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Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA

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Abstract

Field surveys and radiocarbon dating of buried logjams in the floodplain of an old-growth forest river demonstrate the formation of erosion-resistant "hard points" on the floodplain of the Queets River, Washington. These hard points provide refugia for development of old-growth forest patches in frequently disturbed riparian environments dominated by immature forest. Our surveys show that local bed aggradation associated with logjams not only influences channel patterns and profiles but leads to development of a patchwork of elevated landforms that can coalesce to form portions of the valley bottom with substantial (i.e., 1 to >4 m) relief above the bankfull elevation. In addition, logjam-formed hard points promote channel avulsion, anastomosing morphology, and growth of mature patches of floodplain forest that, in turn, provide large logs needed to form more logjam-formed hard points. Hence, our findings substantiate the potential for a feedback mechanism through which hard points sustain complex channel morphology and a patchwork floodplain composed of variable-elevation surfaces. Conversely, such a feedback further implies that major changes in riparian forest characteristics associated with land use can lead to dramatic simplification in channel and floodplain morphology.

Keywords: Woody debris; Fluvial; Floodplain; Terraces; Logjams; Aggradation

Introduction

Human activities greatly reduced the quantity of wood debris in fluvial systems around the world through direct removal of in-channel wood and clearing of riparian forests (e.g., Sedell and Froggatt, 1984; Swift, 1984; Triska, 1984; Benke, 1990; Collins and Montgomery, 2002; Collins et al., 2003). Wood debris can significantly influence the morphology of forest channels (e.g., Heede, 1972; Keller and Swanson, 1979; Gregory et al., 1985, 1993; Gregory and Davis, 1992; Nakamura and Swanson, 1993; Montgomery et al., 1995, 1996, 2003; Gurnell and Sweet, 1998), and sediment deposition around stable logjams can form alluvial surfaces (Abbe and Montgomery, 1996, 2003; Montgomery et al., 1996; O'Connor et al., 2003) and influence patterns of riparian forest development (Fetherston et al., 1995; Naiman et al., 1998; 2000). However, logs and logjams generally have been dismissed as a significant factor in the development of floodplains and terraces (e.g., Kochel et al., 1987; Piégay and Gurnell, 1997; Piégay et al., 1999; Gurnell et al., 2001; Wegmann and Pazzaglia, 2002). Conventional explanations for floodplain development predict relatively uniform topographic surfaces formed by either deposition of bed load material in the wake of channel migration or overbank deposition of fine-grained sediment that settles from suspension during floods (e.g., Wolman and Leopold, 1957; Lewin, 1978). Formation of alluvial surfaces or terraces above the elevation of channel banks are generally attributed to changes in climate or tectonics that alter the discharge, sediment regime, or base level (e.g., Richards, 1982; Knighton, 1998). Here we present evidence for the role of logjam-formed "hard points" on creating and maintaining valley-bottom surfaces that shelter patches of old-growth forest within dynamic, disturbance-prone riparian environments. Our field observations and dating lead us to recognize an end-member model for formation of complex, multi-elevation floodplains due to intrinsic dynamics of forested valley bottoms without changes in climate, sediment supply, or base level.

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Study area

The 1190-km^2 Queets River basin is located on the western slope of the Olympic Peninsula, Washington. Continuously forested for at least the last 17,000 yr (Fonda, 1974; Whitlock, 1992), the unregulated Queets River drains a watershed with large areas of old-growth forest. Development within the Queets River valley is limited to a gravel road, a National Park Service campground, and 19th-century homestead sites abandoned in the 1930s prior to establishment of Olympic National Park. Old-growth temperate rain forest blankets much of the watershed and mature conifers grow in numerous, distinct patches across a valley bottom dominated by younger deciduous forest (Fetherston, 2005).

Previous work in the Queets River basin showed that large logs and logjams redirect flow and divert the course of the river (Abbe and Montgomery, 1996, 2003). These studies showed how deposition of logs large enough to resist transport can alter local flow hydraulics and initiate formation of a logjam and deposition of an associated alluvial surface well above the channel banks. Through this simple process, logjams obstructing the channel can become buried in bars, mantled by overbank sedimentation, and covered by forest to eventually become integrated into the floodplain (Abbe and Montgomery, 1996). Exposure of buried logjams in eroding river banks lying beneath old trees has led to the hypothesis that logjams can form stable “hard points” that can limit future channel migration paths and create long-term sites of forest refugia (Abbe and Montgomery, 1996, 2003; O’Connor et al., 2003).

Based on several-meter-long sediment cores from small channel-like depressions at a site along the Queets River, Greenwald and Brubaker (2001) reported deposition of coarse sand capped by silt on what they termed the first and second terraces at 3.5 and 8 m elevation above the river, respectively. Radiocarbon dating of *Picea sitchensis* and *Tsuga heterophylla* needles at the base of the core from the lower terrace yielded a limiting calibrated age of 477 ± 60 yr B.P., somewhat older than a ≈350-yr-old *T. heterophylla* growing on the same surface. Similarly, a radiocarbon date on needles from the base of the core from the higher terrace yielded a limiting calibrated age of 550 ± 95 yr B.P. Greenwald and Brubaker (2001) concluded that these deposits record either the largest flood in the past half millenia or “a substantial shift in the position of the river channel” (Greenwald and Brubaker, 2001, p. 1382).

