tsunamis, may provide an alternative explanation for emplacement of a tall driftwood stump in an upright position.

Big Stump: Observations Over the Last Century

Big Stump is identified as redwood on the Waldport USGS 7.5' quadrangle map (U.S. Geological Survey 1984). A wood sample sent to the Forest Products Laboratory and Center for Wood Anatomy & Research (Madison, WI) confirmed the identification as redwood. The stump is 200 cm in diameter above the buttressing. During the winter months of 2007 and 2008, when sand levels were at their lowest in recent years, the stump stood 3.5 m tall and was briefly inundated at high tide. Photos of Big Stump from 1955 and present-day indicate that the stump has not shifted its position over time, remaining at approximately 21° from vertical (note that the photos in Figure 2 are taken from different angles). Big Stump is anomalous compared to other Oregon beach stumps with respect to its height and diameter and the absence of nearby similar stumps or paleosols. For example, stumps occurring on the beach platform at Neskowin (78 km north of Big Stump) included several dozen trees in continuous groups (Hart and

TABLE 1. Interpretation of evidence in support of two alternate provenances of Big Stump, a large *Sequoia* stump on the central Oregon coast. False positive arguments are also shown, but those in italics are considered by the authors to be of very low probability. Additional evidence based on the current context and preservation of the stump is presented in the text. Absence of a line of evidence provides no interpretation towards either hypothesis, as fossil evidence may be poorly preserved in beach cliff paleosols or lost to beach dynamics.

Evidence	True-positive interpretation	False-positive interpretation
Support for *in situ* hypothesis		
1. Historical account of organic soils in contact with the stump.	Tree is preserved in its original soil context.	False account.
2. Buried organic soils found currently in contact with roots, or an extensive root system detected, below beach sand.	Tree is preserved in its original soil context.	*Stump emplaced on an existing soil or paleosol.*
3. Stump age is similar to age of a paleosol in the adjacent beach cliff.	The stump was associated with the nearby paleosol.	*Coincidence of age of drift log and paleosol.*
4. Stump age is similar to multiple (> 2) stumps within 3 km.	Dune-building activity was regionally synchronous, creating similarly aged paleosols.	*Synchronous or near-synchronous drift-log emplacement.*
5. Stump age is similar to age of paleosols and stumps within 100 km.	Same as above.	Same as above.
6. *Sequoia* macrofossils in paleosols.	Redwood wood, needles, or cones found in buried forest soils indicates local presence.	*Sea drift of plant parts.*
7. *Sequoia* pollen found in paleosols.	Pollen is locally dispersed from nearby populations (Heusser 1998).	*Long-distance transport.*
Support for sea-drift hypothesis		
8. Stump age is similar to a reconstructed tsunami event.	Emplacement by tsunami.	Age coincidence.

Peterson 2007). There is no evidence of organic soils underlying the stump, nor is the extent of roots easily determined. However, organic soils are quickly lost after becoming exposed on eroding beaches (Hart and Peterson 2007).

An historical account of Big Stump was given by Nellie (Nona) Lenora Reynolds Strake (1877–1963). Nona Strake was the daughter of the first Euro-American to settle near Big Stump in 1883. Her oral memoir from 1959, transcribed and on file in the Lincoln County Historical Society, provides an early eyewitness account of Big Stump.

> There isn't much left of the "Big Stump". It stands well out from the fluff [sic] near three miles south of Waldport. Then [sic] we lived there it was a really big stump. It is redwood and was standing in its own original soil—a thick black muck that used to be covered sometimes by the heavy surf when the gray sand was washed out. There are many places along our beach that are underlaid by this same muck and there are old logs and stumps and roots partly petrified imbedded [sic] in it. My brother and I used to climb the big stump and look down inside—for it was hollow and partly filled with shells. My folks asked the Indians why the shells. They said that it had always been a rule that when an Alsea Indian went to Yachats or one of the Yachats tribe went to the bay they always threw in a shell when they passed—sort of a tollgate. They also said that their ancestors remembered seeing the old stump emerge from the bluff—by erosion, of course. So all this sandstone and top soil was laid down on top of an ancient redwood forest. It shows also, how out [sic] coast line is receding.

Nona Strake's first-hand account of organic soils directly associated with Big Stump provides support for an *in situ* origin. The description of the peaty paleosol is similar to other paleosols that we observed in the area, and it is reasonable to expect that all paleosols were eroded by wave action, leaving the stump in place. She also provides a third-hand account that the stump had emerged out of the receding beach cliff. This is also consistent with the 60-m distance from the existing beach cliff and the history of past subsidence related to subduction zone earthquakes (Nelson et al. 2006). Nona Strake told the account at age

82, recalling an observation from her youth. As with such eyewitness accounts, definitive proof requires additional evidence.

