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Earthquake effects surveyed during the nineteenth century as ecological features of Chinookan tidelands

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Abstract

Lasting effects of a Cascadia earthquake in 1700 were documented during surveys of Chinookan tidelands near the mouth of the Columbia River between 1805 and 1868. The effects resemble estuarine consequences, near Anchorage, of the 1964 Alaska earthquake: fatal drowning of subsided meadows and forests by post-earthquake tides, rebirth of marshes and forests through post-earthquake sedimentation and uplift. Chinookan remains of killed forests were recorded by James Graham Cooper, John J. Lowell, and Cleveland Rockwell. Cooper, attached to a railroad survey and the Smithsonian Institution, wrote of redcedar stumps and trunks standing dead in tidal marshes of Shoalwater (now Willapa) Bay. Two such snags served as bearing trees for Lowell as he platted a Shoalwater Bay township under contract with the General Land Office. Rockwell, of the U. S. Coast Survey, flecked landward edges of tidal flats west of Astoria with symbols that evoke remains of a bygone spruce forest. The Lewis and Clark Expedition, while in that area in 1805–1806, mapped and puzzled over tideland vegetation that post-1700 succession helps explain.

Keywords: earthquake, western redcedar, Sitka spruce, historical ecology

Introduction

The plate-tectonics revolution of the 1960s fostered modern views of Northwest earthquake and tsunami hazards. The Cascadia Subduction Zone, where an oceanic plate descends beneath the continental margin from southern British Columbia to northern California (Figure 1), is recognized today as a source of very large earthquakes and attending tsunamis (Thompson 2011, Doughton 2013, Henderson 2014, Walton et al. 2021). Their geological traces correspond to accounts of shaking and flooding that Native peoples experienced a few centuries ago (Ludwin et al. 2005, Thrush and Ludwin 2007). In that era, a Cascadia tsunami encountered remains of a Manila galleon that had been wrecked on the Oregon coast in 1693 or 1694 (La Follette et al. 2018), and a Pacific Ocean tsunami of remote origin caused documented flooding in Japan that dates a parent earthquake in Cascadia to 26 January 1700 (Satake et al. 1996, 2003, Atwater et al. 2015).

From this modern perspective, ecological effects of a 1700 Cascadia earthquake can be spotted in field notes, reports, and maps from nineteenth-century surveys of Chinookan tidelands of the Columbia River and Shoalwater Bay. The surveys encountered subfossil trees and vegetated wetlands that resemble Anchorage-area effects of the 1964 Alaska earthquake, and which can be ascribed today to land-level change and ecological succession (Figure 2).

Earthquake cycles and their ecological effects

Subduction can change land levels in cycles (Plafker 1969:64–66, Thatcher 1984). Two tectonic plates, one descending beneath the other, are stuck together on a shallow part of the plate-boundary fault, toward which the two plates are moving slowly (Figure 2f). The overriding plate bulges behind this part of the fault. During an earthquake, the bulge collapses as fault rupture allows the leading edge of the plate to lurch seaward. The bulge forms anew in a deformation cycle that repeats. The cycle follows the elastic rebound theory, originally proposed to explain horizontal displacement in the 1906 San Francisco earthquake (Reid 1910:17–26).

Lowland trees may record subduction ups and downs. In general terms, a forest may colonize emerging tidelands between earthquakes, and the trees may die from tidal submergence soon after the land falls during an earthquake (Figures 2a–2e). In detail these effects vary with salinity, tree species, and sedimentation rate. Raising tidelands between earthquakes helps forests spread downstream along salinity gradients. Conversely, lowering land during an earthquake raises salinity in a tidal stream by enlarging the tidal prism that the stream dilutes. Differential decay allows growth-position remains of one tree species to outlast those of another. Stumps and roots persist most reliably where soon buried by tidal deposits. Tidal deposition, by rebuilding land, hastens the establishment of new trees among or above the remains of drowned ones—first in freshwater tidelands, later downstream where brackish marshes emerge through gradual tectonic uplift.

The examples reviewed below include two new findings about tree death from tidal submergence after the 1964 Alaska earthquake. New radiocarbon ages confirm that a victim-spruce root put on its final complete ring during the last of the pre-earthquake growing seasons, while earlywood outside that ring shows that the root briefly lived on.

1964 Alaska earthquake

Subduction warped south-central Alaska during an earthquake of magnitude 9.2 on 27 March 1964. Plafker (1969) mapped a mainly offshore zone of uplift flanked by a mostly onshore downwarp, each more than 700 km long (Figure 1a). He concluded that tens of meters of regional displacement on a gently landward-dipping fault had raised areas above the fault rupture while stretching areas behind it—extension that downwarped land by as much as 2.3 m (Figure 2f). Low-angle faulting on this grand scale, like plate tectonics itself, had yet to be named in 1964. But "subduction" would soon denote the descent of one tectonic plate beneath another (White et al. 1970, Dickinson 1971).

Lowlands at Portage, outside of Anchorage, displayed estuarine effects of the 1964 downwarp. There the much of the land dropped 2 m in all—1.5 m by tectonic deformation, and another 0.5 m by local settlement from shaking-induced compaction. Ensuing tides drowned a town, nearby meadows, and stands of spruce (*Picea*) and cottonwood (*Populus*), while also bringing in sand and silt that built up around the decaying remains of buildings, shrubs, and trees (McCulloch and Bonilla 1970:81–85, Ovenshine et al. 1976). Since the middle 1980s, this Alaskan example of tidal death and burial from coseismic subsidence has served as a modern analog for identifying prehistoric earthquakes in Cascadia and for dating them with uncommon geological precision (Atwater et al. 2015:14–17, 24–25, 96–97, Nelson et al. 2021).

With Cascadia dating in mind, we sampled bark-bearing roots of a 1964 spruce victim near Portage (Figure 3). Its roots were exposed in 1991 in an eroding bank of the tidal Twentymile River (Figures 3a, 3b). Sanded cross-sections revealed wide growth rings and an outermost ring limited to thin-walled earlywood cells (Figures 3c, 3d). Radiocarbon ages were measured on earlywood of the last seven of the complete rings (A–G, Figures 3c, 3f). The ages track a doubling in atmospheric radiocarbon activity that took place during the decade before 1964 (Figure 3g). This doubling results from nuclear-bomb tests (Higuchi 2020), and it registered as a radiocarbon spike in annual growth rings of North American trees (Quarta et al. 2005, Lardie Gaylord et al. 2019). The graphical fit of the Portage spruce ages in Figure 3g is confirmed numerically in Table 1. The results uniquely assign the outermost complete ring (A) to 1963, while its fringe of earlywood implies post-earthquake survival into the first months of the 1964 growing season (Figures 3d and 3e).

Effects of the 1964 earthquake continued at Portage through natural ecological restoration. Tidal flats were succeeded by tidal marshes on which new spruce and cottonwood became established beside the decaying above-ground trunks of pre-earthquake trees (Bartsch-Winkler and Garrow 1982, Atwater et al. 2001). (Figure 2a). The succession was driven by initially rapid sedimentation in the 1960s and early 1970s (Ovenshine et al. 1976), and secondarily by slow uplift that has been ascribed primarily to from glacial unloading (Huang et al. 2020).