Hyatt and Naiman (2001) inventoried large woody debris in four reaches of the Queets River and estimated wood depletion rates by assuming a steady-state wood loading. Their sampling concentrated on wood pieces larger than 0.6 m in diameter and longer than 5 m in length, which they erroneously termed “key pieces” in applying an arbitrary size criterion to a functional classification. [In use since at least the 1880s (Gillespie, 1881; Deane, 1888), the term key piece refers to logs that form foundational structural members of stable logjams; recent work reported by Abbe and Montgomery (2003) has shown that key piece size scales relative to channel size.] Through cross-dating tree rings and radiocarbon dating, Hyatt and Naiman (2001) found that the age of 75 logs ranged from 1 to >1400 yr, with a mean age of 84 yr and a median age of 19 yr. From the cumulative age distribution, they calculated a depletion rate and inferred a mean residence time of ≈30 yr for logs in the Queets River. They further speculated that the oldest logs they had sampled had been recently exhumed after prolonged burial in floodplain sediments.

O’Connor et al. (2003) used historical maps and aerial photographs to document average channel migration rates for the Queets River of 7.5 ± 2.9 m yr^{-1} between 1900 and 1994. They reported that floodplain width narrowed where the river passed through Quaternary moraine complexes and calculated an average floodplain turnover rate of 300–400 yr, although much of the floodplain closest to the river is dominated by alder less than century old. Paralleling observations reported by Abbe and Montgomery (1996; 2003); O’Connor et al. (2003) described the influence of large logjams on local sediment deposition and avulsion and as potentially forming hard points that protect trees long enough to provide a source of new key members. O’Connor et al. (2003) further described clustered stands of *P. sitchensis* of greater diameter than the surrounding forest growing on alluvial surfaces rising 1–2 m above the floodplain of the neighboring Quinault River, a phenomenon which they attributed to nurse logs at sites of old logjams.

Together these prior studies are consistent with the logjam hard point hypothesis in which some percentage of stable logjams can resist erosion for centuries and protect conifer patches that, in turn, eventually provide a source for new key-member logs that can form new logjams.

Methods

Field surveys on the Queets River conducted from 1993 to 1996 included locating buried wood exposed in riverbanks and constraining the age of trees growing on the overlying alluvial landforms. Surveys by foot, raft, and canoe documented the geomorphic effects of individual logjams through topographic mapping and stratigraphic sections of alluvial deposits. Different types of wood accumulations were described and mapped along the main stem channel and in selected tributaries and floodplain side channels. Historical aerial photographs and repeated field surveys were used to assess, where possible, the longevity of individual logjams. Hydrologic records were used to evaluate the magnitude of peak flow events to which observed logjams were subjected. An optical level was used to survey profiles and cross sections of channels and floodplains. Surveyed channel profiles provide a means of measuring the vertical extent of aggradation upstream of logjams. Variations in the elevations of alluvial surfaces at sites throughout the watershed were documented in topographic transects surveyed across floodplains. Local rates of channel aggradation were measured by repeated surveys. Additional details of these field surveys are given by Abbe (2000).

Forty-nine samples for ^{14}C dating were collected at buried logjams identified in and sampled from channel-bank exposures in order to constrain a maximum age for each jam. We also obtained a minimum constraint on the age of each jam from the age of trees growing on the overlying alluvial surface.

Logs exposed in eroding gravel banks were considered part of a buried jam if three or more logs were racked on one another. A hand saw was used to cut small wedges from each log's perimeter to ensure dates representative of the tree's death and provide a maximum age for when the log was deposited. Measured at the University of Washington's Quaternary Research Center Isotope Laboratory, calibrated ^{14}C dates (Stuiver and Reimer, 1993) are reported relative to the 1950 NBS standard. The age of trees too large to core was estimated using age-diameter curves developed from cut logs found along the Queets road and trail in combination with age-diameter data from previous studies (Reid, 1981; Van Pelt, 1994; Fetherston, 2005).

Minimum channel migration rates between river miles 10 and 40 along the Queets River were determined using historical and recent maps and aerial photographs (Fig. 1). Changes in channel position from 1929 to 1985 were measured perpendicular to the valley axis at intervals corresponding to half the meander wavelength of the primary channel. The difference between channel positions was then divided by the time between the photographs to estimate minimum rates of channel migration. Local estimates of the time required for the channel to move across the valley bottom were determined by dividing the floodplain width by estimated rates of channel migration, which do not account for channel avulsion and therefore provide only a limiting constraint on the time over which the channel could traverse its floodplain.