Photos from 1912 and ca. 1920 indicate that there were many fine splinters and little erosion on the top of Big Stump, consistent with the account that the stump was recently exposed (Figure 2). Big Stump and other nearby stumps are frequently buried and re-excavated as sand depth changes seasonally and on longer time scales (Figure 3). Over the past 100 years there has been much erosion of the upper 1.5 m of the stump (Figure 2). Differences in the degree of weathering and the presence of very little weathering of the wood near the stump base (determined from examining growth rings on small cross-section samples) suggest that the lower 2 m of the stump was often under sand. Two increment cores taken near the base of the tree indicated intact wood over the entire length of the 38 cm core. The longer core contained 141 rings with a mean ring width of 2.73 mm ± 1.3 mm, including two periods of suppression (< 0.8 mm) and one ring of deformed cells suggesting frost damage. There is little indication of past colonization by barnacles, as occurs on other stumps within the tidal zone (Hart and Peterson 2007).

Methods

To assess the potential of extensive roots or buried paleosols, we obtained ground-penetrating-radar (GPR) scans of the beach sands directly adjacent to the stump (GPRData Inc., Eugene, OR). Salt water can significantly attenuate radar data in near-surface environments owing to its high conductivity, although there is precedence for using GPR in a near-shore environments having significant fresh water contributions (Baker et al. 1997, Tronicke et al. 1999). To minimize the presence of salt water, we conducted the survey during a minus tide (-0.8 ft) on the evening of 19 February 2008. A SIR-20 GPR system with a 400 MHz ground-coupled antenna was used to collect line scans to a maximum range of 50 nS. The four line-scans were obtained in the cardinal directions, each about 10 m in length and positioned 1 m from the stump. The GPR data were processed following methods of (Butnor et al. 2003) to detect tree roots, including normalization and Hilbert transformation to emphasize hyperbolic reflectors (such as roots or remnant soil horizons). We also attempted to reach a potential buried paleosol 2 m SE of Big Stump using a hand-operated bucket auger during low tide. We were able to penetrate ca. 1.5 m of beach sand before collapsing sand prevented augering to greater depths.

We obtained two accelerator mass spectrometry radiocarbon dates on opposite sides of Big Stump. Dates were obtained on unweathered wood (representing the last years of growth) determined by viewing growth rings that were parallel to the exterior surface. We considered the possibility that algal growth on the wood could have introduced modern levels of radiocarbon into our sample. As a result, one age was obtained on a cellulose extraction (analysis performed by Beta Analytic, Miami, FL).

We obtained additional radiocarbon dates to assess whether the age of the stump is similar to the age of a paleosol in the adjacent beach cliff. Paleosol BSP-A is a 30-cm sandy A horizon in a beach cliff 65 m ESE of Big Stump. This paleosol sits under ca. 1 m of soft Holocene sands and atop a thick dense iron-cemented sand of Pleistocene age (Peterson et al. 2007). After cleaning the cliff face, we sampled a single large piece of wood charcoal for radiocarbon dating.

Radiocarbon dates were obtained on the outermost wood of additional upright beach stumps located nearby, each identified using microscopic wood anatomical features (Figure 4; Hoadley 1990). WA-1 is another redwood stump located 380 m S of Big Stump. It is ca. 45 cm in diameter, cut off at 1 m above sand level (root depth is not evident) and has uneroded bark suggesting recent age or very good preservation. WA-2 is a Douglas-fir stump located 2.01 km S of Big Stump. It is 1.47 m in diameter at its widest point, 1.44 m in height above the beach (in July 2012), and highly eroded and burnt above ground. The outermost wood was sampled from a root 82 cm below the sand surface. WA-3 is another Douglas-fir stump located 1.0 km N of Big Stump. It is 1.30 m in diameter, 0.3 m in height above sand (in July 2012),

