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Owyhee River intracanyon lava flows: Does the river give a dam?

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ABSTRACT

Rivers carved into uplifted plateaus are commonly disrupted by discrete events from the surrounding landscape, such as lava flows or large mass movements. These disruptions are independent of slope, basin area, or channel discharge, and can dominate aspects of valley morphology and channel behavior for many kilometers. We document and assess the effects of one type of disruptive event, lava dams, on river valley morphology and incision rates at a variety of time scales, using examples from the Owyhee River in southeastern Oregon.

Six sets of basaltic lava flows entered and dammed the river canyon during two periods in the late Cenozoic ca. 2 Ma–780 ka and 250–70 ka. The dams are strongly asymmetric, with steep, blunt escarpments facing up valley and long, low slopes down valley. None of the dams shows evidence of catastrophic failure; all blocked the river and diverted water over or around the dam crest. The net effect of the dams was therefore to inhibit rather than promote incision. Once incision resumed, most of the intracanyon flows were incised relatively rapidly and therefore did not exert a lasting impact on the river valley profile over time scales >10^6 yr. The net long-term incision rate from the time of the oldest documented lava dam, the Bogus Rim lava dam (≤1.7 Ma), to present was 0.18 mm/yr, but incision rates through or around individual lava dams were up to an order of magnitude greater.

At least three lava dams (Bogus Rim, Saddle Butte, and West Crater) show evidence that incision initiated only after the impounded lakes filled completely with sediment and there was gravel transport across the dams. The most recent lava dam, formed by the West Crater lava flow around 70 ka, persisted for at least 25 k.y. before incision began, and the dam was largely removed within another 35 k.y. The time scale over which the lava dams inhibit incision is therefore directly affected by both the volume of lava forming the dam and the time required for sediment to fill the blocked valley. Variations in this primary process of incision through the lava dams could be influenced by additional independent factors such as regional uplift, drainage integration, or climate that affect the relative base level, discharge, and sediment yield within the watershed.

By redirecting the river, tributaries, and subsequent lava flows to different parts of the canyon, lava dams create a distinct valley morphology of flat, broad basalt shelves capping steep cliffs of Tertiary sediment. This stratigraphy is conducive to landsliding and extends the effects of intracanyon lava flows on channel geomorphology beyond the lifetime of the dams.

INTRODUCTION

In recent decades, the rate at which rivers incise through bedrock has been viewed as a primary control on regional patterns of landscape evolution in mountainous or uplifted terrain (e.g., Howard, 1994; Whipple and Tucker, 1999; Whipple, 2004). Over time scales of 10^6 yr, valley erosion processes are often considered essentially continuous in both time and space and are modeled with "generic" (sensu Whipple, 2004) incision models such as the unit stream power model. In many environments, however, rivers are disrupted by singular events, such as channel incursions of lava flows or large mass movements. These "extrafluvial" processes can inhibit incision by burying valley-bottom bedrock and altering channel slope, width, and bed character; or they can promote incision by generating cataclysmic floods through natural dam

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failures (O'Connor and Beebee, 2009). Such disruptions to fluvial systems are commonly independent of slope, basin area, or channel discharge, yet they can dominate aspects of valley morphology and channel behavior over reaches spanning many kilometers. Recognition of the potential importance of extrafluvial events in valley evolution and river incision is growing (e.g., Hewitt, 1998; Stock et al., 2005; Cheng et al., 2006; Ouimet et al., 2007, 2008; Pratt-Sitaula et al., 2007; Korup et al., 2010). It remains unclear, however, whether and under what circumstances long-term patterns of landscape evolution are sensitive to extrafluvial events. Korup et al. (2010), for example, argued that the influence of landsliding on fluvial processes and landforms is most effective at $\leq 10^4$ yr time scales, but not over the 10^6 yr time scale. In this study, we document and assess the effects of one type of extrafluvial event, lava dams, on river valley morphology and incision rates at a variety of time scales along the Owyhee River corridor in southeastern Oregon (Fig. 1). This setting exemplifies processes common to many semiarid, predominantly extensional settings in the western United States and around the world.

The impacts of lava dams on long-term landscape evolution depend largely on the duration over which the dams persist and, less obviously, on the secondary effects of hillslope processes involving incised lava flows. The persistence of lava dams is in part related to the emplacement setting and lava-water interactions. Subaqueously emplaced lava can create dams of complex character, as in Grand Canyon, where lavas poured directly over the rim or erupted within the canyon. In Grand Canyon, some lava dams were unstable and failed catastrophically, due to a combination of emplacement on unstable colluvial slopes, hydrothermally weakened or fractured layers within the basalt flows, and/or interbedded accumulations of tephra (Hamblin, 1994; Fenton et al., 2002; Howard and Fenton, 2004; Crow et al., 2008). Catastrophic natural dam failures can generate floods with peak discharges that far exceed those of meteorologically generated floods (Fenton et al., 2006), and thus can enhance transport rates of coarse sediment or bedrock incision rates downstream from the dam failure site.

In contrast, stable lava dams inhibit incision. Intracanyon lava flows can extend both upstream and downstream of the incursion site, depending on lava flow volume and river valley characteristics. The lava flows bury the valley floor in new material for up to tens of kilometers. Upstream of the lava dams, flow energy is too low to accomplish incision during the lifetime of the dam. Hence, sediment can accumulate in impounded reaches and temporarily shield the channel bed from incision even after the lava dam has been incised.

The longevity of stable dams and the specific processes and rates of incision in different environments are not well documented. Howard et al. (1982) documented rapid rates of incision through lava dams on the Boise River in Idaho, which bear many similarities to the lava dams on the Owyhee River. Incision can occur through the lava itself or through the surrounding bedrock, even when the blockage is less resistant to erosion than the bedrock (Howard et al., 1982; Pratt-Sitaula et al., 2007; Ouimet et al., 2008). Ouimet et al. (2008) suggested that epigenetic gorges are generally cut rapidly relative to background rates of incision in most settings. However, the empirical validity and theoretical basis of such claims across diverse settings remain unclear, in part because so few studies have focused on this issue. In analyzing the impacts of lava flows on incision rates of the Owyhee River, this study contributes to a broader discourse about the rates at which individual stream reaches can re-incise after perturbations, relative to long-term rates of river incision.

Little attention has been paid to important secondary effects of lava-dam emplacement on hillslope morphology and process. The lateral displacement of the river channel by lava incursions and the stratigraphic juxtaposition of lava flows overlying unconsolidated sediment in the valley walls could increase the potential for landslides, which could themselves block the river. These secondary effects potentially extend geomorphic influences of the lava incursions on river valley morphology in both time and space.

The Owyhee River system is particularly well suited for investigating the relationships among lava dams, fluvial incision, and valley geomorphology at various spatial and temporal scales. We characterized and quantified the emplacement, duration, and removal of lava dams formed by six sets of Pleistocene basaltic lava flows that entered the study reach (Figs. 2B, 3, and 4; Table 1). To establish the volcanic, fluvial, and lacustrine stratigraphy that reveals the geomorphic response of the river, we conducted extensive field mapping and geochronological analysis of a wide variety of well-preserved geomorphic features. Herein, we first describe the field area, then explain the methods used to map and date landforms in the study reach, summarize the volcanic stratigraphy, and finally interpret the incision history of the river in light of our new data.

Figure 1. Location map of the Owyhee River drainage. Box outlines study area shown in Figure 2A.

