The Outhouse Flood: A Large Holocene Flood on the Lower Deschutes River, Oregon

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Bouldery cobble bars, massive sand deposits, and stripped bedrock surfaces 5 to 19 meters above summer low flow stages along the lower Deschutes River were left by an exceptional Holocene flood, herein termed the Outhouse flood, which was substantially larger than any historic flow. The flood postdates the 7.6 ka Mazama tephra, and probably predates a 2.9-3.1 ka hearth. A 4.4-4.6 ka piece of charcoal from within sandy flood deposits may more closely represent the age of the flood. Step-backwater modeling at Harris Island, a site 17 km upstream from the Deschutes River confluence with the Columbia River, indicates that this flood had a peak discharge of at least 3800 m^3/s and likely as great as 5660 m^3/s. This is substantially greater than the 2000-3000 m^3/s peak historic discharges of the last 150 years caused by rain-on-snow events. Similar results from two upstream sites also indicate that this flood was substantially larger than historic flows as well as any prehistoric flow of the last 2000 years. Because of its exceptional size and the extensive Quaternary history of natural dam failure floods in the Deschutes River basin, we use multiple criteria to specifically address the question of whether this flood was of meteorological or dam-break origin. The downstream increase in peak discharge determined from the three separate sites of step-backwater analysis, coupled with the absence of any readily identifiable breached natural dam of the proper age, is strong evidence that the flood was indeed meteorological. This conclusion is weakened, however, by the lack of evidence for similar flooding in certain tributaries and adjacent basins.

INTRODUCTION

Geologic evidence of prehistoric large floods (paleofloods) is increasingly being used to support analysis of social and scientific issues such as dam and floodplain safety, century- to millennial-scale climatic variation, and the response of channel morphology to floods. The most commonly studied Holocene paleofloods are those that result from precipitation or snowmelt (meteorological floods). The goal of most paleoflood studies is to collect an extensive enough record of such floods to improve estimates of the recurrence interval of exceptional meteorological events. Such assessments are typically used for evaluating hazards to structures such as dams, or to assess the relations between climate and flood magnitude [*National Research Council*, 1988; *Kochel and Baker*,

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1988; *Jarrett and Tomlinson*, 2000]. In many regions, outburst floods from glacial, moraine, landslide, or manmade dam failures also create both significant hazards and long-lasting channel modification [*Schuster*, 1986; *Costa and Schuster*, 1988; *Costa*, 1988; *Walder and O'Connor*, 1997; *Cenderelli and Wohl*, 2001]. With the exception of certain recurring glacial outburst floods, most outburst floods are treated in the literature on a case-by-case basis as local convergences of phenomena, and not as events with predictable recurrence intervals or regional significance.

Because outburst floods and meteorological floods are treated as separate hazards and geomorphic agents, and have different implications with regard to prediction and mitigation strategies, it may be necessary to distinguish between the two types of floods in conducting paleoflood studies. In regions where outburst floods are known to have occurred, paleoflood analyses should ideally be undertaken with a clear set of criteria to distinguish between floods of different mechanisms in the stratigraphic record, although there are no known examples where this has been done.

In this paper we describe evidence for an exceptionally large Holocene flood in the lower Deschutes River of north central Oregon, and evaluate whether this flood was from a meteorological or a dam-outburst source. Prominent landforms along the lower Deschutes River deposited or shaped by this large flood include islands, boulder bars, rapids, and stripped bedrock surfaces. We have informally named the flood that left these features the "Outhouse flood" for the Bureau of Land Management outhouses laboriously built on many of the bouldery bars to serve recreational river rafters. The distribution of these morphologic features and their interaction with the modern flow regime are discussed in detail in *Curran and O'Connor* [this volume].

BACKGROUND

The Deschutes River drains 26,900 km^2 of north central Oregon before joining the Columbia River 160 km east of Portland (Figure 1). The lower Deschutes River, defined as the downstream 160 km of channel below the Pelton-Round Butte dam complex, flows through a canyon deeply incised into Cenozoic volcanic and volcaniclastic rocks [*O'Connor, Grant, and Haluska*, this volume]. Quaternary volcanism, tectonism, and glaciation contribute to the potential for floods generated by a variety of non-meteorological mechanisms. Pleistocene landslide dam remnants and associated outburst flood deposits have been documented for at least three locations in the lower Deschutes River canyon [*O'Connor et al.*, this volume]. These deposits are distinguished from Outhouse flood deposits by their proximity to the breach site, greater height of deposits above the channel, and greater size of clasts moved, recognizing that there is not a clear distinction in all cases. Other documented Quaternary floods in the Deschutes River basin have resulted from Pleistocene volcanic eruptions, spillover of tectonic basins, and failure of moraine dams in upstream areas. Additional possible flood-generating mechanisms in the drainage basin include failure of lava and ice dams [*O'Connor, Grant, and Haluska*, this volume].

Historically, flow in the lower Deschutes River has been remarkably stable due to an extensive, large-capacity aquifer system and a poorly integrated drainage network in the southern part of the Deschutes River basin [*Manga*, 1996; *Gannett et al.*, this volume]. Aquifers and alpine snowpack in the Cascade Range serve as natural reservoirs that provide year-round flow regulation, such that the seasonal range in runoff is much smaller than for adjacent rivers to the west and east. These factors combine to temper the magnitude of floods derived from both isolated meteorological events, such as winter storms, and from seasonal snowmelt [*O'Connor, Grant, and Haluska*, this volume].

The three largest historic floods on the Deschutes River occurred in the winters of 1861, 1964, and 1996. All of these flows were the result of regional rain-on-snow events that affected multiple basins in the Pacific Northwest and western United States. Both the February 1996 and December 1964 Deschutes River peak discharges were about 2000 m^3/s near the confluence with the Columbia River, although the 1964 flow was substantially reduced by upstream storage reservoirs. Inspection of the lower Deschutes River shortly after the 1996 flood showed abundant Holocene coarse gravel bars, fine-grained floodplain deposits, and erosional trim lines standing several meters above maximum stages achieved by the 1996 flood, indicating that a much larger flood had previously passed down the river. The discharge of the flood was originally estimated as over 5000 and probably closer to 14,000 m^3/s at Harris Island (Figure 1), using a single cross-section and Mannings equation (O'Connor, unpublished data). Because this value is 2.5 to 7 times greater than the largest historic flows, the source and size of the flood became outstanding questions with implications for upstream dam safety as well as channel formation processes and the distribution of aquatic habitats [*Curran and O'Connor*, this volume].

DISTRIBUTION AND MORPHOLOGY OF OUTHOUSE FLOOD DEPOSITS

Evidence for the Outhouse flood has been recognized at sites along most of the 160-km length of the lower

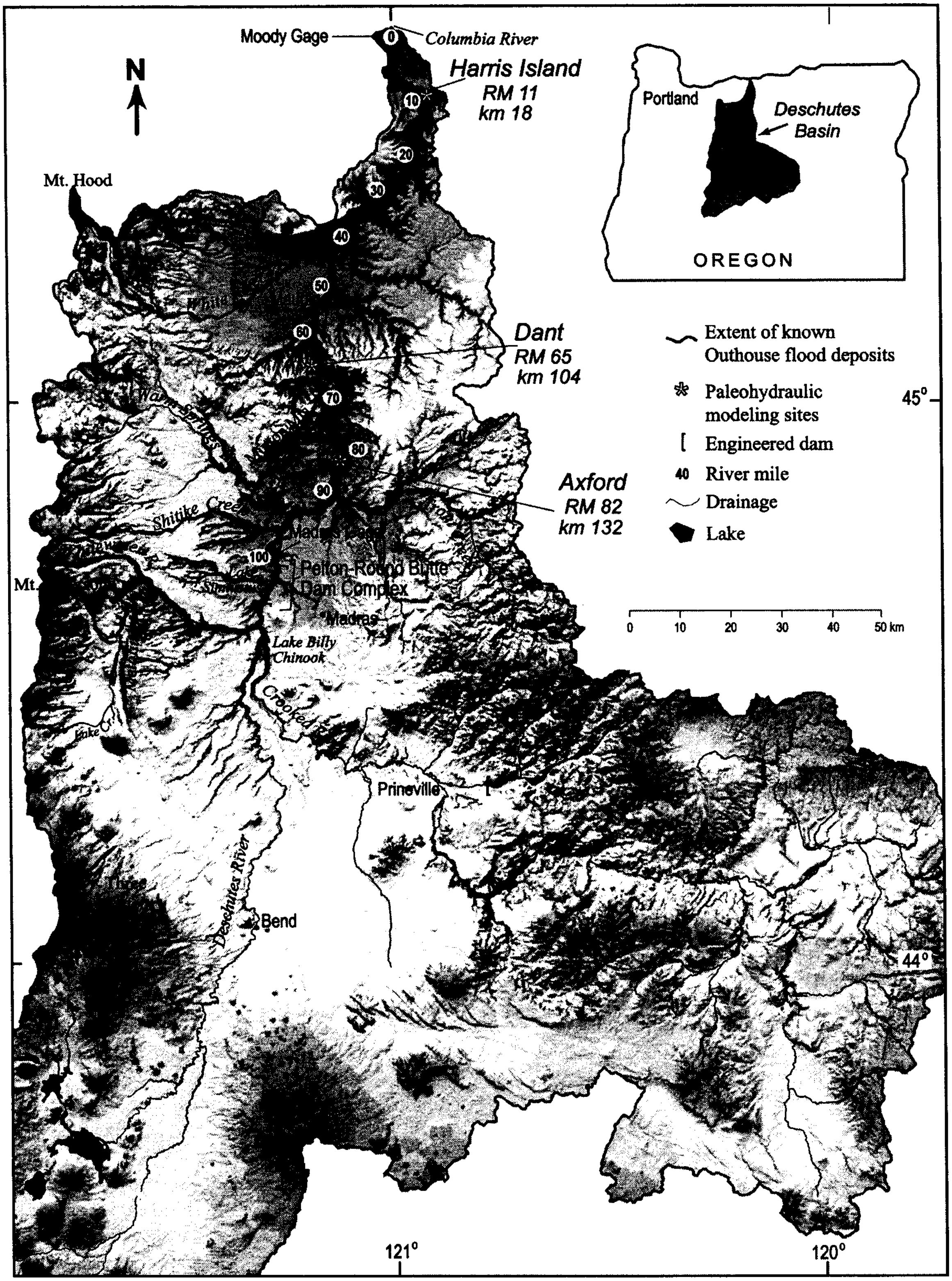

Figure 1. Shaded relief map of the Deschutes River Basin. Outhouse flood features identified so far are located along the 160 km of the Deschutes River downstream of the Pelton-Round Butte dam complex.