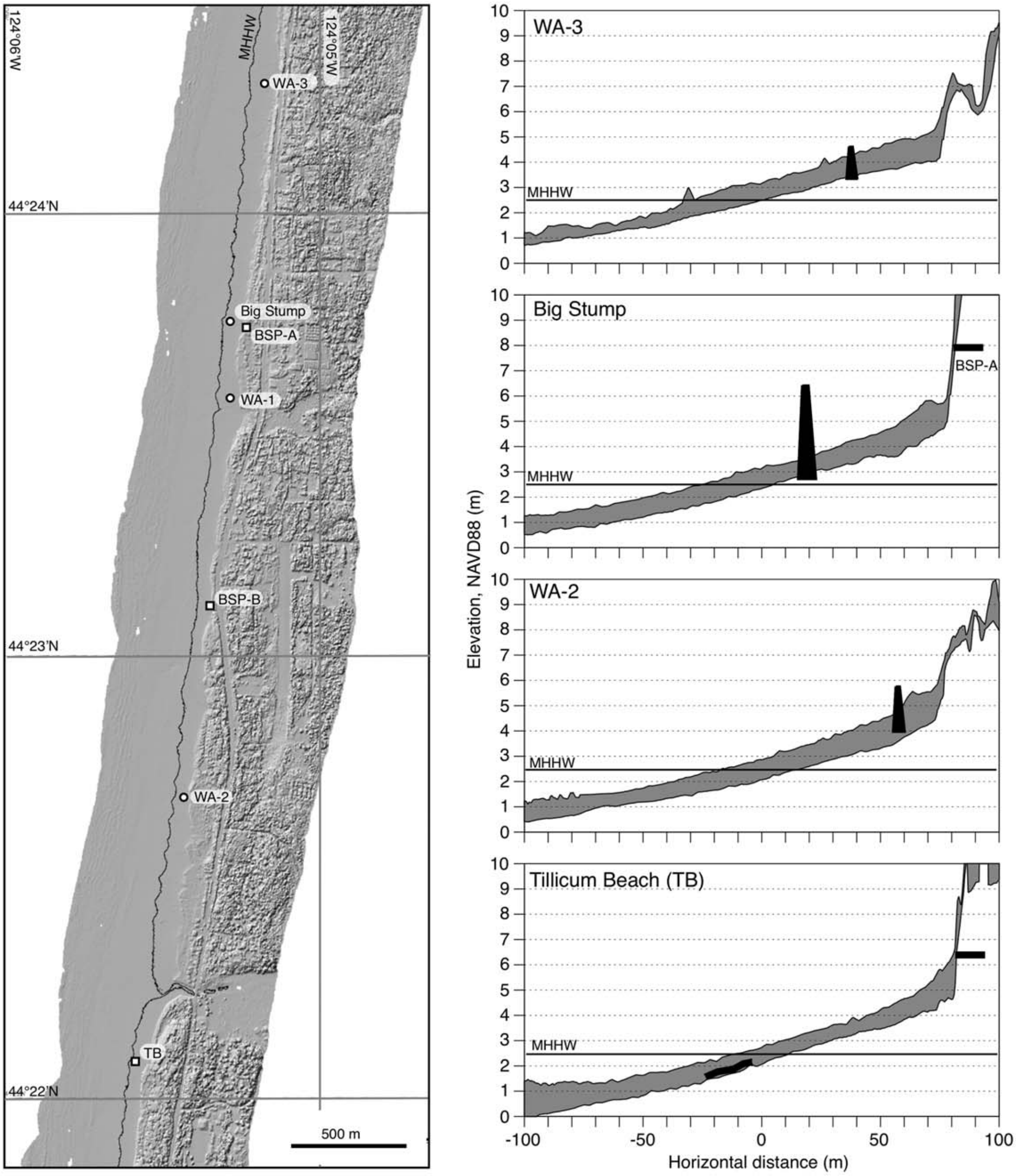

Figure 3. (Left) Shaded relief map of the coastal area indicating the location of the mean high-high water level (MHHW) in 2002, and the location of studied stumps (circles) and paleosols (squares). (Right) Elevational profiles of the beach on transects where stumps were sampled. The gray area is the area between the highest and lowest measured elevations among four LIDAR scenes (October 1997, April 1998, September 2002, and July 2009). For all profiles, the upper line is the elevation in 1997 and the lower line is the elevation in 2002 or 2009. Stump locations are shown by triangular shapes, showing the full height of the stump as measured in the field. Paleosols are shown by thick black lines. Data obtained from NOAA Digital Coast (National Oceanic and Atmospheric Administration 2012).

Figure 4. Additional stumps and paleosols dated in this study. Locations are shown in Figure 3.

and is also heavily eroded. The outermost wood was sampled from a root 80 cm below sand level.

We searched for redwood macrofossils in a large extensive fossil-rich peaty sediment and soil (paleosol TB) from Tillicum Beach 3.13 km south of Big Stump. This paleosol contained abundant logs and twigs when it was exposed on the beach during the winter of 2007/2008. Additional *in situ* stumps < 0.5 m in height were exposed 200 m north of TB. We dated the outermost tree rings of a large log (identified as *Picea*) embedded within this paleosol.

