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Holocene Paleoflood Hydrology of the Lower Deschutes River, Oregon

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Flood deposits at four sites along the lower Deschutes River, Oregon, were analyzed to determine magnitude and frequency of late Holocene flooding. Deposit stratigraphy was combined with hydraulic modeling at two sites to determine ranges of likely discharges for individual deposits. Combining these results with gaged flood data provides improved flood frequency estimates at the Axford site. The completeness and age spans of preserved flood chronologies differed among the four sites, but results were consistent for the largest floods of the last 5000 years. Single floods exceeded 2860-3800 m^3/s ~4600 cal yr BP, 1060-1810 m^3/s ~1300 cal yr BP, and 1210-2000 m^3/s <290 cal yr BP (corresponding to the historic flood of 1861). No floods have exceeded 2860-3770 m^3/s since the flood of ~4600 cal yr BP. Incorporating these results into a flood frequency analysis based on maximum likelihood estimators gives slightly higher flood quantile estimates and narrower confidence limits compared with analysis of gage data alone. Discharge and 2σ uncertainty for the 100-yr flood calculated using combined paleoflood and gaged records is 1120 +310/-240 m^3/s, compared with 930 +650/-250 m^3/s from analysis of only gaged floods. This revised estimate for the 100-yr flood is slightly greater than our estimate of 1060 m^3/s for the February 1996 flood at Axford, a finding consistent with historical records of two floods comparable to the 1996 flood in the last 140 years and with stratigraphic records of several like floods during the last ~1000 years.

INTRODUCTION

Flood-frequency analyses for rivers are commonly based on historical records of limited extent. In the western United States, these records go back a century at most, and are insufficient to determine with confidence the frequency distributions of flood discharges, especially for tail regions of distributions encompassing rare, large floods. To augment short or nonexistent historical records, various geologic methods have been developed and applied to determine the number, timing, and magnitude of past floods and effectively integrate this information into flood-frequency analyses [*Stedinger and Cohn*, 1986; *Stedinger and Baker*, 1987; *Blainey et al.*, 2002; *Jarrett and England*, 2002; *Levish*, 2002; *Webb et al.*, 2002]. Such studies, termed "paleoflood

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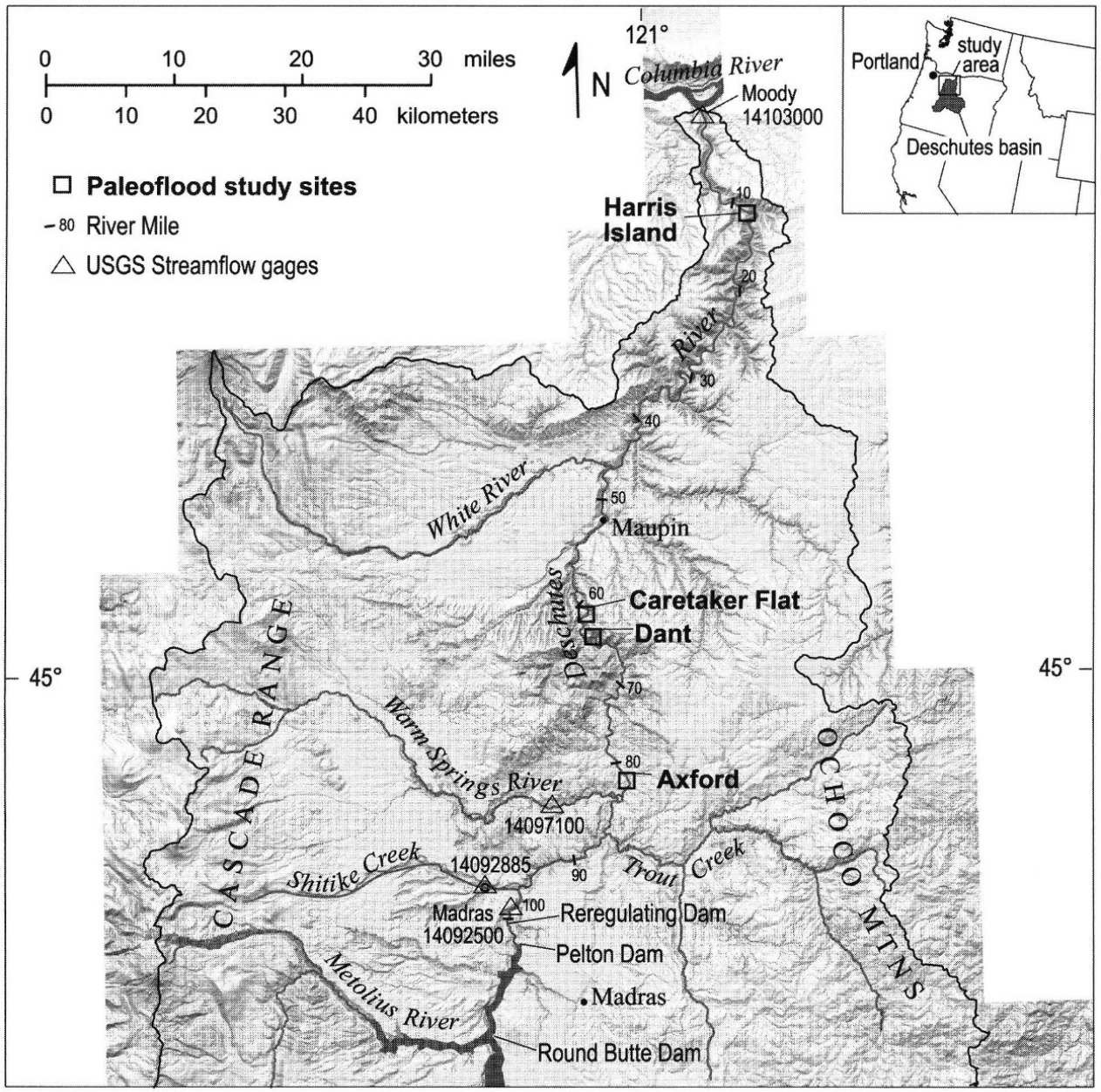


Figure 1. Area map showing study sites, major watercourses, streamflow gage sites, and major dams.

hydrology" by *Kochel and Baker* [1982], can reduce the uncertainty in estimates of long return-period floods, providing information pertinent to the design or retrofitting of dams and other floodplain structures that require robust information on high-magnitude, low-frequency floods [*Baker et al.*, 2002]. On the lower Deschutes River of central Oregon, relicensing of the Pelton-Round Butte dam complex has motivated examination of the frequency of large and rare floods so as to assess the adequacy of existing spillway capacity. The results also bear on regional flood climatology and the effects of large floods on channel geomorphology, two other common applications of paleoflood information [*Ely et al.*, 1993; *O'Connor et al.*, 1986].

The Deschutes River drains approximately 26,860 km^2 of north-central Oregon, delivering an average annual runoff of 125 m^3/s to the Columbia River at its confluence 160 km

east of Portland [*O'Connor, Grant, and Haluska*, this volume]. The flood-deposit sites analyzed in this study are within the lower 160 km of canyon downstream of the Pelton-Round Butte dam complex, a set of three hydropower dams and river regulating structures operated by Portland General Electric and the Confederated Tribes of Warm Springs (Figure 1).

Stratigraphic analysis of four sites of late Holocene slackwater deposits was combined with hydraulic modeling and flood frequency analysis to improve estimates of the magnitude and frequency of floods with long return periods. Fine-grained slackwater sediment is deposited during floods in zones of decreased flow velocity in overbank areas and along the margins of channels [e.g., *Ely and Baker*, 1985; *Kochel and Baker*, 1988]. Where such depositional areas are maintained by relatively long-lived, stable features, such as bedrock protrusions, large boulder bars, or tributary valleys, slackwater deposits can accumulate for thousands of years, forming a stratigraphic record of multiple large floods. This study is similar to others that have been conducted in the western United States and other locations, including the Pecos River, Texas [*Kochel and Baker*, 1982]; Verde River, Arizona [*Ely and Baker*, 1985; *House et al.*, 2002]; Columbia River, Washington [*Chatters and Hoover*, 1986]; Boulder Creek, Utah [*O'Connor et al.*, 1986]; Colorado River, Arizona [*O'Connor et al.*, 1994]; Narmada River, India [*Ely et al.*, 1996]; John Day River, Oregon [*Orth*, 1998; *Orth and Ely*, 1998]; and Snake River, Idaho and Oregon [*Rhodes*, 2001]. Although this study of Deschutes River flood frequency was conducted to assess the adequacy of existing spillway capacity, the results also bear on other ongoing studies, such as regional flood climatology and the effects of large floods on channel geomorphology.

Historical Flooding

Gaged discharge records from the U.S. Geological Survey (USGS) stream gage at Moody, Oregon, near the confluence of the Deschutes River with the Columbia River, extend back to water year 1898 (Figure 2). Additionally, a USGS gage

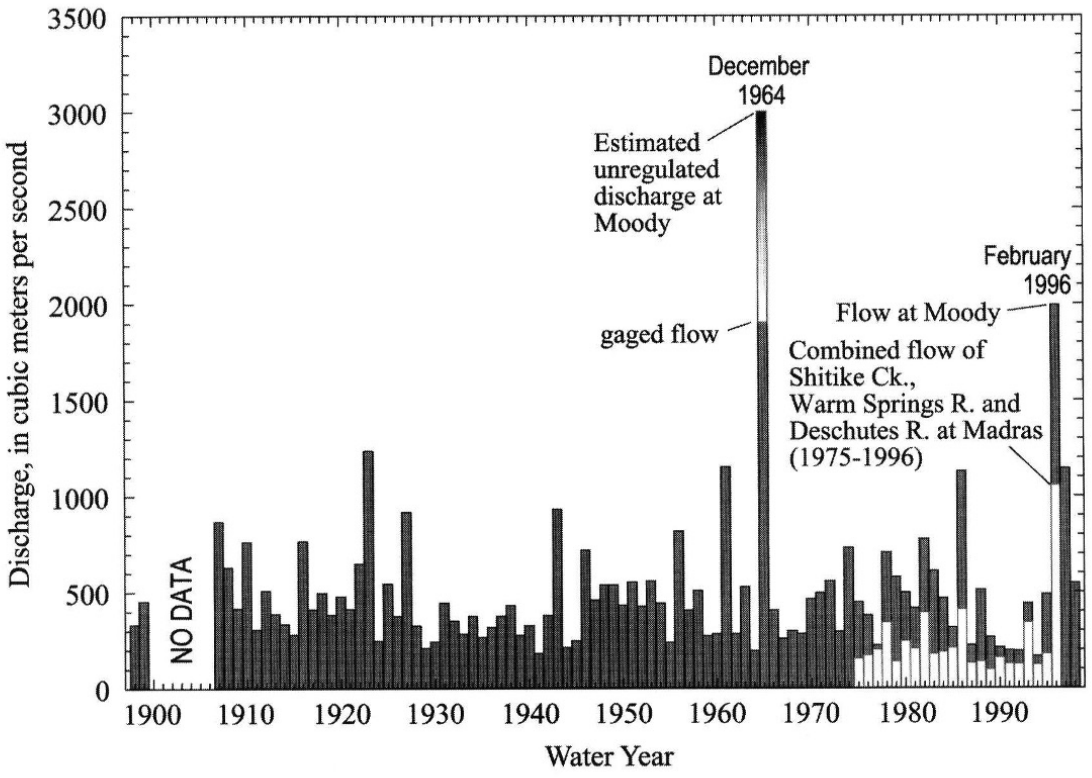


Figure 2. Annual peak flows of the Deschutes River at Moody, Oregon (USGS gage station 14103000). The unregulated discharge for the December 1964 flood was estimated by *Waananen et al.* [1971] from filling rates of Lake Billy Chinook (behind Round Butte Dam) and Prineville Reservoir (behind Bowman Dam on the Crooked River). Dark bars represent the flow at Moody, open bars represent the combined flow of three upstream gages used to estimate the peak flow at the Axford study site.

has operated near the location of the Pelton-Round Butte dam complex since 1923 (Deschutes River near Madras). Two gaged floods stand out in the record at Moody, both of which occurred after completion of the Pelton-Round Butte dam complex. A flood in December 1964 was measured at 1910 m^3/s, and would have been larger if not for substantial flow storage by the recently-completed Pelton-Round Butte dam complex and other upstream reservoirs [*Waananen et al.*, 1971]. Another flood, the largest in the systematic record, occurred in February 1996 and measured 1990 m^3/s. Upstream reservoirs captured much less of this flow than for the 1964 flood [*Fassnacht*, 1998]. No other gaged floods have exceeded 1240 m^3/s at Moody. Prior to the gaged record, newspaper reports indicate that an exceptionally large flood occurred on the Deschutes River in December 1861, during widespread regional flooding [*Engstrom*, 1996; *Miller*, 1999]. The floods of 1861, 1964, and 1996 resulted from regional rain-on-snow events when warm and wet subtropical storms melted substantial low-elevation snowpacks.

Suitability for Paleoflood Studies

The lower Deschutes River is well suited for paleoflood studies based on slackwater deposits [*Kochel and Baker*, 1982]. It is confined along its entire length either by steep bedrock walls or by massive, stable blocks of landslide material. At certain sites, floods deposit silt and sand close to maximum flood stages, commonly in horizontally layered or laterally inset deposits that record several floods. Such sand and silt deposits provide reliable evidence for the maximum stage achieved by the depositing floods, providing a basis for calculating flood discharge. For example, during the February 1996 flood, sand and silt was deposited to within 10 to 20 cm of the maximum flood stage at several places along the lower Deschutes River, as indicated by local organic flotsam and eyewitness accounts.

The channel of the Deschutes River has been laterally and vertically stable for at least the last 100 years, thus increasing confidence in discharges estimated for paleoflood deposits based on present topography. Comparisons between aerial photographs taken prior to the February 1996 flood and current channel and overbank morphology show that there was little lateral channel movement during that flood [*Curran and O'Connor*, this volume]. Likewise, long-term trends in bed elevation at the Madras gaging station show little change [*Fassnacht et al.*, this volume]. The absence of channel gravel interbedded with the slackwater sediment at any of the sites further indicates that the channel bed elevation has probably remained relatively unchanged for at least the period of slackwater sediment accumulation.