1700 Cascadia earthquake

Much as at Portage, earthquake geology in Cascadia includes remains of tidally drowned marshes and forests. Roots of Sitka spruce (*Picea sitchensis* (Bong) Carrière) and trunks of western redcedar (*Thuja plicata* Donn. ex D. Don) are particularly abundant at Copalis River, Grays Harbor, and Willapa Bay in Washington, and along the lower Columbia River in Washington and Oregon (Figures 4a–4c). Both species live today in tidal wetlands of the mainly freshwater reaches of these estuaries (Franklin and Dyrness 1973:295, Benson et al. 2001, Johnson and Simenstad 2015). There, tidal forests are dominated by spruce but locally contain redcedar—on fallen logs and natural levees, and at transitions to floodplains.

Trees dead and living contributed to dating of the most recent great Cascadia earthquake along the southern Washington coast. Radiocarbon analyses of subfossil spruce roots bracket this earthquake between 1680 and 1720 C.E. (Atwater et al. 1991, Nelson et al. 1995). Among eight of the subfossil redcedar dated by ring-width pattern matching in southern coastal Washington, roots of seven died in the dormant months of 1699–1700; in a discrepant eighth, a root draped on a log lived into 1708 (Figures 2b, 4b; Yamaguchi et al. 1997). Narrow rings attest to stress during the first decade after 1700 in living tideland old-growth—in spruce with heavy limbs and wind-broken tops at three of the estuaries, and in one redcedar along the Columbia River at Blind Slough, (Figures 2e, 4d; Jacoby et al. 1997). Tidal forests of all four estuaries were almost entirely reborn after 1700, as judged from ring counts in 146 additional living spruce (Figure 2d; Benson et al. 2001, Atwater 2020: table 15). All this evidence is consistent with 26 January 1700 as the date when the Cascadia plate boundary ruptured along its entire 1,100-km length in one giant earthquake or in part of a swift series of lesser shocks (Satake et al. 2003, Melgar 2021).

Although trees died effects of dormant-season subsidence in Cascadia, many likely managed to continue growing at first, much like the Portage tree in Figure 3. An incomplete outermost ring fringes roots of six out of ten subfossil spruce stumps sampled from tidal banks of the Copalis River and Willapa Bay (Atwater and Yamaguchi 1991: example in their Fig. 3B), and spruce-root death from post-earthquake tides at Humboldt Bay, California, ranged across four years (Jacoby et al. 1995). Already tolerant of brackish water, Sitka spruce may at first resist saltwater poisoning because, in winter, Northwest conifers are at maximum water storage and are taking up little soil water (Waring and Franklin 1979: their Figures 3 and 5). Although saltwater can kill Sitka spruce (Wang et al. 2019), a tree may initially respond to saltwater stress much as it would to drought (Tucker and Pearl 2021), and physiological responses to drought include resource allocation to roots (Gessler et al. 2017). There is a remote possibility that earlywood instead records a wet autumn after months of summer drought—a growth pattern that has been observed in coastal pines (Vieira et al. 2015: their Fig. 2).

Indigenous science of Willapa Bay and the lower Columbia River surely would have mentioned, during the 1700s, landscape changes from post-earthquake tides. Travel by canoe among persistent ghost forests, such as the dead redcedar grove in Figure 5, would have reinforced Chinookan counterparts to a Yurok (northern California) story in which Earthquake, having lowered prairie into the sea, exclaims “Yaha! The brush sticks out" (Kroeber 1976:460, Carver 1998:18). In addition, oral history may have identified pre-earthquake landmarks that post-earthquake tides drowned, such as riparian camps and fish weirs at Willapa Bay (Cole et al. 1996, Atwater and Hemphill-Haley 1997:32, 76, Losey 2010). Although no 1700 earthquake or tsunami is evident among published Chinookan stories, nnearly all those stories were collected in 1890 or later (Boas 1894, Ray 1938, Gibbs [1865] 1955, [1865] 1956, Jacobs 1959, 1962:94–95, Hymes and Seaburg 2013)—after epidemics that reduced Native populations along the lower Columbia River to roughly 10 percent of their pre-1774 numbers (Boyd 1999: Tables 3, 15–17).

Nineteenth-century surveys

This epidemic era overlapped with early documentation of earthquake evidence as attributes of Chinookan tidelands. The Lewis and Clark Expedition, in 1805–1806, noted vegetation patterns that can be tied today to post-earthquake succession; later surveys, in 1854–1868, recorded upright remains of killed trees in tidal marshes and tidal flats. In each instance, mandates unrelated to earthquakes led to observations that can now be tied to seismology.

Presidential directives and national claims

A well-known letter from Thomas Jefferson (1803) set scientific objectives for the Lewis and Clark Expedition. These aligned with the President’s personal scientific interests (Cutright [1969] 2003:2–9) and, more fundamentally, with a drive to expand the United States westward (Goetzmann 1966:3–6). The young nation was then vying with Spain, Russia, and Great Britain over territorial rights to the Pacific Northwest. Under legal traditions deeply rooted in Europe (Williams 1990), the American claim rested on Robert Gray’s 1792 nominal discovery of the mouth of the Columbia River.

The Lewis and Clark Expedition went beyond Gray’s discovery through acts of possession—not just by building and occupying Fort Clatsop (Figure 6), but also by making scientific observations in its vicinity (Miller 2006:3, 111–112), and by recording them throughly in maps (Clark 1806) and journals (Lewis et al. [1803–1806] 2005). Cited below, in relation to Cascadia earthquake history, are Expedition findings about tidal wetlands and Sitka spruce.

Transcontinental rails and museum collections

The United States Congress, in 1853, funded assessments of four competing swaths for the nation’s first transcontinental railroad. The competition was to hinge in part on natural resources the four surveys encountered (Goetzmann 1959:262–275). A northern survey, from Minnesota to Puget Sound, was led enthusiastically by Issac Ingalls Stevens (1818–1862), Washington’s first territorial governor (Richards 2016:102).

Western surveys were then providing specimens of plants, animals, and rocks to the National Museum in the Smithsonian Institution. The museum curator, Spencer Fullerton Baird (1823–1887), in 1852–1854 “was receiving materials and information from twenty-six separate expeditions” (Rivinus and Youssef 1992:85). As a naturalist for the Stevens survey, Baird recommended a young physician, James Graham Cooper (1830–1902) (Coan 1981:21).

Stevens assigned Cooper to the survey’s western division, under George McClellan.

George Gibbs, prominent in “some of the leading intellectual concerns of nineteenth century America” (Beckham 1969:viii), joined as ethnologist and geologist. The McClellan party ranged mainly east of the Cascade Range in summer and autumn of 1853, then disbanded (Overmeyer 1941).

Cooper remained in Washington Territory as a mostly self-funded naturalist into October of 1855. He based himself at Shoalwater Bay, making ends meet as a physician and storekeeper, and residing mainly in the cabin of an oysterman, Charles Russell (Figure 5c). Journals (Cooper 1853–1854, 1855–1856) and a manuscript (Cooper 1856) provide unpublished records his stay.

Published monographs from the four railroad surveys assembled encyclopedic descriptions of the American West (Goetzmann 1959: 336). Among them were natural-history reports that Cooper finalized in 1857–1860, largely while in Washington, D. C. (Coan 1981:10, 11, 86). There he participated in a naturalist’s club under Baird’s tutelage (Rivinus and Youssef 1992:94). The 1856 manuscript and a railroad-survey report (Cooper 1860) both tout western redcedar as a natural resource. In a quote below, as proof that its wood resists decay, Cooper cites redcedar trunks standing dead in tidal marshes of Shoalwater Bay.

Gridded townships and Indian lands

Westward expansion of the United States required land grids to which settlers’ claims and purchases could be tied. The grids established in Washington Territory were surveyed by contractors to the General Land Office (White 1983, Riddle 2010). The GLO instructed contractors to monument corners of sections and quarter-sections, to measure bearings and distances from corner monuments to scribed trees, and to document major changes in vegetation along section lines (Moore 1851).