Pollen analysis was conducted on three paleosols. First, a 2-cm^3 sample was taken from the upper-most organic matter of paleosol BSP-A, described above. Second, a similar sample was taken from paleosol BSP-B, another 30-cm thick A horizon under about 1.5 m of sand and exposed on a beach cliff located 1.22 km S of Big Stump. Third, a 1-cm^3 sample was taken from within a peaty section of paleosol TB, described above. We used standard pollen processing methods (Faegri and Iversen 2000) with the addition of an additional HF treatment on the sandy Big Stump paleosol samples. Approximately 200 pollen

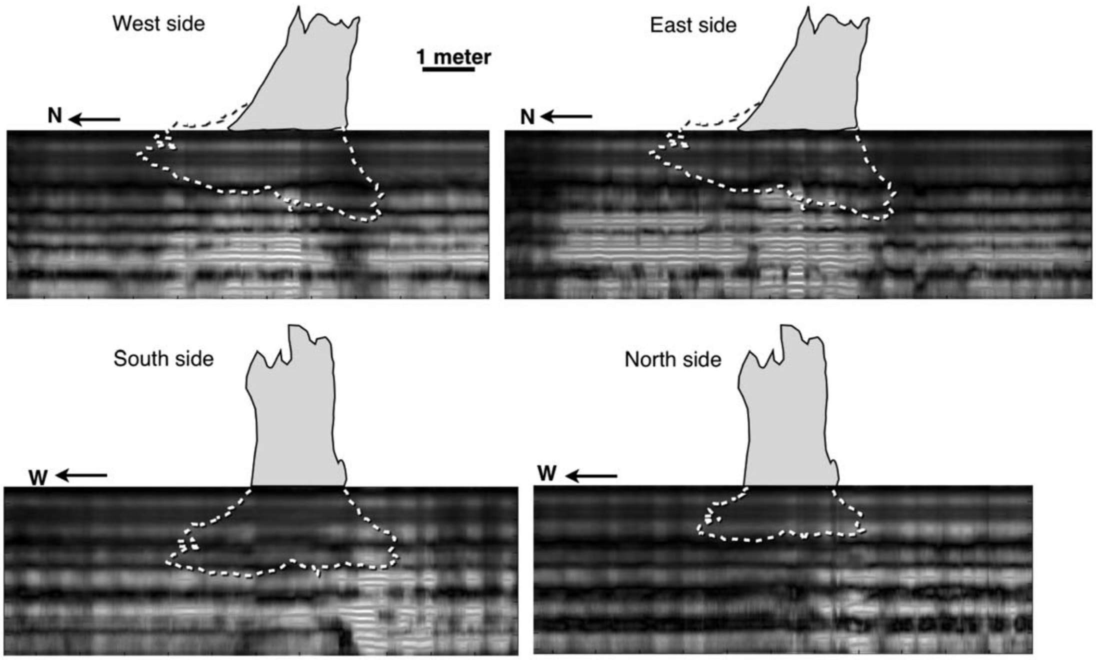

Figure 5. Ground-penetrating radar cross-sectional scans taken in four cardinal directions next to Big Stump. Each cross-sectional scan was placed ca. 2 m in front of the outside of the stump. The data were transformed using a Hilbert filter to emphasize zones of high variability in the dielectric signal. The dashed line shows the estimated size of the rootwad based on photographs of similarly sized *Sequoia* drift logs. The grayscale values reflect dimensionless variations in electromagnetic energy and thus represent relative variation in the signal magnitude (increasing from black to white). Parallel bands reflect bands of low-frequency noise and the effect of the ground surface acting as a plane reflector (Butnor et al. 2003).

grains were identified in each sample. Four wood samples from Tillicum Beach were identified based on microscopic anatomical features following Hoadley (1990).

Last, we compared the age of Big Stump to the ages of *in situ* stumps and paleosols dated over the entire Oregon coast as described in Hart and Peterson (2007). We also compared the age of Big Stump with reconstructed paleoseismic and tsunami history from the Oregon coast (Kelsey et al. 2005, Nelson et al. 2006, Goldfinger et al. 2012).

Results

The profiles generated from the GPR scans indicate large variations in magnetic response, as detected by the Hilbert transform, at depths > 3 m (light areas in Figure 5). These variations in magnetic response likely result from paleosurfaces or roots, and they would not be detectable had salt-water intrusion affected the signal (Figure 5). The GPR data reveal a strong magnetic response in patchy zones below a relatively consistent depth of 2-3 m in each of the scans. This suggests a prominent contrast in dielectric properties of the substrate at depths below the presumed rooting zone of Big Stump. The strong magnetic response is consistent with a contrast in sediment porosity (via changes in sediment composition, grain size, shape, orientation and packing) as well as the presence of pedogenic oxide minerals that may be inherited from paleosols (Neal 2004). Importantly, these strong magnetic signatures are not continuous beneath Big Stump, which is inconsistent with an extensive root network emanating laterally away from or directly below Big Stump. Rather, it suggests a more complex substrate underlying Big Stump.