Results

Patches of the old-growth forest growing on the floodplain were commonly located immediately downstream of where buried logs and logjams were exposed in the banks of the river (Fig. 2). Vegetation that obscured bank exposures along much of the river precluded a complete census even were one to attempt such an accounting. Even so, logjams were found at the upstream end of 98% (i.e., all but one) of the forested islands in the lower Queets and blocked the entrance to major side channels that were formerly the main channel along the entire river. Rootwads were attached to 82% of 319 key-member logs examined in the Queets River; all but one of 112 key members measured in channels >40 m wide had a rootwad.

The basal diameters of 287 measured key-member logs ranged from 0.76 to 3.4 m, with a mean of 1.8 m (Fig. 3). Age-diameter relations derived for logs examined in our Queets River surveys and from previous studies (Fig. 4) indicate that it

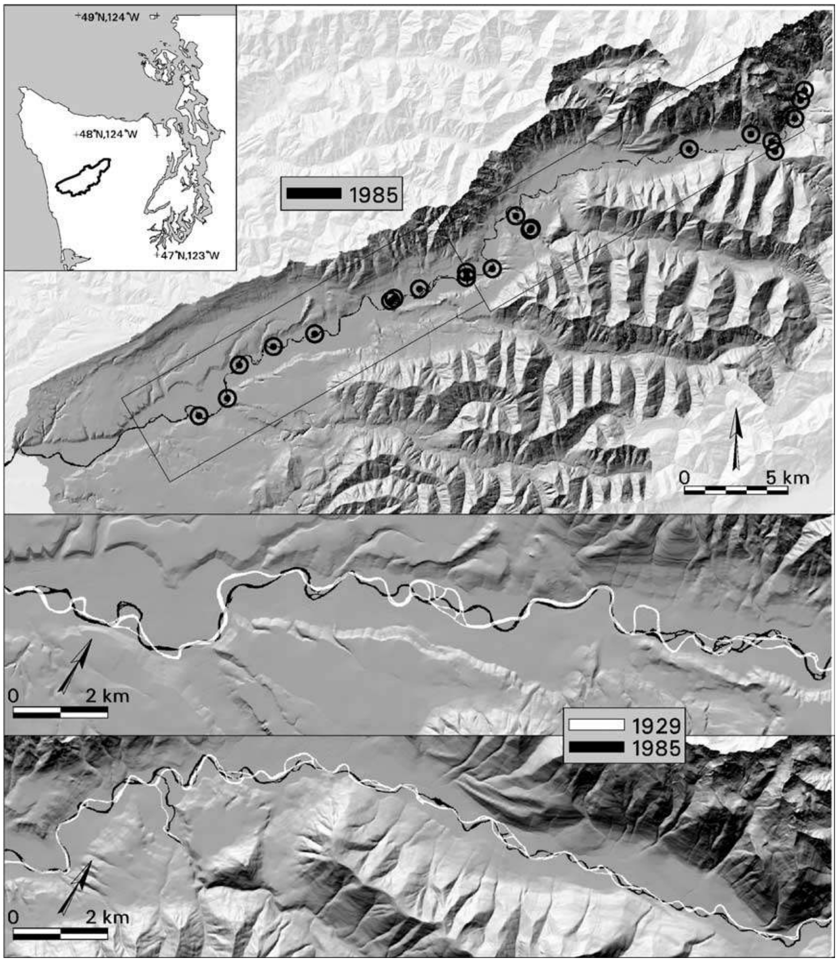

Figure 1. Queets River watershed in western Washington State showing locations of main river channel in 1929 and 1985, and locations of buried logjams sampled for ^{14}C analyses (circles).

Figure 2. Photograph of mature forest patch growing behind buried logjam along the Queets River. Note person for scale.

would take 70–700 yr to grow logs the size of observed key members, and that it would take between 300 and 400 yr to grow a tree as large as the mean size of key-member logs.

Observed channel migration rates in unconfined reaches indicate that the Queets River can sweep across its floodplain in 40–200 yr, with an estimated mean disturbance interval of 100 yr for the active corridor along the main stem river (Fig. 5). The dominant matrix of <100-yr-old, primarily deciduous riparian forest on the valley bottom is consistent with conventional models of floodplain construction, although these fail to account for the numerous riparian stands of >300-yr-old conifers, which are older than the disturbance recurrence interval implied by channel migration rates, and which produce logs the size of the average key member.

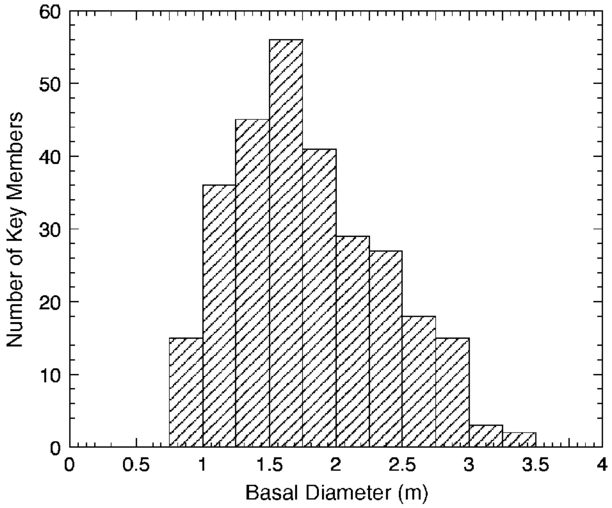

Figure 3. Frequency distribution of the diameter of key-member logs from logjams exposed in banks along the main stem Queets River.