Study Sites

Four sites of fine-grained flood deposits downstream of the Pelton-Round Butte dam complex were subjected to a detailed paleoflood analysis (Figure 1). Three sites, Axford, Dant, and Caretaker Flat, were located within a 32-km reach between River Mile (RM)[1] 81.6 and 62.0. A fourth site at Harris Island was much farther downstream at RM 11.6. No large tributaries enter the Deschutes River between the Axford, Dant, and Caretaker Flat sites. Consequently, there should be little difference in the frequency and magnitude of large mainstem floods at these three sites. The Harris Island site, in contrast, receives runoff from several large intervening tributaries. We measured stratigraphic sections and obtained chronological information at all four sites, but flow modeling and discharge estimation for this study were conducted only at Axford and Dant. Flood frequency analysis was conducted on the basis of the flood chronology and discharges determined at the Axford site. *Beebee and O'Connor* [this volume] report on hydraulic flow modeling for the Harris Island site.

STRATIGRAPHY AND PALEOFLOOD CHRONOLOGY

Stratigraphic analysis and geochronology of flood slackwater deposits formed the basis for our interpretations of the number, magnitude, and timing of large floods on the Deschutes River during the last several thousand years. From deposit elevation and thickness, especially in comparison with local evidence of the stages and deposits of the February 1996 flood, we inferred the relative magnitude of the floods associated with the different deposits.

Methods

Slackwater deposits were measured and described using standard field techniques [e.g., *Webb and Jarrett*, 2002]. We observed and recorded sediment characteristics, presence and type of fluvial structures, cohesiveness, color, moisture content, thickness, degree and type of bioturbation, and types of contacts between beds. Evidence of depositional hiatus between beds, such as soil formation, *in situ* traces of

[1] Units given are metric except for locations, which are given as river miles (RM), or miles upstream from the river mouth as marked on USGS topographic maps. These values are close to, but not necessarily the same as, actual distances along the present channel. Fractional river miles given herein are based on interpolations between these published river miles.

vegetation, and evidence of cultural occupation were used to define separate units recording individual mainstem floods, as well as units formed by locally derived colluvium and tributary deposits. The elevations of key stratigraphic boundaries and surfaces were surveyed and traced between adjacent sections where possible.

While examining stratigraphic sections, we collected samples of volcanic tephra and organic material for identification and radiocarbon dating. All radiocarbon ages are reported in dendro-calibrated years before AD 1950 (cal yr BP) unless otherwise indicated [*Stuiver and Reimer*, 1993; *Stuiver et al.*, 1998].

Results

Axford. The site farthest upstream is near a homestead called Axford at RM 81.6 (Figure 1). Here, the river flows in a narrow channel bounded by steep valley slopes formed in landslide blocks of the John Day Formation and Quaternary fill terraces. The site of Holocene slackwater accumulation is adjacent to one of these Quaternary terraces on the left side of the channel. The slackwater deposits underlie three distinct surfaces, ranging from 3.3 to 5.6 meters above low-flow river level (Figure 3). Recent erosion has exposed the deposits underlying all three surfaces.

Sections 1-3 of Figure 4 were described from vertical cutbanks, and a fourth section was described from a pit dug into the highest surface about 50 m upstream. Each of these sections contains a sequence of silty and sandy flood deposits from the Deschutes River. Beds representing individual floods were distinguishable by sharp contacts showing evidence of subaerial exposure. Other boundaries separating beds of contrasting grain size, color, or sedimentary structures lack evidence of subaerial exposure and were inferred to record pauses or changing flow conditions during individual floods. Additionally, the top of Section 3 has two beds of sandy silt with abundant angular pebbles and granules, which we infer to be colluvium or fan deposits derived from the adjacent hillslope.

Each of Sections 1-3 records six to eleven separate floods, based on the deposits and contacts between distinct beds. Tracing of units and radiocarbon dating indicate that the sections are only partially inset, and some floods are recorded in more than one of the stratigraphic sections, resulting in an estimated nineteen to twenty-one floods represented in the four sections. Samples collected from this sequence (organic detritus, charcoal and shells) yielded radiocarbon ages ranging from about 6000 to 315-0 cal yr BP (Figure 4; Table 1). The oldest age of 6200-5905 cal yr BP was obtained from near the bottom of Section 3, indicating that the flood record at Axford spans parts of the last 6000 years.

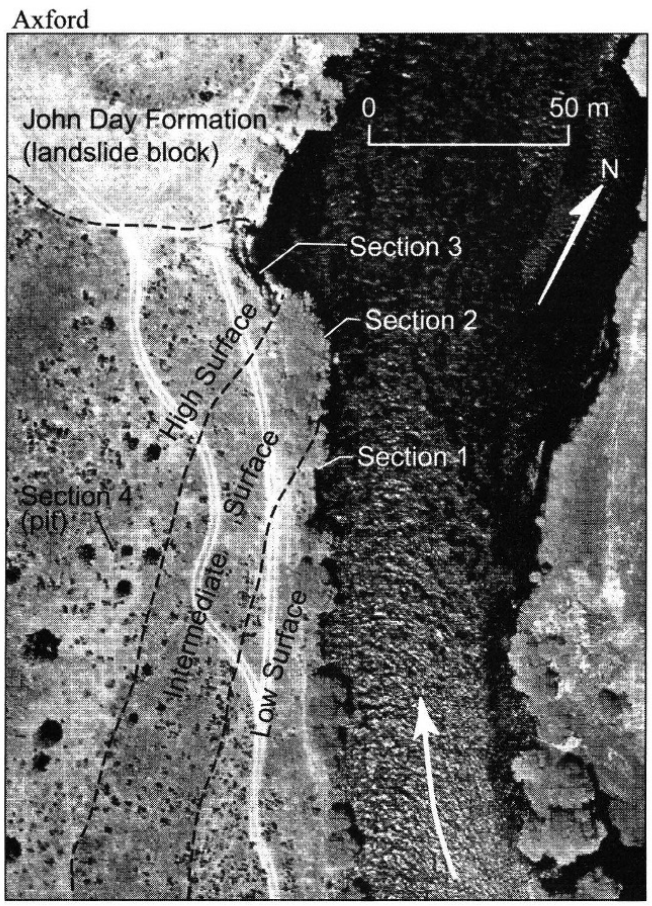


Figure 3. A 1995 1:2000 aerial photograph of the Axford study site showing the locations of Sections 1-4 and the three distinct surfaces composed of fine-grained slackwater flood deposits.

Several radiocarbon ages in Section 2 come from freshwater clamshell fragments. Dates on shells using radiocarbon analysis are often subject to hard-water effects (^{14}C levels lower than atmospheric CO_2 due to incorporation of older carbon dissolved in the water) and generally yield erroneously old ages [*Trumbore*, 2000]. Radiocarbon dating of freshwater clamshells and water on the Crooked River in the upper Deschutes River basin indicate that the shell dates may overestimate actual ages by approximately 300 years (D. Levish, U.S. Bureau of Reclamation, written communication, 2000).

Two prominent units can be physically traced between Sections 2 and 3. A thin, dull-orange, silty unit with abundant root and burrow vesicles forms a prominent ledge that is traceable across much of the outcrop (Figure 5).

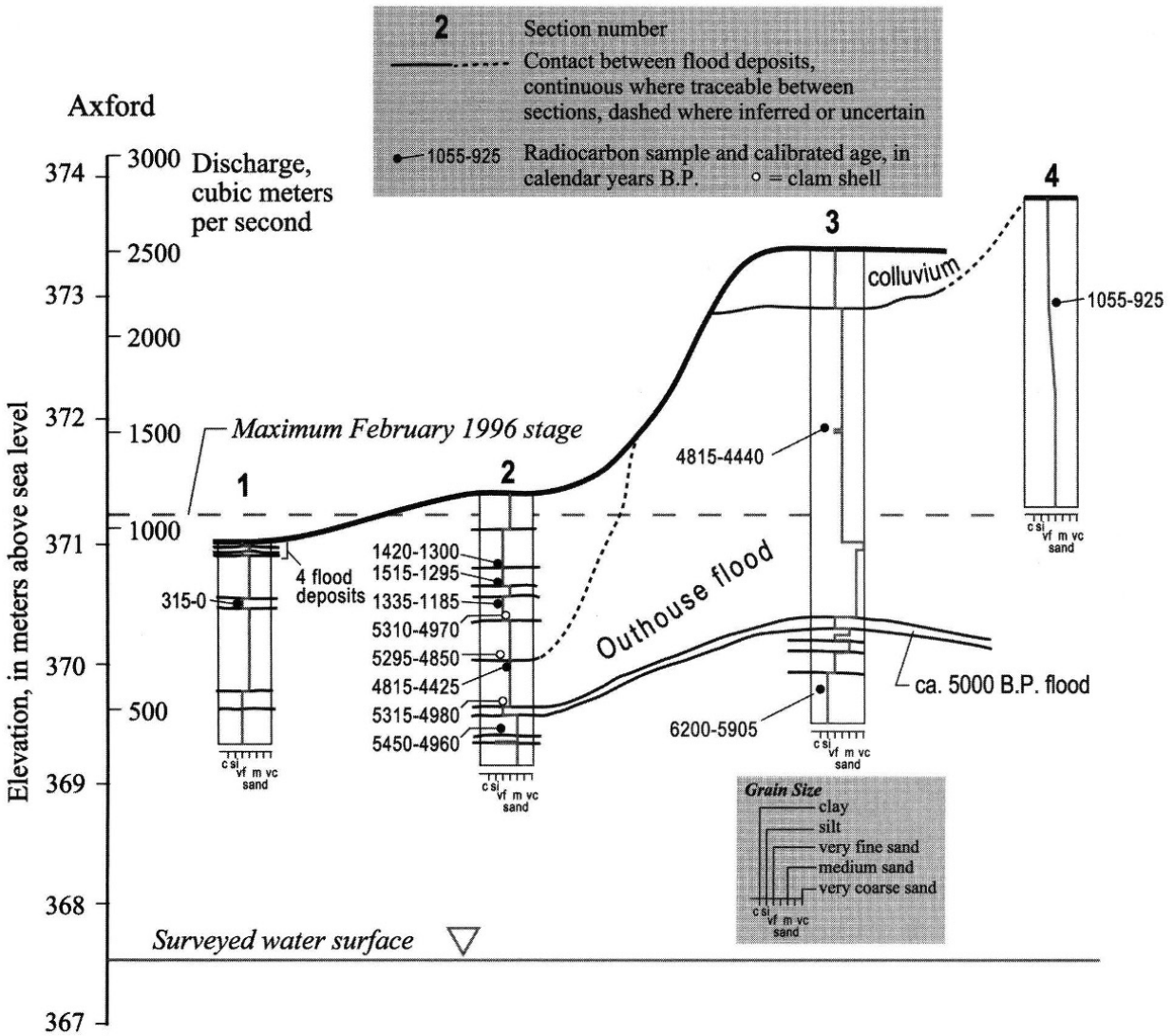


Figure 4. Stratigraphy of slackwater flood sediments at Axford site. Scale at base of sections indicates grain size.

Radiocarbon ages from units above and below in Section 2 constrain this deposit to be about 5000 cal yr BP (Figure 4)

The thin orange bed is overlain in Section 3 by a 2.5-m thick deposit of gray, medium-to-coarse sand with pebbly zones, grading up to a tan fine sand with silt lenses. This thick bed forming much of Section 3 can be traced to a 35-cm thick deposit of fine sand overlying the ~5000 cal yr BP flood bed near the bottom of Section 2. Detrital charcoal sampled from this unit in both Section 2 and 3 gave ages of about 4600 cal yr BP, consistent with a 5315-4980 cal yr BP age from a clamshell also collected from this deposit. At Section 2, the deposit is capped by an accumulation of clamshells (5295-4850 cal yr BP) exposed for 10 m along the cutbank. Associated pieces of tooled flint indicate that this shell midden is a cultural feature left by aboriginal humans who occupied the site after the deposition of this unit.

We infer that this high, thick, and coarse deposit of ~4600 cal yr BP records a single, exceptionally large, flood. Apparent stratigraphic boundaries within the deposit are gradational zones of changing grain size without any of the common indicators of depositional hiatus, such as incipient soils, colluvium, or erosional surfaces [*Kochel and Baker*, 1988; *Retallack*, 1988]. This is the highest and thickest slackwater deposit at Axford, with a deposit top nearly 1.5 m higher than any other flood deposit. Additionally, the deposit also contains the coarsest clasts of any mainstem

Table 1. Radiocarbon ages of samples from stratigraphic sections.

Site/ Section	Sample (field label)	Material	Corrected Conventional ^{14}C Age BP ±1sigma[a]	Dendrocalibrated 2σ Age Range(s), in calendar years B.P.[b]	$^{13}C/^{12}C$ Ratio ($^{o}/_{oo}$)	Laboratory ID#
Axford/1	D2-1b	charcoal	220±40	315- 0	-25.8	Beta 131826
Axford /2	D2-1	shell	4420±60	5295-4850	-8.7	Beta 136513
Axford /2	D2-2	charcoal	1480±40	1420-1300	-25.8	Beta 131827
Axford /2	D2-3	charcoal	1490±45	1515-1295	-25.3	AA36673
Axford /2	D2-5	shell	4500±45	5310-4970	-9.48	AA36674
Axford /2	D2-7	charcoal	4530±70	5450-4960	-23.8	Beta 131829
Axford /2	D2-8	charcoal	1360±50	1335-1185	-27.7	Beta 131830
Axford /2	D2-10	charcoal	4080±50	4815-4425	-24.9	Beta 131831
Axford /2	D2-11	shell	4520±45	5315-4980	-9.6	AA36675
Axford /3	5/14/99-2(1)	charcoal	4090±40	4815-4440	-20.7	Beta 131835
Axford /3	5/14/99-2(3)	charcoal	5260±70	6200-5905	-24.1	Beta 131836
Axford /4	7/8/99-1(1)	charcoal	1060±40	1055-925	-26.4	Beta 136512
Dant/2	D5-8	charcoal	1310±50	1305-1155	-26.5	Beta 131833
Dant/2	D5-10	charcoal	140±40	290-5	-24.7	Beta 131834
Dant/2	3/17/00-1(3)	charcoal	1836±42	1875-1630	-25.3	AA37926
Dant/2	8/23/00-1(1)a	conifer charcoal[c]	2980±40	3310-3000	-22.3	Beta 152465
Dant/2	8/23/00-1(1)b	charcoal	2020±40	2060-1880	-26.9	Beta 152466
Dant/2	8/23/00-1(2)a	conifer charcoal[c]	2150±40	2310-2010	-24.6	Beta 152467
Dant/2	8/23/00-1(2)b	Rosaceae charcoal[c]	2000±40	2030-1870	-24.3	Beta 152468
Dant/2	8/23/00-1(2)c	charcoal	2530±40	2750-2470	-23.5	Beta 152469
Dant/2	8/23/00-1(3)a	Alnus charcoal[c]	2160±40	2320-2030	-26.9	Beta 152470
Dant/2	8/23/00-1(3)b	conifer charcoal[c]	1380±40	1330-1260	-23.7	Beta 152471
Caretaker/low	7/16/98-1(1)	charcoal	100±50	280-5	-26.8	Beta 121605
Caretaker/low	7/16/98-1(6)	charcoal	270±40	435-365 325-275 175-150 5-0	-26.3	Beta 121606
Caretaker/low	7/16/98-1(7)	charcoal	910±50	930-705	-26.4	Beta 121607
Caretaker/low	7/16/98-1(3)	charcoal	850±50	910-675	-23.4	Beta 121605
Caretaker/low	7/16/98-1(4)	charcoal	900±60	935-685	-24.6	Beta 124897
Caretaker/high	5/17/99-2(1)	charcoal	2850±50	3160-2825	-28.9	Beta 131837
Caretaker/high	7/16/98-1(18)	shell	7730±90[d]	7920-7570	--	Beta 121608
Caretaker/high	7/16/98-1(22)	shell	7730±60[d]	7895-7610	--	Beta 121609
Harris Island	7/1/98-1(17)	bone collagen	280±40	445-355 330-280 170-155 5-0	-20.3	Beta 121604
Harris Island	7/1/98-1(15)	charcoal	140±50	290-0	-24.8	Beta 124901
Harris Island	7/1/98-1(16)	charcoal	580±70	665-500	-25.6	Beta 121603
Harris Island	7/1/98-1(11)	charcoal	410±40	520-425 390-320	-25.7	Beta 121601
Harris Island	7/1/98-1(13)	charcoal	310±40	475-285	-27.7	Beta 121602
Harris Island	7/1/98-1(7)	charcoal	400±50	525-310	-26.1	Beta 124896
Harris Island	7/1/98-1(8)	charcoal	370±50	515-300	-27.7	Beta 121599
Harris Island	7/1/98-1(1)	charcoal	780±40	745-660	-25.1	Beta 124895
Harris Island	7/1/98-1(2)	bone collagen	300±40	465-285	-21.6	Beta 121598
Harris Island	7/1/98-1(6)	charcoal	300±40	465-285	-24.3	Beta 124900
Harris Island	7/1/98-1(10)	charcoal	520±40	555-500	-29.4	Beta 121600