GEOGRAPHIC AND GEOLOGIC SETTING

The Owyhee River drains ~30,000 km^2 of Nevada, Idaho, and southeastern Oregon, flowing northward into the Snake River just upstream of Hells Canyon (Fig. 1). In the absence of previously designated river miles, we specify sites by river kilometer (Rk) downstream (north) along the modern course of the Owyhee River from a starting datum of 0 at Rome, Oregon (42°50′N, 117°37′W), to Rk 78 at the confluence with Birch Creek (Figs. 2B and 3). This study focused on the 50 km of river corridor from Rk 25 to 76, encompassing the reach most affected by Quaternary lava flows.

The study area lies within the synvolcanic Oregon-Idaho graben southwest of the western Snake River Plain at the juncture of the High Lava Plains, the Basin and Range, and Columbia River Basalt Provinces (Cummings et al., 2000; Shoemaker and Hart, 2002; Shoemaker, 2004).

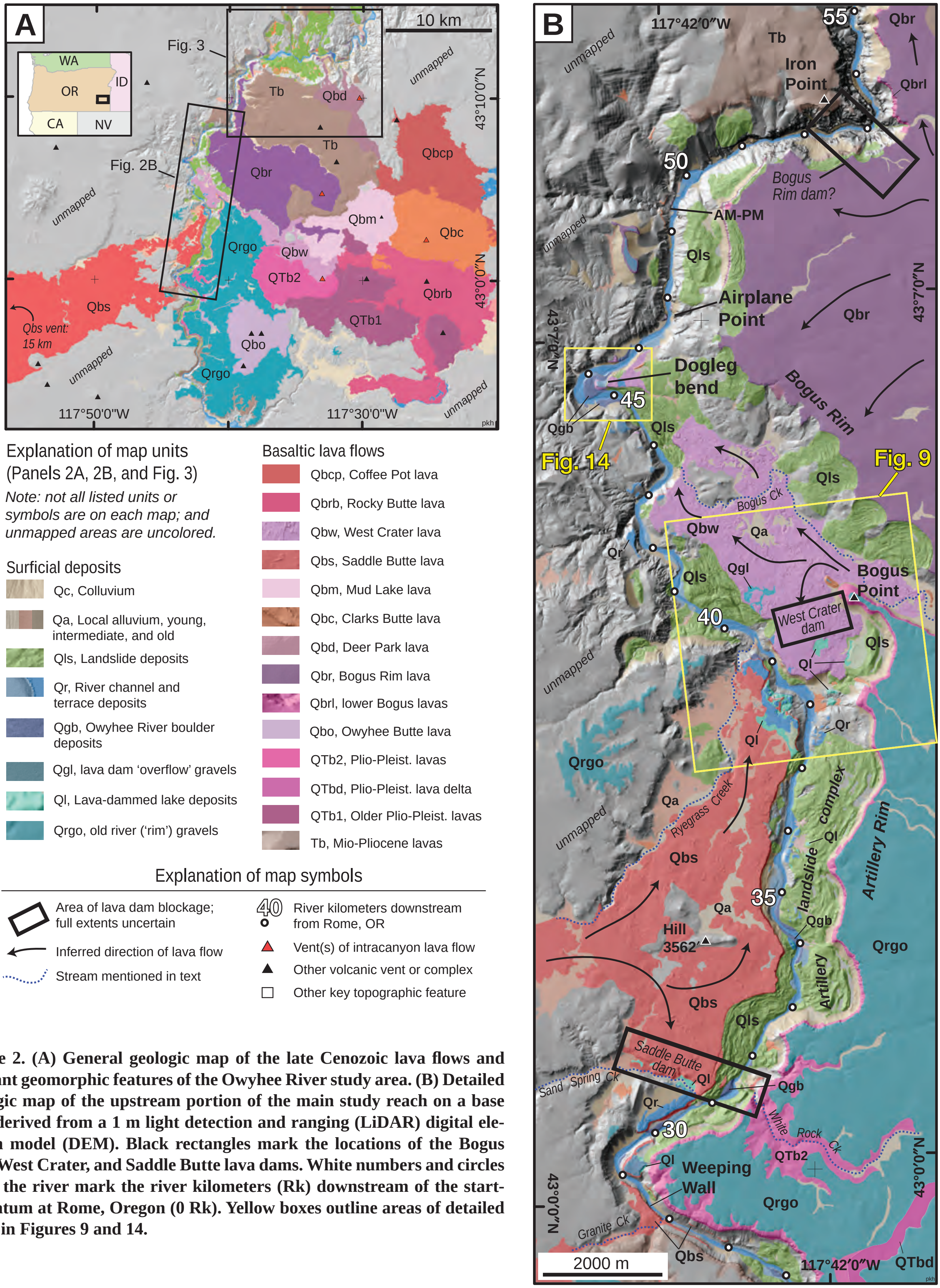

Figure 2. (A) General geologic map of the late Cenozoic lava flows and relevant geomorphic features of the Owyhee River study area. (B) Detailed geologic map of the upstream portion of the main study reach on a base map derived from a 1 m light detection and ranging (LiDAR) digital elevation model (DEM). Black rectangles mark the locations of the Bogus Rim, West Crater, and Saddle Butte lava dams. White numbers and circles along the river mark the river kilometers (Rk) downstream of the starting datum at Rome, Oregon (0 Rk). Yellow boxes outline areas of detailed maps in Figures 9 and 14.

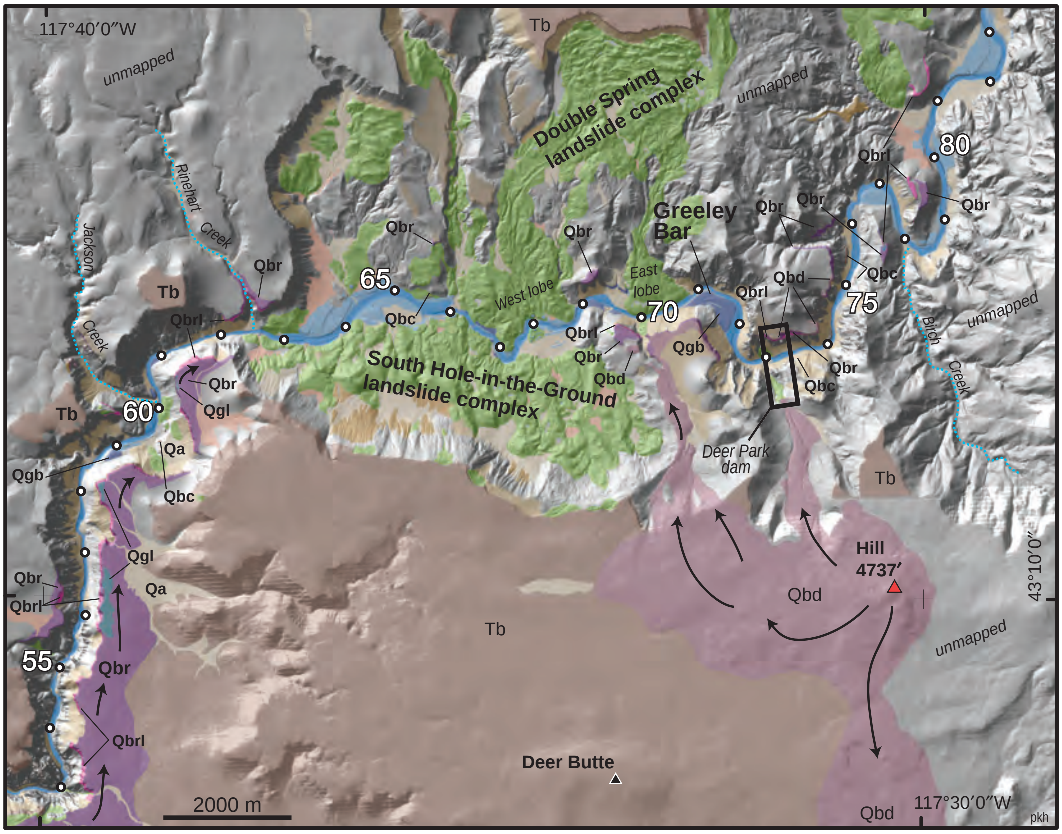

Figure 3. Detailed geologic map of The Hole in the Ground and surrounding area, which forms the downstream portion of the study reach outlined in Figure 2A. Black rectangle marks the location of the Deer Park lava dam. Base map and legend are the same as in Figure 2.