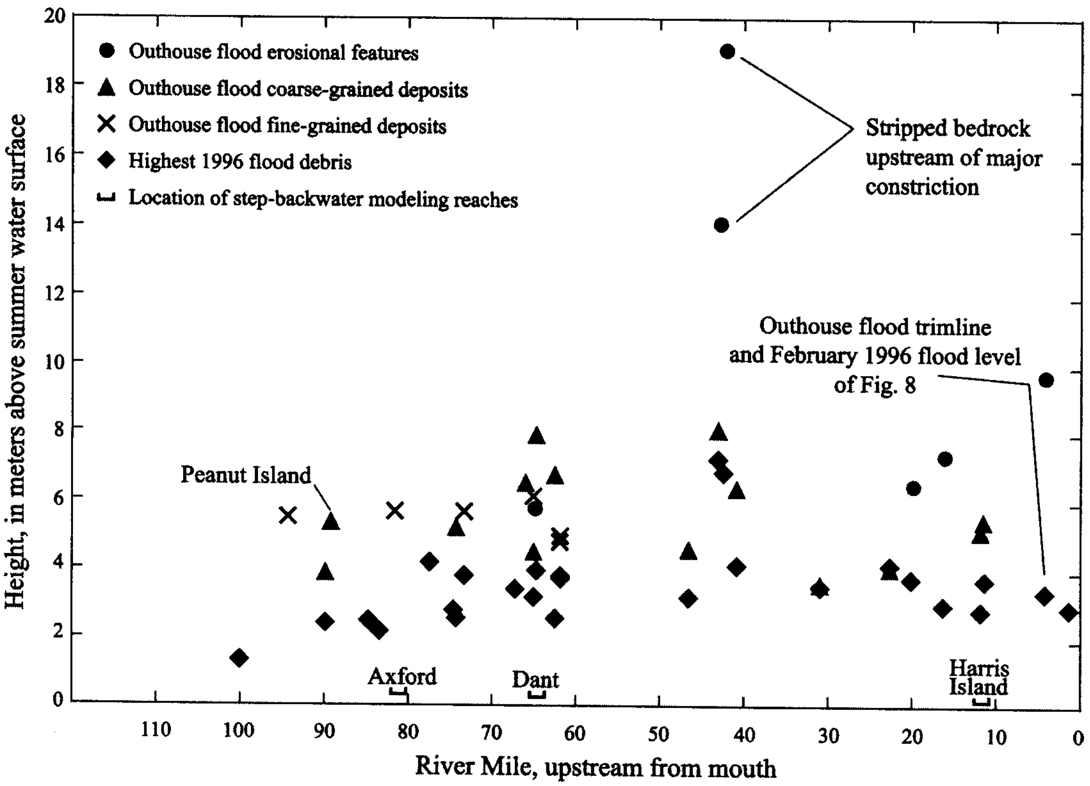

Figure 2. Height of Outhouse flood features (boulder bars and fine-grained deposits) and 1996 flood debris (primarily flotsam and fine woody debris) above summer water level.

Deschutes River (Figures 1 and 2). Depositional features include bouldery cobble bars and fine-grained slackwater deposits. Erosional features, more common in the lower 80 km, include stripped bedrock surfaces and trimlines in thick Pleistocene silt deposits that mantle the banks in the lower canyon. Variation in the height of these features above summer water surface[1] has no discernable downstream trend, but rather is highly dependent on local channel and floodplain width, in a manner similar to the elevations of 1996 flood debris (Figure 2).

Coarse-grained Outhouse flood deposits with surfaces well above historic flood limits are found on the insides of meander bends, and as mid-valley bars and islands (Figures 3 and 4). Maximum bar height varies from 3.5 to 8 m above summer water surface, depending on local channel and floodplain width (Figure 2). The cobbles and boulders are all volcanic rocks, but many of the larger boulders are traceable to local canyon wall lithologies. Boulders are subrounded to rounded, and cobbles are usually well rounded to very well rounded. Limited exposures into coarse-grained Outhouse flood deposits reveal imbricated cobbles and boulders.

Although some of these coarse-grained Outhouse flood deposits could be interpreted as terrace deposits, several attributes point to genesis by an exceptional flood or floods. The bars generally have streamlined shapes and surfaces that begin near summer water level and ramp up in the downstream direction unlike terrace treads, which have steep cut banks facing the river, and are typically flat or gently sloped downstream. The upstream ends of many Outhouse flood bars are mantled with boulders with diameters as great as a meter—much larger than the 3-10 cm gravels found in fill terraces (Figure 5). Maximum clast size consistently diminishes in the downstream direction, similar to patterns observed on other flood-formed bars [e.g. *O'Connor*, 1993]. Individual bars are positioned in zones of diminished flow velocity on insides of valley bends and at canyon expansions, consistent with the hydraulics of a large flood (Figure 4).

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[1] Analysis of stages and discharges along the lower Deschutes River indicate that summer water surface (May through September) fluctuates 10-30 centimeters, while discharge fluctuates 15-40 m^3/s.

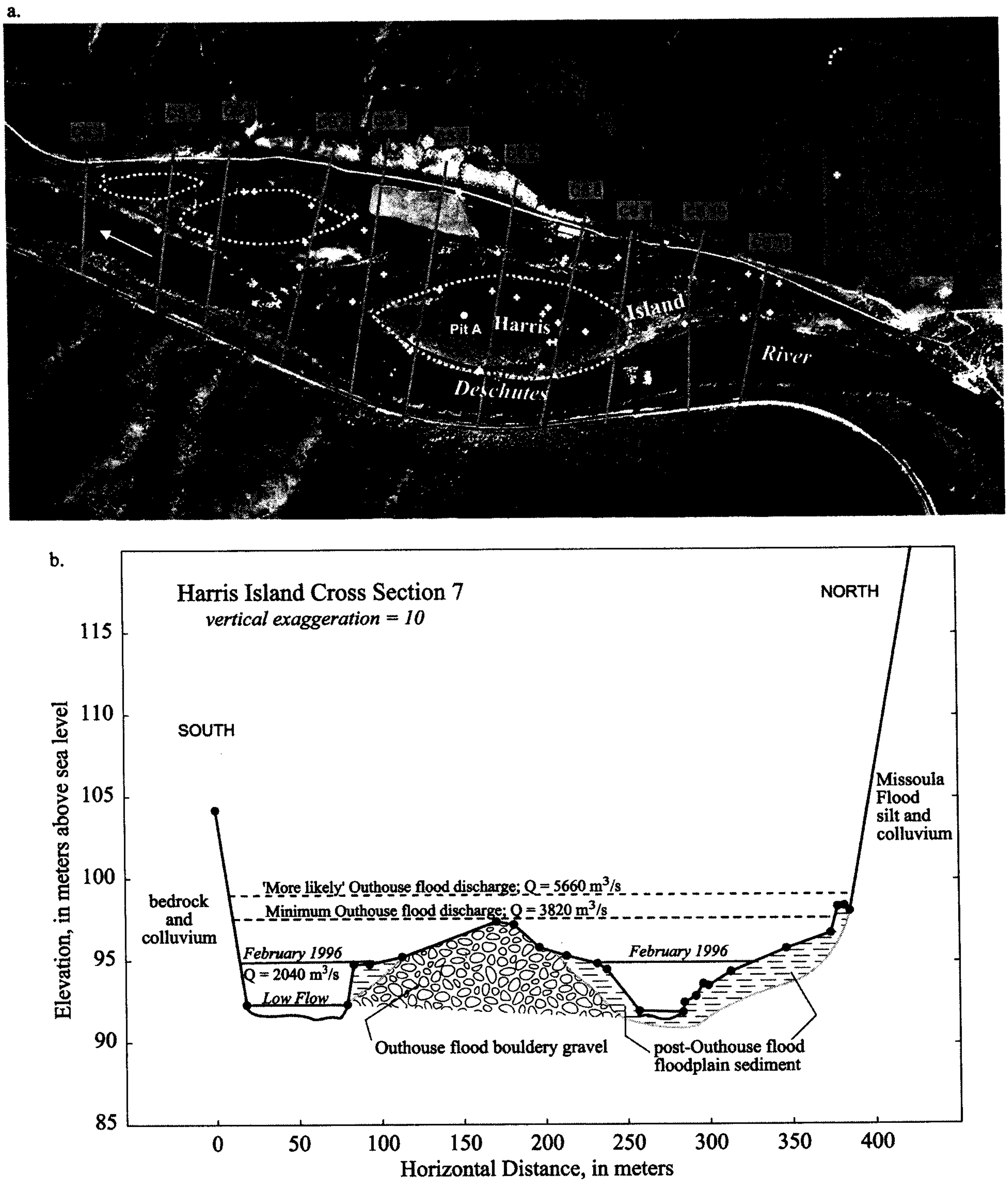

Figure 3. Harris Island study site at 18 km (RM 11) upstream of the Columbia River confluence. a. Vertical aerial photograph (1995) showing location of surveyed cross sections, three Outhouse flood bars, and limits of February 1996 flooding. b. Schematic geologic section of cross section 7, showing hydraulic model results for the February 1996 flood and the Outhouse flood.