[a] Radiocarbon ages (in ^{14}C yr BP) are calculated on basis of Libby half-life for ^{14}C (5568 years). The error stated is ±1σ on basis of combined measurements of the sample, background, and modern reference standards. Age referenced to AD 1950. Where no measurements of $^{13}C/^{12}C$, a value of -25‰ assumed for determining corrected conventional age.

[b] Calibration on basis of INTCAL98 [*Stuiver et al.*, 1998] and a laboratory error multiplier of 1, referenced to AD 1950. The 2σ range(s) encompass the intercept of the corrected conventional radiocarbon age ± 2σ with the calibrated calendar time-scale curve.

[c] Sample identification by Paleo Research, Golden, Colorado.

[d] Corrected conventional radiocarbon age includes a local reservoir correction of 390±25 yr.

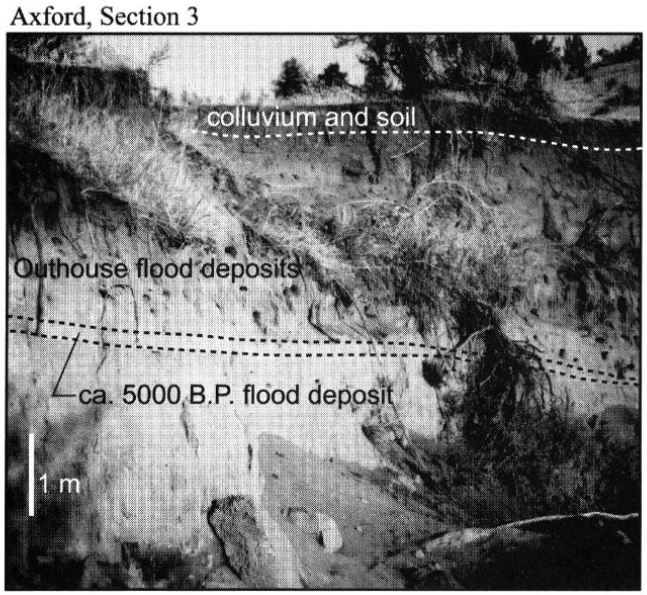


Figure 5. Photograph of Section 3 at Axford. The ~5000 BP flood deposit is a thin, light-colored resistant unit. The overlying >2-m thick Outhouse flood sediment is less cohesive. Capping the section is ~0.5 m of darker colluvium and fan deposits from the adjacent hillslope. The Deschutes River flows from left to right and the top of the exposure is 5.6 meters above river level.

fluvial deposits exposed at Axford. This deposit probably correlates to other features associated with an immense Holocene flood, known as the "Outhouse flood," that deposited large bouldery bars standing up to several meters higher than the limits of historical flooding at several locations along the lower Deschutes River [*Beebee and O'Connor*, this volume].

Section 4 is a 2.5 m pit in the highest surface of fine-grained sediments at Axford, contiguous with the surface at Section 3, but 40 cm higher and ~50 m upstream (Figures 3 and 4). The entire exposure consists of fine sand grading up to silty fine sand with no visible stratigraphic discontinuities suggesting depositional hiatuses. The upper 50 cm of the deposit is extensively bioturbated with small (~5 mm) silt-filled burrows and roots. On the basis of its thickness, sedimentology, and position, we infer that this deposit correlates with the ~4600 cal yr BP Outhouse flood deposit in Section 3. A single charcoal fragment from 70-cm depth in Section 4 yielded an age of 1055-925 cal yr BP, much younger than the radiocarbon ages on the Outhouse flood deposit and several overlying deposits in Sections 2 and 3. This charcoal was probably transported down from the surface by burrowing animals, and may not indicate the actual age of the deposit.

The stratigraphy and radiocarbon ages in Sections 2 and 3 at Axford contain deposits from at least twelve separate floods. Stratigraphy of the lower portions of Sections 2 and 3 at Axford indicates three or four flood deposits between 6200 and 4960 cal yr B.P, followed by four floods between 5450 and 4425 cal yr BP (including the distinct orange-colored bed, the Outhouse flood deposit, and the layers immediately above and below these). The upper part of Section 2 indicates at least three floods from 1335 to 1185 cal yr BP, and two subsequent flood deposits capping the section. There are no apparent flood deposits between 4400 and 1300 cal yr BP in the stratigraphic record at Axford. The uppermost unit in Section 2 could correlate with the inferred AD 1861 flood deposit that caps Section 2 at the Dant site, based on the relative stratigraphic position and calculated discharges, as described in more detail later in this paper.

One ambiguity in this chronology is the age of the deposit immediately overlying the Outhouse flood unit in Section 2. This flood has been included in the 5450-4425 ca yr BP age group based on the bracketing radiocarbon ages on shells. However, three factors indicate that it could be closer in age to the overlying 1335-1185 cal yr BP units: grain size and sedimentary texture are similar to the overlying units; the surface of the underlying Outhouse flood deposit is compacted and littered with shell middens and worked lithic flakes, perhaps indicating a long period of human occupation; and the upper bracketing radiocarbon age of 5310-4972 cal yr BP is from a single shell fragment that may have been reworked from the extensive shell middens underlying this flood deposit. The age of this deposit is not relevant for the flood-frequency analysis conducted for this study, but is mentioned here for the benefit of future studies that might make use of the chronological data from this site.

Section 1 exposes nine separate flood deposits that form a lower surface inset against the older sediments of Sections 2 and 3. A single radiocarbon age indicates that the youngest six deposits postdate 315 cal yr BP The limited bioturbation and absence of substantial pedogenic alteration at any of the contacts leads us to infer that all or most of the nine floods recorded by deposits in Section 1 postdate those of Sections 2 or 3. It is possible, however, that the two uppermost flood deposits of Section 2 could correlate with some of those in Section 1.

Although the elevation of local flotsam from the February 1996 flood indicates that it overtopped Section 1 by about 20 cm, there was no evidence of sediment from this flood on the surface. From the combined stratigraphic and chronologic evidence, we conclude that at least three floods at Axford equaled or exceeded the 1996 flood stage in the last 4600 years—the Outhouse flood and the upper two deposits

in Section 2, the heights of which are all above or within 10 cm of the 1996 flotsam. Several of the other deposits in Sections 1 and 2 could also represent floods comparable to that in 1996, particularly those within a meter of the maximum 1996 flood stage. However, the relative magnitudes of these paleofloods compared to the flood of 1996 are impossible to determine with certainty, because the depth of water that covered the deposits is not known. This type of vertically-accreting stack of flood deposits undergoes progressive self-censoring, as each successive deposit raises the threshold stage required for subsequent floods to be preserved in the record. The lower deposits could therefore have been emplaced by smaller floods than those later in the record. Similarly, a flood of the magnitude of the one in 1996 would have been more likely to leave a deposit if it had occurred earlier in the stratigraphic sequence and prior to Section 1 attaining its present height.

Dant. The second site is about 27 km downstream of Axford at RM 65.0, and is named for the nearby vacation community of Dant (Figure 1). At this site the river turns west and then south around a tight bend, as it flows through the resistant volcanic rocks of the Clarno Formation. A high, bouldery, gravel point bar has formed on the inside of this bend and is presumed to be a deposit of the Outhouse flood [*Beebee and O'Connor*, this volume]. Fine-grained flood deposits overlie and are inset against this bar at its downstream end, forming three surfaces with elevations ranging between 2.0 and 6.1 m above low-flow river level (Figure 6). The two lower surfaces are exposed in a cutbank along the left edge of the Deschutes River (Figure 7). Stratigraphic analysis and chronology at this site indicate that these three surfaces broadly correlate with those at Axford, with an upper surface most probably deposited by the large Outhouse flood, an intermediate surface of floods that largely pre-date the historical record, and a lower inset surface composed of relatively recent floods.

Three sections were analyzed at the Dant site (Figure 8). Sections 1 and 2 were described along the exposed vertical cutbank that transects two prominent surfaces about 2.0 and 3.8 m above low-flow river level (Figure 7). Section 3 is from an excavated pit on the highest surface approximately 20 m away from the left bank (Figure 6).

Section 2 consists of nine beds of silt and sand inferred to represent separate flood deposits. Along two contacts, pedogenic features, including extensive burrowing and accumulation of organic material, indicate significant depositional hiatuses. The other contacts between flood beds are also marked by evidence of subaerial exposure, including charcoal staining (indicating burning of surface vegetation) and isolated angular pebbles and granules inferred to be colluvium from the adjacent hillslope.

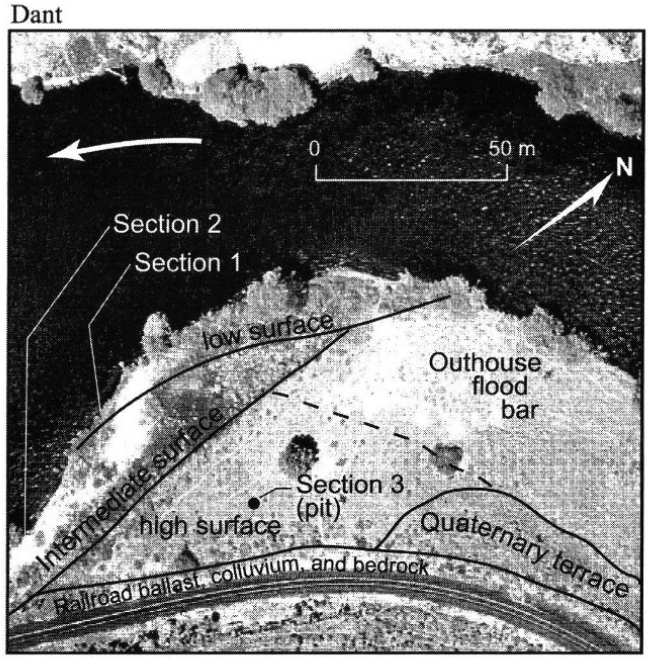


Figure 6. A 1995 1:2000 aerial photograph showing the Dant study site, including prominent fluvial surfaces and locations of Sections 1-3.

Ten radiocarbon ages were obtained from Section 2 (Table 1, Figure 8). Three were isolated charcoal fragments collected in the field; the remaining seven were charcoal and plant fragments separated from three bulk sediment samples. The bulk sediment samples were collected from the lower 10 cm of the second and third units from the top, and the upper 10 cm of the fourth unit from the top. Despite some ages inconsistent with stratigraphic position, the results from this section indicate that it was mostly deposited during the period 3300-1200 cal yr BP A charcoal fragment at the base of the uppermost unit of this section returned an age of 290-5 cal yr BP, indicating the uppermost unit is significantly younger than the rest of the section. An uncertainty in the ages of deposits in this section is presented by an age of 1305-1155 cal yr BP for an isolated charcoal fragment in the sixth unit from the surface. Given the seven older dates higher in the section and their general consistency with stratigraphic position, we consider the 1305-1155 cal yr BP age erroneous.

The stratigraphic record therefore indicates that the lowest five flood deposits in Section 2 at Dant are older than 2060-1880 cal yr BP These deposits likely correlate with some of the flood deposits in Section 2 at Axford. The two subsequent floods in the stratigraphic record probably occurred ca. 2060-1880 cal yr BP, a time period not repre-

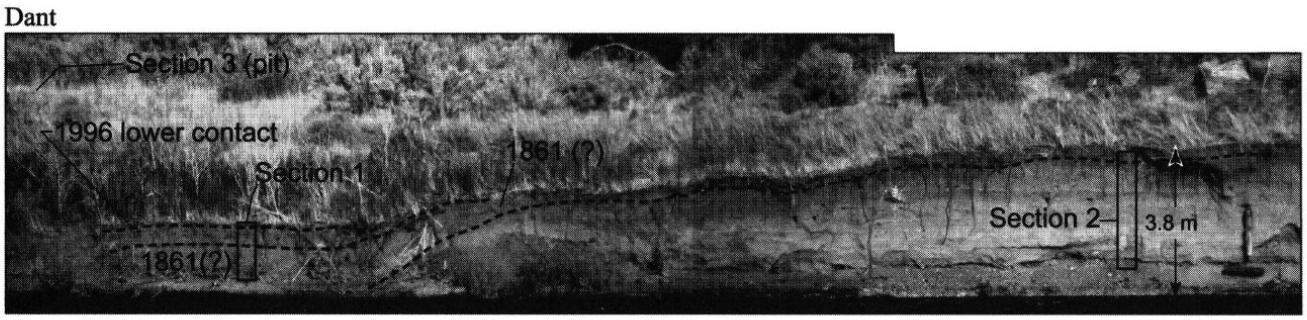


Figure 7. Two-photograph panorama of cutbank exposure at Dant, showing locations of Sections 1 and 2 and the approximate location of the pit from which Section 3 was described. Traceable contacts bounding the 1861(?) and 1996 floods are shown. The tops of Sections 1 and 2 are 2.0 and 3.8 m above river level, respectively.