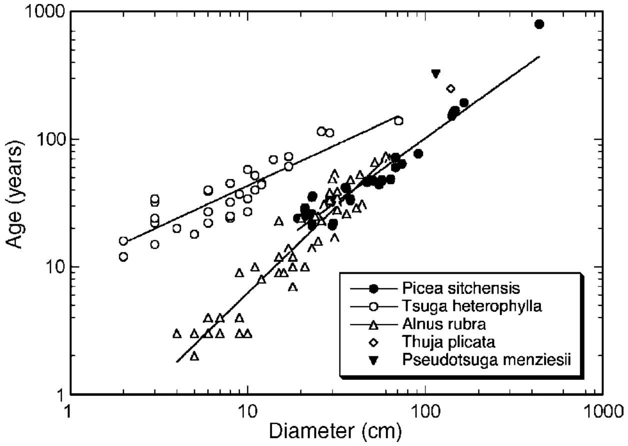

Figure 4. Age versus diameter data for trees compiled from measurements of diameters and tree ring counts collected in the field along the Queets River, and from previously published sources (Reid, 1981; Van Pelt, 1994; Fetherston, 2005). Least squares linear regression yields $y = 1.0x^{1.00}$ ($R^2 = 0.95$) for *P. sitchensis*; $y = 9.8x^{0.64}$ ($R^2 = 0.85$) for *T. heterophylla*; and $y = 0.27x^{1.36}$ ($R^2 = 0.86$) for *Alnus rubra*.

At locations throughout the Queets River valley, stable logjams obstruct enough of the valley floor to locally aggrade the channel bed and create elevated, low-gradient alluvial surfaces. Calibrated radiocarbon dates of up to 1258–1401 cal yr B.P. (calibrated 2σ range; ^{14}C age of 1400 ± 50 yr) for jams buried immediately upstream of mature conifer patches show that such influences can be long lasting (Fig. 6) (Table 1). For the logjams less than about 300 yr old, the calibrated ages of the buried logs are close to the age of the oldest trees growing on the overlying alluvial surface. Given that the buried logs cannot be younger than the trees growing on top of them, the death of the trees forming the foundation of logjams immediately preceded initiation of the conifer patches. Many of the older buried logjams are substantially older than the oldest trees on the overlying surface and therefore record either a substantial delay between tree death and deposition in the river (a possibility we consider unlikely given the short residence time for in-channel wood reported by Hyatt and Naiman (2001)), or that stable logjams can form persistent "hard points" that can resist erosion when excavated by river migration.

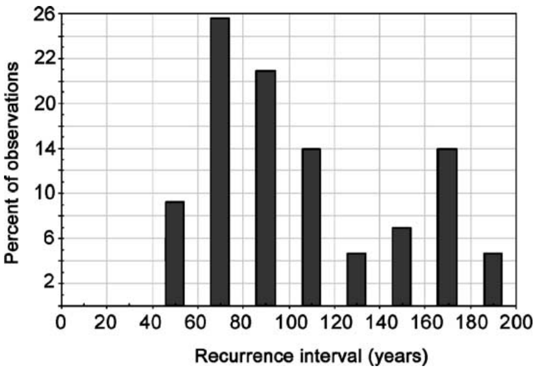

Figure 5. Recurrence intervals for migration of the Queets River across its floodplain between river miles 10 and 44, calculated by dividing the average floodplain width by average migration rate between 1929 and 1985 for each river mile.

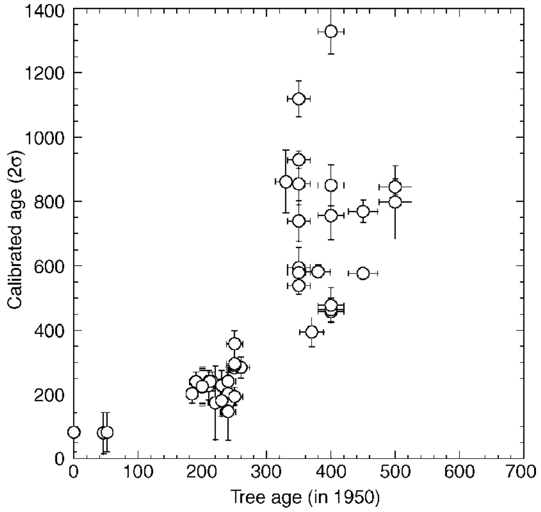

Figure 6. Calibrated radiocarbon dates for material from buried logjams versus ring-counted, or diameter-estimated tree ages for oldest tree growing on alluvium above the corresponding buried logjam for locations sampled throughout Queets River basin. Open circles represent mean of range of calibrated ^{14}C dates (yr B.P.) of wood samples taken from buried logjams. Error bars represent 2σ range of calibrated ^{14}C age and 5% for estimated tree ages.