The two radiocarbon dates from Big Stump were nearly identical, and the cellulose-based

TABLE 2. Accelerator mass spectrometry radiocarbon dates obtained from Big Stump, three additional stumps, and two paleosols, south of Waldport, Oregon.

Sample	Location	Lab code[1]	Material dated	Radiocarbon age[2]	Calibrated age (cal yr BP)[3]
Big Stump	44° 23.7602' N 124° 5.2779' W	OS-65934	*Sequoia* wood (outermost 4 yr)	1830 ± 30	1700 (1730,1810) 1860
Big Stump		Beta-242046	*Sequoia* wood (outermost 4 yr, cellulose extraction)	1840 ± 40	1640 (1720,1820) 1870
Stump WA-1	44° 23.5842' N 124° 5.2836' W	Beta-242045	*Sequoia* wood (outermost 3 yr)	129.7 ± 0.6 pMC	1978 – 1980 AD
Stump WA-2	44° 22.6782' N 124° 5.4282' W	CAMS-158569	*Pseudotsuga* wood (outermost 5 yr)	120 ± 30	10 (20, 260) 270
Stump WA-3	44° 24.2932' N 124° 5.1673' W	CAMS-158570	*Pseudotsuga* wood (outermost 5 yr)	90 ± 30	0 (30, 250) 260
Paleosol BSP-A	44° 23.7390' N 124° 5.2380' W	CAMS-151602	Charcoal (1 piece)	625 ± 30	550 (560,650) 660
Paleosol TB01WA	44° 22.086' N 124° 05.583' W	CAMS-158568	*Picea* wood (outermost 5 yr)	3475 ± 30	3640 (3690, 3830) 3840

[1] Lab codes: OS=Woods Hole National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) Laboratory; CAMS=Lawrence Livermore Center for Accelerator Mass Spectrometry; Beta=Beta Analytic, Miami FL.

[2] All ages are years BP except Stump WA-1 which indicates a post-0 BP age and is reported as percent of the modern reference standard.

[3] Calibrated ages are based on the INTCAL09 calibration curve (Reimer et al. 2009) except for Stump WA-1 and Stump WA-2, based on the Bomb04NH1 calibration curve (Hua and Barbetti 2004). Calibrated age ranges (in years before AD 1950) are given as -2σ (-1σ,+1σ) +2σ, representing the outermost age limits if the calibrated age includes multiple age ranges. Stump WA-1 is reported in years AD.

date calibrated to a 1σ error of 1820–1720 cal yr BP (calendar years before present; Table 2). The nearby redwood stump (WA-1) had an age containing 'bomb' (post-1950) levels of radiocarbon, and calibrated to ca. 1979 AD. The other two Douglas-fir stumps both had radiocarbon ages that place them older than 1950 AD but overlapping with the historical period.

The radiocarbon age of the charcoal in the paleosol proximal to Big Stump (BSP-A) calibrated to 650–550 cal yr BP, and is thus 1100 years younger than the death-date of Big Stump. In contrast, the paleosol south of Big Stump (TB01) has a calibrated age of 3840-3640 cal yr BP, and is thus 2000 years older than the death-date of Big Stump.

Pollen in all three paleosols was abundant, but it was poorly preserved in the two beach-cliff paleosols (Table 3). BSP-A, located near Big Stump, was composed mainly of pine (*Pinus*), alder (*Alnus*), and western hemlock (*Tsuga heterophylla*) pollen. BSP-B was composed of pine, alder, western hemlock, waxmyrtle (*Myrica*), and heath family (Ericaceae) pollen. TB, the peaty paleosol from Tillicum Beach, was composed mainly of alder, pine, and western hemlock. The four wood samples from the TB paleosol were identified as redcedar (*Thuja*) (2), hemlock (*Tsuga*), and spruce (*Picea*).

The age of Big Stump falls within the range of previously dated *in situ* subfossil stumps from Oregon beaches (Figure 6). The age is statistically indistinguishable from stumps at Lincoln Beach (50 km away) and Neskowin (78 km away; Hart and Peterson 2004). In addition, the paleosol TB01 is similar in age to several paleosols and stumps located north of Big Stump.

TABLE 3. Pollen percentages from three paleosols near Big Stump, calculated as a percentage of the sum of all terrestrial pollen types. BSP-A and BSP-B are beach-cliff paleosols located 65 m and 1.22 km from Big Stump, respectively. TB is a paleosol on the shore platform at Tillicum Beach, 3.13 km S of Big Stump.