John J. Lowell (1823–1856) headed contract surveys of two Shoalwater Bay townships in autumn of 1855. This was Chinookan land the United States had not purchased; treaties of 1854–1855 had recently extinguished Indian title to much of Washington Territory but not around Shoalwater Bay (Ruby and Brown 1976:224–231, Fisher and Jetté 2013). Another surveyor submitted the notes and plats (Lowell 1856a, 1856b) after Lowell, during Indian resistance, drowned as a military messenger (Olson 2018:238).

Transcribed Lowell notes cited below locate a quarter-section corner with respect to a pair of redcedar trunks in a tidal marsh. Also cited is a vegetation change by which these bearing trees lacked foliage.

Career topographer along a Northwest artery

The U. S. Coast Survey achieved eminence under Alexander Dalles Bache, its director between 1843 and 1867 (Odgers 1947). Bache himself identified a Japanese source for an 1854 tsunami recorded by California tide gauges (Bache 1856, Kusumoto et al. 2022). The agency’s early Northwest work (Vouri 2016), begun while I. I. Stevens was Bache’s deputy, included charting of Shoalwater Bay in 1852 and 1855 under James Alden (Hydrographic party under command of Lieut James Alden 1852, Hydrographic party under the command of Cmdr James Alden 1855).

Cleveland Rockwell joined the Coast Survey as a teenager in 1856. A biography tells of his mentoring by Bache, his topographic service with the Union Army, and his eventual acclaim as a landscape painter (Stenzel 1972). Rockwell embarked in 1868 upon topographic mapping along the tidal Columbia River. Across most of two decades he surveyed—at a map scale of 1 mm to 10 m—shorelines, wetland vegetation, and riparian land use of this Northwest artery (Thomas 1983, Graves et al. 1995). Available today as sharp color scans are the three 1:10,000-scale topographic sheets used below—T-1112 (Rockwell and Sengteller 1868a), T-1123 (Rockwell and Sengteller 1868b), and T-1138 (Rockwell 1869).

Coast Survey standards of Rockwell's time called for "features of peculiar character" on tidal flats to be represented by imitation (Whiting 1861:222). Of particular concern were obstacles in the water (Shalowitz 1964:188). Cited below are Rockwell symbols that likely represent a discontinuous fringe of subfossil spruce on tidal flats west of Astoria. Also noted, as an indicator of post-earthquake succession, are conifers he depicted in tidal wetlands.

Ecological anomalies

Drowned redcedar

Redcedar standing in Shoalwater Bay tidal marshes provided Cooper with a natural example of resistance to decay:

> On the salt meadows about Shoalwater Bay dead trees of this species are standing sometimes in groves, whose age it would almost impossible to tell. They must have grown when the surface was above salt water mark, as they are still abundant along the fresh borders of the meadows, together with other trees. But a gradual sinking of the land, still going on, has caused the tide to overflow and then killed the forests of which these Cedars are the only remains. Their wood is perfectly sound and so well seasoned as to be the very best of the kind. It is intensively used in that vicinity (Cooper 1856:27, 1860:22 contains similar text).

Cooper's Shoalwater journals identify but one instance in which he observed a redcedar ghost forest firsthand. Coming upon the bay for the first time, Cooper (1853–1854:76) noted that "stumps of Cedar stand on the meadows." These stumps likely stood in a tidal marsh near historical Tarlatt (location, Figure 4b). Cooper had just crossed over from the Columbia by way of an upland portage described as an adventure (Swan 1857:239–241) and plotted on a GLO plat (Gile 1859). Cooper's 1854 notes identify this portage with a "Mr. M—" (March 14) and with "Martin" (August 28)—evidently Thomas Martin, who operated a Tarlatt post office in 1854–1855 (Secretary of State 1855:395, Weathers [1989] 2018). Tidal marshes bordered Tarlatt Slough into the 1870s (Baker's Slough of Gilbert 1873) but have since been diked and plowed (Allen 2003).

Shoalwater Bay companions may have told Cooper of additional ghost forests to which his 1856 manuscript and 1860 report allude. Russell, his primary host, was regarded by Alden (1856), of the Coast Survey, as "a pioneer in these quarters." An Alden party that mapped a Tarlatt portage (Hydrographic party under the command of Cmdr James Alden 1855) hosted Cooper aboard their survey steamer from Shoalwater Bay to San Francisco Bay (Cooper 1856:47 1/2). James Gilchrist Swan (1857:77, 323), residing at the mouth of the Querquelin (now Bone) River, paddled upstream past places where dead redcedar still stand in tidal marshes (Figure 5c).

Lowell, the GLO contractor, pinpointed two redcedar trunks along another tidal creek. Between 12 September and 2 November 1855—with a crew of four chainmen, two axemen, and a compassman—Lowell subdivided terrestrial parts of T. 13 N., R. 10 W. into mile-square sections (location, Figure 4a; Lowell 1856a). Chaining northward in forest along the line between sections 34 and 35 (line, Figure 5c), the crew emerged onto "marsh land" traversed by a tidal slough—today's South Fork Palix River, a serpentine arm of Willapa Bay (Figure 5c). On this line the quarter-section corner coincided with the slough. The crew set a witness post on the south bank, from which they measured bearings and chained distances to two trees identified as "Cedar." One of these bearing trees was described as 76 cm in diameter, 17 m distant at N 70º W; the other, 91 cm across, 22.7 m away at S 43º E (dimensions converted here from inches, chains, and links). The crew continued chaining the section line northward across additional marsh to a forest edge where trees changed from dead to living: "Leave bottom land and enter green timber" (Figure 5d).

A modern surveyor, R.E. Zenkner (2004), recovered the site of Lowell's witness post and identified remains of both its bearing trees. Zenkner described the northwest tree as reduced to a "root collar" and the southeast one as a "cedar stump (no visible scribe) badly decayed." In 2020 we could not relocate the collar, but we did find a moss-covered, waist-high mound of rotten redcedar 22.7 m S 43º E from a Zenkner monument.

Drowned spruce

Four nineteenth-century records locate stumps, probably all Sitka spruce, in tidelands of the Columbia River estuary. First is a Cooper journal entry about ascending the tidal Wallacut River (location, Figure 4a): "In the banks of the creek are frequently seen stumps 'in situ' showing that it was once thickly timbered" (Cooper 1853–1854:75).

The next two documents are the Rockwell topographic sheets T-1112 and T-1123, surveyed in summer and autumn (Rockwell and Sengteller 1868b, 1868a, Stenzel 1972:27). These maps delineate a high-water shoreline where sparsely wooded tidal marshes adjoin tidal flats of Youngs Bay (Figure 6). Beside parts of this shoreline, Rockwell flecked the tidal flat with unexplained, radiating symbols. Figure 6b, on a base map from 1805–1806, summarizes the extent of these symbols, and Figure 6c reproduces examples. The symbols imitate, in plan view, modern examples of exhumed spruce stumps that retain horizontal roots meters long, and which have fallen from banks eroded by waves of Youngs Bay. Viewed at ground level, some of these stumps retain roots anchored in a buried forest soil exposed near the mouth of the Lewis and Clark River (Figure 6d). Northeast of there, along the nearest 0.5 km of Youngs Bay shore, Rockwell's radiating symbols coincide with spruce stumps that sprawl in July 2014 imagery on Google Earth. The symbols also coincide with shores where erosion later carried away triangulation stations of 1868 (Stenzel 1972:46–50). Sprawl typifies root systems of Sitka spruce where drainage is poor (Fraser and Gardiner 1967: plates 5–7, 18).