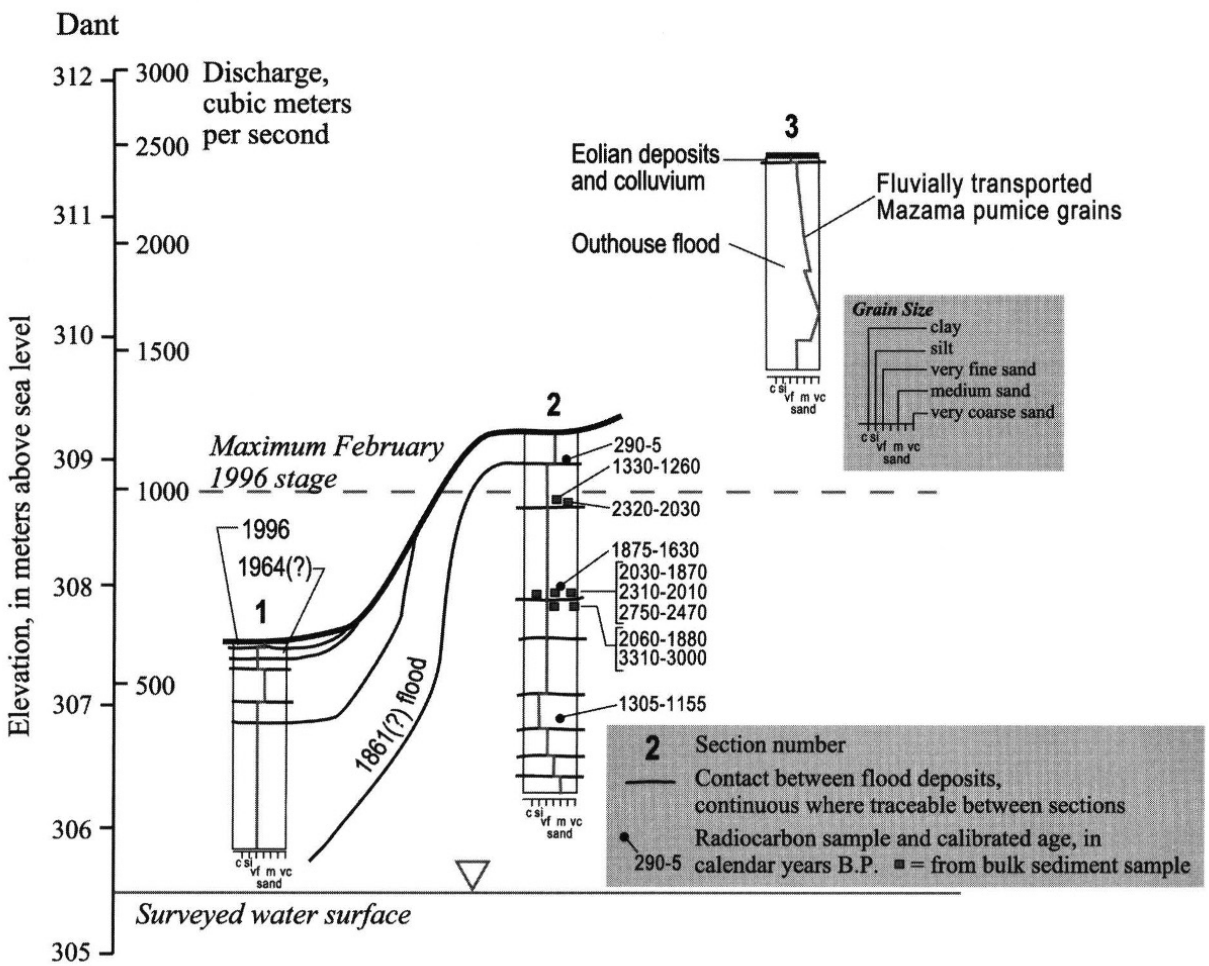


Figure 8. Stratigraphy of slackwater flood sediments at the Dant site. Scale at base of sections indicates grain size.

sented by deposits at the Axford site. The second deposit from the surface yielded an age of 1330-1260 cal yr BP Section 2 is capped by the flood deposit that postdates 290-5 cal yr BP.

The topmost, post-290 cal yr BP deposit in Section 2 (Figure 8) is a distinctive bed of tan silt that can be traced laterally for several tens of meters (Figure 7). The lower boundary contains abundant small fragments of disseminat-

ed charcoal along its length, indicating that the dated sample was from a surface burned prior to deposition and is a secure maximum limiting age. To the north (upstream) this bed descends, coarsens to silty sand, and thickens to more than 1 m, forming the lowermost unit of Section 1 (Figures 7 and 8). To the south (downstream), it rises and thins, pinching out in colluvium underlying railroad ballast where the river closely approaches the left valley slope. The stratigraphic position of this deposit, its elevation with respect to the highest flotsam of the February 1996 flood, and the young radiocarbon age lead us to infer that this deposit was left by the large historical flood of December 1861.

The winter of 1861-62 was one of exceptionally large floods in many western U.S. river basins [*Engstrom*, 1996; *Miller*, 1999]. On the Deschutes River, the December 1861 flood was reported to be "higher than was ever known to white man or aboriginal" (Salem Statesman, Dec. 23, 1861). On the Crooked River, a major upstream tributary to the Deschutes River, evidence of an exceptionally large flood was dated to the early 1860s by dendrochronological evidence of flood-damaged trees [*Levish and Ostenaa*, 1996]. At this Crooked River site, deposits from the 1861 flood buried an alluvial surface with an age of 3300-1900 cal yr BP This flood also eroded channels into parts of a higher surface with an age of ~5000 cal yr BP, indicating that the 1861 flood was one of the largest in the last 1900-5000 years on the Crooked River.

In Section 1, five flood beds overlie the 1-m-thick layer presumably deposited by the 1861 flood. These deposits all likely resulted from floods of the last 140 years. The uppermost unit of fine sand, ranging from 5 to 40 cm thick, has only very young surface vegetation and contains an aluminum soda can, indicating that this deposit resulted from the 1996 flood. Similarly, the December 1964 flood likely deposited the underlying unit. Identification of the three underlying units is more speculative, but two of them may have resulted from large gaged flows in January 1923 and February 1961 (Figure 2).

Section 3 was described in a 1.8 m deep pit excavated into the higher surface, away from the cut bank (Figures 6 and 8). Deposits in this section range from silty sand to coarse sand, including lenses of pumice grains and angular red and black volcanic fragments with diameters up to 2 mm. No primary sedimentary structures were visible. Samples retrieved by auger to a total depth of 2.5 m were of similar composition and texture. The uppermost 7 cm is silty very-fine sand, with abundant grass stems and rootlets. Aside from the contact beneath this uppermost 7-cm layer, contacts exposed in the pit consist of only gradual changes in grain size and color. There is no evidence of pedogenic alteration or depositional hiatus at any of these boundaries. Pumice grains collected from 95-100 cm from the top of the unit were identified as Mazama tephra (F.N. Foit, Washington State University, written communication, 2000), indicating that this deposit postdates the 7627±150 cal yr. BP age of the Mazama eruption [*Zdanowicz et al.*, 1999]. The position, thickness, coarse-grained texture, and post-Mazama age lead us to infer that this >2.5-m-thick deposit correlates to the Outhouse flood deposits at Axford and elsewhere along the lower Deschutes River [*Beebee and O'Connor*, this volume]. Sections 1 and 2 at Dant are apparently inset into this deposit, and probably entirely postdate the Outhouse flood.

In total, the stratigraphy at Dant records at least fifteen floods. These floods likely include the large Outhouse flood of about 4600 cal yr BP, up to five floods before 2060 cal yr BP, two floods ca. 2060-1880 cal yr BP, a flood dating to 1330-1260 cal yr BP, the exceptional historical flow of A.D.1861, and five post-1861 historical flows, probably including the floods of 1964 and 1996. The Outhouse flood and the floods ca. 1300 BP and A.D. 1861 all had maximum stages surpassing the flood of February 1996.

Caretaker Flat. "Caretaker Flat" is a 200-m wide, 500-m long alluvial surface on the right bank of the Deschutes River at RM 62, near the residence of the caretaker for a private fishing club. A vertical cutbank in this surface extends for nearly 100 m, exposing several beds of fine-grained flood deposits (Figure 9). A low surface, 2.7 m above the low-flow river stage, is inset into the higher and more extensive surface, which is about 5.0 m above the low-flow stage (Figure 10). The February 1996 flood did not inundate the upper surface, whereas the lower surface was flooded by about 1 m at peak stage (Floyd Patterson, Deschutes Club caretaker, oral communication, 1998).

The high surface consists of basal gravel, interpreted as a mid-channel bar or point bar, that is overlain by silt, sand, and gravel overbank flood deposits. A prominent layer in this exposure is fallout Mazama tephra (identified by Andrei Sarna-Wojcicki, USGS, written communication, 1999), which varies from 0 to 20 cm thick and ranges from 1.8 to 3.5 m below the surface. This ash layer defines the surface topography at the time of the eruption. Overlying the tephra and fine-grained flood deposits is a fining-upward gravel, sand and silt deposit that contains abundant 0-2 mm pumice clasts and lenses of broken and whole freshwater clamshells. This unit was probably left by a single large flood that overtopped a then-low floodplain near a channel that ran near the western end of the exposure. Primary sedimentary structures such as cross bedding and planar lamina are common in the sandy parts of the unit. The upper 70 cm

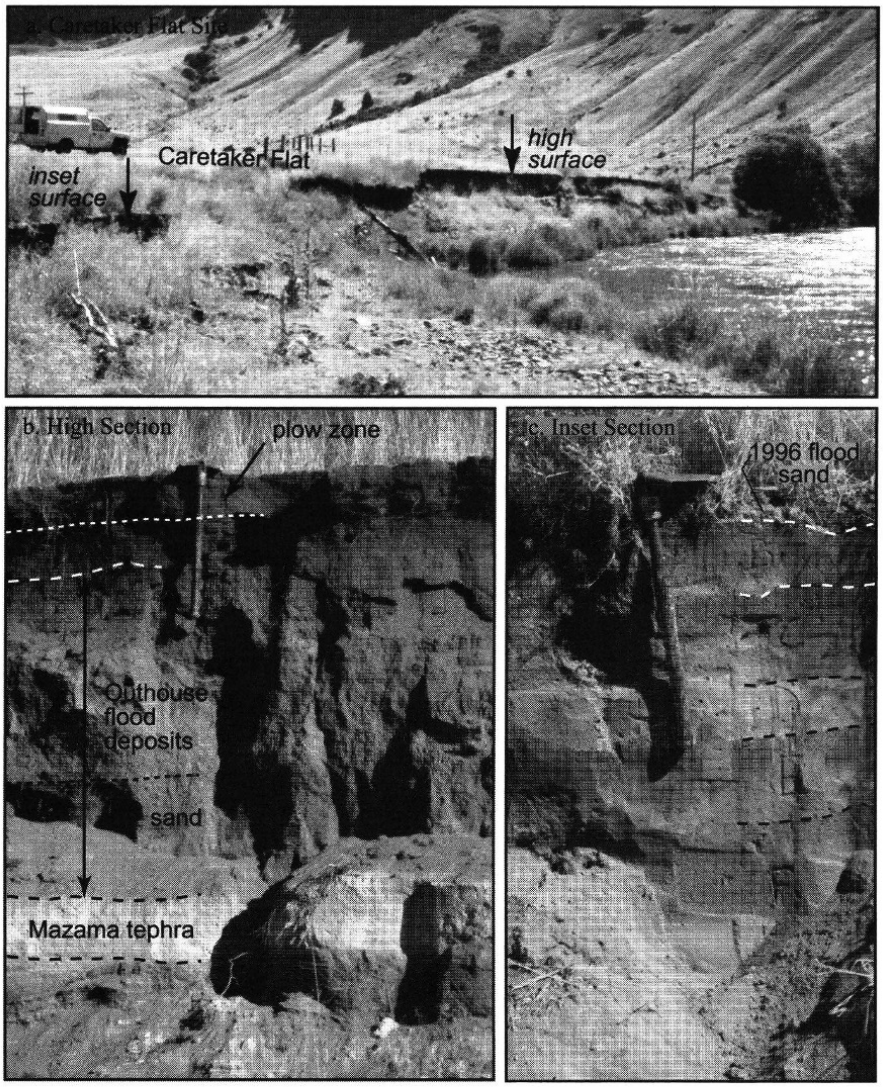


Figure 9. Outcrop photographs of the Caretaker Flat study site. An upstream overview of the entire exposure is shown in (a). Approximate locations of closer views of the stratigraphy of the higher section (b) and inset section (c) indicated by arrows. High surface is about 5.0 m above the low-flow water surface. Inset surface is about 2.8 m above the low-flow water surface. Shovel handle is about 0.5 m long.

is indurated, silty, fine sand with abundant matrix-supported gravel and granule clasts, which has been extensively burrowed and pedogenically altered such that the upper part of the deposit weathers to a coarse prismatic structure (Figure 9b). The uppermost 10 cm of this unit contains abundant pebbles and pieces of flint and obsidian tools, as well as a hearth, indicating human occupation. The degree of soil development and the concentration of pebbles and other anthropogenic features indicate that this surface was stable for an extended period. This unit is capped by 40 cm of silty sand, which is also bioturbated throughout. This uppermost 40 cm is also interpreted to record at least one large flood, which because of its elevation must have been substantially greater than the flood of February 1996. This surface was historically cultivated as a hay field, and the top of the section has apparently been plowed, destroying the upper 20 cm of the original stratigraphy. The base of the plow zone is marked by a sharp and planar horizon.