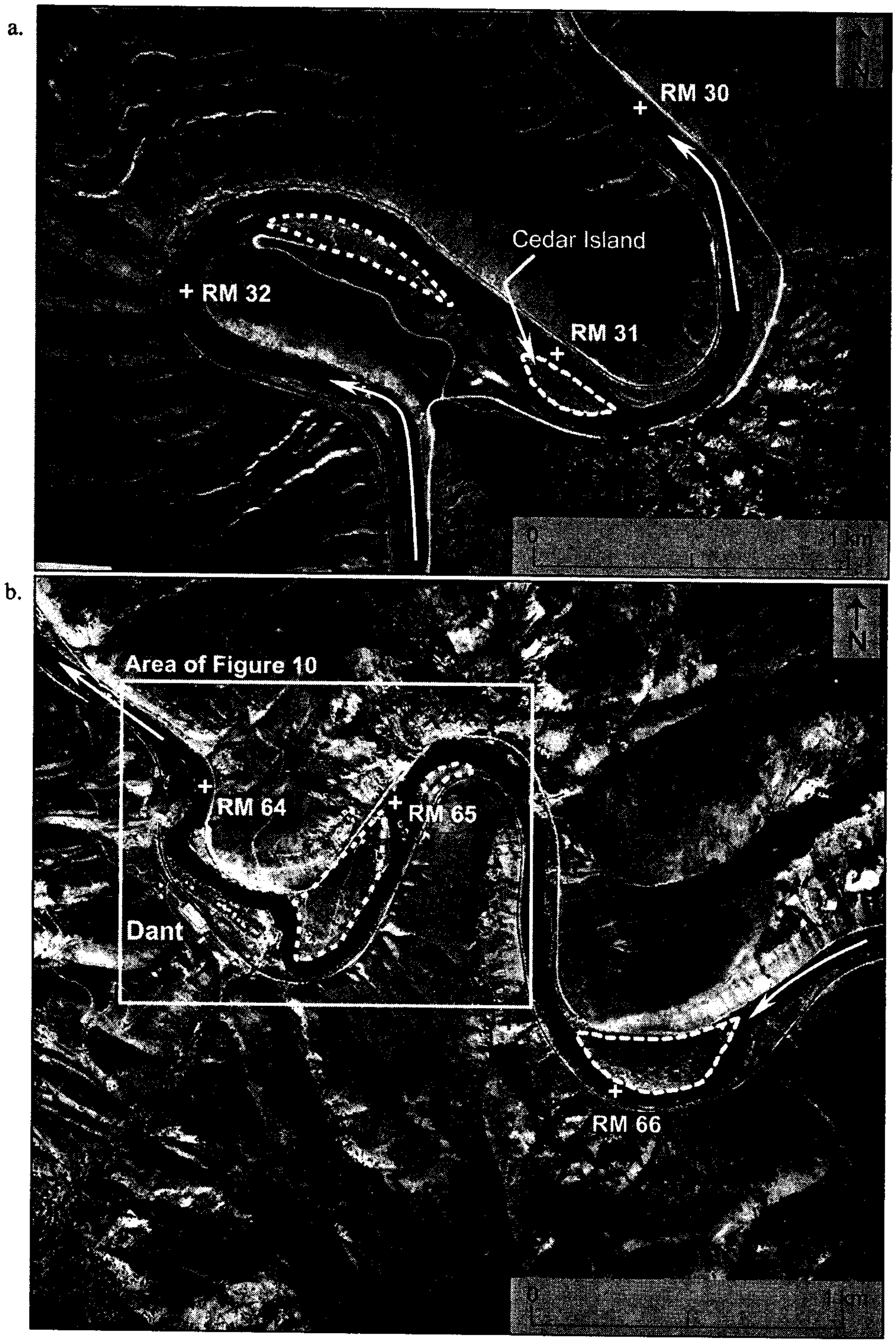

Figure 4. Typical valley geometries resulting in deposition and preservation of Outhouse flood bars. a. Two bars deposited near RM 31 (river kilometer 50), forming Cedar Island (in a channel inflection and valley expansion) and, just upstream, the alluvial surface of Beavertail Campground along the inside of a valley bend. Both of these surfaces were almost completely inundated by February 1996 flooding, but their cobbly and boulder surfaces indicate that they were deposited by a much larger flow. b. Outhouse flood bars on insides of sharp valley bends in the Dant study reach. The tops of these bars stand up to 4 m above the limits of February 1996 flooding.

Figure 5. Photograph of pit excavated in Outhouse flood gravels at the crest of Harris Island (Pit A of Figure 3a). Mazama pumice grains (identified by microprobe analysis conducted by Andrei Sarna-Wojcicki, U.S. Geological Survey) were in the sand matrix at a depth of 1.1 m. Graduations on the stadia rod are 0.3 m.

Massive sand and silt deposits inferred to be a fine-grained facies of the Outhouse flood are on the lee side of flow obstructions and other areas where there would likely be flow separation during exceptional floods. Two sites of well-exposed stratigraphy are near the Axford homestead at RM 82 (Figure 6)[2] and near the community of Dant at RM 65 (Figure 7). At these locations, fine-grained Outhouse flood deposits have surfaces up to 6 m above summer water levels and are, in places, thicker than 3 m. At both sites, sandy deposits of younger, smaller floods inset into Outhouse flood deposits have been the focus of the late Holocene paleoflood research by *Hosman et al.* [this volume]. Outhouse flood sands are internally structureless, homogeneous, and moderately to well sorted. Grain size ranges from silty fine sand to medium sand, with interspersed reworked pumice grains up to 4 mm in diameter. Soil development on fine-grained Outhouse flood sands varies with grain size from virtually none (except 2-3 cm of surficial organic material) in medium to coarse sand to stage I calcareous horizons [*Gile et al.*, 1966] and minor illuvial clay accumulation in silty sand. The fine-grained facies of the Outhouse flood lacks the buried soil surfaces found in the inset deposits of younger floods, suggesting deposition by a single event.

Erosional features indicative of a large Holocene flood are also found along the Deschutes River, especially in the lower 70 km. Broad basalt benches in constricted, bedrock-dominated reaches between RM 45 and 50 have been stripped of Missoula Flood silts and Mazama tephra up to 18 m above summer water level (Figure 2). Small channels and potholes occur on these surfaces where the dominant erosive mechanism appears to be plucking of blocks from the highly jointed basaltic bedrock. Accumulations of these blocks are found at sites where only flotsam accumulated during the February 1996 flood. Surficial soil material is minimal on the stripped bedrock, although grasses and other sparse vegetation grow along joints and in closed depressions. Although these channeled surfaces were probably occupied during a Pleistocene level of the Deschutes River, the absence of overlying Missoula Flood silts and Mazama tephra indicate that they were scoured during the Holocene. Silt and fine sand deposited by the *ca.* 15-12 ka Missoula Floods[3] that mantles the canyon slopes downstream of RM 40 is locally etched by distinct erosional scarps and trimlines reaching 6-9 m above summer water surface and 2-6 m above the maximum stage of the February 1996 flood (Figure 8).

STRATIGRAPHY, CHRONOLOGY AND PALEOCLIMATE

Stratigraphic relations, radiocarbon dating and tephrochronology have provided upper and lower bounds on the age of the Outhouse flood. Trimlines in Missoula Flood deposits of *ca.* 15-12 ka indicate that the flood occurred after the last of the Missoula Floods (Figure 8). The presence of Mazama pumice clasts within the fine-grained deposits at Dant and within coarse-grained deposits at Harris Island (Figures 1, 3, and 5) require that the flood post-dates the 7627±150 cal yr BP climactic eruption of Mt. Mazama

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[2] 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.

[3] 'ka' = kilo-annum, or thousands of years before present.

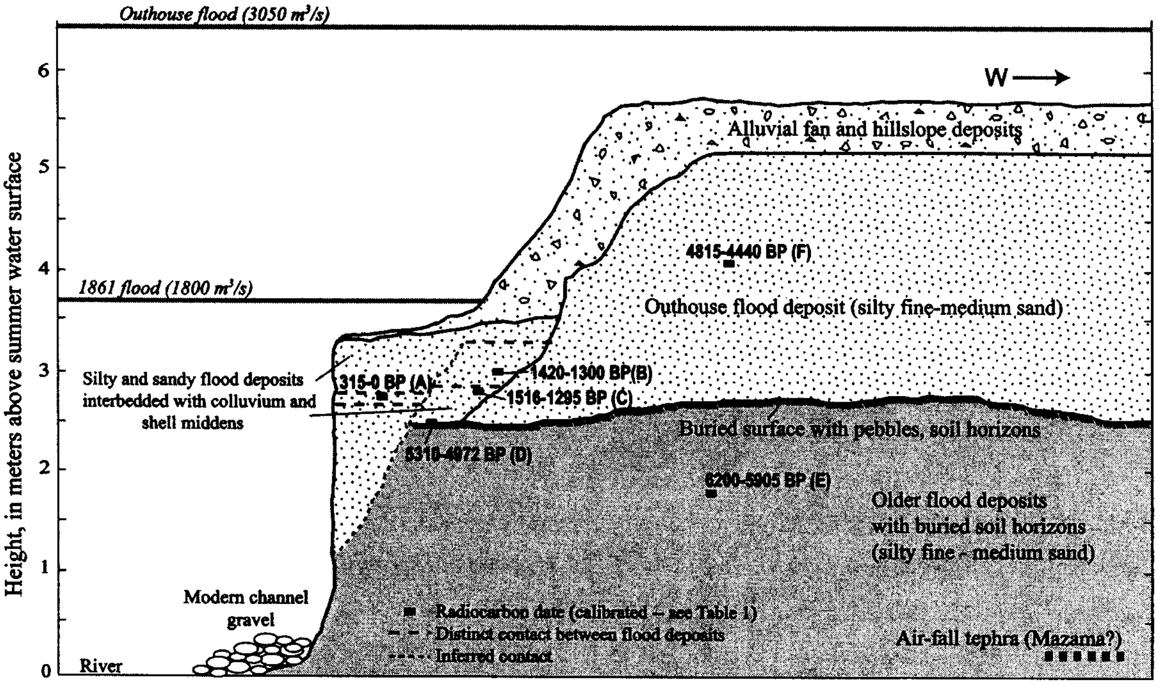

Figure 6. Schematic diagram of stratigraphic relations and chronologic data at Axford (RM 82). Radiocarbon results are presented in Table 1.

[*Zdanowicz et al.*, 1999]. The only datable material found so far within Outhouse flood deposits is from the Axford site, where an isolated charcoal fragment within the 3-m-thick sand and silt unit yielded a date of 4.4-4.6 ka (Table 1), providing a closer maximum limiting age for the flood.

Minimum bounding ages are provided by radiocarbon dates from deposits inset into or overlying Outhouse flood deposits, although the potential for reworking of charcoal must be considered. Several radiocarbon ages from inset fine-grained stratigraphy at Axford and Dant are in the range of 1.8 to 3.3 ka (Table 1), which is consistent with dates obtained from inset deposits at Caretaker Flat, a study site at RM 62 [*Hosman et al.*, this volume]. Charcoal from a hearth overlying likely Outhouse flood sand and gravel at Caretaker Flat yielded at date of 2.9-3.1 ka (Table 1). Taken together, the radiocarbon dating and tephrochronology indicate that the flood was certainly between 7.6 and 3.3 ka, and probably younger than 4.4-4.6 ka.