Floodplains along the Queets River and its primary tributaries are composed of a complex mosaic of individual topographic surfaces with several meters of local relief (Fig. 7). In addition, the characteristic alluvial stratigraphy exposed in the banks of the Queets River – sand and silt mantling imbricated gravel that thickens downstream – is rarely contiguous over more than a few hundred meters. Together these observations indicate that the floodplain developed as a patchwork of individual depositional surfaces.

Another defining characteristic of these floodplain patches is that their surface(s) does not parallel the main channel slope; they are much flatter. We consistently observed that the great majority of local depositional surfaces that form the floodplain of the Queets River have slopes much gentler than the main stem channel itself.

Direct observations of the creation of local alluvial surfaces document that logjam complexes extending across the valley bottom can elevate the channel bed above the active floodplain, allowing relatively low-magnitude flows to deposit bedload sediments on surfaces formerly well above inundation during even rare high flows. For example, we located the 1901 channel at river kilometer 45 and found it to be situated 2.5 m above the 1995 floodplain. At another site, recent channel aggradation upstream of a valley-spanning jam complex deposited 1–1.5 m of upstream thinning gravel on a 3000-m^2 patch of 1.75- to 2.5-m-diameter *P. sitchensis*. These 200- to 300-yr-old trees began growing on an older alluvial surface that now sits below the active channel bed.

Between 1993 and 1996, we documented local aggradation of 1.5 m yr^{-1} on the main stem river at two sites where deposition of stable logjams reduced the river gradient from 0.031 to 0.0008 and 0.011 to 0.0006, respectively, along the 500-m-long surveyed profiles. In these locations, deposition created new topographic surfaces elevated one to several

Table 1
Radiocarbon ages (yr B.P.) for buried old-growth logs exposed along the Queets River and dendrochronologically estimated ages of live trees growing on associated alluvial surfaces

Location (river mile)	Sample ID[a]	^{14}C age ($\pm 1\sigma$)	Calibrated age (2σ)[b]	Tree age (in 1950)[c]
38.78	4779	26 ± 50	22–143	0
25.40	4849	40 ± 50	15–145/214–267	46
–	4870	50 ± 45	21–144/216–266	52
41.00	4780	68 ± 50	*12–148*/211–269	215
43.40	4869	75 ± 45	*12–148*/211–269	190
–	4871	100 ± 20	*27–140*/221–259	210
31.00	4782	102 ± 50	*9–151*/173–274	200
26.50	4785	103 ± 50	*9–151*/173–275	200
43.00	4841	110 ± 20	*9–151*/182–274	210
–	4872	110 ± 45	*9–151*/182–274	230
41.50	4786	119 ± 50	*7–151*/171–280	200
–	4873	120 ± 20	*56–147*/213–268	240
41.50	4836	125 ± 20	*57–148*/211–269	212
–	4853	130 ± 45	*52–152*/170–281	200
38.78	4837	140 ± 20	172–231	184
25.41	4848	140 ± 20	172–231	184
17.10	4860	140 ± 20	172–231	240
–	4876	140 ± 20	172–231	240
43.40	4868	150 ± 50	*56–158*/163–286	200
43.00	4781	155 ± 50	58–286	240
–	4874	160 ± 40	60–233	240
25.41	4847	160 ± 50	59–289	220
42.20	4839	170 ± 20	165–222	250
41.50	4879	190 ± 40	132–229	230
42.20	4840	200 ± 20	*146–189*/268–296	250
–	4852	210 ± 45	*131–230*/251–317	260
18.50	4858	225 ± 20	*151–173*/274–305	250
21.99	4856	240 ± 15	284–305	250
41.50	4867	310 ± 20	349–439	370
43.00	4880	350 ± 20	316–399/422–488	250
29.20	4846	355 ± 20	*318–394*/424–491	400
29.20	4845	370 ± 20	*321–378*/427–500	400
29.20	4784	414 ± 50	*316–399*/422–532	400
–	4855	550 ± 40	512–566/585–646	350
16.00	4877	590 ± 45	532–656	350
16.00	4859	630 ± 20	556–607/624–660	380
–	4854	650 ± 20	560–598/632–666	350
41.50	4878	670 ± 20	563–590/640–671	450
16.00	4861	840 ± 50	676–803	350
28.5	4843	850 ± 50	681–832	400
28.40	4851	860 ± 60	686–911	500
28.50	4842	890 ± 25	735–804/847–906	450
–	4844	920 ± 20	787–914	400
16.00	4863	930 ± 25	790–920	350
41.50	4865	960 ± 50	764–960	330
28.40	4850	970 ± 20	821–870/898–932	500
16.00	4864	990 ± 20	903–956	350
16.00	4862	1200 ± 20	1063–1176	350
28.50	4783	1400 ± 50	1258–1401	400

[a] Sample ID refers to the sample identification number from the University of Washington's Quaternary Research Center Isotope lab; sample weights ranged from 5 to 224 g.