The fourth and latest document is a feature article about diking and farming of tidal wetlands west of Astoria (The Pacific Farmer 1888). Its unnamed author asserts "indisputable evidence that an old forest of spruce ages ago grew where this tide land now is, along the west side of Young's bay"—the floor of this bygone forest having dropped four feet "through some convulsion of nature."

Spruce decay probably explains why none of these Columbia River stumps were described or drawn as tall. Cooper (1860:22) described Shoalwater Bay ghost forests as redcedar "only." Today along the Bone River, subfossil spruce roots jut out from tidal-creek bank (Figure 5a) below a brackish marsh above which only redcedar extend (Figure 5b).

The Lewis and Clark Expedition, though attuned to submerged forests upstream along the Columbia River (O'Connor 2004:402–405, Reynolds et al. 2022), recorded no subfossil trees at Youngs Bay during the winter of 1805–1806. The Expedition had no mandate to map tidal flats and "peculiar features" upon them, nor opportunities to observe tidal flats during low daylight tides of summer and autumn (tides hindcast at NOAA/NOS/CO-OPS (2023)). But the Expedition did record hints that a successional clock in the Columbia River estuary had recently been reset.

"Marsey prairie"

One such hint can be seen in descriptions of vegetation south of Youngs Bay. Reconnoitering by canoe on November 30, 1805, Lewis found a plain "marshey and untimbered for three miles back" (Lewis et al. [1803–1806] 2005:codex Ia)—a "Marsey prairie" stippled on an accompanying map (Figure 6a). Clark extended such a stipple southward past Fort Clatsop (Figure 6b). Neither captain recorded any counterpart to Rockwell's radiating symbols. But both captains recorded evidence that post-earthquake succession had reached a tidal-marsh stage within the first 100 years after 1700 (Figure 2c).

Observations in later Chinookan surveys compare pre-earthquake vegetation with post-earthquake vegetation. Cooper (1853–1854:75), along the tidal Wallacut River, contrasted lands "once thickly timbered" with adjacent tidal meadows having "scattered spruce trees of perhaps 20 years growth" (Figure 2d). Rockwell plotted asterisks—a standard Coast Survey symbol for conifers (Thomas 1983:4)—not just along the Wallacut (Rockwell 1869) but also in some of the tidal wetlands south of Youngs Bay that adjoin his radiating symbols.

"A distinct species"

A 1700 Cascadia earthquake may have occasioned Lewis's ([1803–1806] 2005) two-fold division of Sitka spruce near Fort Clatsop—into upland old growth (his tree "No. 1") and a bottomland species ("No. 7").

Tree No. 1 enters Lewis's journal for February 4, 1806 as the first of "sveral species of fir in this neighbourhood which I shall discribe as well as my slender botanicall skil will enable me."

> [It] grows to immence size; very commonly 27 feet in the girth six feet above the surface of the earth, and in several instances we have found them as much as 36 feet in the girth or 12 feet diameter perfectly solid and entire. they frequently rise to the hight of 230 feet, and one hundred and twenty or 30 of that hight without a limb.

Tree No. 7, recorded two weeks later, is "a species of pine peculiar to the swamps and marshes frequently overflown by the tide." It resembles No. 1 in most respects and its cone, as sketched by Lewis, is unmistakably Sitka spruce. But it "seldome rises to a greater hight than 35 feet and is from 2½ to 4 feet in diameter." And "as this is a distinct species I shall call it No. 7."

Environment alone, irrespective of earthquake history, produces spruce variants. Where tidal, Sitka spruce has gangly limbs (Figure 6d) that give the tree a distinctively "sprawling, open-growth" look (Franklin and Dyrness 1973). Still, a 1700 Cascadia earthquake may have set No. 7 apart—whether through survival of pre-earthquake spruce, youth of post-earthquake spruce, or both.

Where already "2½ to 4 feet in diameter" in 1806, No. 7 may have included pre-earthquake Sitka spruce that post-1700 tides had yet to kill. Such trees would have been siblings of the few earthquake survivors in some of those same remnant tidal forests to the north and east (Figures 2e, 4d). Most may have adventitious roots, as judged by survivors' root systems exposed in the 1990s by bank erosion along the Columbia River at Price Island (Atwater et al. 2015:97). These showed dead roots nearly 1 m deep near a buried 1700 ground surface, as well as live roots near the modern ground surface (Atwater 1994:10, 48). The live roots had evidently sprouted into post-earthquake deposits. *Picea* elsewhere has produced adventitious roots from trunks surrounded by debris-flow deposits (Strunk 1997) and from cuttings planted commercially (Ragonezi et al. 2010).

Young spruce of in freshwater tidal forests undoubtedly adjoined upland old growth upstream of Fort Clatsop, before logging. Freshwater tidelands of the Copalis River, Grays Harbor, Willapa Bay, and the Columbia River estuary all display post-earthquake spruce that had become established before the time of the Lewis and Clark Expedition (Figures 2d, 4d; Benson et al. 2001).

Raised shell beds

Did Cooper know of land-level changes that happened suddenly? Coastal uplift that accompanied Chilean earthquakes in 1822 (Graham and Greenough 1835, Kölbl-Ebert 1999, Thompson 2012) and 1835 (Darwin 1839:379, FitzRoy 1839:412–414). Did Baird's naturalist's club discuss those findings while Cooper was on hand in 1857–1860?

Whatever he knew of land-level changes in Chile, Cooper invoked nothing sudden to explain the redcedar submergence at Shoalwater Bay. To the contrary, in the railroad report (much as in the 1856 manuscript) he proposed "a gradual, slow sinking of the land (which seems in places to be still progressing, and is perhaps caused by the undermining of quicksands)" (Cooper 1860:22). But he also anticipated that "continued and careful examination of [the submerged redcedar] may afford important information as to the changes of level in these shores."

Here the railroad report turns to an apparent contradiction: "beds of marine shells" exposed in bluffs overlooking Shoalwater Bay. Gibbs ([1854] 1855:466), on a geological reconnaissance for Stevens, had noticed these beds and had interpreted them as uplifted. In Gibbs's footprints, Cooper (1853–1854:87) reexamined shell beds near the site of modern Bay Center (location, Figure 5c). He found that the shells were "mostly of existing species," and he estimated that they had been "elevated about 10 ft. above the present high tides."

Today, the emergent shells near Bay Center can be seen as fully compatible with submerged redcedar forests nearby, for two reasons. First, the shells underwent little if any net change in elevation if deposited when sea levels were about as high as they are today. Twentieth-century geologists assigned these fossils to Pleistocene ancestors of Willapa Bay (Clifton 1983:367). The shells contain mixes of right-handed and left-handed amino acids consistent with ages in the range 90,000–170,000 years (Kvenvolden et al. 1979:1517, 1519) or close to 80,000 years (Kennedy et al. 1982: their locality 7). These ages are consistent with net uplift in the approximate range 0–40 m. Second, to end up near present sea level, the shells could follow a sawtooth trajectory through repetitions of the subduction cycle in Figure 2f—falling during earthquakes but rising in between (Atwater and Hemphill-Haley 1997:8–11). Subsidence during subduction earthquakes may then negate, in the long run, most of the gradual uplift that takes place between them.