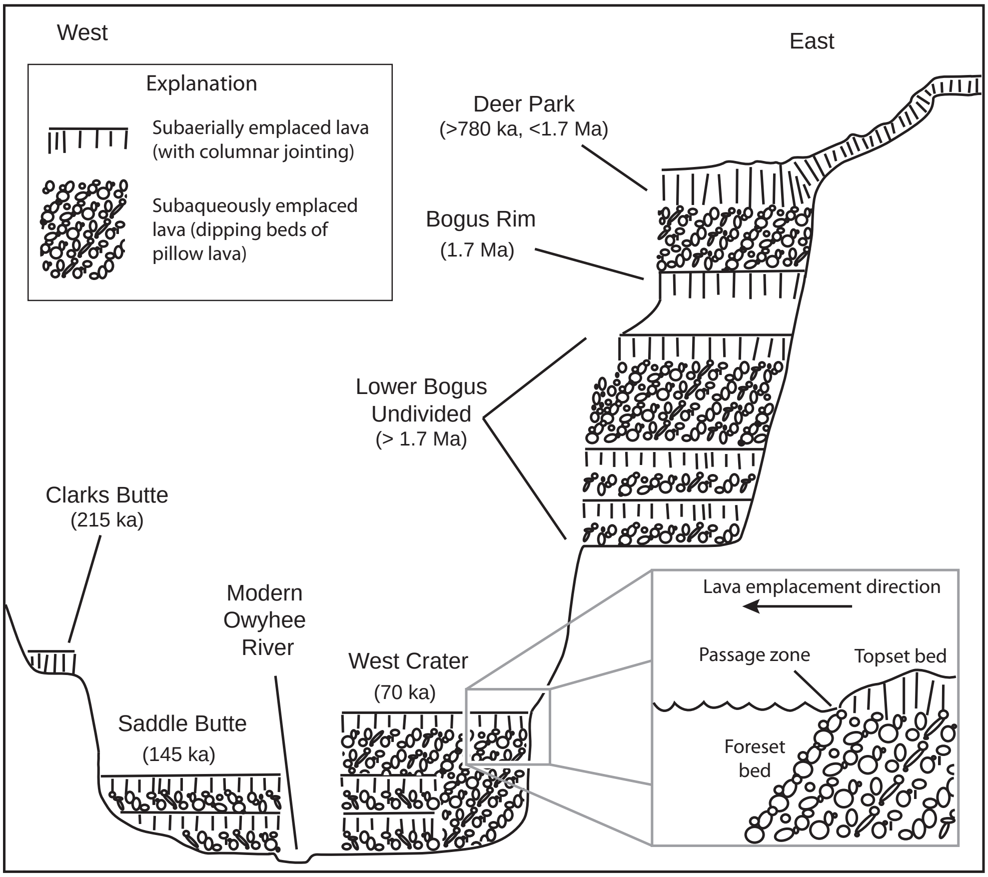

Figure 4. Schematic representation of the relative stratigraphic positions and ages of the Pleistocene lava flows that have entered the Owyhee River canyon. This figure is a generalized compilation from multiple locations, as no single cross section of the Owyhee canyon contains outcrops of all of the lava dams shown. Vertical and horizontal dimensions are not to scale. The inset in the lower right illustrates the passage zone (Jones and Nelson, 1970) that marks the elevation of the water surface at the boundary between the topset beds of subaerial lava and the subaqueous foreset beds that form as the pillow-lava delta advances into a dammed lake of its own creation.

TABLE 1. CHARACTERISTICS OF OWYHEE RIVER LAVA DAMS

					Height above modern river (m)	
Lava flow	Dam location	Age*	Length (km)	Elevation of crest (m)	Base	Crest
Undivided lower Bogus	No remaining evidence of exact dam location	>1.7 Ma	~30?	?	>115 to 190	?
Bogus Rim	Iron Point (Rk 53)	1.69 ± 0.03 Ma (1.7 Ma)	>30	1210	~260	310
Deer Park	Deer Park and Greeley Bar (Rk 70–73.2)	780 ± 50 ka (780 ka)	>5	1066	177	210
Clarks Butte	Rk 39–41	214 ± 9 ka (215 ka)	>26.5	>969	~45	>55
Saddle Butte 1	Granite Creek (Rk 28)	144 ± 14 ka (145 ka)	≥4	1018	5	
Saddle Butte 2	Ryegrass Creek (Rk 31–33)	144 ± 14 ka (145 ka)	>12	1044	45[†]	85
West Crater	Bogus Point (Rk 38–41)	69 ± 9 ka (70 ka)	12	1030	~8	83

*The reported age is a weighted mean average and standard error of the reliable ^{40}Ar/^{39}Ar geochronological data for each lava flow. Individual determinations were weighted by the inverse of their squared uncertainties (standard deviations) and summed. The uncertainty of the weighted mean is the reciprocal square root of the sum of all the individual weights. See GSA Data Repository (see text footnote 1) for a complete list of sample ages and sources, and an explanation of samples used to calculate representative ages. The representative age in parentheses is the rounded value of the lava-flow age used in the text and in Table 2.

[†] Saddle Butte 2 flow overlies Saddle Butte 1 flow; no significant channel incision occurred between these events.

Within the study reach, the Owyhee River is incised into Neogene and Quaternary volcanic and sedimentary rocks (Plumley, 1986; Evans, 1991; Malde, 1991; Ferns et al., 1993). Downstream of Rome, the river enters a series of steep-walled bedrock gorges up to 400 m deep formed in massive Miocene rhyolite flows. The narrow gorges alternate with broad valleys, 1–2 km wide, through Neogene volcaniclastic and lacustrine sediment capped by basalt flows.

Several changes in the regional landscape were important factors in the evolution of the Owyhee River canyon. The presence of detrital zircons derived from the Owyhee headwaters in sediment deposits in the western Snake River Plain records the capture of the paleo–Owyhee River watershed by the western Snake River Plain ca. 7 Ma (Beranek et al., 2006). The demise of Pliocene Lake Idaho in the western Snake River Plain concurrent with the incision of Hells Canyon on the Snake River, and the resulting integration of the Snake River into the Columbia River system occurred between 3.8 and 2 Ma (Malde and Powers, 1962; Othberg, 1994; Wood and Clemens, 2002). Regional incision followed in southwestern Idaho and southeastern Oregon, draining many of the lake basins in the area (Smith et al., 2000; Van Tassel et al., 2001; Wood and Clemens, 2002) and leading to early Quaternary integration and further incision of the Owyhee River valley. The lava dams on the Owyhee River are broadly contemporaneous with several other lava dams within the last 2 m.y. on the nearby Snake and Boise Rivers of southwestern Idaho (Howard and Shervais, 1973; Howard et al., 1982; Malde, 1982, 1987; Othberg, 1994; Brand and White, 2007).