[b] Two-sigma range for calibrated ages (yr B.P.) based on Stuiver and Reimer (1993) and determined using CALIB REV.5.0.1; ranges reported for all peaks with $P > 0.25$. Potential age ranges shown in italics are refuted by older ages of trees growing on overlying alluvial surfaces.

[c] Estimated tree age in 1950 determined from tree diameter and growth rate curves. Values reported to individual year based on ring counting; values estimated to decade precision based on growth curves and data presented in Figure 4.

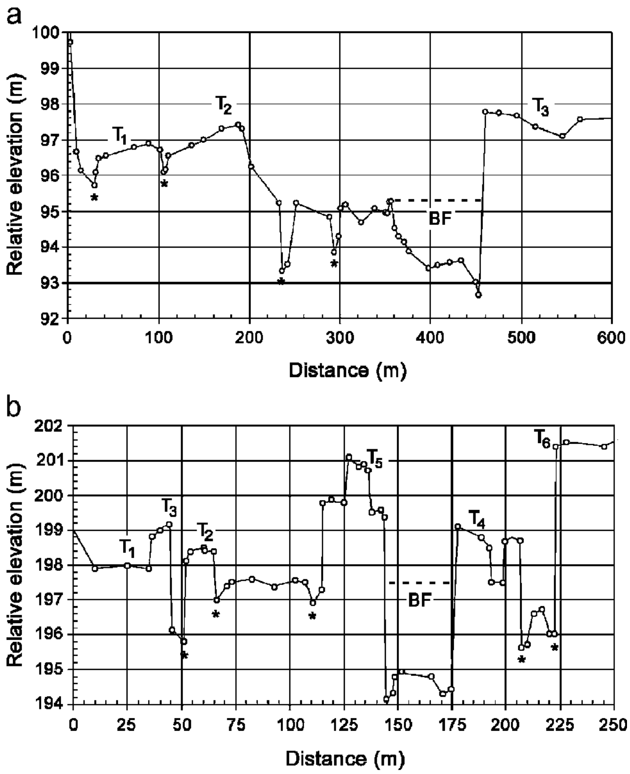

Figure 7. (a) Cross-section across Queets River floodplain from a transect surveyed between river miles 28 and 29 in 1995, at a location with a drainage area of 314 km^2 and a 1-yr recurrence peak flow of approximately 229 m^3/s. Terrace T_1 is approximately 1.5 m, T_2 is just over 2 m, and T_3 is almost 3 m above the bankfull elevation (BF). (b) Cross-section across floodplain of Alta Creek 1 km upstream from the confluence with the Queets River in 1994; drainage area of 23 km^2 and a 1-yr recurrence peak flow of approximately 17 m^3/s. Terrace surfaces range from about 0.5 m (T_1) to 4 m (T_6) above the bankfull elevation (BF). Asterix (*) mark locations of perennially flowing side-channels. Small circles represent surveyed points along each transect.

meters above the prior valley bottom. At each of these main stem sites, individual logjams coalesced to form jam complexes up to 450 m in width, 200 m in length, and 4–8 m in height above the channel banks. Although the influence of logjams on the vertical variability of floodplain elevations diminished with increasing drainage area, logjam complexes affecting floodplain development were found as far downstream as the Olympic National Park boundary, where the 110-m-wide river exceeds 3 m depth.

Figure 8. Photograph of logjam that raised the channel bed several meters after deposition of a key-member log. Note people and 3-m long stadia rod for scale.

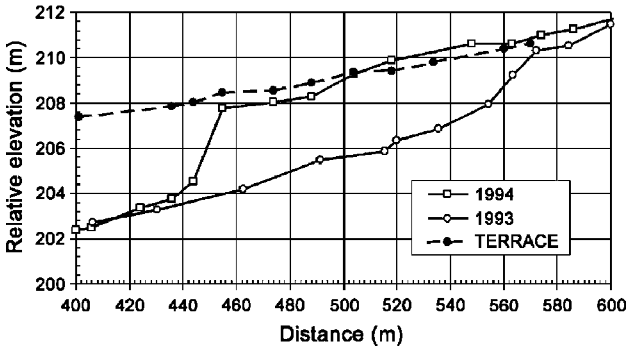

Figure 9. Longitudinal profile of Alta Creek in 1993 and 1994 showing active channel in both years, terrace surface with trees over 300 yr old. A channel-spanning logjam formed during the winter of 1993 at a location between 445 and 455 m along the profile.

The ability of logjams to form alluvial surfaces up to several meters higher than the bankfull elevation has been recognized for many years in steep confined channels (e.g., Keller and Swanson, 1979; Montgomery et al., 1996). In our surveys of the Queets River basin, the effects of logjams on channel aggradation were most dramatic in steep tributaries (those with slopes of 0.04–0.20) where valley-spanning jams elevated channels up to 5–11 m (Fig. 8), transforming boulder-cascade and step-pool reaches into gravel-bedded pool-riffle reaches (Abbe, 2000; Abbe and Montgomery, 2003). At one location along Alta Creek recruitment of a large, key-member log into a channel triggered aggradation such that within a year the channel rose over 4 m, depositing bedload material on a terrace surface and burying the trunks of >200-yr-old trees (Fig. 9). During this time, the maximum flow recorded at the Queets River gage only had a <2-yr recurrence interval. Formation of the new terrace did not require an unusually large discharge or an increased sediment supply. Instead it occurred after recruitment of logs capable of forming stable jams that could force local bedload deposition.