	Paleosol		
Pollen taxa	BSP-A	BSP-G	TB
Alnus	14.6	29.9	47.0
Asteraceae	1.0	0.6	0.6
Cupressaceae	1.0	0.0	4.2
Cyperaceae	0.5	0.0	1.8
Ericaceae	1.0	17.1	0.0
Myrica	1.0	11.6	1.8
Nuphar	0.0	0.0	3.0
Picea	7.1	6.1	11.3
Pinus	56.6	13.4	7.1
Poaceae	2.5	0.0	0.0
Pseudotsuga	0.0	1.2	6.0
Salix	0.0	0.6	0.6
Tsuga heterophylla	14.6	19.5	16.7
Pteridophyta spores			
Monolete	52.0	6.1	17.4
Trilete	0.0	10.4	1.2
Pollen concentration (grains cm^{-3})	56,400	187,000	76,600

Discussion

Very strong support for an *in situ* position of Big Stump would have been additional evidence of local redwood populations in the form of pollen or macrofossils in a soil context and hence very likely to be locally derived, or evidence that Big Stump is still rooted in remnants of organic soil. While neither of these lines of evidence could be supported, fossil absence is rarely justification to claim a real absence of a species (e.g., McLachlan and Clark 2004). Thus, we are required to build arguments on more indirect lines of evidence. We discuss our findings and show that, between the competing hypotheses (*in situ* or sea drift origin), an *in situ* origin is most congruent with the complement of information on the history of Big Stump.

We found no additional evidence of local redwood populations in paleosols and sediments near Big Stump. Rather, the pollen spectra, dominated by regionally dispersed pollen types (alder and pine) and locally dispersed shrub pollen (heath family and waxmyrtle), suggest a wetland environment along the Oregon coast. The few existing palynological studies on the Oregon coast make no mention of redwood pollen. No redwood pollen was detected in a 7000-year pollen record from Woahink Lake near Florence, OR (Kusler 2012) and a 4600-year pollen record from Taylor Lake near Astoria, OR (Long and Whitlock 2002). Despite the abundance of dune-dammed lakes along the central and southern Oregon coast, the only other pollen stratigraphic studies from this area are coarsely sampled peat profiles by pioneering palynologists Henry P. Hansen (Hansen 1941, 1943; Hansen and Allison 1942) and Calvin J. Heusser (Heusser 1960). Neither author reported Cupressaceae family (the family that contains redwood and redcedar, the latter of which is abundant in the region) pollen in their results, nor did they acknowledge that redwood pollen is distinguishable from the remainder of the Cupressaceae.

The beach-cliff paleosol near Big Stump is much younger than the stump, and sits atop what appears to be much older cemented sand, most likely of Pleistocene age (Peterson et al. 2007). According to the model presented in Hart and Peterson (2007), stumps that emerge on the shore platform are sometimes associated with a paleosol in the truncated dune revealed in the neighboring beach cliff. Although no such paleosol was found at Big Stump beach, several factors may account for this. There may have been sufficient beach sand to bury a stump but not enough to build a dune ramp. Alternatively, a dune ramp can erode away during a severe winter, but the stump remains buried under beach sand. For example, the paleosol at Tillicum Beach, 2000 years older than Big Stump (Table 2), is very discontinuous in the adjacent beach cliff.

We confirmed that GPR can image structures several meters under sand in near-shore environments, likely due to the combined effect of high winter runoff and the timing of the survey at a very low tide, both of which limited salt-water intrusion. Importantly, the GPR scans did not reveal extensive roots or a paleosol at depths expected for a paleosol related to Big Stump. Rather, the