METHODS

Individual lava flows were mapped, dated, and correlated on the basis of stratigraphic and geographic position, mineralogy, geochronology, geochemistry, and remanent paleomagnetism. Supporting data are included in the GSA Data Repository.[1]

Field Observations, Measurements, and Mapping

Field observations to determine the relative age and correlation of the intracanyon lava flows included hand-sample mineralogy, surface morphology of the lava flows, amount of soil development and weathering, geomorphic location in the canyon, and stratigraphic position. Descriptions of the hand-sample mineralogy and general petrologic characteristics of each lava flow are included in GSA Data Repository Table DR4 (see footnote 1) and Brossy (2007). Geologic mapping of the study area and elevation surveys of the lava flows and relevant geomorphic features were performed using a combination of extensive field reconnaissance using a laser rangefinder and high-precision GPS (Trimble GeoXH Global Positioning System), and interpretation of imagery derived from light detection and ranging (LiDAR) data and aerial photography. Mapping was compiled in ArcGIS (ver. 9.2, 9.3, and 10.1) using various representations of these image types as base layers.

Net long-term incision rates through the lava flows were calculated from the highest evidence of water overflow on the downstream side of the dam, such as rounded gravels or water-scoured basalt, down to either the current mean summer water surface of the river or a strath surface of known age. The river flows on a shallow bedrock strath surface throughout much of the reach of the West Crater and Saddle Butte lava flows. The water depth in this reach was no more than 2–3 m at the low to moderate discharges when the field measurements were made.

Geochronology

Absolute ages of lava flows and dams were determined by ^{40}Ar/^{39}Ar radiometric age analysis of basalt flows in this and previous studies (GSA Data Repository Table DR1 [see footnote 1]). Samples in this study were analyzed at the New Mexico Geochronology Research Laboratory at the New Mexico Institute of Mining and Technology, Rutgers University Department of Earth and Planetary Sciences, and the Nevada Isotope Geochronology Laboratory at the University of Nevada, Las Vegas. The GSA Data Repository includes descriptions of the procedures for the sample preparation, analysis and interpretation of the ^{40}Ar/^{39}Ar radiometric ages from each of the laboratories, as well as the full analytical results (see footnote 1). The data evaluation protocol was based on Fleck et al. (1977) and Dalrymple and Lanphere (1969, 1974).

We conducted cosmogenic radionuclide surface-exposure analyses on the youngest of the Owyhee River lava dams, the West Crater lava dam (70 ka; Table 1), and associated river-eroded channels, strath terraces, and boulder deposits. The surface-exposure ages were determined through the analysis of cosmogenic ^{3}He, henceforth referred to as ^{3}He$_{c}$ (GSA Data Repository Tables DR1 and DR2 [see footnote 1]). These analyses provided age estimates of erosional and depositional features that were used to calculate incision rates through the West Crater lava dam (Table 2). Samples for cosmogenic dating were collected and prepared according to the methods described by Gosse and Phillips (2001) and Fenton et al. (2002, 2004). Analyses were completed at the University of Rochester and the U.S. Geological Survey in Denver.

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[1] GSA Data Repository item 2012321, supporting data and explanatory text for ^{40}Ar/^{39}Ar age analyses, tephrochronology, ^{3}He cosmogenic radionuclide exposure ages, paleomagnetic correlations, geochemical correlations, and petrologic descriptions of the Owyhee Canyon lava flows and associated features, is available at http://www.geosociety.org/pubs/ft2012.htm or by request to editing@geosociety.org.

TABLE 2. INCISION RATES

Lava flow/feature	Location (Rk)	Height above river (m)*	Mean age (ka)[†]	Incision rate to present[§] (mm/yr)	Incision rate to intermediate points[#]	
					(mm/yr)	(mm/yr)
Lower Bogus lavas	50–73	115–230	1700–2000	0.06–0.16		
Bogus Rim						
Bogus Rim dam crest	~53	310	1690 ± 30 (1700)	0.18	BR to CB = 0.17	BR to WC = 0.18
Bogus Rim highest overflow gravels	55.5	270				
Deer Park						
Deer Park dam crest	71	210	780 ± 50 (780)	0.27		
Clarks Butte						
Clarks Butte lava, highest flow remnant	49.5	54	214 ± 9 (215)	0.25	CB to WC = 0.33	
Saddle Butte						
Saddle Butte 2 dam crest	~31	85	144 ± 14 (145)	0.59	SB2 to WC = 1.0	
Highest overflow gravels	31.5	84				
West Crater						
West Crater dam crest	39	83	69 ± 9 (70)	1.2		
Highest overflow gravels	39.5	82				
Paleochannel and dated boulders on dam	43.25	58	62±3	0.95		
Airplane Point river polished and eroded flow surface	47.75	24	39±2	0.66		
Dogleg Bend T5 slightly eroded flow top	45	50	58±3	0.86		
Dogleg T5 strath terrace boulders**	45	50	45±3	1.1	T5 to T4 = 1.8	T5 to T2 = 1.2
Dogleg T4 strath terrace boulders	45	38	39±3	0.97		T4 to T2 = 1.0
Dogleg T3 boulder bar	45	15	17±1	0.88		
Dogleg T2 boulder bar	45	11	12±1	0.92		
Dogleg T1 boulder bar[††]	45	4	9±1	–		

Note: Abbreviations: BR—Bogus Rim lava; CB—Clarks Butte lava; SB1 and SB2—Saddle Butte 1 and 2 lavas; WC—West Crater lava; T5–T1—terraces at Dogleg Bend, from highest to lowest.

*Height above river refers to the surveyed height above the water surface at low to moderate discharge, which is ≤2 m above the channel bed in most cases.

[†] Weighted mean and representative ages (in parentheses) of the lava flows from Table 1. The ages of the West Crater eroded surfaces and Dogleg terrace boulders are the weighted mean of the cosmogenic ^{3}He exposure ages on each (Tables DR1 and DR2 [see text footnote 1]).

[§] Incision rates are calculated from the dam crest to the modern river surface unless otherwise indicated. Incision rates within the West Crater dam are based on the elevations of the outer edges of the terrace or strath surfaces.

[#] Base of West Crater and Clarks Butte flows are 7.5 m and 45 m, respectively, above the water surface of the modern river; elevations of Dogleg terraces are as indicated in the table.

**Age of abandonment of Dogleg T5 terrace is based on the mean of the three youngest cosmogenic radionuclide exposure ages of boulders on the strath surface.

[††] Dogleg T1 is inundated by high flows from present-day Owyhee River and was not included in incision calculations. Because of the wide range in cosmogenic radionuclide exposure ages of boulders on T1, the age in Table 2 is the mean of only the two youngest boulder exposure ages.