Figure 10. Photograph showing large logjam buried beneath >4-m-high terrace exposed along the main stem Queets River at river km 24 (Table 1; RM 16, drainage area of 552 km^2). The 1500-m^2 terrace surface had a slope of 0.0003, an order of magnitude less than the 0.0025 gradient of the active channel. Growing on the terrace surface are trees 250–350 yr old; the 2σ range of calibrated ^{14}C dates (cal yr B.P.) for buried logs and organic debris range from 532–656 cal yr B.P. to 1063–1176 cal yr B.P.

The most dramatic example we found of a fill terrace terminating above a buried logjam was in an almost 100-m-wide reach of the lower Queets River with an upstream catchment area of 556 km^2. The buried jam was exposed from within a >4-m vertical section of imbricated gravel mantled by <10 cm of sand (Fig. 10). The associated terrace surface was close to horizontal and supported 2- to 2.5-m-diameter trees estimated to be 250–300 yr old. Calibrated ^{14}C dates for five of the logs in this buried jam ranged from 600 to 1200 cal yr B.P.

Discussion

Many studies have shown how large wood introduces physical complexity to streams and rivers, but the close correspondence between the age of buried logjams and the associated patches of old-growth forest confirm the hypothesized role of logjams as a significant factor in the formation of valley-bottom landforms such as floodplains and terraces. The dynamic and variable nature of wood debris accumulation and its effect on lateral and vertical channel positions creates complex alluvial landscapes in old-growth forest river valleys. Lateral channel migration rates estimated from bank erosion rates provide minimum estimates of how far the channel would be expected to migrate over a set time interval in the absence of avulsion to a previous channel position. Persistence of logjam-formed hard points would lead to forest patches hundreds of years older than the surrounding floodplain and riparian forest. Such old-growth forest patches would provide a source of large logs necessary to form stable jams, resulting in a positive feedback between logjam formation, the creation of stable hard points, and development of old-growth forest patches in the riparian forest. Our surveys along the entire main stem Queets River indicate that rather than simply augmenting conventional processes of floodplain formation, logjam-induced processes produce a complex mosaic of alluvial surfaces across the valley bottom.

How much of the valley floor may be formed in this manner? In every reach surveyed, we found a patchwork morphology distinct from conventional floodplains. Local channel bed aggradation associated with stable logjam formation imparts up to several meters of vertical relief to the composite surface of individual fluvial landforms on the active valley bottom. Upon first inspection in the field, many such features would be erroneously interpreted as inactive Holocene terraces. Unfortunately, detailed topographic data, such as Lidar-surveyed digital elevation data, are unavailable to estimate the extent of such patches across the valley bottom of the Queets River.

While the scale of individual logjam-constructed alluvial surfaces is much smaller than terraces formed by changes in base level or climate, the number and extent of such surfaces along the Queets River show that such processes can affect a substantial portion of the valley bottom. Greenwald and Brubaker's (2001) finding that the two lowest terraces at their study site on the Queets River both date from ca. 500 yr B.P. despite a 4.5-m difference in elevation (3.5 vs. 8 m above the river level) shows that height above the river is not a simple surrogate for landform age, as is commonly assumed (e.g., Fonda, 1974; McKee et al., 1982). Moreover, their results indicate that the channel was locally 5 m or so higher just a few centuries ago. Compilation of field measurements from western Washington rivers shows that logjam-forced aggradation commonly causes >1–2 m vertical variability in channel bed elevation above the bankfull stage (Brummer et al., unpublished data), providing additional support for the generality of observations reported elsewhere (Abbe and Montgomery, 1996, 2003; O'Connor et al., 2003). As the height above the floodplain to which bedload aggrades reaches up to several times the diameter of key-member logs capable of initiating a logjam (Montgomery et al., 2003), channels flowing through old-growth forests are likely to move up and down by at least a few meters over the time scale for senescence of a site-potential tree, leaving depositional surfaces of varying elevation in its wake under the current climate and without tectonic forcing. Bank exposures along the Queets River are dominantly gravel, indicating a floodplain composed primarily of bedload material. Because conventional models for floodplain formation cannot explain these landforms, and they are consistently associated with individual stable logjams, we conclude that the morphology of the Queets River floodplain results from integration of local, logjam-mediated deposition.

Conventional models for floodplain formation invoke either point bar or overbank deposition. Consequently, valley bottoms formed by a complex of logjam-forced alluvial surfaces are not conventional floodplains. Consider, however, that floodplains may be defined as follows:

> The floodplain is the flat area adjoining a river channel constructed by the river in the present climate and overflowed at times of high discharge (Dunne and Leopold, 1978, p. 600).

Moreover, floodplains need not be uniformly flat.

> The flood plain may be highly uneven and dissected by irregular scour channels... (Leopold et al., 1964, p. 319).