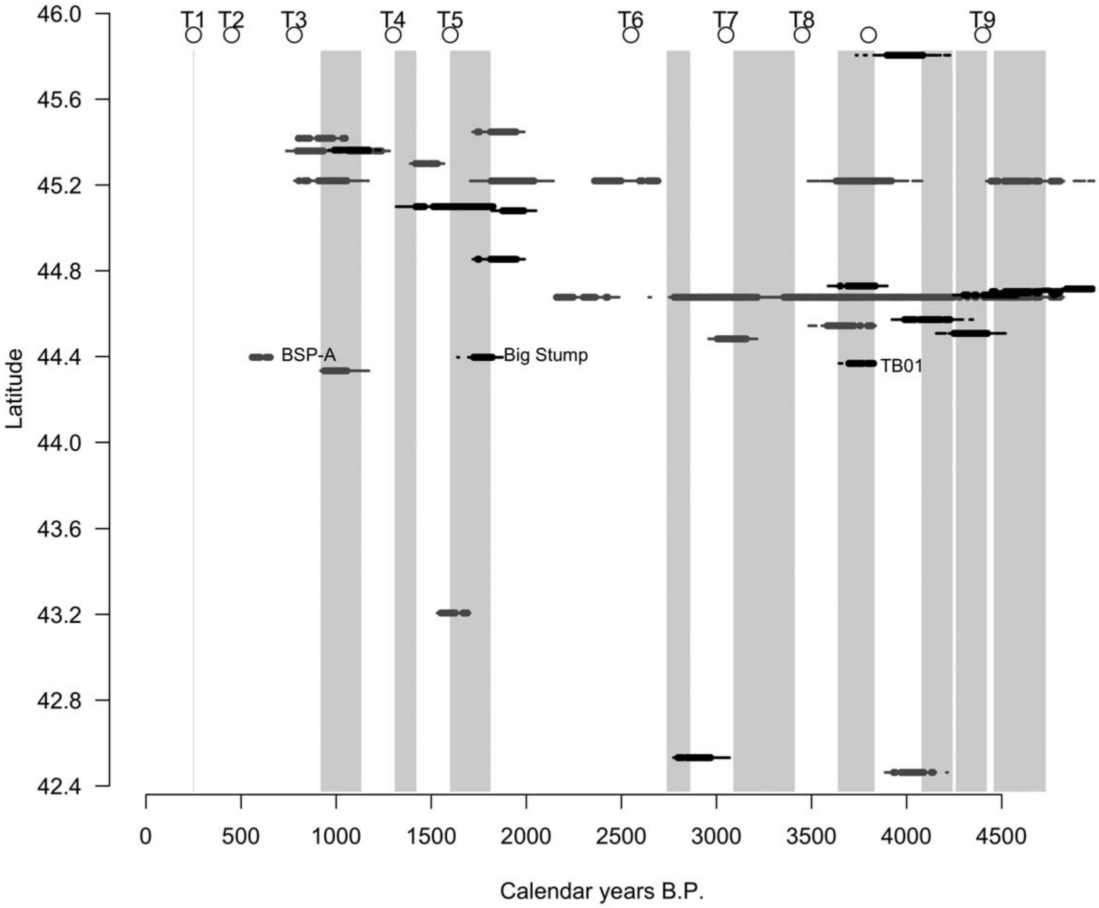

Figure 6. Calibrated radiocarbon ages of *in situ* stumps (solid bars) and beach-cliff paleosols (gray bars) along the Oregon coast. Data are from Hart and Peterson (2007) except for the labeled ages of Big Stump and the proximal paleosols. Vertical shaded bars are age ranges of radiocarbon-dated tsunamis determined from sediment cores from Bradley Lake (Figure 1, Kelsey et al. 2005). Cascadia subduction events, determined by multiple sources, are labeled T1-T9 (Nelson et al. 2006, Goldfinger et al. 2012).

structure we detected is consistent with changes in soil porosity and presence of iron oxides of an old soil or sand surface (Neal 2004). However, this surface is much deeper (> 3 m) than would be expected for a paleosol associated with Big Stump. The surface is discontinuous, perhaps indicating that it was eroded or dissected.

Despite the lack of additional redwood subfossil material in our limited search of paleosols or evidence of organic soil associated with the stump as observed by Nona Strake (see Introduction), the age of the stump provides support for the *in situ* hypothesis. The age of Big Stump (1820–1720 cal yr BP) is similar to other Holocene paleosols and stumps from Oregon beaches. This indicates the age is sufficient to allow for all the steps of burial and re-appearance. The age of Big Stump is coeval with *in situ* beach stumps at Lincoln Beach (50 km north) and Neskowin (78 km north) and with paleosols at three additional sites (Figure 6, Hart and Peterson 2007). Considering that dune building and changes in beach extent (and forest burial) are controlled by changes in sea level and climate, a regional similarity of ages of buried forest is to be expected. Such synchrony can be seen across the entire set of dates from the Oregon coast, with two main clusters of ages at 4200 and 1700 cal yr BP (Figure 6).

We explored the alternative hypothesis of a sea-drift origin. Any drift log hypothesis must explain its upright position and its remarkable preservation for almost two millennia since death (i.e., fresh-appearing splinters in a photo from 1912; Figure 2). Therefore, we compared the age of Big Stump to the paleoseismic and tsunami history developed from the Oregon coast. Records of large earthquakes are recorded in relative sea-level changes in the Alsea estuary (Nelson et al. 2006), in off-shore turbidites (Goldfinger et al. 2012), and a record of tsunami deposits from Bradley Lake (Figure 1; Kelsey et al. 2005). This comparison reveals that the death-date of Big Stump precedes a major earthquake event (T5) by less than 150 years. The T5 earthquake was likely of similar magnitude to the 1700 AD earthquake that was triggered by a major rupture of the Cascadia subduction zone (Nelson et al. 2006). The Bradley Lake sediment record indicates two tsunami events at this time separated by 22 lake-sediment laminations, which are likely annual (Kelsey et al. 2005).