The ^{3}He$_{c}$ method is well-suited for dating the exposure time of the geomorphic surfaces and boulders derived from the olivine-rich, young basalt flows in the Owyhee study area (Cerling, 1990; Cerling and Craig, 1994; Cerling et al., 1994, 1999; Fenton et al., 2002; Kurz, 1986). The West Crater lava flow contains a high percentage of olivine phenocrysts, which produce and retain ^{3}He$_{c}$ (Gosse and Phillips, 2001). In most cases, the Owyhee River basalts are too young to have accumulated significant radiogenic helium, and hence contain only mantle gas and cosmic ^{3}He. We collected a shielded sample from the unexposed ceiling of a >2 m overhang under the base of the uppermost West Crater lava flow unit at Dogleg Bend (Rk 45; Fig. 2B) to determine the amount of helium in the samples from noncosmogenic (mantle) sources. The resulting helium isotopes from the shielded sample were used to correct the final cosmogenic ages for any mantle contribution of helium.

Tephra layers from lacustrine deposits that accumulated in the reservoir behind the West Crater lava dam and behind landslide blocks were analyzed for a geochemical match with a regional tephra database at the Geoanalytical Laboratory at Washington State University.

The representative ages for each lava flow or group of cosmogenic surface-exposure ages are weighted mean averages of the relevant geochronological data. Individual determinations were weighted by the inverse of their squared uncertainties (standard deviations) and summed. The uncertainty of the weighted mean is the reciprocal square root of the sum of all the individual weights (Taylor, 1997). The inclusion or exclusion of samples from the calculations of the representative weighted mean ages was based on our confidence in the quality of the sample, the stratigraphic or geologic relation to other geologic features of known ages, and the degree of analytical uncertainty. The rationale for the selection of samples for each representative age calculation is described in the GSA Data Repository (see footnote 1).

Geochemistry

We analyzed the geochemistry of the lava flows to correlate the lava-flow outcrops in the canyon and link them to previously dated source vents. New geochemical data on major and trace elements produced for this study were compared with existing data on the Owyhee Plateau (Hart, 1982; Hart and Mertzman, 1983; Hart et al., 1984; Bondre and Hart, 2004, 2006; Shoemaker and Hart, 2002; Shoemaker, 2004; Bondre, 2006). Major-element analyses were conducted at Miami University in Oxford, Ohio, using direct current argon plasma spectroscopy following the methods of Katoh et al. (1999). Trace-element analyses were conducted at Miami University using direct current argon plasma spectroscopy and at Franklin and Marshall College using the X-ray fluorescence techniques of Mertzman (2000).

For major elements, 22 existing analyses (Bondre, 2006) were used to identify fields that characterize the Al_2O_3, Fe_2O_3, CaO, K_2O, and

MgO concentrations of the Rocky Butte and Clarks Butte, West Crater, and Owyhee Butte lava flows. Nine new samples from this study were compared against these major-element fields (GSA Data Repository Fig. DR1A [see footnote 1]). For trace elements, 19 existing analyses (Bondre, 2006) of the Rocky Butte, West Crater, Bogus Rim, and Owyhee Butte lava flows defined characteristic fields for La, Nb, Rb, Sr, Ba, and Zr, against which trace-element analyses of five new samples from this study were compared (GSA Data Repository Fig. DR1B [see footnote 1]).

Paleomagnetic Correlations

Changes in the direction of remanent magnetism (McElhinny, 1973; Kuntz et al., 1986) were used to distinguish among the lava flows found in the Owyhee Canyon and to correlate isolated lava outcrops to previously dated lava fields or vents. Changes in remanent magnetization direction that occur on time scales of $1–10^5$ yr are termed geomagnetic secular variation (Butler, 1992) and can occur at geologically rapid rates of ~4° per century (Champion and Shoemaker, 1977). These changes are not cyclic and can be characterized as a random walk about a mean on a path that can cross itself (Butler, 1992).

Individual lava flows from known source vents were sampled to characterize the remanent magnetism and provide a base value to compare with isolated lava flow outcrops, following the methodology of Champion (1980). Paleomagnetic sample sites were chosen in outcrops from 10 different lava fields (Table DR3 [see footnote 1]). The sites were selected in horizontal, stable areas of the lava flows that had not been tilted after cooling and magnetization. Where possible, sample sites were located in road cuts or where the surface of the flow had been removed recently by erosion to reduce the presence of isothermal remanent magnetization (IRM) resulting from lightning strikes. A hand-held, water-cooled, gasoline-powered coring drill was used to collect eight independently oriented, 2.5-cm-diameter samples at each site. A sun compass was used to orient the azimuth of the field cores because the magnetic character of mafic volcanic rock influences a magnetic compass. The remanent magnetization of the cores was measured using an automatic cryogenic magnetometer at the U.S. Geological Survey in Menlo Park, California. The mean directions of magnetization for each site were then calculated and plotted on an equal-area diagram (GSA Data Repository Fig. DR2; Table DR3 [see footnote 1]).

OWYHEE RIVER LAVA FLOWS AND DAMS

The lava flows in the Owyhee canyon are compound pahoehoe flows, composed of multiple overlapping flow lobes (Self et al., 1998; Walker, 1971). The lava dams typically exhibit three distinct components in vertical section: subaerial topset beds, a transitional passage zone, and subaqueous foreset beds (Fig. 4; Jones and Nelson, 1970). The uppermost sheet of lava forms a topset bed that supplies lava to the front of the flow, where it contacts the water surface. Pillow lavas and shattered volcanic glass (hyaloclastite) indicative of lava-water interaction often break off the toe of the upstream-advancing lobe of the lava flow and form dipping deltaic foreset beds below the water surface of the dammed lake. The passage zone is the transitional boundary between the subaerial and subaqueous portions of the lava flow, and it marks the elevation of the water surface into which the lava flowed (Jones and Nelson, 1970). In some instances, this three-tiered structure is repeated or stacked in vertical section. Multiple or rising passage zones within a lava-flow dam indicate that the water level rose during the construction of the dam but did not exceed the rate of lava influx.

The six distinguishable sets of Pleistocene basaltic lava flows entered the Owyhee River canyon between Granite Creek (Rk 25) and the Birch Creek confluence at Rk 78 (Fig. 2B). The lava flows entered and dammed the river during two time intervals: an early Pleistocene period from ca. 2 Ma to 780 ka, and a later period from 215 to 70 ka (Table 1). The flows issued from vents on both sides of the present river canyon and interacted with the river in diverse ways. Many of the lava flows that we mapped in this study are unnamed or were assigned informal names by previous workers. Where appropriate, we retained these informal names or assigned new informal names on the basis of local geographic features shown on U.S. Geological Survey (USGS) 7.5′ topographic maps.

Undivided Lower Bogus and Bogus Rim Lava Flows

The lava of Bogus Rim and the undivided Lower Bogus lavas beneath it are the oldest intracanyon lava flows included in this study (Table 1). The lava of Bogus Rim (hereafter Bogus Rim lava) is an informal name for the widespread lava flow, the southwestern margin of which forms Bogus Rim on the Lambert Rocks 7.5′ USGS topographic quadrangle map (Fig. 2B). This lava flow was identified as the lava of Bogus Bench by Bondre (2006), but because the topographic feature Bogus Bench is also associated with other older lava flows, we have renamed the flow in accord with the prominent geomorphic feature of Bogus Rim. The sequence of undivided lava flows stratigraphically beneath, and older than, the Bogus Rim lava is hereafter referred to with the informal name of lower Bogus lavas. This sequence includes the undivided Pliocene–Pleistocene lavas (QTb2, QTbd) shown in Figure 2B.