Ages of the deposits in the high surface are constrained by the 7775-7475 cal yr. BP Mazama tephra, and a radiocarbon age of 3160-2825 cal yr BP from charcoal in the hearth 40 cm below the surface (Table 1; Figure 10). Clamshells dated

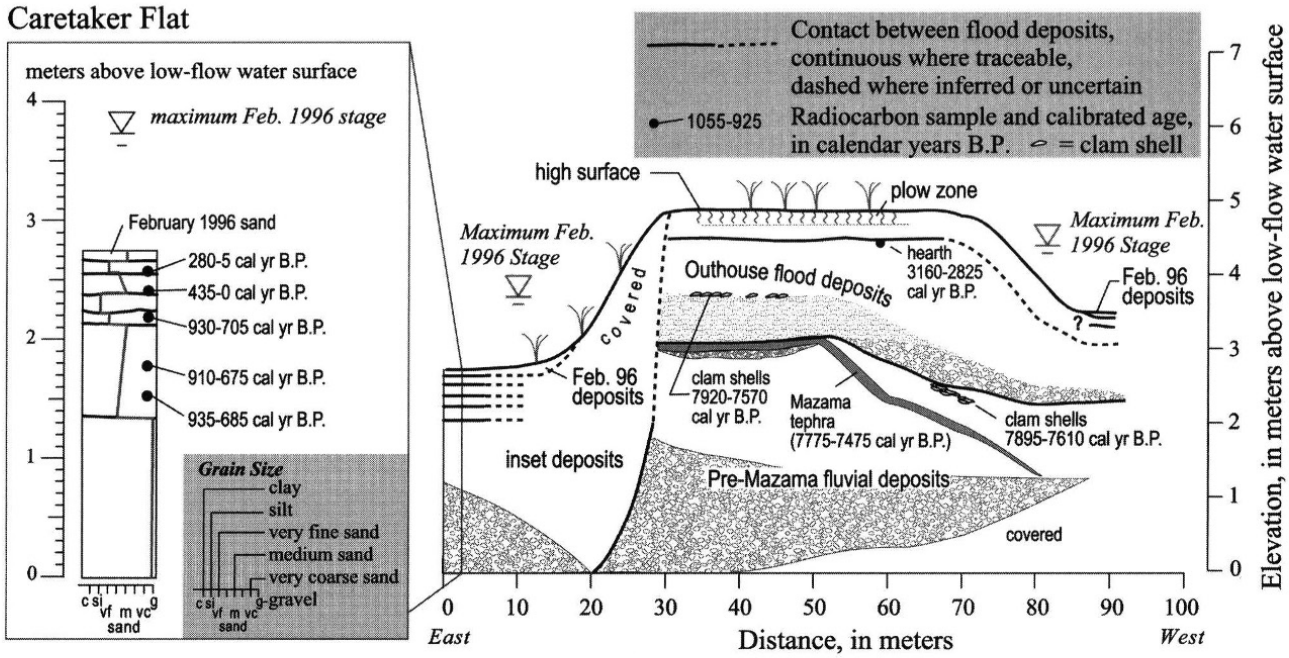


Figure 10. Schematic diagram of exposure at Caretaker Flat, showing primary stratigraphic relations and locations of dated samples.

at two locations overlying the Mazama tephra both yielded radiocarbon ages slightly older than the underlying ash. The locally coarse grain size and thickness of the extensive gravel, sand and silt deposit overlying the Mazama tephra are consistent with evidence elsewhere of the Outhouse flood, as are the bracketing ages provided by the Mazama tephra and the overlying hearth. The much older clamshell fragments within this deposit were likely entrained from older middens or accumulations, such as the similar-aged midden underlying the Outhouse flood deposit to the west (Figure 10).

At Caretaker Flat, inferred deposits of the Outhouse flood are covered by about 40 cm of sandy silt, representing deposits of at least one other flood that overtopped the high surface. This does not necessarily indicate that these subsequent floods were larger than the Outhouse flood. The high sand and gravel deposits left during the Outhouse flood indicate considerable current and flow depth across the surface during the flood, making it unlikely that the height of Outhouse flood deposits at the this exposure closely correspond to the maximum flood stage of the Outhouse flood. Later floods, such one or both of the two large post-1420 cal yr. BP floods recorded at Axford and Dant, likely overtopped this section by much smaller depths, leaving finer-grained deposits (forming the uppermost 40 cm of the section) that are closer to the elevations of their maximum stages.

The lower inset surface at Caretaker Flat is composed of a basal gravel and six silt and sand layers, 9 to >70 cm thick, distinguished on the basis of grain size and color (Figures 9c and 10). The uppermost unit is a 9-cm thick, loose, gray, silty sand deposit containing abundant organic fragments. Only fine rootlets, less than 1 mm diameter, are found within this unit. The lower contact is sharp and continuous, separating it from an extensively bioturbated sandy silt. On the basis of its position, the fresh organic detritus within it, and the absence of large roots, this unit was probably deposited by the February 1996 flood. The underlying silt and sand deposits may represent up to five additional floods.

Radiocarbon ages from charcoal incorporated in these deposits indicate that the six fine-grained flood beds all post-date 910 cal yr BP The fifth and sixth units from the surface may have both been deposited between 900 and 700 years ago. The upper three units, including the February 1996 deposit, were all deposited much more recently, probably since 435 cal yr BP These ages are consistent with the stratigraphic relations showing that this lower sequence is inset into much of the higher section. It is possible that the uppermost unit underlying the higher surface correlates with one or more of the beds in the lower inset section, but exposure was not adequate to determine this.

The overall stratigraphy at Caretaker Flat is similar to that of the Axford and Dant sites, although fewer flood beds are

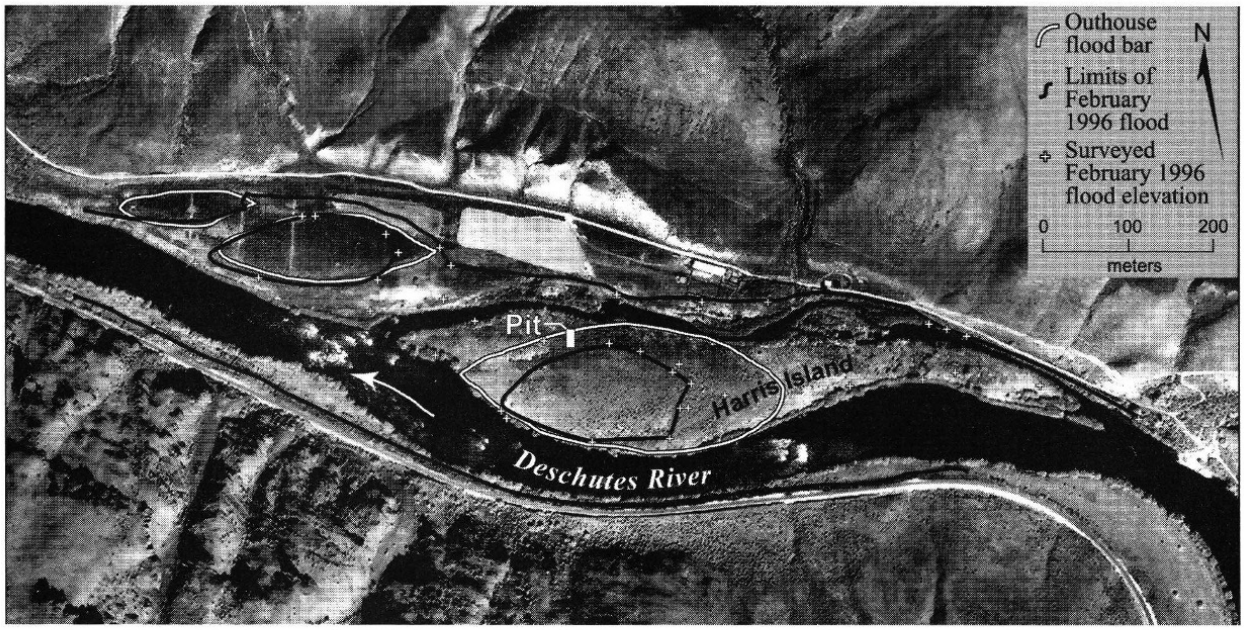


Figure 11. Aerial photograph of Harris Island and vicinity, annotated with outlines of Outhouse flood bars, limits of 1996 flooding (from surveyed flotsam elevations) and location of trench. Aerial photograph courtesy of Portland General Electric (1995, scale 1:20,000).

Figure 12. View north of the trench excavated on Harris Island. Trench log (Figure 13) was done for the eastern (right) wall.

exposed. The highest surface at Caretaker Flat has accumulated sediment for at least 7500 years, and probably includes deposits of the Outhouse flood and at least one subsequent flood much larger than the February 1996 flood. The inset deposits record at least six younger floods during the last ~900 years, including three in the last ~400 years.

Harris Island. The Harris Island site is the most downstream locale, at RM 11.6. Harris Island and the adjacent valley bottom are underlain by coarse gravel deposited in three large bars presumably by the Outhouse flood [Figure 11; *Beebee and O'Connor*, this volume]. A 2-m deep, 6-m long trench was excavated on the north side of the large Outhouse flood bar that forms Harris Island (Figures 11 and 12). The trench location was chosen so as to expose post-Outhouse flood deposits lapped onto the bar surface. The excavation site was near the limits of the February 1996 flood, and inundated by only 20 to 40 cm at peak stage, judging from nearby flotsam.

The trench revealed a complex stratigraphy of gravel, sand, and silt beds (Figure 13). A basal cobbly gravel, containing clasts with intermediate diameters as great as 30 cm, is interpreted as part of the bar deposit left by the Outhouse flood. Overlying this basal gravel are several beds of silt and sand, as well as a 0.5-m thick zone of cobbly gravel beds 0.5-1.0 m below the surface. At the north end of the excavation, 0.5 m of thin sand and silt beds are inset into thicker subhorizontal beds composing most of the upper meter of the trench wall. A thin layer of very fine sand caps most of the surface at the excavation.

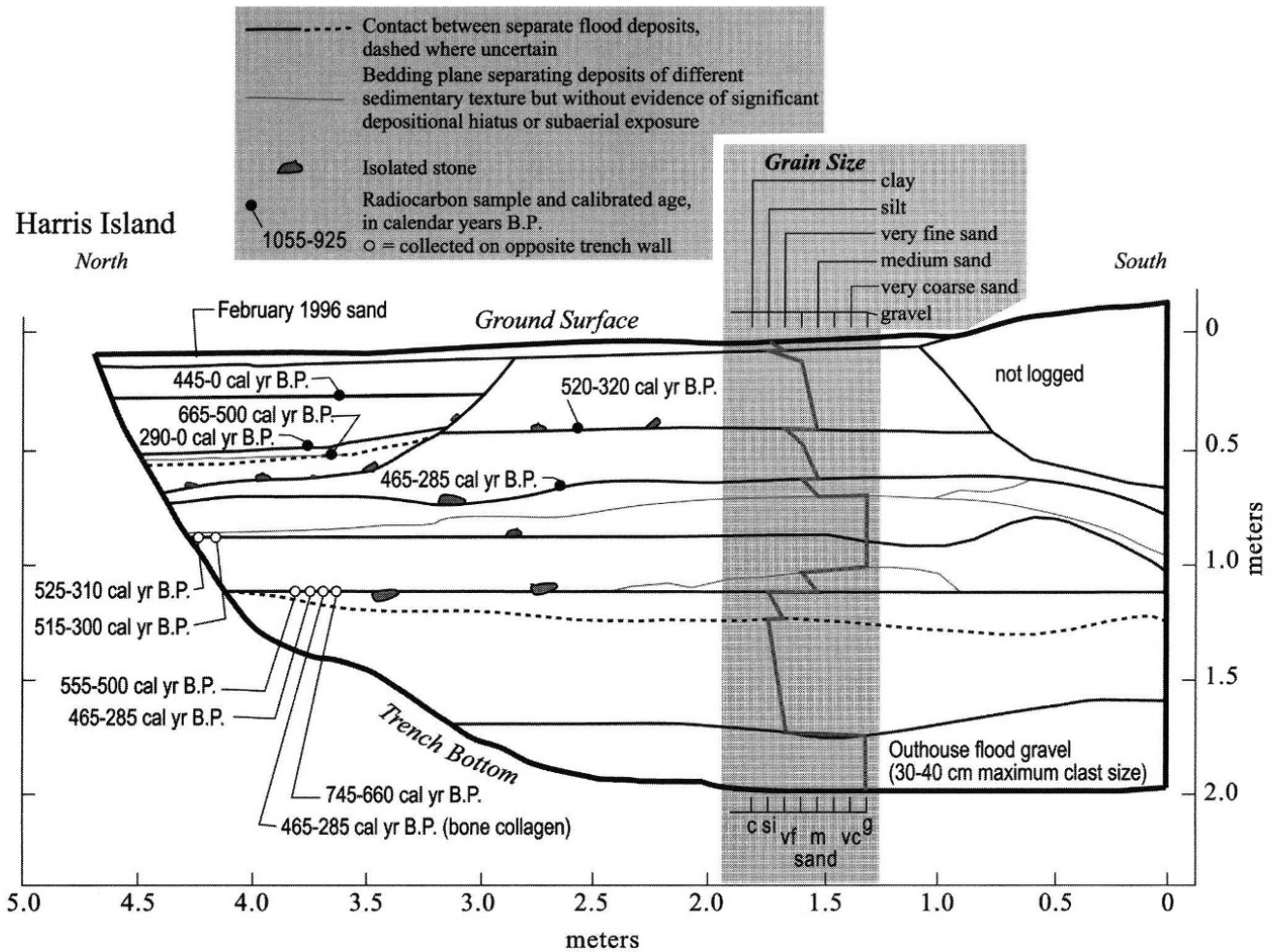


Figure 13. Diagram of eastern wall of Harris Island trench, showing flood beds and locations of radiocarbon samples.

Contacts between deposits range from conformable to disconformable. Many of the conformable contacts are marked by evidence of subaerial exposure in the form of isolated stones, charcoal, and bone fragments. For other contacts, interpretation is less clear, especially for disconformable contacts, where erosion removed any possible surficial evidence of temporal hiatuses. Nevertheless, our interpretation of the stratigraphy is that nine to eleven flood deposits are preserved on top of the Outhouse flood gravels, including three or four separate flood deposits inset into the sequence of thicker flood beds, and the thin, sandy deposit capping most of the exposure that was probably left by the February 1996 flood (Figure 13).

Results from eleven radiocarbon analyses constrain the ages of deposits exposed in the Harris Island excavation (Table 1, Figure 13). In addition, volcanic glass in pumice clasts in the Outhouse flood bar gravel excavated near the bar apex geochemically matches Mazama tephra (Andrei Sarna-Wojcicki, written communication, 1999), indicating that all deposits postdate 7627±150 cal yr. BP A prominent stone line with associated charcoal and bone occurs at the upper surface of the second unit on top of the Outhouse flood gravel, about 1.2 m below the surface. A bone fragment and charcoal clast from this horizon both have ages of 465-285 cal yr BP, providing a maximum age for the overlying eight to nine flood deposits (including the February 1996 deposit). Because of the large fluctuations in atmospheric ^{14}C during the last 500 years, the remaining ages do not provide additional resolution to the timing of floods, although the three youngest deposits must postdate 290 cal yr BP On the basis of the elevations of the deposits, all the floods postdating 465-285 cal yr BP had stages within 1.3-1.5 m of the February 1996 maximum stage. Judging from the thicknesses and grain sizes of many of their deposits,

compared to the deposit left by the February 1996 flood, several of the earlier recorded floods likely exceeded it in magnitude.