Regional climatic conditions at the time of the Outhouse flood may have been either warmer and drier than today or in a transition to present conditions, although resolution of paleoclimate and flood chronology do not permit firm conclusions. Three pollen studies from the Pacific Northwest indicate that slightly warmer, drier conditions than today prevailed between 9 ka and 3-5 ka, and a transition to modern conditions occurred between 5 and 3 ka [*Mack et al.*, 1978; *Sea and Whitlock*, 1995; *Whitlock et al.*, 2000]. Pollen is more useful for studying long-term, average conditions than the short-term fluctuations that are more likely responsible for anomalous floods. Events such as the "Little Ice Age" that immediately preceded the 1861 flood may not even appear in the pollen record [*Davis*, 1982; *Wright*, 1982]. However, the pollen record does suggest that regional climatic conditions during the middle Holocene were not substantially different from modern conditions.

STEP-BACKWATER MODELING

As noted above, most of the depositional and erosional features left by the Outhouse flood were not overtopped by the 1996 flood (Figures 2 and 3). Furthermore, many Outhouse flood features stand well above the limits of the 1861 flood, which was the largest flow known to European settlers or Native Americans at the time [*Salem Statesman*, December 12, 1861]. This relationship is best illustrated at the Dant study site at RM 65 (Figure 7). Here, the 1861 flood left a thick deposit of sand and silt that can be followed as it pinches out into a thin silt line within valley-margin colluvium. It attains a maximum elevation of 4 m above the summer water surface [*Hosman et al.*, this vol-

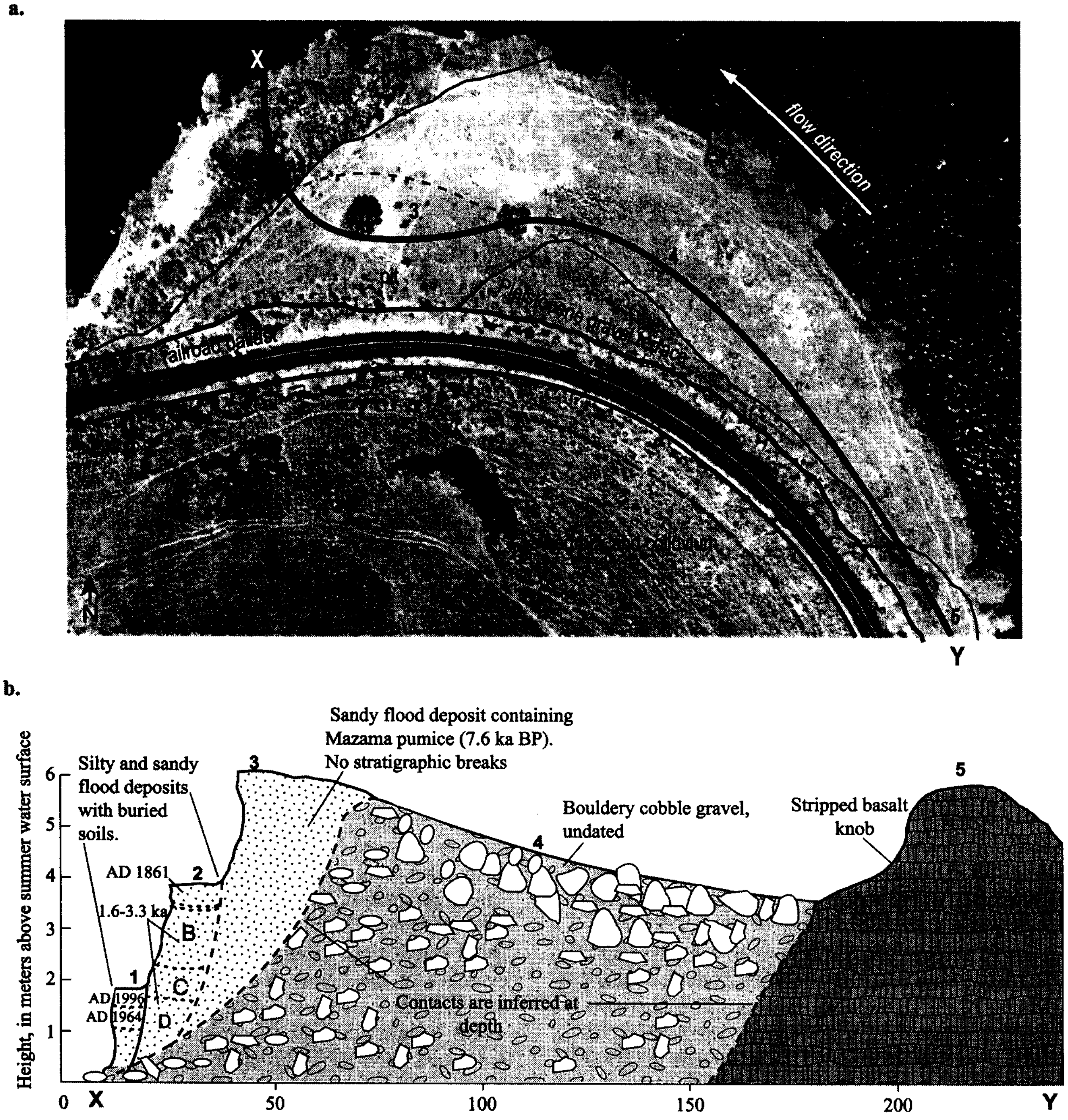

Figure 7. a. Vertical aerial photograph (1996) of a portion of the Dant study reach (RM 65), showing relations of Outhouse flood features to older bedrock and Quaternary terrace deposits as well as inset younger flood deposits. b. Schematic geologic cross section along profile X - Y. Mazama pumice grains at 1.0 m depth in the pit excavated into the fine-grained facies of the Outhouse flood deposits were identified by Nick Foit, Washington State University.

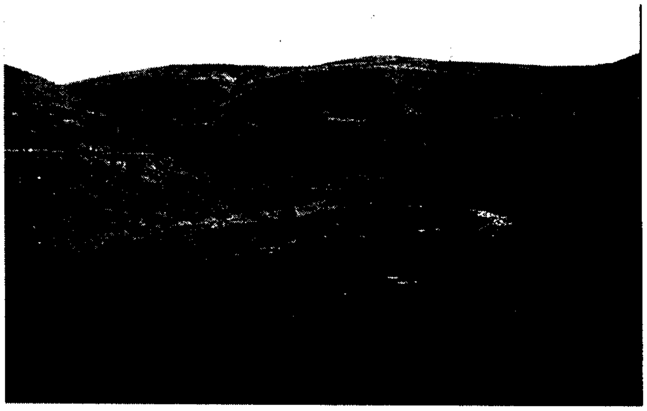

Figure 8. June 2, 1998 view downstream of the Deschutes River valley near RM 4.3 (river kilometer 7), showing pronounced trimline etched into Missoula flood silts presumably by the Outhouse flood. The maximum stage of the February 1996 flood was more than 4 m lower, near the base of the juniper tree.

ume], but is still a full 2.5 m below the top of a bar of medium sand deposited by the Outhouse flood.

To better estimate a discharge for the Outhouse flood, reaches with paleostage evidence near Dant, Axford (RM 82) and Harris Island (RM 11) were surveyed and analyzed with the step-backwater model HEC-RAS [*U.S. Army Corps of Engineers*, 1998]. The model simulates one-dimensional, steady, gradually varied flow between specified cross-sections along a reach for a given discharge. The calculated water surface is then matched with paleostage evidence and the model discharge is varied until a best fit to the data is achieved. Other input parameters include Mannings *n*, an empirical coefficient that accounts for frictional resistance due to the channel and floodplain boundary roughness, and upstream and downstream boundary conditions. *O'Connor and Webb* [1988] and *Webb and Jarrett* [2002] provide additional discussion of the application of step-backwater calculations for paleoflood analysis.

The use of surveyed cross-sections to estimate past discharges requires that channel boundaries have not changed significantly in the interim. Reworking of channel boundaries along the lower Deschutes River by the February 1996 flood of record was minimal, indicating that the modern channel is extremely stable and rarely modified by floods [*Curran and O'Connor*, this volume]. Exposures of overbank flood sediments with buried soil surfaces near the present summer water surface at Axford and Dant allow us to evaluate the extent of post-flood incision into older channel fill. These sediments date back to 3.1-3.3 ka at Dant, where the lowest buried surface is 1 m above summer water surface, and 4.9 - 6.2 ka at Axford, where the lowest buried surface is 1.9 meters above summer water surface. At both sites, channel gravel occupies only the lower half-meter of section, within the active high-flow channel, indicating that little or no incision has taken place since the overbank sediments were deposited.

Assuming channel geometry is properly represented, the accuracy of the step-backwater model varies depending on the hydraulic characteristics of the flow. A highly unsteady, two-dimensional flow may not be well approximated by models based on the one-dimensional energy equations for steady flow. There is additional uncertainty in selection of the Mannings *n* factor, which may change for a particular cross-section with increasing discharge. The extent to which the model is appropriate for a given channel geometry can be tested using historical floods with known stages in the reach and known discharges. Debris from the February 1996 flood was still evident in many places along the Deschutes River at the time of our field studies, and the discharge of the flood was recorded by gages on the Deschutes River at Madras (RM 100) and Moody (RM 1.4), and on major intervening tributaries. No direct discharge measurements are suitable for comparison to model results at the Axford and Dant reaches; however, results at the Harris Island reach (RM 11) are directly comparable to discharge at the Moody gage (RM 1.4). Modeling of the 1996 discharge was also used to test the choice of Mannings *n* values and boundary conditions at Dant and Harris Island. Where reasonable choices for these factors yield calculated water-surface profiles that closely match field evidence for maximum flood stages, we consider the modeling appropriate for determining reasonable estimates of the Outhouse flood. The sensitivity of a given modeled reach to uncertainty in *n* values can also be tested by calculating how discharge varies with different choices of *n*. For each reach, we conducted sensitivity tests with values of *n* ranging from 75-125% of the values assigned in the field (Table 2).

A third limitation commonly faced in applying step-backwater calculations to analysis of paleofloods is the scarce evidence of maximum flood stages. In most cases, paleoflood evidence consists of sedimentary deposits and erosional features that provide minimum constraints on the maximum flood stage. It is much more difficult to find compelling evidence of altitudes that floods did not reach. Thus, the lower bound on discharge is tied directly to physical evidence, whereas a "more likely" discharge can only be estimated by consideration of depositional or erosional environment and sediment size. We did not attempt to estimate a maximum discharge for any of these reaches due to a lack of evidence limiting maximum stages. At the two study reaches in which bouldery deposits were used as minimum stage

Table 1. Location and description of radiocarbon dates used in this report. Conventional 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. Calibrated ages are dendrochronologically calibrated by Beta Analytic Inc. using the INTCAL98 calibration data of *Stuiver et al.* [1998] and a laboratory error multiplier of 1. The 2-sigma range is the intercept of the conventional radiocarbon age ± 2σ with the calibrated calendar time scale curve. The intercept(s) are the intersection of the conventional radiocarbon age with the calibrated calendar time-scale curve. All $^{13}C/^{12}C$ rations were calculated relative to the PDB-1 international standard.