Undivided Lower Bogus Lava Flows

The lower Bogus lava flows filled an Owyhee River canyon that was much wider, shallower, and higher than present. A 6-m-thick deposit of river gravel overlying a bedrock surface at the base of the lower Bogus lava group, 115 m above the modern river (965 m elevation) at Rk 74, provides a minimum channel elevation (Fig. 3; Table 1). Farther upstream near the Bogus Rim dam site (Rk 50; Fig. 2B), the exposed basal contact of the lower Bogus lava flows is 190 m above the modern river. The contact is with older bedrock, not Owyhee River gravel, and therefore the contemporaneous channel was presumably lower. The basal contact elevation of the Bogus lava flows in the intervening reach gradually decreases between these two end-member elevations.

The lower Bogus lava flows are exposed only in the cliffs of the Owyhee Canyon. An $^{40}Ar/^{39}Ar$ age of 1.672 ± 0.03 Ma on the flow immediately underlying the capping Bogus Rim lava flow provides a minimum limiting age for the lower Bogus lavas. Another age of 1.92 ± 0.22 Ma on a vent east of Bogus Rim (Bondre, 2006; Fig. 2B; GSA Data Repository Table DR1 [see footnote 1]) is most likely from one of the lower Bogus lava flows. They are well exposed downstream of Iron Point (Rk 53) but flank the river as far upstream as Rk 32–38 near Bogus Point (Figs. 2 and 3).

The sequence of flows composing the lower Bogus Lavas could have caused multiple episodes of river damming. The exact location of the lava dam(s) formed by the lower Bogus lavas is not evident, but a likely area is near Rk 53, where the high terrain of the uplands surrounding Deer Butte and Iron Point constricted the Owyhee River paleocanyon. Sequences of pillow lavas, hyaloclastite, and lacustrine sediment up to 25 m thick occur in the lower Bogus lavas for at least 10 km upstream of Rk 50, suggesting the presence of a lake. A 32-m-thick pillow-lava delta with an elevation of 1158 m at the upper boundary (Rk 25–26; unit QTbd in lower right of Fig. 2B) is capped by 6 m of subaerial lava that erupted from Owyhee Butte. Although the Owyhee Butte lava flow is not part of the lower Bogus lava group, it flowed into a lake that was probably dammed by one of the lower Bogus lava flows. An ^{40}Ar/^{39}Ar age of 1.86 ± 0.12 Ma (Bondre, 2006; GSA Data Repository Table DR1 [see footnote 1]) on the Owyhee Butte lava flow is within the age range of the undivided lower Bogus lava flows.

Bogus Rim Lava Flow

The Bogus Rim lava flow is the most voluminous and laterally extensive of the intracanyon flows. It erupted from vents east of the Owyhee Canyon, flowed westward, and created a broad, gently sloping surface (Fig. 2B). The age of the Bogus Rim lava flow is constrained by a ^{40}Ar/^{39}Ar age of 1.67 ± 0.06 Ma on the uppermost unit of the lower Bogus lava group immediately underlying it (GSA Data Repository Table DR1 [see footnote 1]). Its reversed magnetic polarity also places it after the Olduvai period of normal polarity from 1.77 to 1.95 Ma. These data suggest an age of ≤1.7 Ma for the Bogus Rim lava flow (Table 1). The lava filled and dammed the paleo–Owyhee River canyon from Rk 49 to 53 (Fig. 2B). The narrow section of the modern Owyhee Canyon along the dam reach resulted from river incision at the contact between the thick canyon fill of the Bogus Rim lava and the rhyolite of the Iron Point area. The flow(s) traveled ~40 km downstream to at least 10 km past Birch Creek (Rk 78), beyond which there are no clearly visible lava remnants (Fig. 3).

The Bogus Rim lava dam was well above the modern river. A surveyed elevation of 1210 m on the rim of the canyon at the most likely position of the Bogus Rim lava dam (Rk 53) places a maximum limit on the elevation of the crest of the dam. This point is ~310 m above the modern river channel. River gravels at elevations of 1170 m (Rk 50) and 1080 m (Rk 56) place the base of the dam at 200–260 m above the modern river (Fig. 2B; Table 1). Subrounded to well-rounded basalt and banded rhyolite boulders, cobbles, and gravel on the surface of the dam downstream of the crest document the eventual overtopping of the lava dam by the river. The overflow deposits occur up to an elevation of 1168 m at Rk 55.5, and the thickest deposit (6 m) is at an elevation of 1143 m at Rk 58 (Fig. 5A).

Areally extensive deposits of river cobbles and fine-grained sediment several meters thick have been mapped on the canyon rim upstream of the Bogus Rim lava dam (Evans, 1991; Ferns et al., 1993) at elevations up to 1200 m (3940 ft) (unit Qrgo on Fig. 2B). Similar elevations of the dam crest and the highest river cobbles and lacustrine sediments provide evidence that sediment completely filled the lake blocked by the Bogus Rim lava dam. The lower portion of this fine-grained lacustrine stratigraphic sequence could be associated with either the Bogus Rim lava dam or an earlier dam from one of the undivided lower Bogus lava flows.