Conclusions

Nineteenth-century explorers and immigrants recorded subfossil trees today interpreted as victims of a 1700 Cascadia earthquake. Western redcedar standing in tidal marshes of Shoalwater Bay struck a naturalist as incongruous and provided a land surveyor with bearing trees. Sitka spruce, more prone to decay, had already been reduced to short stumps when observed along the Columbia River. These various remains of tidally drowned forests record lowering of land during a great subduction earthquake in 1700—a modern interpretation partly founded on analogy with estuarine effects of an Alaskan earthquake in 1964.

In Cascadia as in Alaska, drowning by post-earthquake tides helped rebuild land on which new trees became established. Along the Columbia River, a plain described in 1805 as "untimbered" had become lightly wooded another half-century later.

Acknowledgments and author roles

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Table

TABLE 1. Radiocarbon ages of rings of a dead spruce root collected in 1991 from a receding bank of Twentymile River near Portage, Alaska (Figure 3).

Ring (Figure 3c)	Lab number (OS-)	Fraction modern (FM)	FM error	Year if ring A formed in 1963 C.E.	Age on rising limb of bomb-carbon curve (Figures 3f and 3g)	Age on falling limb of bomb-carbon curve (Figure 3g)
A	159632	1.8272	0.0043	1963	1963.47–1965.53 (age range crosses curve crest, partly on each limb)	
B	159633	1.3914	0.0041	1962	1962.41–1962.86	1973.94–1975.95
C	159634	1.2362	0.0025	1961	1959.26–1961.98	1982.14–1984.99
D	159635	1.2324	0.0025	1960	1959.25–1961.97	1982.17–1984.88
E	159636	1.2879	0.0026	1959	1959.43–1962.18	1979.12–1980.81
F	159637	1.1449	0.0024	1958	1957.79–1958.41	1990.32–1993.07
G	159638	1.0774	0.0021	1957	1956.92–1957.35	2001.11–2004.97

Notes

Age ranges in the two columns at right are at two standard deviations and were computed at http://calib.org/CALIBomb/ with calibration data of Hua et al. (2013: Table S3a, NH zone 1) and Hammer and Levin (2017). Rings A–G, as annual increments of growth (Figure 3c), increase in tree-ring age in successive one-year steps, in which case their corresponding radiocarbon ages plot uniquely on the rising limb of the bomb-carbon curve in Figure 3f; the collection year (1991; Figure 3b) excludes the falling-limb ages for rings F and G. The tabulated rising-limb age ranges for rings B, E, and F then require that ring A represent the 1963 growing season. All the ages were measured in 2021 and are previously unreported.

Figure captions

Figure 1. Land-level changes during (a) the 1964 Alaska earthquake and (b) during earthquakes of the past few thousand years along the Cascadia subduction zone. Alaskan points digitized from Plafker (1969: plate 3). Cascadia compilation after Leonard et al. (2010).

Figure 2. Schematic views: (a–e) Forest death by coastal subsidence during an earthquake and subsequent forest renewal. (f) Land-level changes between and during earthquakes at a subduction zone.

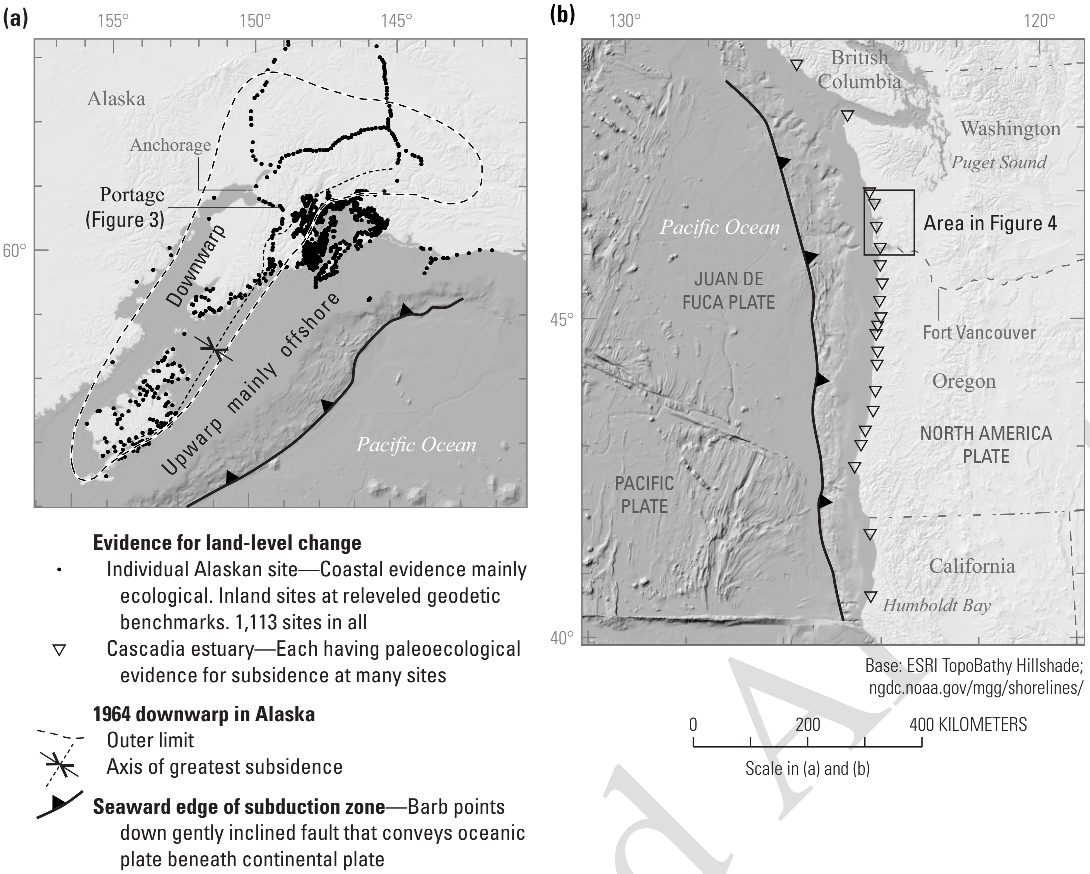
Figure 3. Dated spruce along Twentymile River near Portage, Alaska. (a) Setting on airphoto taken 1966. (b) Tree sampled dead in 1991. (c) Sanded cross-section of root subsampled for radiocarbon analysis (rings A–G). (d, e) Fringe of earlywood cells outside ring A. (f) Radiocarbon results plotted on graph of atmospheric radiocarbon activity excerpted from (g). Radiocarbon activity in (f) and (g) is expressed as fraction of modern, pre-bomb levels ($F^{14}C$ of Reimer et al. 2004). Root ^{14}C data in (f), for rings A–G, from Table 1; ^{14}C curve in (f) and (g) from Hua et al. (2013: Table S3a, NH zone 1) and Hammer and Levin (2017); bomb yield in (g) from Yang and others (2003). Airphoto in (a) from collection of A.T. Ovenshine; other photos by the authors.

Figure 4. Maps of southwest Washington estuaries, locating (a) places cited in the text; (b) individual dead western redcedar whose death likely resulted from lowering of land during the 1700 Cascadia earthquake; (c) areas of multiple spruce stumps submerged at high tide; and (d) live Sitka spruce that either survived the 1700 earthquake or became established in the first century thereafter. Tree locations from compilations in Atwater (2020). Tree ages in (d) from Jacoby et al. (1997) and Benson et al. (2001).