Summary of stratigraphy and geochronology. All four study sites show broadly consistent stratigraphic and chronologic relations, especially for the largest floods, although there are differences in the number of floods preserved at each site and their ages. All sites contain evidence of an exceptionally large Holocene flood, known as the Outhouse flood [*Beebee and O'Connor*, this volume]. At Axford and Dant this flood left high, thick, fine-grained deposits in recirculation eddy zones downstream of gravel bars, where the geometry of the sites is most favorable for deposition of slackwater sediments at heights that approach the peak water surface. At Caretaker Flat, Outhouse flood deposits comprise overbank gravel and sand, whereas at Harris Island, the same flood left immense gravel bars. At both of these sites, fine-grained flood deposits from subsequent smaller floods mantle Outhouse flood deposits. Radiocarbon ages at Axford indicate that the Outhouse flood postdated (perhaps closely) 4815-4440 cal yr BP This is consistent with stratigraphic relations at Caretaker Flat, where inferred Outhouse flood deposits are bracketed by the 7775-7475 cal yr BP Mazama tephra and a 3160-2825 cal yr BP hearth.

At both the Axford and Dant sites, two comparatively thick and high deposits indicate at least two floods since the Outhouse flood that were significantly larger than the February 1996 flood. Radiocarbon dating indicates that one of these floods was ~1300 cal yr BP and the other within the last 290 cal yr BP, and may correspond to the large historic flood of 1861. Similarly, at Caretaker Flat there is evidence of at least one large flood subsequent to 3160-2850 cal yr BP Although these two floods were larger than most others in the stratigraphic record, their deposit elevations, thicknesses, and grain sizes show that they were not as large as the Outhouse flood.

All sites have deposits from several post-Outhouse floods: thirteen to fifteen at Axford and Dant, seven to eight at Caretaker flat and nine to eleven at Harris Island. Approximately half of the post-Outhouse flood deposits at Axford and Dant are older than 1300 cal yr BP The lowermost inset deposits at Axford, Dant and Caretaker Flat record up to nine floods, with one or two deposits between ~900 and 700 cal yr BP and the rest mainly in the last 400 years. There are eight or nine flood deposits from the last ~500 years preserved at Harris Island, slightly more than at the other sites. February 1996 flood deposits cap the stratigraphy on the low, inset sections at Dant and Caretaker flat, as well as the bar surface near the excavated section at Harris Island.

The paleoflood chronologies are broadly consistent among sites, particularly with respect to the highest and thickest flood deposits. However, every site preserves a slightly different record of lower magnitude floods. For example, Axford is the only site containing slackwater flood deposits older than the Outhouse flood, with five deposits between approximately 6200 and 5000 cal yr BP This site also records multiple floods from ~1300-1200 cal yr BP, whereas only one is distinguishable at Dant. At Dant, two or more of the flood deposits have ages ca. 2000 cal yr BP, a time of no apparent deposits at the other sites. The Harris Island site records more recent floods than the other sites.

The lack of precise correlation between study locations probably owes to the different depositional environments at each site [e.g., *Blainey et al.*, 2002; *House et al.*, 2002]. As deposits accrete vertically with layers of flood deposits, the flood stage required for subsequent deposition increases. At different sites, depending on the local hydraulic setting, the discharge required for formation of a new flood deposit will vary. Only the very largest floods will be preserved at all sites. Likewise, the development and erosion of inset deposits will vary between sites, depending on local conditions. Hence, the development and preservation of lower, inset sections will likely differ between sites. Nevertheless, evaluation of multiple sites allows for more confident assessment of the completeness of the record at any one site, as well as for firm conclusions regarding the number and timing of the largest floods that have affected the river system.

DISCHARGE ESTIMATION

Quantitative estimates of flood discharges associated with the deposits at the Axford and Dant sites were obtained by surveying the adjacent channel and floodplain reaches and relating results of step-backwater flow modeling to flood-deposit elevations.

Methods

The U.S. Army Corps of Engineers' Hydrologic Engineering Center River Analysis System, HEC-RAS [*Hydrologic Engineering Center*, 1998], was used to model discharges associated with individual paleoflood deposits. Input parameters for HEC-RAS include cross-sectional geometry, reach lengths, energy loss coefficients, starting water-surface elevations, flow regime and specified discharges. The two parameters having the greatest effect on the outcome are channel geometry and specified discharge value [*Feldman*, 1981; *O'Connor and Webb*, 1988; *Orth*, 1998; *Webb and Jarrett*, 2002].

Reach lengths and cross-sectional geometry were obtained by geodetic survey of the study reaches. Multiple cross sections were surveyed upstream and downstream from both sites (Figure 14). Additional control points were surveyed to model the topography of the bars at both sites and the tops of all described stratigraphic sections. The survey datum was mean sea level, as determined from nearby USGS benchmarks.

For all water-surface profile calculations, subcritical flow was assumed. Initial estimates of roughness coefficients were based on comparison with photographs from *Barnes* [1967]. These values were adjusted so that the computed water-surface profiles for the gaged discharges at the time of surveys closely matched the surveyed water-surface profiles. In the Dant reach, abundant evidence of the maximum February 1996 flood stage was also used to calibrate energy-loss coefficients. Final assigned values for Mannings n ranged from 0.030 to 0.033 for the channel and 0.040 to 0.045 for the overbank areas at both sites. Expansion and contraction coefficients for frictional loss were assigned as 0.01 and 0.03, respectively, for all trials, as advised in the HEC-RAS user's manual [*Hydrologic Engineering Center*, 1998]. For both the modeled reaches, the stratigraphic sections are far enough upstream from the downstream end of the modeled reach that uncertainty in specified starting conditions has negligible effects on the calculated water-surface profile at the locations of the flood deposits [e.g., *O'Connor and Webb*, 1988].

Discharges corresponding with flood deposits were estimated by comparing the surveyed elevations of the flood deposits with computed water-surface profiles calculated with the calibrated model for multiple discharges [Figure 15; *O'Connor and Webb*, 1988]. The top elevations of individual flood deposits provide reliable minimum estimates of associated flood stage because it is unlikely that fine-grained slackwater sediment is deposited at elevations greater than peak stage [*Jarrett and England*, 2002]. However, there remains substantial uncertainty in what the maximum stage may have been because of the unknown depth of water above the resulting deposit [e.g., *Webb et al.*, 2002]. For the purpose of determining best estimates of discharge corresponding to individual flood deposits, which we could later use for flood frequency analysis, we assumed that maximum flood stage overtopped its corresponding deposit by 0 to 1.2 m. The 1.2 m value is based on the 1.0-1.2 m difference between the February 1996 maximum flood stage and the maximum elevations of the corresponding 1996 flood deposits at Dant and Caretaker Flat, where vertically accreting sections of fine-grained flood sediment likely represent typical depositional conditions for long-

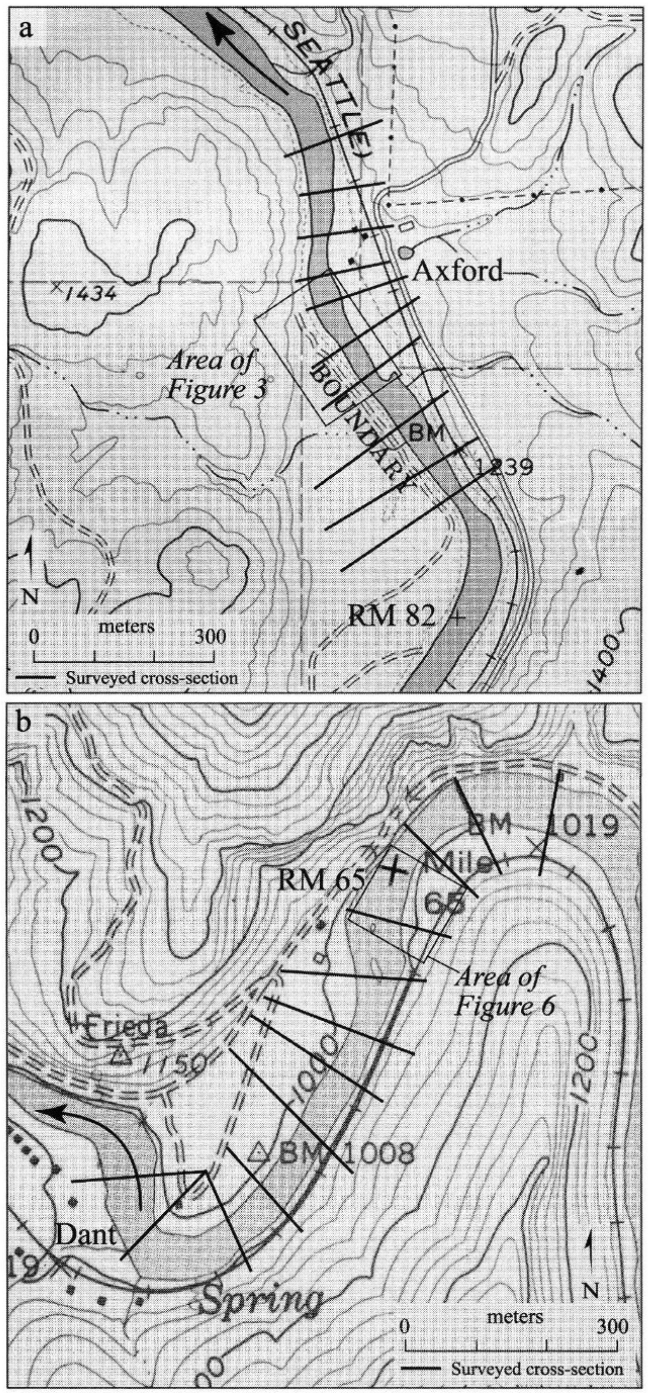


Figure 14. Maps of (a) Axford and (b) Dant study reaches, showing surveyed cross-sections used for hydraulic modeling. Topographic base from the Kaskela and Dant, Oregon, USGS 7.5-minute topographic quadrangles. Contour interval is 12 meters (40 feet).

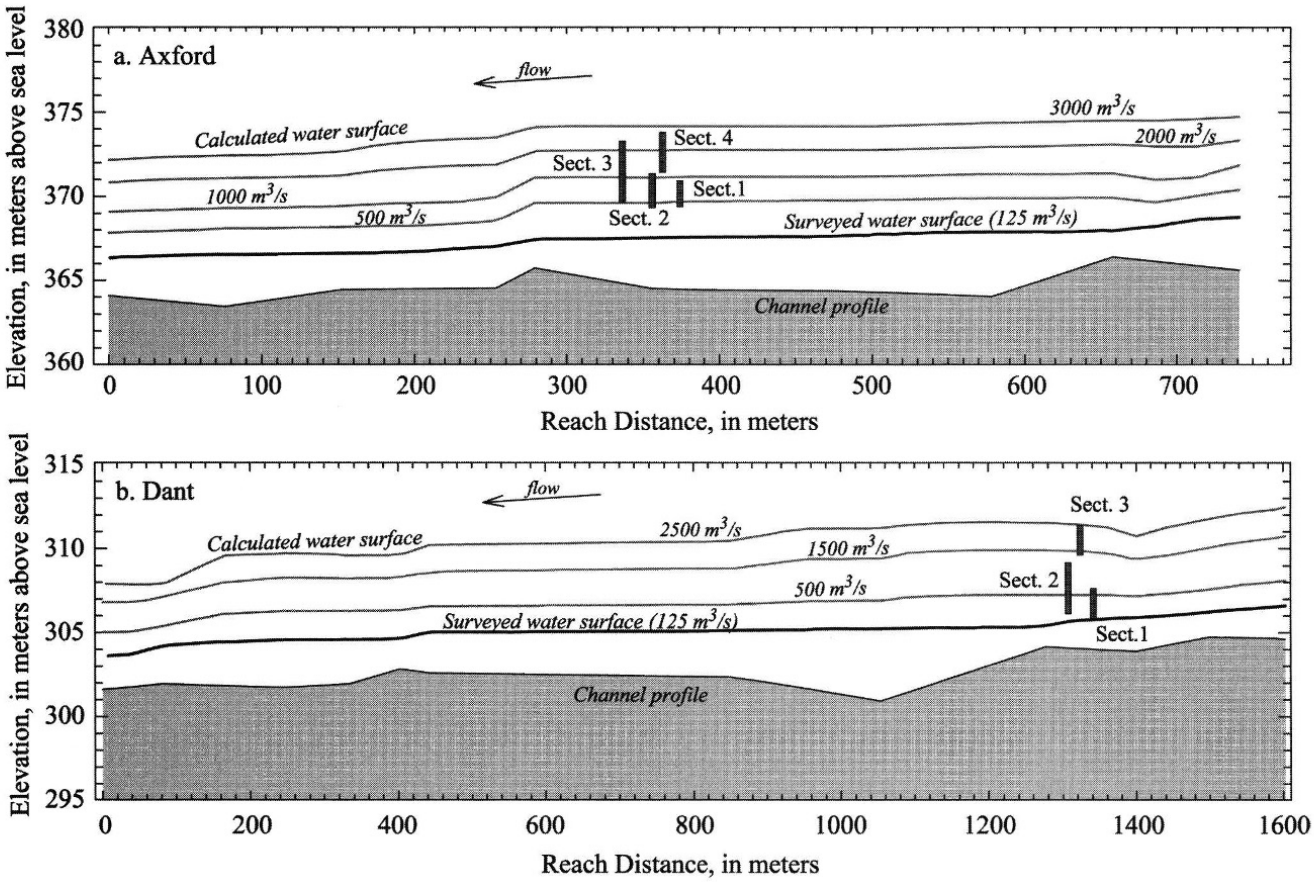


Figure 15. Surveyed and calculated water-surface profiles for the (a) Axford and (b) Dant study sites. Surveyed water-surface profiles are for a flow of 125 m^3/s at both the Axford (9/14/99) and Dant (9/16/99) study sites. Calculated water-surface profiles shown for 500 m3/s increments. Also shown are the positions and elevations of the stratigraphic sections, numbered as shown in Figures 4 (Axford) and 8 (Dant).

lived stratigraphic sections. At some sites the difference may be smaller, such as the 20 to 40 cm difference between maximum deposit elevation and maximum flood stage at the Harris Island site. Depending on depositional setting, even these ranges may result in significant underestimation of the actual corresponding discharge. This is clearly the case for the top of the Outhouse flood deposit in Section 2 at Axford and the 1861 flood deposit in Section 1 at Dant, which are both 2-3 m lower than the tops of correlative deposits at adjacent sections. Hence, the discharge ranges reported in this section are most accurately viewed as ranges bounding a minimum discharge estimate.