We propose the following series of events are required to support a sea-drift origin. First, following its demise, the stump was transported to the ocean possibly over a period of decades; coarse woody debris may remain in rivers for centuries. Second, the stump was beached a short time later near its current location. Third, a large tsunami, or possibly a very high storm surge, lifted the stump and deposited in its current, near upright, position. It is common for stumps with large root masses to float upright in the ocean (so-called dead heads). Fourth, aggrading beach sands and dunal activity subsequently buried the entire stump, preserving the fresh broken surface that was visible in the 1912 photograph (Figure 2). Finally, the stump was exposed on the shore platform where winter storms and/or shifts in littoral drift patterns could excavate sands and expose much of the full height of the stump. The 1700 AD earthquake resulted in subsidence of up to 0.5 m in the Waldport region (Hawkes et al. 2011), which could have promoted beach recession.

Our investigation of three other shorter upright stumps within 2 km of Big Stump casts doubt on a sea-drift origin. All three stumps dated to within the historical period and may have originated from land clearance and casting of stumps into rivers of the Oregon Coast Range. The two Douglas-fir stumps were highly degraded in less than 100 years. The stumps all had greater widths of the root mass than their overall height, resulting in their upright deposition. The redwood stump (WA-1) that dated to only 1979 AD may have been planted nearby, cut, uprooted and deposited on the beach within the last 100 years. The rapid erosion of wood in these other stumps suggests it would be highly unlikely for Big Stump to have been transported down a stream channel to the ocean, floated northward hundreds of km, deposited in an upright position, and then buried by sands, all before the wood was eroded. Redwood wood weathered at a rate of 75μm/year over a 16-year trial in Wisconsin (Williams et al. 2001); the erosion rate should be much greater when adding the effects of abrasion by windblown sand. Furthermore, we believe it is very unlikely that a large tree could snap as shown in the 1912 photo after becoming uprooted, unless it snapped upon impacting the ground. In support of this is our observation that large drift logs that have an attached rootwad tend to be very long (> 10 m) unless they originated by logging. The potential origin of Big Stump, with a top snapped at 4-m above ground, is more parsimoniously explained if the tree snapped in its current position and was buried shortly thereafter.

Conclusions

We found that the age of a large upright coast redwood stump on the shore platform near Waldport Oregon (1820–1720 cal yr BP) is very similar to the reported ages of *in situ* beach stumps at two sites to the north. Its very good preservation is consistent with an historical account of the stump associated with a paleosol that has since been eroded. However, we failed to obtain strong support via additional fossil or paleosol evidence of redwood populations. The alternative hypothesis, that the stump was deposited in an upright position in a tsunami or storm, is difficult to support. We are not aware of similarly tall, upright, emplaced stumps. Therefore, the balance of evidence suggests that Big Stump represents a late Holocene disjunct population of redwood.

Providing very strong support for the existence of central Oregon redwood will require detailed paleoecological studies or, possibly, novel methods using ancient DNA. An abundance of lakes and paleosols along the coast provides ample opportunity to study the biogeographic history of the coastal environment.

A recent extinction of redwood on the Oregon coast raises important questions about the conservation of this species under climate change. How extensive was the disjunction, for how long did it exist, and what conditions led to its demise? Was the local extinction the result of decreasing minimum temperature, or decreasing fog, during the late Holocene? Or was a small population exterminated by coseismic subsidence and burial by beach deposits? Ongoing climate change within the range of redwood may eventually affect its growth, jeopardize southern populations, and invoke a need to assist its migration northward (Douhovnikoff and Dodd 2010, Johnstone and Dawson 2010). Evidence of a recent natural disjunction, as presented here, provides a precedent for redwood as a component of central Oregon coastal ecosystems. This precedent could be used in the future to help justify a plan for assisted migration and extension of the northern limit of redwood.

Acknowledgements

We thank Cris Piccioni for chemical processing of the pollen samples. We thank the manager of Cape Cod Cottages, Waldport for providing the scan of the 1920 photograph of Big Stump and the Waldport Museum for providing the scan of the 1912 photograph. We thank Tom Brown at Lawrence Livermore National Laboratory for assistance with radiocarbon dating. The manuscript was greatly improved by comments from Curt Peterson and Patrick Pringle.

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Received 1 April 2012
Accepted for publication 12 December 2012

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