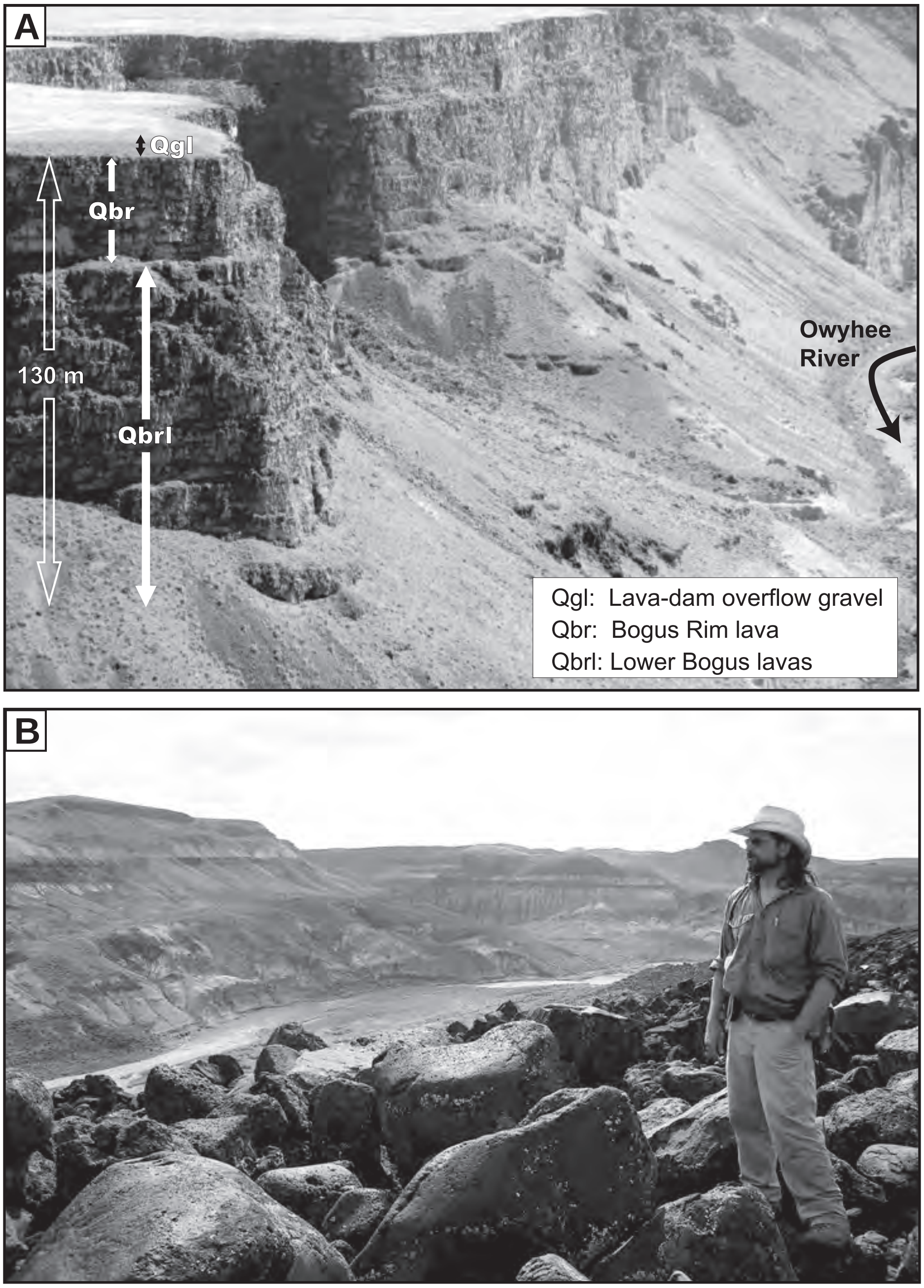

Figure 5. Fluvial deposits on lava-dam surfaces indicating the overtopping of the dams by the river. (A) Deposit of rounded boulders, cobbles, and gravel up to 6 m thick on top of the Bogus Rim lava dam, downstream of the dam crest (Rk 58.5). Total thickness of Bogus lavas in this section is ~130 m. (B) Large, rounded basaltic boulders on the upper rim of the West Crater lava dam (1029 m elevation; Rk 39.75) possibly demarcating the pre-incision path of the river along the outer margin of the lava flow (photo by Josh Michaels).

Deer Park Lava Flow

The lava of Deer Park (hereafter called Deer Park lava) is an informal name defined in this study by the place name “Deer Park,” where the lava flow spilled into the Owyhee River canyon. The location is shown on USGS 7.5′ topographic quadrangle "The Hole in the Ground." The Deer Park lava is equivalent to the Greeley Bar basalt identified and informally named by Brossy (2007).

The Deer Park lava entered The Hole in the Ground reach of the Owyhee River from the southeastern canyon rim by way of two steep lava cascades (Fig. 3). Our mapping separates the Deer Park lava from a group of older lava units surrounding Deer Butte, refining mapping by Plumley (1986). The lava likely erupted from vents on Hill 4737 (Fig. 3), flowed westward across older lavas, and cascaded into the canyon. It then flowed across the Bogus Rim lava, which is below the canyon rim at this location, and dammed the Owyhee River at Rk 70–71. A second lobe from the same vent entered the canyon by a cascade at Deer Park at Rk 73 (Fig. 3). An ^{40}Ar/^{39}Ar age of 780 ± 50 ka and the reversed polarity of both lobes indicate that the Deer Park lava flow must closely predate the paleomagnetic reversal at 780 ka. The remanent paleomagnetic signature of the two lobes is similar, but not identical, indicating that the Deer Park lava dam might be constructed of flows of slightly different ages, but both close to 780 ka. At just over 5 km in length, the Deer Park lava dam has the shortest footprint along the river, pinching out near Rk 75.5.

At least three passage zones within the Deer Park lava dam indicate a sustained period of lava-river interaction and a rising lake behind the lava dam (Jones and Nelson, 1970). The Deer Park lava effectively dammed the river, judging from the 20- to 30-m-thick sections of hyaloclastite in sections upstream of the dam (Rk 70–71), and no observed hyaloclastite at downstream exposures between Rk 73 and 75.5. The elevation of the dam crest was at least 1054 m. The channel at that time, marked by the base of the lava flow on unweathered river cobbles at an elevation of 1008 m, was ~200 m above the modern river (Table 1).

Clarks Butte Lava Flow

The lava of Clarks Butte (hereafter Clarks Butte lava) is the informal name adopted by Hart and Mertzman (1983) and Bondre (2006) for lava flows from the vent named Clarks Butte (Fig. 2A) on the Jordan Craters South USGS 7.5′ topographic quadrangle (43°2′N, 117°25′W). A weighted mean age of 214 ± 9 ka (rounded to 215 ka; Table 1) was determined from a combination of samples collected at different locations (GSA Data Repository Table DR1 [see footnote 1]). The Clarks Butte lava is well exposed in the upper Bogus Creek drainage, but it is buried by the younger West Crater lava flows 7 km east of the modern Owyhee River, preventing continuous tracing of Clarks Butte lava from the broad flow surfaces on the uplands (Fig. 2A) to the isolated remnants within the canyon (Figs. 2B, 3, and 6). The Clarks Butte lava entered the Owyhee River from the Bogus Creek drainage somewhere to the east of Rk 39–41, much like the younger West Crater lava, and flowed downstream for at least 34 km.

Isolated outcrops of the Clarks Butte lava, all less than 10 m thick, are perched on bedrock strath terraces and deposits of Owyhee River gravels at a height of 42–46 m above the river at Rk 49. Major- and trace-element geochemistry and remanent magnetism support correlation of the discontinuous outcrops in the canyon to the Clarks Butte source (GSA Data Repository Figs. DR1 and DR2 [see footnote 1]). The relatively uniform thickness, outcrop height, and consistent geochemistry (GSA Data Repository Fig. DR1 [see footnote 1]) suggest that the dam is composed of only a few flow units, or perhaps even a single unit. The elevations of these Clarks Butte remnants consistently decline to a height of 23 m above the river at Rk 75.25. The perched lava flow remnants throughout this reach allowed us to reconstruct the river channel gradient immediately prior to the Clarks Butte eruption.

The AM-PM site (Rk 49–49.5; Fig. 2B) illustrates the relation between the Clarks Butte lava and the river. Here a 10-m-thick unit of Clarks Butte lava overlies ~1 m of unweathered fluvial gravel on the highest of three fluted and polished rhyolite strath surfaces, 44 m above the river (Fig. 6A). Less than 0.5 m of hyaloclastite at the base