Sample	Site/unit	Material	Conv.^{14}C age BP +/-1sigma	2 sigma cal. range BP (intercepts)	$^{13}C/^{12}C$ Ratio (%)	Laboratory/ ID#
D2-1b	Axford A	charcoal	220+/-40	315 (290) 0	-25.8	Beta 131826
D2-2	Axford B	charcoal	1480+/-40	1420 (1350) 1300	-25.8	Beta 131827
D2-3	Axford C	charcoal	1490+/-45	1516-1426 1424 (1352) 1295	-25.3	UofAz AA36673
D2-5	Axford D	shell	4500+/-45	5310 (5277,5172, 5123,5108,5068, 5055,) 5026 5021-4972	-9.48	UofAz AA36674
5/14/99-2(3)	Axford E	charcoal	5260+/-70	6200 (5995) 5905	-24.1	Beta 131836
D2-10	Axford F	charcoal	4080+/-50	4815 (4540) 4745 4720-4425	-24.9	Beta 131831
D5-10	Dant A	charcoal	140+/-40	290 (265,215,140, 25,0) 5	-24.7	Beta 131834
3/17/00-1(3)	Dant B	charcoal	1836+/-42	1873 (1815,1797, 1775,1757,1739) 1692 1668-1661 1651-1629	-25.3	UofAz AA37926
D5-8	Dant C	charcoal	1310+/-50	1305 (1265) 1155	-26.5	Beta 131833
8/23/00-1(1)a	Dant D	charcoal	2980+/- 40	3310-3000 3260 (3160) 3000	-22.3	Beta 152465
5/17/99-2(1)	Caretaker Flats	charcoal	2850 +/- 50	3090 (2950) 2850	-28.9	Beta 131837

indicators, we use a relationship between shear stress and particle size to estimate depth of overtopping and calculate a "more likely" discharge. Shear stress (τ) is defined as

$$\tau = \gamma D S_e \qquad [1]$$

in which γ is the specific weight of water (9800 N/m), D is the depth in m, and S_e is the local energy gradient. Several relationships between τ and maximum transported particle size have been reported in the literature [*Buffington and Montgomery*, 1997; *O'Connor*, 1993; and *Williams*, 1983 contain summaries]. We use a regression relationship calculated by *O'Connor* [1993] for two reasons. First, the relationship assumes boulder-depositing flow, rather than incipient motion, and the shear stress required to accelerate a particle at rest is substantially greater than that required to keep it in motion. Second, the relationship was developed using the calculated local energy gradient as opposed to channel slope. In reaches upstream of constrictions, such as Dant, energy gradient is often substantially lower than channel gradient, leading to lower values of shear stress along the reach than would be calculated simply using channel slope. The shear stress associated with boulder deposition was related to particle size using the following regression equation:

$$\tau = 0.33 d^{1.12} \qquad [2]$$

where d is the median diameter of the five largest particles in cm [*O'Connor*, 1993]. For d = 30 cm, which is the approximate median diameter of the largest clasts on the highest point of the bars at Harris Island and Dant (e.g.

Table 2. Step-backwater modeling results for paleo- and historic floods, and gaged discharges for the 1964 and 1996 floods. The "natural" peak discharge estimate for the 1964 flood at the Moody gage is obtained by adding the 425 m^3/s rates of storage for Lake Billy Chinook and Prineville Reservoir during the flood [*Waananen et al.*, 1970a] to the gaged peak at Moody. Because it is unknown whether the maximum flow stored in the reservoir would have would have coincided with maximum runoff derived from downstream of the Pelton-Round Butte dam complex, this value for "natural" peak may be an overestimate. The values in parentheses in the Outhouse flood column represent the range of minimum and "more likely" discharges obtained by varying Mannings *n* from 75 –125% of the field-assigned value.

Location	Outhouse Flood (m^3/s)	1861 Flood (m^3/s)	1964 Flood (m^3/s)	1996 Flood (m^3/s)
Madras Gage (RM 100, km 160)	**	**	peak (Dec 28) 450	peak (Feb 8) 541
Axford (RM 82, km 132)	2200-3050 (1850-2400) (2570-3500)	1060 - 1800	**	**
Dant (RM 65, km 104)	2000-3500 (1800-2100) (3400-3700)	1100 - 1700	**	1000 - 1100
Harris Island (RM 11, km 18)	3800-5660 (3370-4250) (5150-6100)	**	**	2040
Moody Gage (RM 1.4)	**	**	peak (Dec 22) 2140 "natural" (Dec 22) 2990	peak (Feb 8) 1990

Figure 5), this implies a minimum shear stress value of 15 N/m. We use this value as a basis for estimating flow depths above Outhouse flood deposits to provide 'more likely' estimates of the peak discharge than the minimum estimates provided by assuming the maximum flow stage just overtopped the deposits. Table 2 summarizes results, including comparison with calculated and gaged discharges for historic Deschutes River floods.

Axford Study Reach

Ten cross-sections were surveyed along an 800-m reach near Axford, OR (Figures 9 and 10, RM 82). This reach was chosen because there is an excellent exposure of fine-grained stratigraphy representing nearly 7000 years [*Hosman et al.*, this volume] (Figure 6). It is not otherwise ideal for modeling for several reasons. First, there is only one site containing paleostage evidence within the reach, thus hindering comparison of calculated water-surface profiles to stage evidence. Second, the position of the site with respect to major tributaries is such that the gaged records of the 1964 and 1996 floods are not directly comparable with results from the site, also hindering assessment of the results. Finally, without a downstream constriction creating a backwater effect, the accuracy of the model is more dependent on the choice of Mannings *n* (discharge varies 550-930 m^3/s over the range of *n* values compared to 300 m^3/s at Dant). Nevertheless, the modeling results indicate that a minimum discharge for the Outhouse flood of 2150 m^3/s was necessary for flow to have achieved a stage represented by the top of the fine-grained deposits. A 'more likely' discharge of 3050 m^3/s is estimated assuming flow overtopped the surfaces by 1.2 m. This depth is based on the average height difference between flotsam from the February 1996 flood (approximating the exact high water surface) and 1.22 m-deep sand and silt deposits from the same flood in this reach [*Hosman*, 2001]. *Hosman et al.* [this volume] use a higher deposit further from the channel at Axford to calculate a discharge of 2860 – 3800 m^3/s for the Outhouse flood. We did not use the surface of this deposit as a paleostage indicator because a charcoal clast from 70 cm depth yielded an age of 1055 – 925 cal. BP, but it is possible that the date does not represent the true age of the deposit and that the Outhouse flood reached this stage.

Dant Study Reach

The Dant reach (RM 65) (Figure 11) has hydraulic conditions much more suitable for discharge estimation, although the gaged records of historic flows do not apply here, either. Several coarse Outhouse flood bars and one well-exposed section of fine-grained sediments are upstream of a substan-

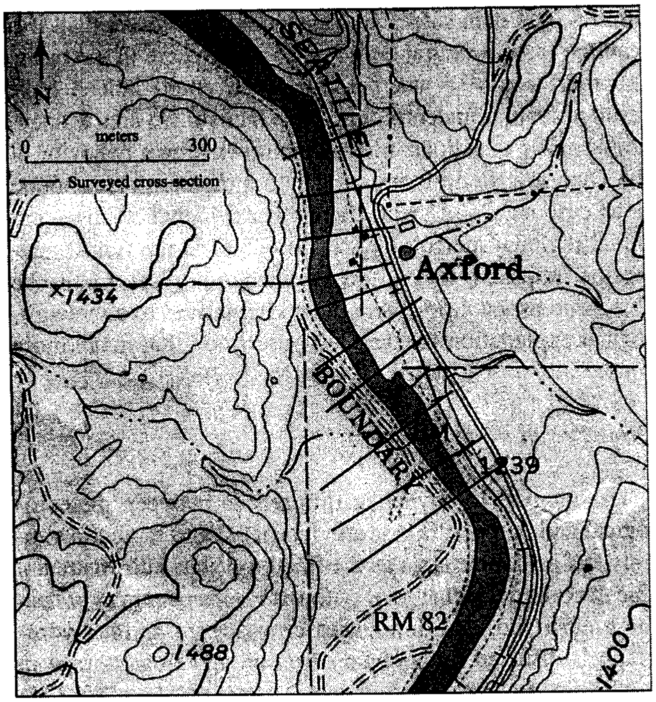

Figure 9. Location of cross-sections along the Axford reach.

tial valley constriction that served as a hydraulic control for large floods. Thirteen cross-sections were surveyed along a 2000-m reach. An additional cross-section spanning a channel constriction downstream of the surveyed reach was measured from aerial photos and topographic map. The site of exposed fine-grained stratigraphy is at the downstream end of an Outhouse flood bar and partly in the lee of an older Quaternary terrace (Figure 7). A minimum discharge estimate of 2000 m³/s for the Outhouse flood at Dant results from assuming flow just reached the top of the highest boulder bar. A 'more likely' estimate of 3500 m³/s was calculated using a shear stress of 15 N/m, a local energy gradient of 0.0004 and a depth of overtopping of 3.8 m (Figure 12).

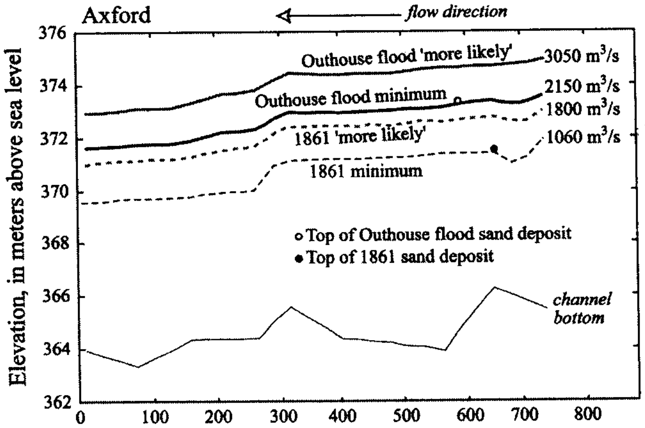

Figure 10. Calculated water surface profiles and relations to maximum stage evidence for the 1861 flood and the Outhouse flood for the Axford reach.