Results

Axford. Discharge estimates associated with flood deposits at Axford range from about 590-1050 m^3/s for the lowest deposits in Sections 1-3, to 2860-3770 m^3/s for the Outhouse flood deposit at Section 4 (Figures 4 and 15a). For comparison, the February 1996 flood had a peak discharge of about 1060 m^3/s at this location (derivation of this estimate is discussed later in this paper). Likely minimum discharges range from 590 to 1320 m^3/s for the four five oldest, pre-Outhouse flood deposits at the base of Sections 2 and 3, including the ~5000 cal yr BP flood. Estimated discharges associated with the six post-Outhouse flood deposits recorded in Section 2 range from 730-1340 m^3/s for the lowest one to 1210-2000 m^3/s for the uppermost unit, indicating that these events were mostly larger than the February 1996 flood. The >25 cm thickness of the top two units in Section 2 suggests that the associated floods may have been much larger than the 1996 flood. Discharges for the seven uppermost flood deposits in Section 1 likely ranged from 760-1330 m^3/s to 1010-1840 m^3/s.

Dant. Discharge estimated for deposits at Dant range from 490-850 m^3/s to 2420-3390 m^3/s (Figures 8 and 15b). The elevation of the Outhouse flood deposit requires a discharge of 2420-3390 m^3/s, similar to the 2860-3800 m^3/s discharge required by the highest deposit at Axford, lending support to the correlation of these units between sites. The deposit presumably left by the 1861 flood had a minimum discharge of 1260-2090 m^3/s. For the five highest flood deposits below the 1861 deposit in Section 2, discharge estimates range from 490-850 m^3/s to 1140-1790 m^3/s. The five post-1861 flood deposits recorded in Section 1 (including the capping 1996 deposits) had discharges corresponding with their deposit elevations that ranged from 490-850 m^3/s to 670-1110 m^3/s.

Summary of discharge estimates. The discharge estimates, stratigraphic relations, and age information for the Dant and Axford sites can be combined to provide millennial-scale information on the number, timing, and magnitude of floods (Figure 16). The Outhouse flood produced minimum discharge estimates of 2860-3770 m^3/s at Axford and 2420-3390 m^3/s at Dant. The discharge of this flood is significantly higher than for any other floods in the ~6000-year slackwater paleoflood record, and it is apparently the largest flood since the 7626±150 cal yr BP deposition of the Mazama tephra. It is uncertain whether this flood is meteorological in origin or the result of a natural dam failure [see *Beebee and O'Connor*, this volume]. For the purposes of the flood-frequency analysis in this study, we conducted separate analyses in which we included and excluded the Outhouse flood discharge as a meteorological paleoflood. It is likely that the two highest flood deposits that post-date the Outhouse flood at both the Axford and Dant sites (the two units capping Section 2 of both locations) represent the same two floods; a flood of ~1300 cal yr BP and a flood post-dating 290 cal yr BP, which probably corresponds to the 1861 flood. These two floods may have had local peak discharges as great as 2000 m^3/s.

Aside from the evidence for the three floods mentioned above, stratigraphic records at the two sites do not match exactly in terms of the recorded time periods. Consequently, we have combined records from both sites to provide a more complete synopsis of the flood history of the lower

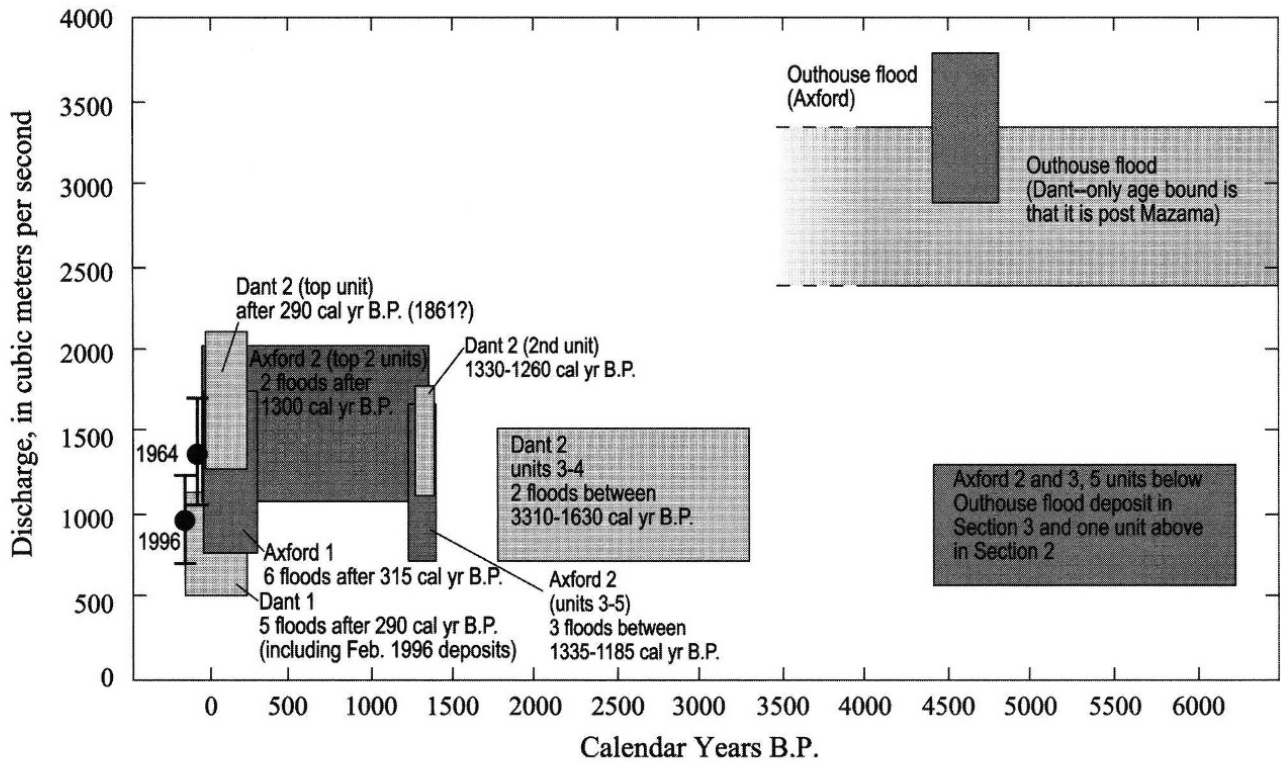


Figure 16. Summary diagram of stratigraphic record of flooding at Axford (dark gray boxes) and Dant (light gray boxes) study sites, showing ages, discharges and numbers of floods. Ages are in calendar years BP (with A.D. 1950 regarded as "present"). Also shown are estimates for the 1964 (adjusted for regulation) and 1996 flood discharges at the Axford study site.

Deschutes River (Figure 16). Like most paleoflood records of this type, the combined record of flood discharges and ages is almost certainly not complete [*House et al.*, 2002]. Both erosion of deposits and bioturbation of contacts may have resulted in lost or obscured records. Some floods are likely unrepresented by deposits, due to the progressively increasing stage necessary to overtop the vertically accreting deposits. Only a few deeply buried deposits predate the Outhouse flood. There were surely many large floods prior to ~4600 cal yr BP whose records were destroyed or covered by the Outhouse flood. The record of floods subsequent to the Outhouse flood is probably more complete, especially for floods large enough to emplace thick deposits on high, long-lived surfaces, such as Section 2 at Axford and Section 2 at Dant. However, bioturbation of deposits forming these sections may have reduced the number of recognizable flood beds. The lack of flood deposits with ages between ~4600 and 3300 cal yr BP might reflect lack of age data for parts of some sections or erosion of deposits. Nevertheless, the lack of thick deposits from that period at any site in our study, coupled with strong evidence that the 1861 flood was the largest of the last 5000 years on the tributary Crooked River [*Levish and Ostenaa*, 1996], makes it unlikely that there were any floods from ~4600 to 3300 cal yr BP with discharges as large as the two large ~2000 m^3/s discharges of the last ~1300 cal yr BP.

FLOOD FREQUENCY ANALYSIS

Appropriate consideration of paleoflood data like that obtained for the Deschutes River can improve estimates of flood frequency, especially for low frequency floods [*Stedinger and Cohn*, 1986; *Stedinger and Baker*, 1987; *Blainey et al.*, 2002; *O'Connell et al.*, 2002]. Recent techniques and applications have used paleohydrologic data and interpretations to establish "bounds" of flood occurrence—that is, statements of flood exceedence and non-exceedence over specified time periods [*Levish*, 2002]. These bounds are commonly combined with gaged records to produce estimates of flood frequency, resulting in narrower constraints on likely flood frequency distributions at long return periods than can be obtained from consideration of the gaged data alone [e.g., *O'Connor et al.*, 1994; *O'Connell et al.*, 2002].

Methods

For this study, we have calculated flood frequency with an algorithm developed by the Bureau of Reclamation for a model called FLDFRQ3 [*O'Connell*, 1998; *O'Connell et al.*, 2002] that is specifically designed to incorporate paleoflood data into flood frequency analysis for dam safety assessment [*Levish*, 2002]. This method employs a Bayesian approach [*Tarantola*, 1987] in conjunction with the maximum likelihood methods of *Stedinger and Cohn* [1986]. It combines gaged records and paleoflood data, and allows for specification of the uncertainty in the magnitude and timing of paleohydrologic bounds that inevitably results from uncertainties in stratigraphic interpretations, deposit chronology, and paleoflood discharge. In addition, uncertainty in the gaged measurements can also be specified.

Such an analysis for the Deschutes River presents some challenges. First, the stratigraphic records of flooding at each of the four sites are different, as are the discharge estimates associated with possibly correlative paleoflood deposits at the two sites of flow estimation. Second, neither of the sites with quantitative estimates of paleoflood discharge is directly comparable to gaged locations on the Deschutes River. Third, the gaged record includes periods of regulated and unregulated flow and therefore is not consistent over the period of record. Each of these issues was treated in a manner to maximize the overall confidence in the results. These complications are typical for studies such as this, and add unquantified uncertainties to the final flood frequency assessment.

Multiple sites. To simplify the issue of multiple sites with different records, we applied only results from the Axford site to the flood frequency analysis and only used paleoflood information on the large floods that were common to multiple sites. We consider the potential reduction in information due to limiting the flood probability distribution to results from a single site to be outweighed by the increased reliability resulting from using only paleoflood bounds that rely on more certain correlations between sites. This approach is supported by the observation that only a few bounds are necessary to significantly improve flood frequency estimates [*Blainey et al.*, 2002; *Levish*, 2002]. The appropriateness of this approach is also bolstered by the overall similarity of the stratigraphic records between all study sites in terms of the timing and relative magnitude of the largest floods. The greatest loss of information due to not considering the Dant site is the estimate for the inferred 1861 flood discharge, although this inference is uncertain. Nevertheless, the 1861 flood is probably represented by one of the high deposits at Axford and thus indirectly included in the analysis.

Relation to gaging records. The closest gaging station to the Axford site is the "Deschutes River near Madras," 30 km upstream at RM 100.1 (Figure 1), for which peak flows have been measured since 1924. The longest record on the Deschutes River is from the Moody gage, 130 km down-

stream at RM 1.4 near the Columbia River confluence, where annual peak discharge records extend back to 1897 (Figure 2). Three major tributaries join the Deschutes River between the Madras gage and the Axford study site. Shitike Creek and the Warm Springs River both drain the eastern slopes of the Cascade Range and have mostly continuous flow records extending back to 1975 and 1972, respectively. Trout Creek drains the Ochoco Mountains to the east and has no systematic record of streamflow.

Shitike Creek and the Warm Springs River both contribute substantial flow to the Deschutes River, so the gage record at Madras alone does not adequately reflect the peak flows at Axford. Examination of the 1975-1998 annual peak flow records for all of these stations indicates that the total flow at Axford (the combined discharges for the Deschutes River at Madras, Shitike Creek, and Warm Springs River) averages 51 percent of the measured flow at Moody for the same floods (Figure 2). Consequently, we have multiplied the discharges from the Moody gage by 0.51 to establish an approximate systematic record for the period 1897-1998 at Axford. There are uncertainties with this transformation, such as the unknown contributions from Trout Creek and the applicability of such a ratio to the very large floods recorded by the slackwater deposits. However, this relation is broadly consistent with the highest measured flows during the period of overlap in the upstream and downstream records for the 1964 and 1996 floods. For the two large floods in 1964 and 1996, about 75 percent of the peak discharge at Moody was derived from downstream of the Madras gage [*Beebee and O'Connor*, this volume], although it may have been as low as 50 percent without the regulation caused by upstream dams. The incremental increase in drainage area between the Madras gage and the Axford site is about 54 percent of the total area contributing to the Deschutes River between the Madras and Moody gage locations. On this basis and assuming uniform flow generation for area downstream of Madras, the peak discharges at Axford would be expected to be about 65 percent of the Moody discharges. To reflect uncertainty in the local discharge during large floods, we assigned uncertainty (2s) values of ±30% to each gage discharge value for Axford.

Flow regulation. Flows have been regulated in the Deschutes River basin since 1919. Consequently, USGS estimates of flood frequency at the Moody gage are based only on 1898-1919 flow records [*Wellman et al.*, 1993]. Nevertheless, early storage projects were small and substantial flow regulation only began with Bowman Dam on the Crooked River (closed 1960) and Round Butte Dam on the Deschutes River (closed 1964). Both dams stored substantial water during the 1964 flood, perhaps reducing the peak discharge at the Madras and Moody gage locations by 850 m^3/s [*Waananen et al.*, 1971]. During the February 1996 flood, however, the large reservoirs behind both the Bowman and Round Butte dams were much closer to capacity and there was substantially less attenuation of flood discharge [*Fassnacht*, 1998]. For the purposes of flood frequency analysis, we have assumed that the unregulated 1964 peak discharge at Moody would have been about 2750 m^3/s (with a 2s uncertainty of ±50%)(Figure 2), compared to the actual gaged flow of 1910 m^3/s (Figure 2), reflecting *Waananen's* [1971] estimate of reservoir storage. All other annual peak discharges were left unchanged.

Paleohydrologic bounds. The primary manner in which paleoflood data are considered in maximum-likelihood approaches to estimating flood frequency is as a series of constraints, or bounds, on the timing and magnitude of floods. These bounds include information on discharge levels that have and have not been exceeded in specified time periods (Table 2). Non-exceedence bounds are flood discharges that have not been exceeded for a known time period and supply important limiting information for flood frequency distributions in this type of analysis [*Blainey et al.*, 2002; *Levish*, 2002]. The non-exceedence bound assumed from the stratigraphy at Axford is that no flood has exceeded the 3770 m^3/s best-estimate discharge of the Outhouse flood during the last 4865-4490 cal yr BP (Table 2).