These definitions of a floodplain hold for an alluvial valley bottom formed by a patchwork of local logjam-forced surfaces, given that the composite land surface is constructed by contemporary processes active in the current climate and tectonic regime. Yet individual logjam-formed surfaces can rise higher than the bankfull channel elevation, and thus are inundated less frequently than a typical floodplain. What then should we call a valley bottom composed dominantly of such surfaces—a composite floodplain or a suite of pseudo-terraces?

We propose calling these composite surfaces "patchwork floodplains" to distinguish them from floodplains formed by conventional processes of point bar and overbank deposition. While local hydraulic effects of wood debris can influence local overbank deposition and rates of vertical accretion on active floodplains (Jeffries et al., 2003), patchwork floodplains form under the modern climate by coalescence of local depositional features with up to several meters of relief on the surface of the active valley bottom (i.e., floodplain). Consequently, we propose that formation of individual floodplains may be considered to reflect the competing influences of point bar migration, overbank deposition, and logjam-forced aggradation.

In short, our observations from extensive field surveys in old-growth forest along the Queets River indicate that logjam-mediated processes provide a distinct mechanism of floodplain development. The formation of stable logjams founded on large key-member logs creates “hard points” that form local alluvial surfaces and which act as natural revetments that protect patches of riparian forest from disturbance by channel migration. Logjam-protected patches of old-growth conifers, in turn, produce the large trees necessary to initiate stable logjams. This feedback promotes development of a patchwork floodplain composed of a mozaic of alluvial surfaces that impart substantial local relief to the active floodplain.

The integrated effects of stable logjam formation result in morphologically complex floodplains that create a diverse range of physical habitats such as ecologically important side channels. A number of studies have described channel avulsions triggered by wood accumulations in a variety of environments (Harwood and Brown, 1993; McKenney et al., 1995; Piégay and Marston, 1998; Collins and Montgomery, 2002; Abbe and Montgomery, 2003; Jeffries et al., 2003). In forested regions, the formation of stable logjams promotes formation of an anastomosing channel morphology (Harwood and Brown, 1993; Collins and Montgomery, 2002; Montgomery et al., 2003; O’Connor et al., 2003). In addition, local deposition catalyzed by logjams can form alluvial surfaces up to several meters higher than the active floodplain in response to intrinsic channel dynamics rather than the changes in external boundary conditions required by conventional models.

Due to the long history of river clearing in the temperate latitudes, it is difficult to constrain the degree to which the dramatic reduction in mature riparian forests in the continental United States and Europe has reduced the role of fluvial logjams as a fundamental biogeomorphic process. Large riparian trees historically grew in a far wider range of regions and climates than today: the extensive historical riparian forests in the Midwestern and Northeastern portions of the United States included 5-m-diameter, 50-m-tall sycamores (*Platanus occidentalis*) growing on the Wabash River floodplain of Southern Illinois (Ridgway, 1872); 2-m-diameter, 55-m-tall white pine (*Pinus strobus*) in New England (Whitney, 1994); and 2-m-diameter, 24-m-tall Tulip trees (*Liriodendron tulipifera*) along the Ohio River (Atwater, 1818). Toulin’s description of timber in Kentucky and Virginia in 1793 notes wood large enough to function as key members in even relatively large rivers:

> As to the size of the timber, it is not uncommon to see the burr oak, in the best lands, five to seven feet through; the sycamore much larger, but generally hollow; the popular ten feet; and the hickory, which in the eastern country seldom exceeds one foot, often three feet through (Toulmin, 1948, p. 74).

Our findings demonstrate the need for care in interpreting alluvial terraces in forested environments and areas that previously hosted large trees, as well as for interpreting fluvial sequences in the geologic record after forests first evolved over 350 Myr ago. In particular, stratigraphic patterns observed in fluvial deposits that have been interpreted as climate fluctuations to some degree may simply record previously unrecognized influences of logjams on the vertical variability of forest rivers. Moreover, the observation that active floodplains of forest rivers can encompass a multi-elevation patchwork of alluvial surfaces violates the common assumption that elevation provides a surrogate for the age of valley-bottom landforms.

Naturally, we would expect logjam-formed patchwork floodplains to be most significant along rivers with a high supply of large trees capable of forming stable logjams and where more decay-resistant woods are found. Hence, we expect this process to have been far more widespread and important historically than at present since native riparian forests have been cleared across most of Europe, North America, and Asia. Still, the fundamental effects of big trees on the floodplains of forest rivers like the Queets mean that changes in wood size and abundance can result in loss of side channels and topographic complexity of the valley bottom. While the development of patchwork floodplains requires active bedload transport typical of tectonically active regions and valley floor turnover rates slow enough to allow the initial growth of large trees, it appears that the primary requirement to maintain the system, once established, is a supply of trees large enough to form key-member logs and initiate the processes of stable logjam formation and the associated forest succession leading to a positive feedback that can transform valley floors. In this sense, large trees function like a keystone or foundational species that catalyze environmental changes that not only foster their own success but reshape their ecosystem as well.

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