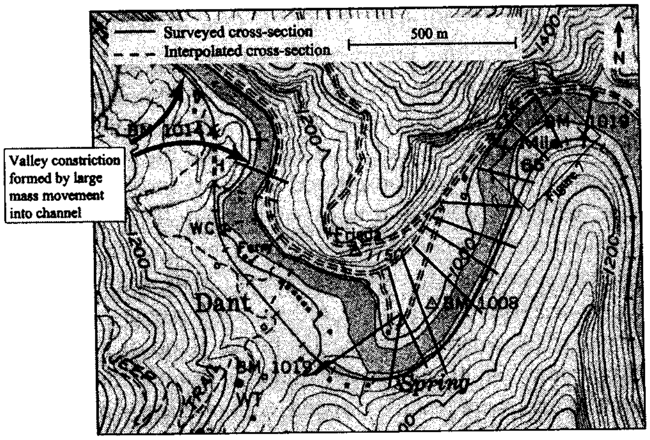

Figure 11. Map of Dant reach showing cross-section locations.

Harris Island Study Reach

Eleven cross-sections were surveyed along a 1200-m reach at Harris Island (Figure 3, RM 11). No major tributaries enter the Deschutes River between this reach and the Moody gage near the mouth, thus modeled discharges are directly comparable to gaged discharges for historical meteorological floods. Furthermore, the model can be calibrated using multiple surveyed locations of maximum 1996 flood debris (Figures 3 and 13) and the gaged discharge at the

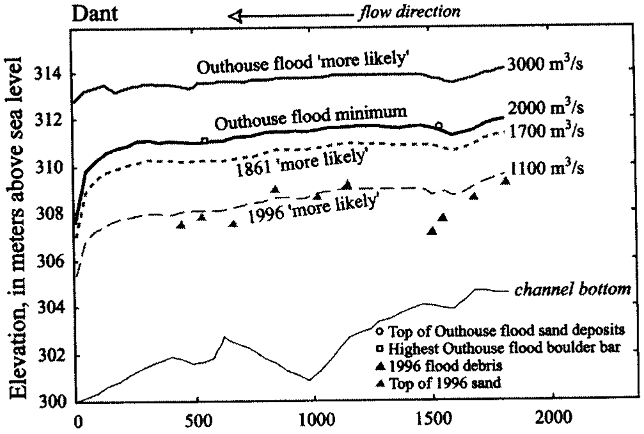

Figure 12. Calculated water-surface profiles and relations to maximum stage evidence for the 1996 and Outhouse floods for the Dant reach.

Moody gage (1990 m³/s, Table 2). One drawback of this reach for modeling purposes is that the 1996 flood split around the two prominent Outhouse flood bars, resulting in flow conditions not entirely suitable for applying a one-dimensional flow model. In addition, the only paleostage indicators for the Outhouse flood are the prominent boulder bars, which would have been submerged at an unknown depth during deposition. Nevertheless, the close fit between discharge modeled for the 1996 flood (2040 m³/s) and discharge measured at Moody (1990 m³/s) suggest that the model is reasonable. For the Outhouse flood, a minimum discharge of 3800 m³/s is calculated assuming the highest boulder bars were just overtopped. A 'more likely' discharge of 5660 m³/s produces a local shear stress value of 15 N/m² with a local energy gradient of 0.001 and a depth of overtopping of 1.5 m.

ANALYSIS OF POSSIBLE SOURCES

The estimated discharges range from 2000 to 5660 m³/s and show that the Outhouse flood was 1.3 to 3 times larger than the greatest historical floods at each of the three study sites. Furthermore, results reported by *Hosman et al.* [this volume] indicate that the Outhouse flood was substantially larger than any flow of the last 2000 years. Although these discharge estimates for the Outhouse flood are much smaller than the original Mannings equation estimate, the possibility of recurrence of such a flood could substantially affect risk assessment for the Deschutes River. Because of this, the cause of the flood becomes an important consideration. If the Outhouse flood was meteorological, then hazard implications with respect to advance warning, mitigation opportunities, and dam safety are substantially different than if it resulted from a natural dam failure somewhere in the basin. In order to assess whether this flood could indeed have resulted from a meteorological mechanism we address several specific questions: a) Was the downstream behavior of the Outhouse flood more similar to a meteorological flood or an outburst flood?; b) Is there other evidence of an exceptional regional meteorological flood?; c) Is the runoff generation required to produce a meteorological Outhouse flood unreasonable?; d) Are there alternatives to a meteorological explanation for the Outhouse flood that make more sense?

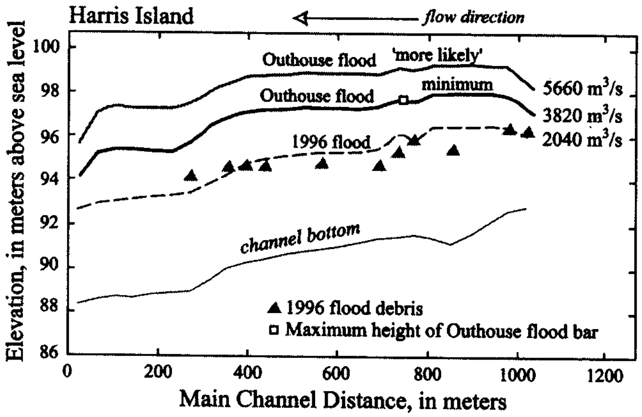

Figure 13. Calculated water-surface profiles and relations to maximum February 1996 stages and the crest of the Outhouse flood bar for the Harris Island reach.

Downstream Flow Behavior

The major hydrodynamic differences between meteorological and outburst floods are the spatial and temporal evolution of peak discharge as the flood translates downstream. The maximum discharge of outburst floods occurs at or near the breach site, and diminishes downstream as the hydrograph is diffused by boundary friction and flow storage in the valley bottom. An empirical equation developed by *Costa* [1988] that defines an envelope curve for the attenuation of discharge downstream for historical failures of constructed dams is

$$Q_x = \frac{100}{10^{(0.0021x)}} \qquad [3]$$

in which Q_x is the discharge at location x, expressed as a percentage of the discharge at the breach location, and x is the distance downstream from location of peak discharge in km. In contrast, tributary input causes most meteorological floods in the Deschutes River basin to increase in discharge downstream (Figure 14). Step-backwater modeling using Outhouse flood features at Axford, Dant, and Harris Island indicates that the peak discharge did increase substantially downstream. The observation that the peak discharges of both the Outhouse flood and the 1996 flood increased substantially between Dant and Harris Island is strong evidence that the Outhouse flood was meteorological as well. More discharge estimates for the Outhouse flood, particularly those that span confluences of significant tributaries such as the Warm Springs and White Rivers, could increase confidence in this conclusion.

Regional Evidence for Exceptional Floods

The atmospheric conditions leading to the largest meteorological floods in the Deschutes River basin commonly

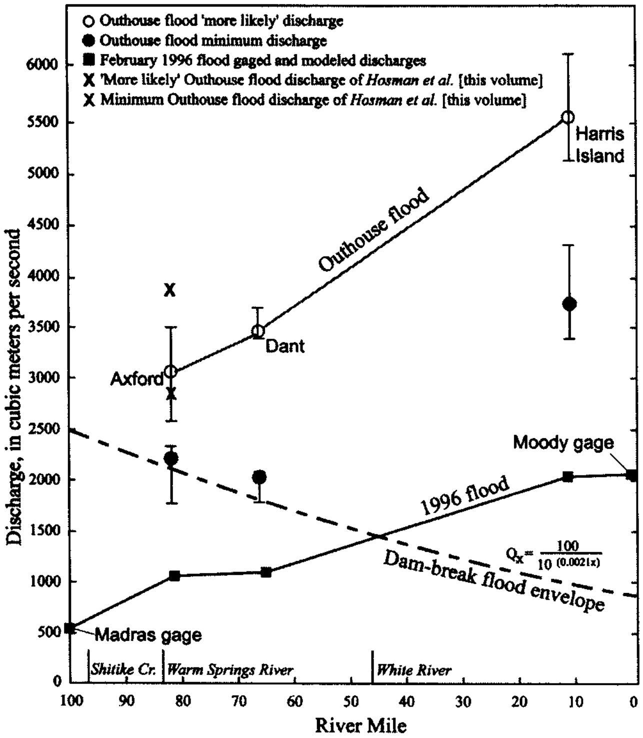

Figure 14. Comparison of downstream discharge evolution between the February 1996 flood measured values, Outhouse flood discharge estimates, and the envelope curve based on historical dam-break floods in narrow valleys [Costa, 1988]. Error bars on the Outhouse flood estimates indicate the range of discharges resulting from changing Mannings n from 75% to 125% of the assigned values.

affect adjacent rivers and occasionally several western states. The region affected depends on the type of storm causing the flooding, and how the storm interacts with the drainage basin. The three largest historic floods of Deschutes River—in December of 1861, December of 1964, and February of 1996—all occurred in midwinter when heavy snowpacks in the Cascade Range were rapidly melted by warm rainstorms. In all three cases, extended periods of low-elevation snow accumulation were followed by intense precipitation and warm temperatures carried into the Pacific Northwest by a subtropical jet stream that shifted north [*Taylor and Hannan*, 1999]. Newspapers reported record flooding on the Willamette and Deschutes Rivers in 1861, as well as heavy snowstorms in California [*The Oregonian*, November 30, 1861]. The winter storms of 1964 caused floods of record on rivers in five western states [*Waananen*, 1970a]. The February 1996 floods were focused in northwest Oregon and southwest Washington and produced large flows on the Willamette River as well as record flows for several eastern Oregon Rivers. These historical data show that large flows on the Deschutes River are usually accompanied by extreme regional flooding. A meteorological source for the Outhouse flood would thus be supported by evidence of contemporaneous flooding in adjacent basins.

Sparse paleoflood data in the region do not provide evidence for an exceptional regional flood at the time of the Outhouse flood. A study of the John Day River (the adjacent river basin to the east) indicates that the largest paleofloods occurred *ca.* 1.6 ka, and the earliest large Holocene flood occurred *ca.* 1.8 ka [*Orth and Ely*, 2000]. A paleoflood analysis of the Crooked River (the major tributary draining the eastern part of the Deschutes River basin) identified the 1861 flood as the largest post-Mazama flood [*Levish and Ostenaa*, 1996]. Similarly, extensive exposures of Mazama tephra capping floodplain stratigraphy along the upper Deschutes River [*Cameron and Major*, 1987] are evidence that there have not been exceptional post-Mazama flows in the southern part of the Deschutes River basin. The absence of evidence for exceptional flooding in other parts of the region, especially the Crooked River and upper Deschutes River basins, weakens the hypothesis that the Outhouse flood resulted from a regional meteorological event.