Figure 5. Dead trunks and stumps of western redcedar east of Willapa Bay. Examples in (a) and (b) from a salt marsh along the Bone River. Oblique airphoto in (b) from Washington Department of Ecology (2016). (c) Mapped distribution along Bone River and South Fork Palix River. (d) Bearing trees near South Fork Palix River surveyed 1855 (Lowell 1856a).

Figure 6. Wetlands beside Youngs Bay. (a, b) Maps by Meriwether Lewis (Lewis et al. [1803–1806] 2005: codex Ia) and William Clark (1806: images 1008620 and 1008624), respectively; typed labels and stump symbols added. (c) Map by Rockwell and Sengteller (1868a), illustrating radiating symbols on tidal flat that probably represent spruce stumps. (d) Modern exposure of stumps on and beside tidal flat near mouth of Lewis and Clark River. Index map in Figure 4c.

Figure 1



Base: ESRI TopoBathy Hillshade;
ngdc.noaa.gov/mgg/shorelines/

Figure 2

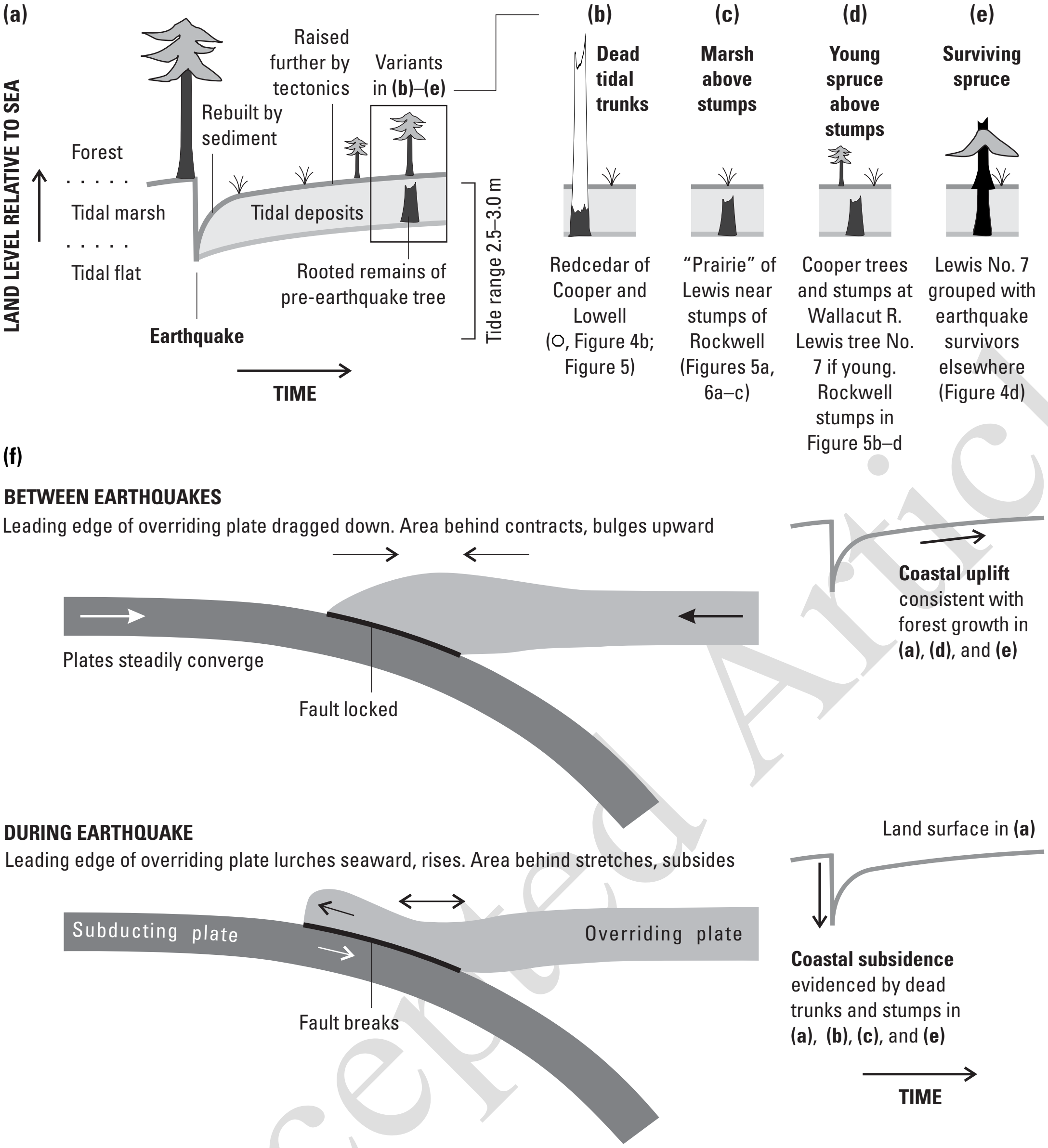

(a)
LAND LEVEL RELATIVE TO SEA
Forest
Tidal marsh
Tidal flat
Earthquake
Rebuilt by sediment
Raised further by tectonics
Variants in (b)–(e)
Tidal deposits
Rooted remains of pre-earthquake tree
Tide range 2.5–3.0 m
TIME
(b)
Dead tidal trunks
Redcedar of Cooper and Lowell (○, Figure 4b; Figure 5)
(c)
Marsh above stumps
"Prairie" of Lewis near stumps of Rockwell (Figures 5a, 6a–c)
(d)
Young spruce above stumps
Cooper trees and stumps at Wallacut R. Lewis tree No. 7 if young. Rockwell stumps in Figure 5b–d
(e)
Surviving spruce
Lewis No. 7 grouped with earthquake survivors elsewhere (Figure 4d)
(f)
BETWEEN EARTHQUAKES
Leading edge of overriding plate dragged down. Area behind contracts, bulges upward
Plates steadily converge
Fault locked
Coastal uplift consistent with forest growth in (a), (d), and (e)
DURING EARTHQUAKE
Leading edge of overriding plate lurches seaward, rises. Area behind stretches, subsides
Subducting plate
Overriding plate
Fault breaks
Land surface in (a)
Coastal subsidence evidenced by dead trunks and stumps in (a), (b), (c), and (e)
TIME