Information on specific large paleofloods also constrains the flood frequency distribution [*O'Connell et al.*, in press]. For this analysis, we considered the three largest floods recorded in the stratigraphy at Axford. These floods are the ~4600 cal yr BP Outhouse flood, and the two large floods post-dating 1420 cal yr BP at the top of Section 2. From the age results at Dant, we have assigned ages of ~1300 cal yr BP and <290 cal yr BP to these two floods (Table 2). While many other floods are recorded in the stratigraphy at Axford, these three large floods have left records at multiple sites along the Deschutes River and likely represent the largest floods of the last ~5000 years. For the presumably smaller floods that left many of the lower deposits at Axford, the record is not as likely to be complete, and thus our confidence in the number and timing is not as high. By restricting the analysis to the three largest floods, we only considered paleoflood information deemed complete and reliable, thus reducing the errors and unquantifiable uncertainty owing to incomplete records [e.g., *Blainey et al.*, 2002].

Uncertainty values for corresponding flood discharges were assigned from the ranges of discharges required to overtop corresponding deposits by 0 to 1.2 m (Table 2). The discharge necessary to overtop the deposits by 1.2 m was selected as the best estimate of the paleoflood discharge, a

Table 2. Summary of paleoflood data considered in flood frequency analysis.

Data Type	Minimum Discharge Estimate (m^3/s)[a]	Maximum Discharge Estimate (m^3/s)[b]	Best Estimate for Discharge (m^3/s)[c]	Flood Age, in calendar years BP[d]
Nonexceedence bound[a]	2860	4680	3770	4815-4440
Paleofloods				
<290 cal yr BP	1210	2790	2000	90[e]
~1300 cal yr BP	1060	2560	1810	1300
Outhouse flood[f]	2860	4680	3770	4600

[a]Discharge for flow with a stage equal to elevation of the top of the highest deposit.
[b]Best-estimate discharge plus difference between best-estimate and minimum discharges
[c]Discharge for flow that overtops highest deposit by 1.2 m.
[d]Dendrocalibrated from radiocarbon age and referenced to AD 1950. For flood frequency analysis, which was based on data through AD 2000, 50 yrs were added to each of these ages.
[e]Assigned age reflects likelihood that this flood occurred in 1861.
[f]Entered as a paleoflood in the primary analysis shown in Figure 17a.

required input value for the model. This value was chosen based on the 1.2 m depth of water above the 1996 flood deposits during the peak flood stage. The discharge required to reach the elevation of the deposit provides a minimum limit to the discharge range, and an equivalent difference above the best-estimate discharge was chosen as a reasonable maximum limit. For purposes of estimating the shape of the probability density function about the discharge estimate, the "best-estimate" value, represented by flow overtopping the deposit by 1.2 m, was estimated to be ten times more likely than either of the bounding values of the input discharge range. All analyses were conducted assuming a Log Pearson Type III frequency distribution.

Results

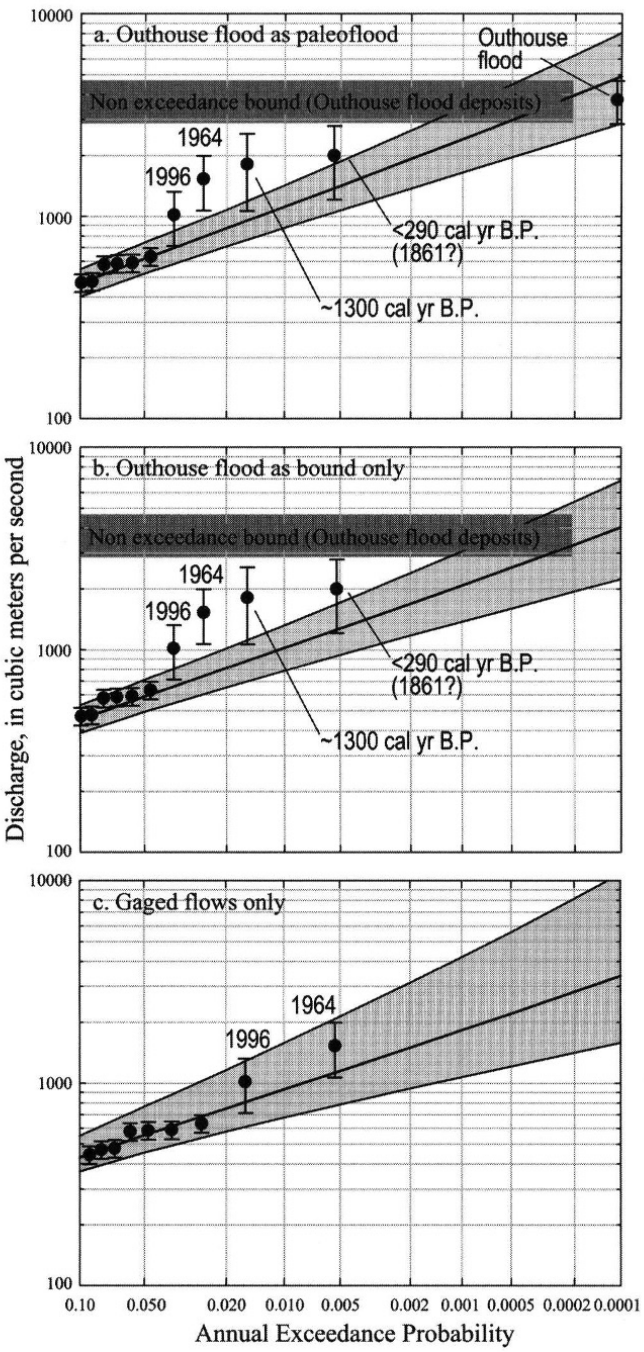
Three specific cases were analyzed (Figure 17, Table 3). The primary analysis (Figure 17a) includes the 94 years of transformed gage data, the non-exceedance bound indicated by the height of the Outhouse flood deposit, and the three large paleofloods, including the Outhouse flood. A secondary analysis (Figure 17b) was performed using the same gage data and the exceedance bound defined by the height of the Outhouse deposit, but not including the Outhouse flood as a specified paleoflood. This case reflects the possibility that the Outhouse flood resulted not from meteorological conditions, but from some type of natural dam failure in the basin, and thus is not appropriately considered as part of the same population of floods. *Beebee and O'Connor* [this volume] specifically addressed this question with the tentative conclusion that the Outhouse flood was indeed a meteorological flood. The third case was for comparative purposes and simply considers the transformed gage data without any paleoflood information (Figure 17c).

All three cases resulted in estimated flood discharges within ±30 percent of each other for floods with annual recurrence intervals of 10 to 10,000 yrs. For recurrence intervals >100 yr, inclusion of the paleoflood data in the primary case results in discharge estimates 20 to 30 percent greater than does the analysis of the transformed USGS gage data alone (Table 3; Figure 17a, 17c). However, the most striking result of including the paleoflood data is the much narrower confidence limits on the calculated distribution function (Figure 17). For example, the 100-yr recurrence interval flood at Axford, determined solely from the transformed Moody gage record is 930 +650/-250 m^3/s. Addition of the paleoflood record results in an estimate of 1120 +310/-240 m^3/s for the 100-yr flood. Excluding the Outhouse flood as a specified meteorological flood results in quantile estimates very similar to those from analysis of the gage record alone (Table 3), but also with much narrower confidence limits (Figure 17b, 17c). At longer recurrence intervals, the improvement in quantile estimates is even greater (Table 3).

These quantitative flood-frequency results from analysis of the Axford stratigraphy are consistent with the overall stratigraphic record of flooding in the lower Deschutes River canyon. The frequency analysis of the combined gage and paleoflood records indicate that the February 1996 flood (about 1060 m^3/s at Axford) was slightly less than the 100-yr

flood. This is consistent with the stratigraphy at all four sites, which indicates that there have been several floods of February 1996 magnitude or greater during the last ~1000 years. The 2000 m^3/s best-estimate discharge for the inferred 1861 flood deposit is slightly larger than a 500-yr flood, and the stratigraphic record of indicates two such events in the last ~1300 years. The 2860-3800 m^3/s discharge of the ~4600 cal yr BP Outhouse flood has a calculated recurrence interval of 2000-5000 yr, consistent with evidence of only one such flood since the 7626±150 cal yr BP Mazama tephra fall.

As for all such analyses, these flood frequency results are based on the assumption of stationarity. Because climate, watershed conditions and perhaps the mechanisms of producing floods vary over timescales encompassed by the stratigraphic records, these estimates of flood frequency should be considered only as long-term averages.



SUMMARY AND CONCLUSIONS

The stratigraphic records from Axford, Dant, Caretaker Flat, and Harris Island preserve evidence of over twenty floods during the last ~6200 cal yr BP At least fifteen floods post-date the Outhouse flood of ~4600 cal yr BP, and this number could be greater depending on the degree of overlap among the records at the different sites [details in *Hosman*, 2001]. All four study sites show broadly consistent stratigraphic and chronologic relations, especially for the largest floods. Notable floods that can be identified in the depositional records at multiple sites include the exceptionally large ~4600 cal yr BP Outhouse flood; two large late-Holocene floods at ~1300 cal yr BP and <290 cal yr BP, the latter of which may be the large historical flood of 1861; and the recent flood in February 1996.

Figure 17. Plotting positions and flood-frequency analysis for gaged floods and paleofloods on the Deschutes River, calculated using the Bureau of Reclamation FLDFRQ3 program [*O'Connell*, 1998; *O'Connell et al.*, 2002]. Plotting positions calculated using the Hazen method. Flood-frequency analyses were conducted for log10 Pearson Type III distributions. For all cases, gaged discharges greater than 700 m^3/s (adjusted for the Axford study site) were assumed to have fractional 2σ standard errors of 0.3, except for the value for the 1964 flood, which was also adjusted for effects of regulation and assigned a fractional 2σ standard error of 0.5. Gaged flows less than 700 m^3/s were assigned fractional 2σ standard errors of 0.1. The discharges, ages, and likely ranges of paleoflood data were prescribed as shown in Table 2. In all cases, the "best estimate" of Table 2 was assumed to be 10 times more likely than the minimum and maximum estimates, thus providing an estimate of the shape of the probability distribution about the true discharge. Plots (a) and (b) summarize results of analyses that include the 94 years of gaged annual floods, the <290 and ~1300 cal yr BP paleofloods, and the non-exceedance bound provided by the ~4600-yr old Outhouse flood deposits. Plot (a) also includes the Outhouse flood as a paleoflood, whereas (b) only includes it as a non-exceedance bound, accounting for the possibility that the Outhouse flood was generated by a non-meteorological event. Plot (c) summarizes results from a similar analysis including only the 94 years of gaged flows.

Table 3. Summary of flood frequency results for the Deschutes River (at Axford) using Bureau of Reclamation FLDFRQ3 program [*O'Connell*, 1999; *O'Connell et al.* in press]

Annual Exceedence Probabilities	94-yr Gage Record, 1 non-Exceedence Bound and 3 Paleofloods (primary case)	94-yr Gaged Record, 1 Non-Exceedence Bound and 2 Paleofloods	94-yr Gaged Record
0.1	470	450	430
0.05	620	590	550
0.02	870	810	750
0.01	1120	1020	930
0.005	1420	1270	1150
0.002	1920	1690	1500
0.001	2400	2080	1820
0.0005	2990	2540	2200
0.0002	3970	3300	2820
0.0001	4910	4010	3380

The Outhouse flood was by far the largest flood at the two sites where hydraulic modeling was used to reconstruct paleoflood magnitudes. At Axford, Outhouse flood deposits correspond to a discharge of 2860-3770 m^3/s, a value just slightly greater than associated with correlative deposits at Dant, and much greater than the 1060 m^3/s estimate for the February 1996 flood. The two large late Holocene floods of ~1300 cal yr BP and post-290 cal yr BP had discharges of ~1060-2000 m^3/s and may have been twice the size of the February 1996 flood. Many of the remaining floods preserved in the stratigraphic record at Dant and Axford probably had discharges close to or slightly greater than the February 1996 flood.

These paleoflood data were combined with an adjusted gage record (reflecting the watershed position of the Axford site and regulation of the 1964 flood) to calculate long-term flood frequency. Flood frequency calculations were based on maximum likelihood analysis with a Bayesian approach [*O'Connell*, 1998; *O'Connell, et al.*, 2002]. Key paleohydrologic results constraining the flood frequency distribution were: (1) there have been no floods greater than 2860-3770 m^3/s since 4815-4450 cal yr BP; and (2) there were single floods of 2860-3800 m^3/s about 4600 cal yr BP, 1060-1810 m^3/s about 1300 cal yr BP, and 1210-2000 m^3/s about 140 cal yr BP Compared to analysis of the gage record alone, incorporating the paleoflood information increases flood quantile estimates by about 15 to 30 percent for recurrence intervals ranging from 100 to 10,000 yrs. The increase is much smaller if the Outhouse flood is not considered as a meteorological paleoflood. Perhaps more important for dam safety analysis, addition of the Axford paleoflood data significantly narrows the confidence intervals around the estimated frequency distributions compared to analysis of gage data alone. Confidence in the resulting flood frequency estimates is bolstered by the overall agreement of the calculated return periods of specific floods, such as the February 1996 flood, with the flood stratigraphy at multiple sites along the Deschutes River.

The only apparent gap in the stratigraphic flood record is between 4400 and 3300 cal yr BP, for which there are no dated flood deposits. This period could be a time of few or no large floods on the Deschutes River, or it could be a time period for which deposits were not preserved at any of the study sites. Regardless, the absence of flood deposits from that time period on high, long-lived, surfaces indicates no floods were substantially larger than the February 1996 flood between 4400 and 3300 cal yr BP Gaps in the stratigraphic records at all sites, plus the inherent uncertainty of deposit ages, makes it difficult to speculate about long-term changes in flood frequency and magnitude.

While quantitative flood frequency was assessed for only one site, and flow modeling was conducted for only two of the four sites, stratigraphic analysis of all four sites strengthened the overall conclusions regarding flood frequency and magnitude. All four sites had stratigraphic records of flooding which were slightly different, encompassing different time periods and recording different numbers and sizes of floods in different positions in the basin. Nevertheless, evidence of certain large floods was seen in multiple sections, indicating that the stratigraphic record is likely complete for the largest floods included in the flood frequency analysis. This is an important determination for flood-frequency analysis [e.g., *Blainey et al.*, 2002], and is one that in most situations can be assessed only by study of multiple sites.

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