Are Peak Discharges Too High To Be of Meteorological Origin?

Given the discharge estimates of the Outhouse flood and lack of evidence for similar major flooding in the Crooked River and upper Deschutes River basins, is it still possible that the Outhouse flood resulted from rainfall and snowmelt generated primarily from the northern part of the Deschutes River basin? We assess this by evaluating patterns and volumes of runoff generated during the gaged flows of 1964 and 1996 (Figure 15, Table 3), adjusting for reservoir storage by using flow records from stations above reservoirs. The most striking pattern is that runoff per unit area from western tributaries draining the Cascade Range is an order of magnitude greater than the combined runoff from the Crooked and upper Deschutes River basins. During major historical floods, more than 75 percent of the peak discharge at the mouth of the Deschutes River entered the river in the lowermost 160 km downstream of Lake Billy Chinook. This imbalance between runoff upstream and downstream of Lake Billy Chinook was exaggerated by flow regulation in the Crooked River reservoirs and Lake Billy Chinook in 1964, when less than 7 percent of the peak discharge recorded at the mouth of the Deschutes River was derived from upstream of Lake Billy Chinook. This effect was less pro-

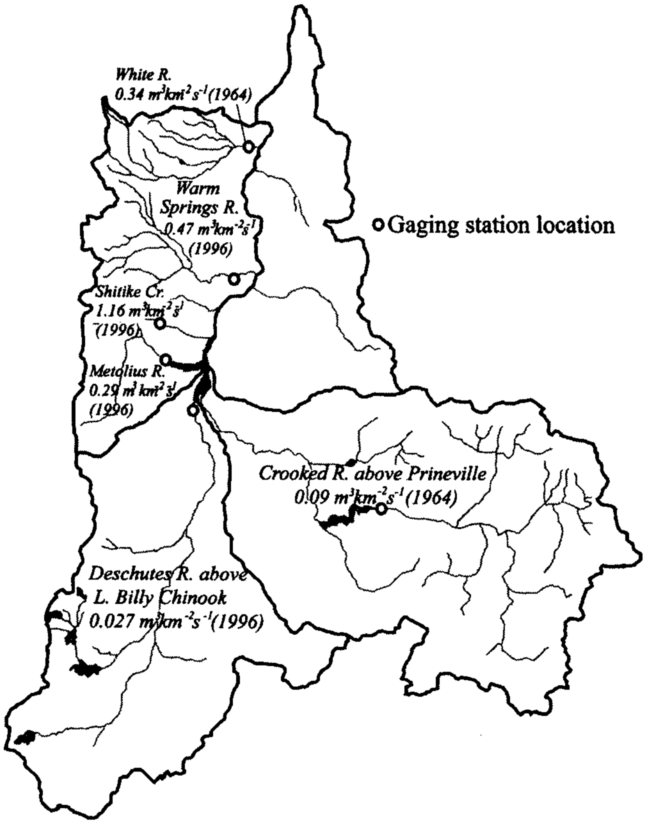

Figure 15. Runoff values during recorded floods in Deschutes River sub-basins. Values were calculated by dividing peak recorded discharge (either during the February 1996 or December 1964 floods) by drainage area (Table 3.)

nounced in 1996, when the reservoirs had less storage capacity available [*Fassnacht et al.*, this volume].

The low relative runoff values for the southern and eastern parts of the Deschutes River basin reflect regional geologic and climatologic conditions [*O'Connor, Grant, and Haluska*, this volume]. Runoff values for the Crooked River basin are low because the Cascade Range rain shadow inhibits precipitation, limiting snowpack storage on the eastern slopes of the basin. The upper Deschutes River basin south of Lake Billy Chinook does not have a well-developed surface drainage network to deliver rain and snowmelt rapidly to the mainstem [*O'Connor, Grant, and Haluska*, this volume], so although slopes of the southern Cascade Range accumulate substantial snowpacks, the storm runoff from the upper Deschutes River basin that reaches Lake Billy Chinook is even less than from the eastern subbasins. In contrast, the northern Cascade Range tributaries entering the mainstem below Lake Billy Chinook have incised, dense, and well-integrated channels that drain areas of substantial precipitation and snow accumulation; thus, this part of the basin can efficiently deliver large flows into the Deschutes River during heavy precipitation and snowmelt.

Table 3. Data from USGS gaging stations used to calculate runoff for Figure 15. Data for 1964 flood from *Waananen et al.* [1970b]; February 1996 flow records from *Hubbard et al.* [1997].

River	Gaging Station Number	Drainage Area (km^2)	Peak Flood Discharge (m^3/s)	Unit Peak Runoff (m^3/km^2s)
Crooked River	14079800	6213	558 (1964)	0.09
Deschutes River	14076500	7003	189 (1996)	0.027
Metolius River	14091500	839	239 (1996)	0.28
Shitike Creek	14092750	59.3	69 (1996)	1.16
Warm Springs River	14097100	1362	640 (1996)	0.47
White River	14101500	953	320 (1964)	0.34

We evaluated the runoff per unit area below Lake Billy Chinook necessary to produce the modeled Outhouse flood discharges at Dant and Harris Island by setting a reasonable upper bound on discharge at Madras (Figure 16). Although we have no discharge estimates of the Outhouse flood or the 1861 flood (the apparent Holocene flood of record on the Crooked River) upstream of Dant, we can approximate the discharge of the unregulated December 1964 flood at the Madras gage (RM 100) by adding the measured discharge to the peak gaged upstream reservoir storage rates during that flood [*Waananen et al.*, 1970b]. This adjusted discharge is 1300 m^3/s. Dividing the increase in drainage area between Madras and Dant by the increase in discharge yields a unit runoff of 0.18 – 0.3 m^3/km^2s for the minimum and 'more likely' Outhouse flood discharges, respectively. Between Dant and Harris Island, the required runoff is 0.65 – 0.78 m^3/km^2s. Runoff per unit area for the 1996 flood was 0.14 m^3/km^2s between Madras and Dant and 0.36 m^3/km^2s between Dant and Harris Island. The twofold increase in average runoff between these reaches is most likely due to basin physiography. The east side of the Deschutes River contributes much less runoff per unit area than the west side, and at least half of the drainage area between Madras and Dant is on the east side of the river. Between Dant and Harris Island, the majority of the drainage area is on the west side of the river, and includes some of the steepest, densest tributary networks in the lower Deschutes River basin [*O'Connor, Grant, and Haluska*, this volume].

Assuming that the contribution above RM 100 during the Outhouse flood was no greater than the largest historical flow, the runoff per unit area below Lake Billy Chinook

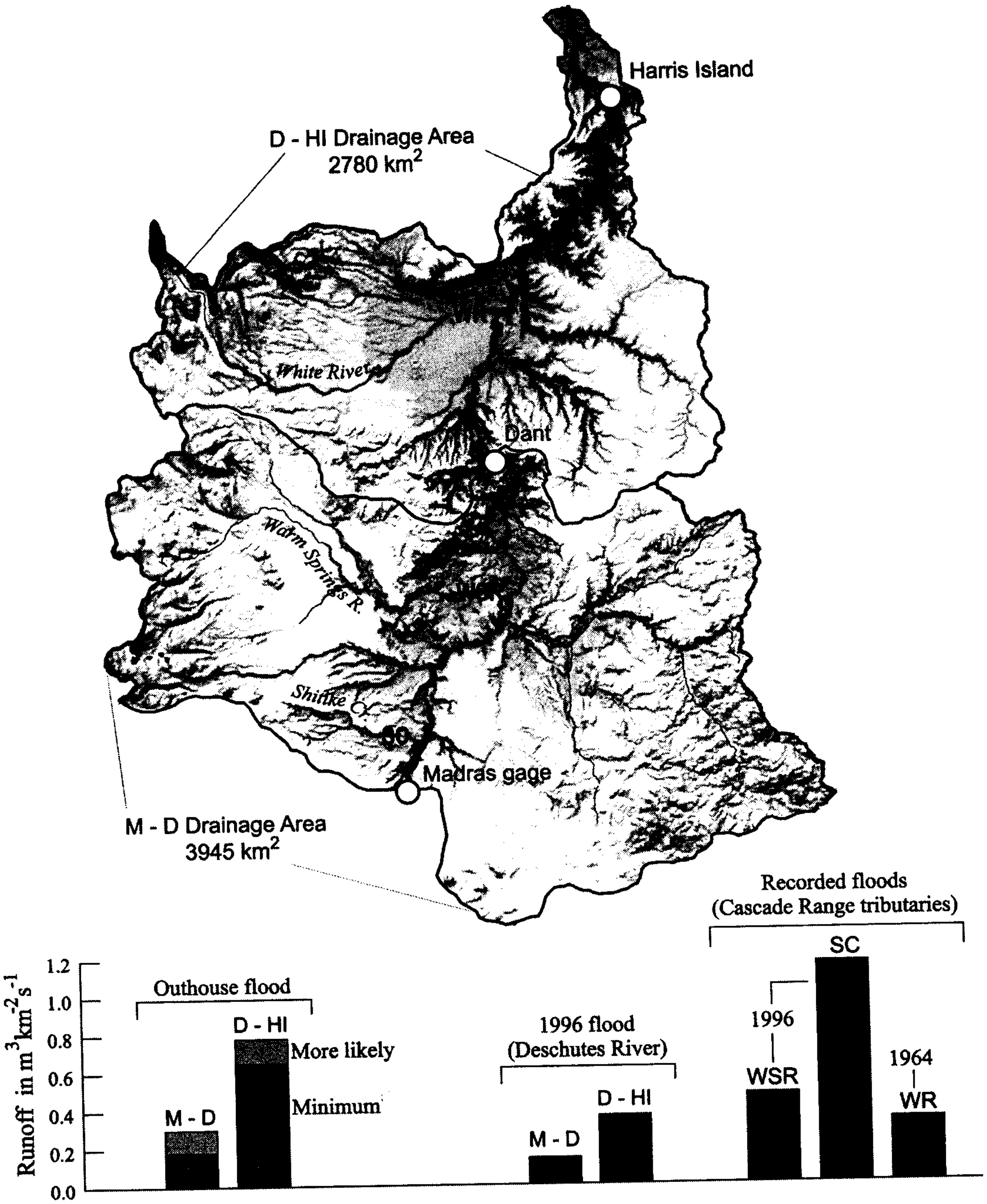

Figure 16. Runoff values calculated for the contributing areas between the Madras gage and Dant (M - D), and Dant and Harris Island (D - HI) for the Outhouse flood and the February 1996 flood. Outhouse flood discharge at Madras is approximated by the peak 1964 discharge adjusted for regulation. Runoff values are compared to recorded peak runoff from three Cascade Range tributaries: Shitike Creek (SC), Warm Springs River (WSR), and White River (WR).

required to produce the modeled discharges is at least 30-120% greater than peak 1996 flood runoff. These values are within the range of runoff delivered by tributaries to the lower Deschutes River during the 1964 and 1996 floods (Figure 15). Neither the 1964 nor the 1996 events occurred during episodes of record snowpacks (Oregon Climate Service data), so it is plausible that larger meteorological floods could be produced under conditions of heavy snow

Table 4. Estimates of downstream peak discharge attenuation for specified source volumes and peak discharges for a breach near the location of Peanut Island (RM 89, km 142). The relation of maximum discharge to source volume from *Walder and O'Connor* [1997]. Downstream attenuation based on envelope of *Costa* [1988].