Figure 3

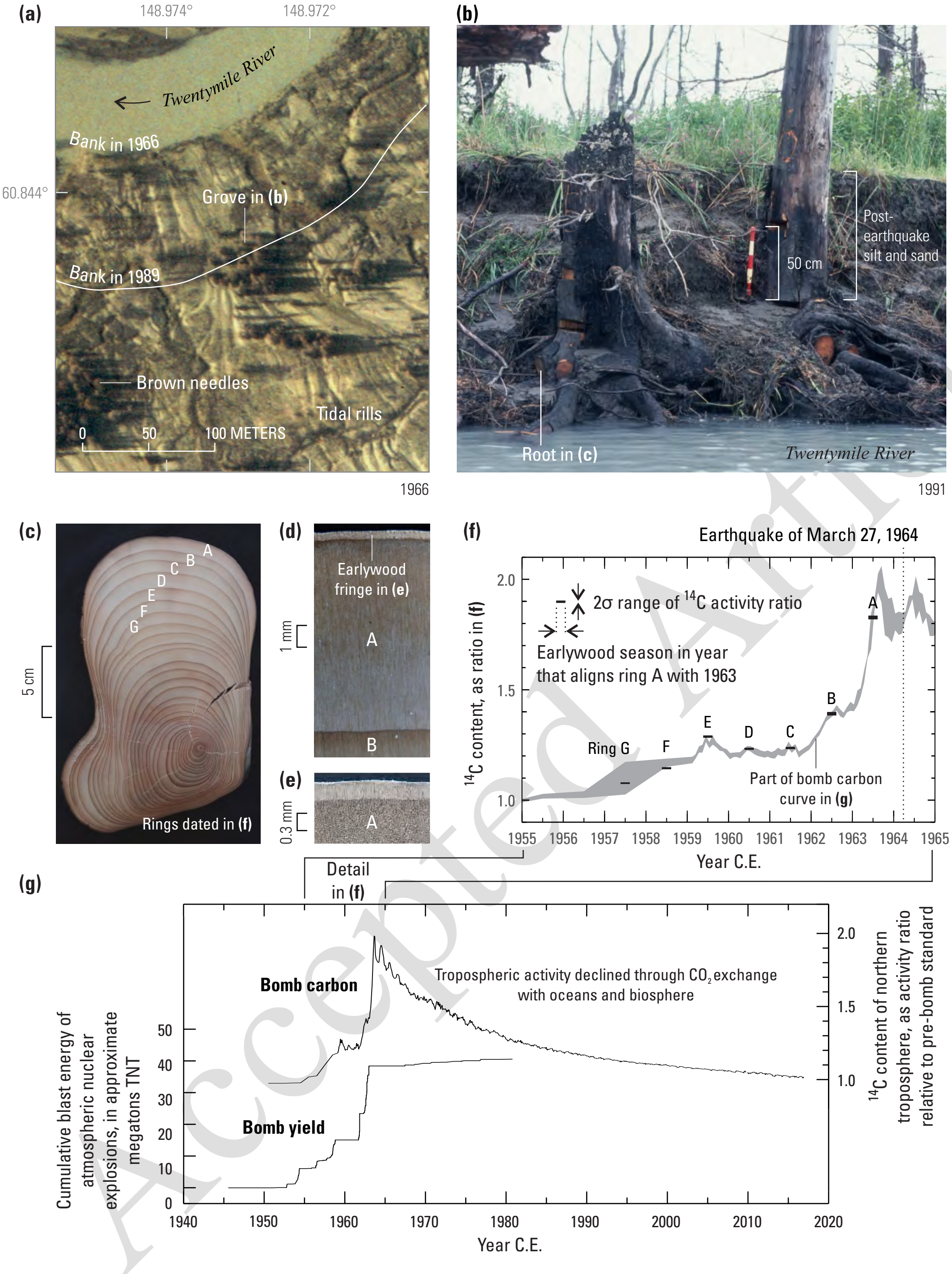
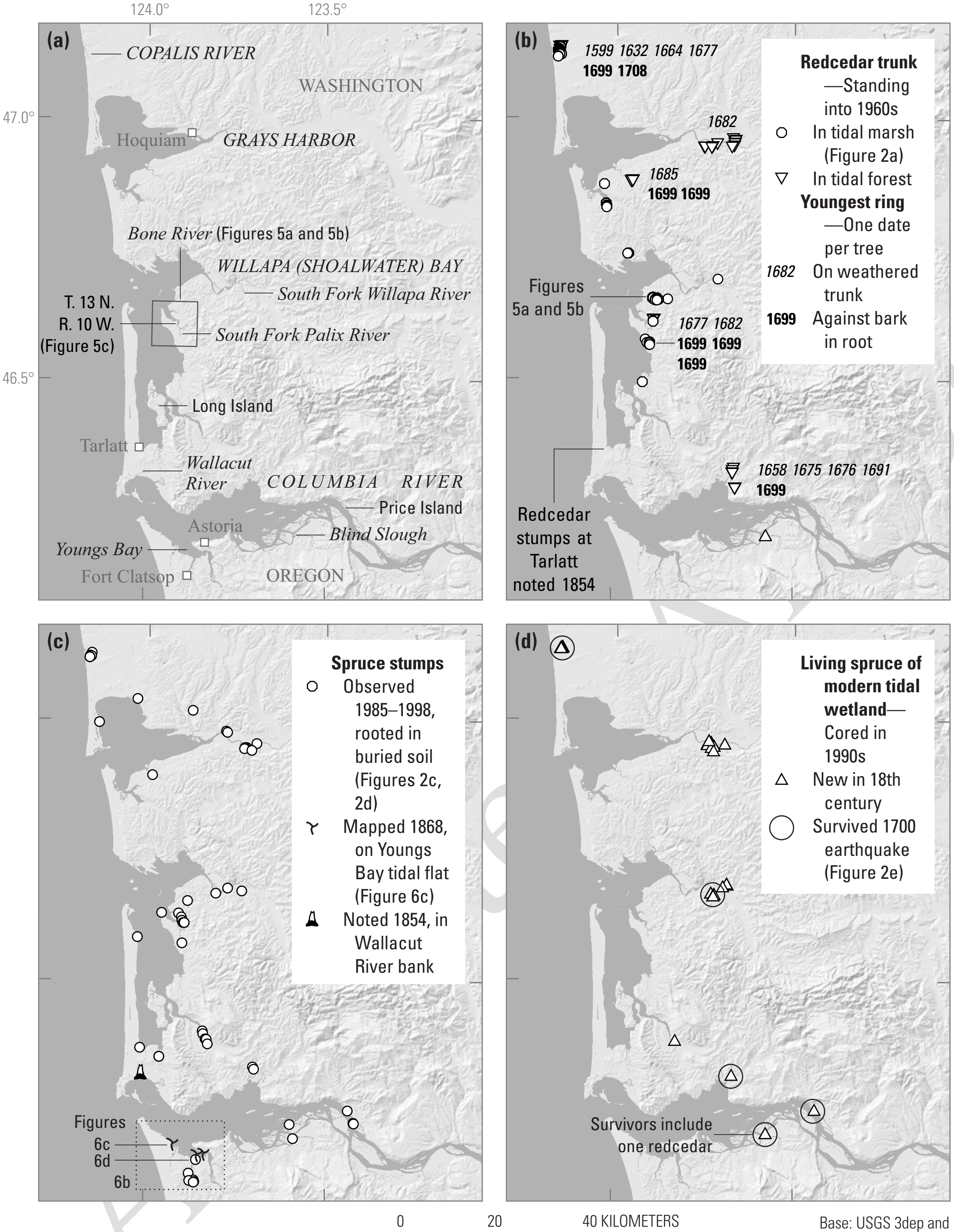
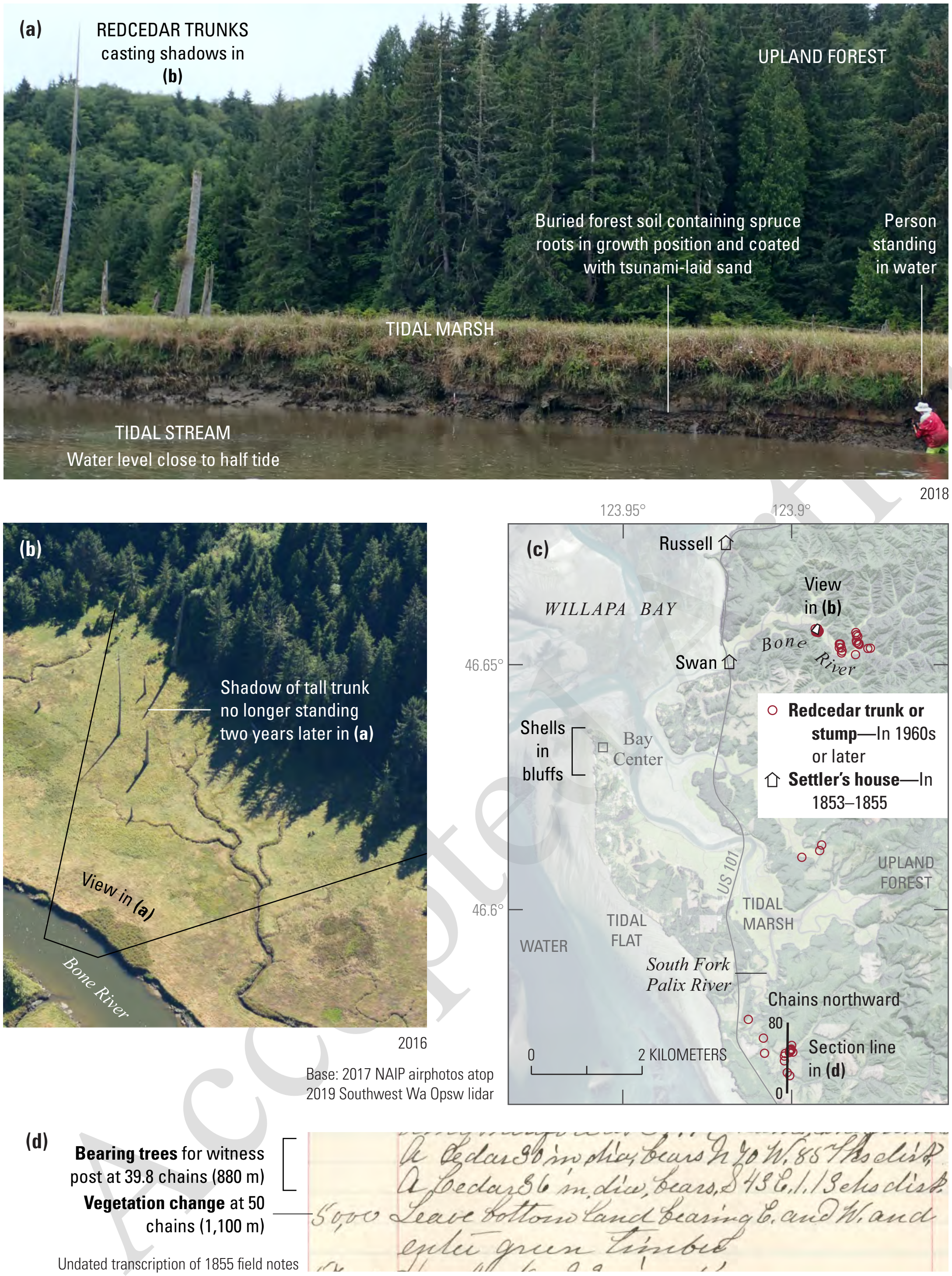

(a)
148.974°
148.972°
60.844°
Twentymile River
Bank in 1966
Grove in (b)
Bank in 1989
Brown needles
Tidal rills
0
50
100 METERS
1966
(b)
Post-earthquake silt and sand
50 cm
Root in (c)
Twentymile River
1991
(c)
A
B
C
D
E
F
G
5 cm
Rings dated in (f)
(d)
Earlywood fringe in (e)
1 mm
A
B
(e)
0.3 mm
A
(f)
Earthquake of March 27, 1964
2σ range of ^{14}C activity ratio
Earlywood season in year that aligns ring A with 1963
A
B
E
D
C
F
Ring G
Part of bomb carbon curve in (g)
^{14}C content, as ratio in (f)
2.0
1.5
1.0
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
Year C.E.
Detail in (f)
(g)
Bomb carbon
Tropospheric activity declined through CO_2 exchange with oceans and biosphere
Bomb yield
Cumulative blast energy of atmospheric nuclear explosions, in approximate megatons TNT
50
40
30
20
10
0
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year C.E.
2.0
1.5
1.0
^{14}C content of northern troposphere, as activity ratio relative to pre-bomb standard

Figure 4



Base: USGS 3dep and national hydrography

Figure 5



2018

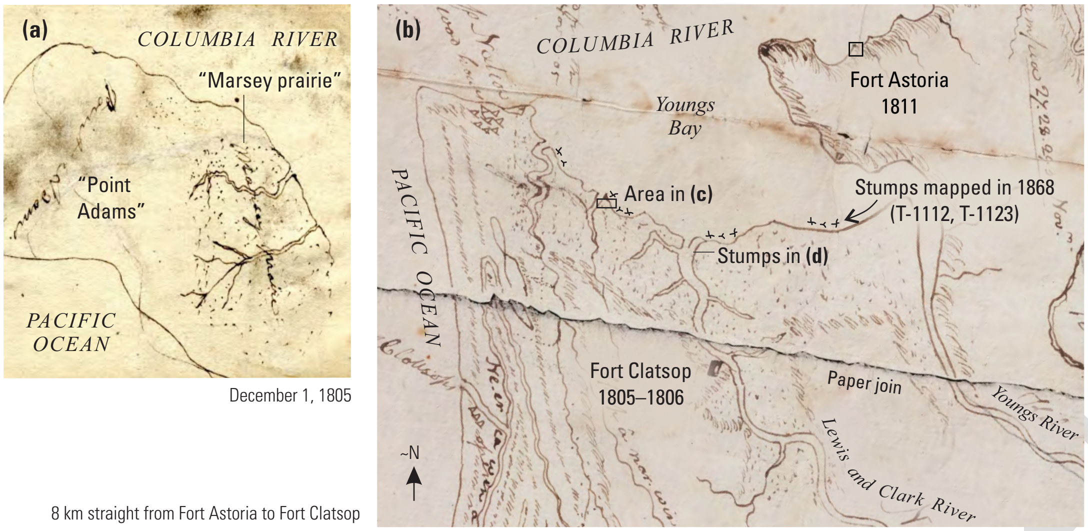
2016

Base: 2017 NAIP airphotos atop 2019 Southwest Wa Opsw lidar

Undated transcription of 1855 field notes

A Cedar 30 in. dia, bears N 70 W. 85 lks dist.
A Cedar 36 in. dia, bears S 43 E. 1.13 chs dist.
50,00 Leave bottom land bearing E. and W. and
enter green timber

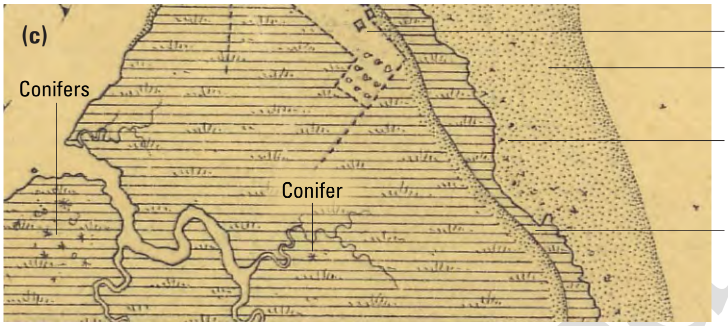
Figure 6



December 1, 1805

8 km straight from Fort Astoria to Fort Clatsop

Winter 1805–1806



Fenced farm

Tidal flat stippled

Symbols (redrawn here, enlarged) on marginal tidal flat that evoke spruce stumps like those in **(d)**

Tidal marsh—Contains beach (linear stipple) and few live spruce (asterisks)

T-1112, surveyed autumn 1868

Small live spruce of modern tideland

Large dead spruce (s) in cross section. Its horizontal roots (h), where jutting from the bank, mark the level of a former forest floor

Arms of this stump, and of others in view, have dropped onto a tidal flat after being undercut by waves at high tide

Tide out in summer 2006