Maximum Discharge (m^3/s)	Reservoir Volume (m^3)	Q_{max} at 5 km	Q_{max} at Axford (12 km)	Q_{max} at Dant (38 km)	Q_{max} at Harris I. (124 km)
2500	$1.07 \bullet 10^7$	2440	2360	2080	1373
3000	$1.40 \bullet 10^7$	2928	2830	2496	1647
3500	$1.76 \bullet 10^7$	3416	3304	2912	1922

accumulation followed by an intense subtropical cyclonic system, even if precipitation was focused primarily on the northern part of the Deschutes River basin. Thus, our assessment is that the apparent size and limited regional extent of the Outhouse flood do not preclude the rainfall-runoff hypothesis. This conclusion could be more completely tested by rainfall-runoff modeling.

Could the Outhouse Flood be an Outburst Flood?

The original working hypothesis developed after discovery of the Outhouse flood features was that there was some sort of outburst flood in the Deschutes River basin. This hypothesis followed from the apparent large magnitude of the flood coupled with the extensive Quaternary history of floods from natural dam failures in the Deschutes River basin [*O'Connor, Grant, and Haluska*, and *O'Connor et al.*, this volume]. Considering the age, magnitude, and geologic setting of the Outhouse flood, the most plausible types of natural dams that could have impounded sufficient water are landslide dams, lava flows, or Pleistocene moraine dams that failed several millennia after formation. The studies by *Levish and Ostenaa* [1996] on the Crooked River and by *Cameron and Major* [1987] along the upper Deschutes River indicate that there have been no exceptional post-Mazama floods debouching from those parts of the Deschutes River basin. These observations limit the possible source areas for an outburst flood to the Deschutes River canyon between Peanut Island (RM 88.9), the upstream-most feature clearly produced by the Outhouse flood (Figure 1), and the study sites of *Cameron and Major* [1987] upstream of RM 180, the Metolius River basin, or the Shitike Creek basin. We have not yet found evidence for middle to late Holocene natural dam failures in any of these areas, although our search has not been thorough.

Without a readily identifiable source for the outburst flood, we can only speculate on possible source conditions based on downstream peak discharge estimates and empirical relations developed from documented natural dam failures. One simple method is to use a regression equation based on documented landslide dam outburst floods. Data from *Walder and O'Connor* [1997] of reservoir volume and peak discharge yield the following relationship:

$$V_o = 116.48 Q_{max}^{1.4615} \ (r^2 = 0.74) \qquad [4]$$

where V_o is volume in m^3, and Q_{max} is discharge in m^3/s. Reservoir volume and downstream attenuation [Eq. 3] were calculated assuming maximum discharges of between 2500 and 3500 m^3/s at Peanut Island (Table 4). According to this regression, the reservoir volume necessary to create the Outhouse flood peak discharge is on the order of 10^7 m^3. For comparison, the volume of Lake Billy Chinook above Round Butte Dam (134 m high) is 6.5×10^8 m^3 and the volume of Lake Simtustus below Round Butte Dam and above Pelton Dam (62 m high) is 4.5×10^7 m^3. The volume values in Table 4 should be viewed as minima because the farther upstream of Peanut Island the dam is located, the greater the volume of impounded water necessary to produce the discharges at Axford, Dant, and Harris Island. This exercise cannot reproduce the increase in discharge downstream indicated by the modeling. Thus, our investigation into the outburst flood hypothesis requires that we discount either the accuracy of the modeled discharge at Harris Island or our original interpretation that the boulder bars were deposited by the same flood that deposited the features at Axford and Dant.

CONCLUSIONS

The Outhouse flood occupies an ambiguous place in the Holocene paleoflood record on the lower Deschutes River and in the Pacific Northwest. Because its inclusion in a flood-frequency analysis could substantially affect the perception of risk from meteorological floods in the Deschutes River, it is important to consider alternative flood-generating mechanisms to explain its large magnitude. Outburst floods from the breaching of natural dams occur in many rivers, especially where tectonic and glacial activity has created landslide-prone conditions. Evidence of several Pleistocene landslide dams in the Lower Deschutes River canyon at first seem to make this alternative an attractive explanation for the Outhouse flood. However, systematically applying criteria to distinguish between meteorological and outburst floods in the ancient record, including evaluating downstream discharge evolution, basin runoff characteristics, and potential sites of breached natural dams, leads us to tentatively infer that the Outhouse flood was from a meteorological source. The strongest evidence for this conclusion is the remarkably similar patterns of downstream increases in peak discharge between the Outhouse flood and historic flows. Counter to this finding is the absence of evidence for similar magnitude floods in other parts of the Deschutes River basin and in the adjacent John Day basin, although evaluation of historical runoff magnitudes suggests that the Outhouse flood could have been generated primarily from the northern Deschutes River basin.

The inference that the Outhouse flood was of a meteorological source could be further tested by (1) more confidently assessing downstream patterns of discharge evolution by finding more sites where precise discharge estimates could be determined, (2) continued searching for potential outburst flood source areas, and (3) identifying evidence for contemporaneous flooding in tributaries draining the northwest part of the basin, which would have to have been major contributors in a meteorological event. These activities are presently underway. Additionally, these criteria for distinguishing between outburst and meteorological floods are being applied in other western rivers, where there are commonly multiple causes for extreme floods.

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Section III

Geomorphic Effects of Dams on the Deschutes and Other Rivers

Our studies of the Deschutes River were initially motivated by the relicensing of the Pelton-Round Butte hydropower dam complex. These dams are only three of literally hundreds of non-Federal hydropower dams slated for relicensing in the next decades by the Federal Energy Regulatory Commission (FERC) under the Federal Power Act. On the Deschutes River, as elsewhere, relicensing typically involves a suite of studies intended to evaluate the dams' effects on the environment, and provide the technical foundation for the relicensing application as well as any changes in dam operation. Our examination of the downstream effects of the dam complex on the geomorphology of the Deschutes River was only one of multiple studies looking at all types of project effects, including impacts on fish population dynamics, fish passage, water quality, and temperature regimes.

Some background on the dams and relicensing is useful. The Pelton-Round Butte complex consists of two dams (Pelton and Round Butte) and a reregulating structure located on the Deschutes River 160-180 km upstream of its confluence with the Columbia River. The dams were constructed by Portland General Electric between May 1956 and August 1964. Total capacity is 427 megawatts, 408 of which are owned by Portland General Electric, with the remaining capacity owned by the Confederated Tribes of Warm Springs, who installed a 19-megawatt powerhouse on the regulating dam in 1982. The original license issued to Portland General Electric by the Federal Power Commission (the predecessor to FERC) expired December 31, 2001. Initial studies and preparation of the license application began in 1995. A final draft license application was submitted to FERC by Portland General Electric in December 1999 and was amended in June 2001 by a final application amendment jointly submitted by Portland General Electric and the Confederated Tribes of Warm Springs. Currently the project operates under annually issued licenses while FERC reviews and decides upon the final conditions of the relicense, which will have a term of thirty to fifty years.

As specified by the 1986 Electric Consumers Protection Act, FERC must consider both power and non-power interests in evaluating the suitability and terms and conditions of a license application. For U.S. rivers, such non-power interests affected by hydropower operations typically include recreation, reservoir- and river-side development, cultural resources, water quality, and fisheries. For the Deschutes River, fisheries are a major issue. The original facilities were constructed to promote passage of anadromous fish (chinook and sockeye salmon and steelhead, the sea-run form of rainbow trout) to upstream spawning and rearing areas and to allow downstream passage to the Pacific Ocean. These facilities were not successful and, since 1968, passage has been eliminated. Reestablishing passage is being considered as part of future operations. Downstream of the dam complex, the Deschutes River and tributaries support spawning and rearing of remaining anadromous stocks as well as a world-renowned sports fishery targeting native salmon and trout. Thus, a specific question driving much of the research conducted as part of the Pelton-Round Butte relicensing is: "What are the likely effects of past and future dam operations on fisheries in the Deschutes River

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basin?" This question has many facets, but the aspect motivating much of the research presented in this volume is the possible effect of the Pelton-Round Butte dam complex on downstream channel geomorphology and physical habitat conditions.

Aware of other studies on other rivers that showed dramatic changes in channel morphology below dams, such as the erosion of beaches in the Colorado River below Glen Canyon Dam, we anticipated finding similar responses on the Deschutes River. The surprisingly few detectable geomorphic effects below the Pelton-Round Butte dam complex first alerted us to the unique character of the Deschutes River. As discussed in *Fassnacht et al.*, no discernible coarsening of the bed was observed downstream from the dams, nor was there evidence of significant and systematic erosion of islands or the channel bed, even in the reaches immediately below the dams. While unexpected, these results were interpretable in light of the rarity of bedload transport: hydraulic modeling predicted that bedload transport occurred less than 1% of the time in comparison to 5-10% of the time on other gravel-bed rivers. Infrequency of transport was linked to the uniformity of flows without major peaks and with relatively high entrainment thresholds for the coarse bed material.

But as the paper by *Grant et al.* points out, although the studies revealed the Deschutes River to be quite different from other dammed rivers in the absence of downstream response, it does fit within a continuum of rivers and dam effects when viewed across the spectrum of sediment and flow conditions of rivers affected by dams. This offers some hope that by viewing dams within their broader geological and geomorphic settings, downstream effects of dams can be predicted, at least in terms of direction and magnitude, even for peculiar rivers, such as the Deschutes.