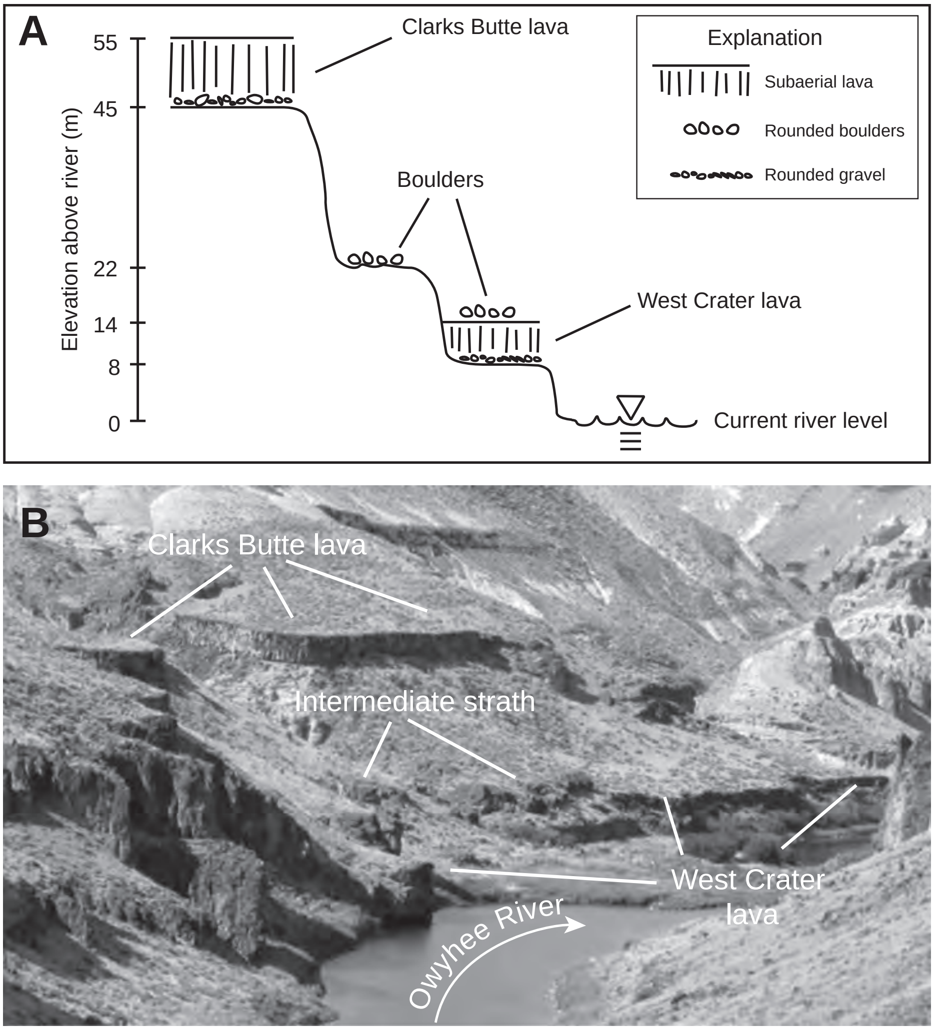

Figure 6. Schematic representation with vertical scale (A) and photograph (B) of Clarks Butte and West Crater lava flows and strath terraces at the AM-PM site, river left (Rk 49, Fig. 2B). Each lava flow overlies 0.5–1 m of gravel and cobbles that rest on rhyolite strath surfaces. Rounded boulders rest on both the West Crater flow and on an intermediate strath surface that is not covered by a lava flow.

of the lava flow indicates minimal water in the river channel at the time of lava flow emplacement, as the river had been mostly dewatered where the lava flow blocked the Owyhee Canyon upstream. The river subsequently incised to an intermediate, lava-free strath terrace 22 m above the river, which hosts several rounded basalt boulders. The 70 ka West Crater lava is perched upon the lowest set of strath-terrace remnants, 8.5 m above the modern river.

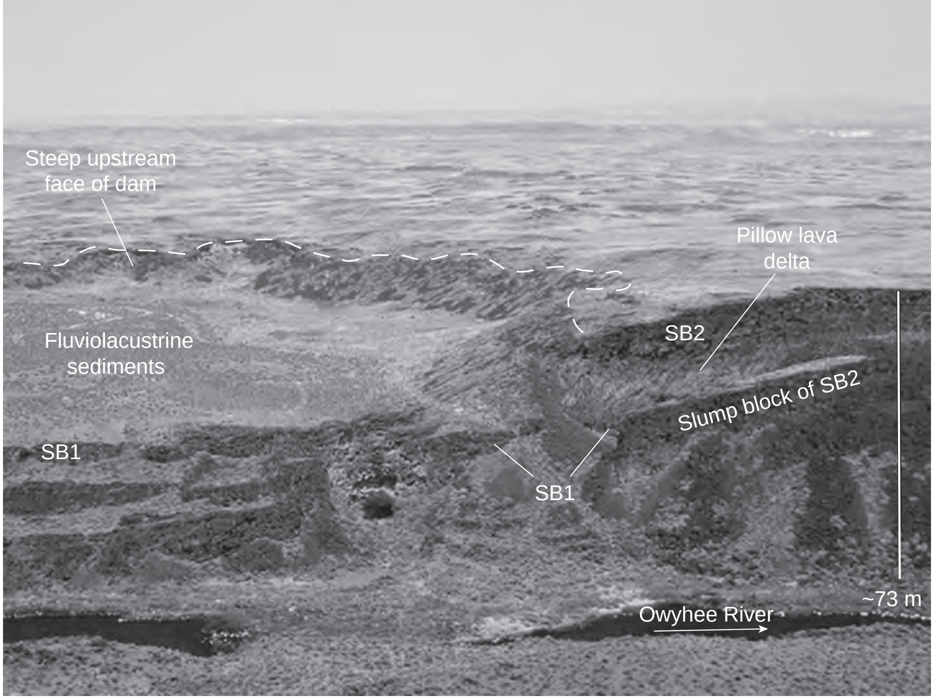

Figure 7. Saddle Butte 2 (SB 2) lava dam at Sand Springs Wash (Rk 30.7), which is one of the best examples of a lava dam in the field area. Here, the younger SB 2 dam overlies the older Saddle Butte 1 (SB 1) lava flow. The SB 2 dam contains a well-developed lava delta with pillow-laden foreset beds that dip up valley. The upstream face of the dam is a steeply sloping surface of chilled lava aligned perpendicular to the course of the valley, typical of lava dams on the Owyhee River. The surface of the older SB 1 lava is buried by lacustrine silty sediment capped by fluvial gravel that accumulated upstream of the SB 2 dam.

Saddle Butte Lava Flows

The lavas of Saddle Butte (hereafter Saddle Butte lava flows) follow the terminology of Ciesiel and Wagner (1969) and Evans (1991) for lava flows forming the “Saddle Butte” lava field delineated on the Iron Mountain USGS 7.5′ topographic quadrangle. The source vents for the extensive lava field of Saddle Butte lie ~30 km southwest of the Owyhee Canyon (Fig. 2A). The first Saddle Butte lava flow (Saddle Butte 1) entered the Owyhee Canyon at Granite Creek at Rk 28. It extended upstream for nearly 1 km and downstream for at least 3 km (Fig. 2B). A second flow (Saddle Butte 2) entered the canyon at Rk 33 via Ryegrass Creek. It flowed upstream 2 km and buried the downstream end of the Saddle Butte 1 lava (Figs. 2B and 7). Outcrops of the second Saddle Butte flow also extend at least 6 km downstream to Rk 39. Together, the two Saddle Butte flows created a blockage at least 73 m tall and produced a lake stretching ~30 km upstream (Table 1).

A sample of the Saddle Butte lava 8 km from the source vent yielded an ^{40}Ar/^{39}Ar age of 144 ± 14 ka (Table DR5; Fig. DR3 [see footnote 1]), which we have rounded to 145 ka (Table 1). It was not possible to determine whether the dated sample was from Saddle Butte lava flow 1 or 2, as the lava advanced many kilometers farther downslope before splitting into separate lobes. Paleomagnetic analyses of samples from Saddle Butte flows 1 and 2 in the canyon show overlapping remanent directions, indicating that they are very close in age (Fig. DR2 [see footnote 1]). They also match the paleomagnetic signature of the dated sample 8 km from the source vent. For these reasons, the two Saddle Butte lava flows are regarded as one damming episode.

The Saddle Butte 1 lava at Rk 28.25 rests directly on 9 m of unweathered river cobbles, gravel, and sand. The basal contact of these fluvial deposits is at the elevation of the modern river. This exposure is the site of a perennial spring known as the Weeping Wall (Fig. 2B), where spring water issues from the contact between the lava and the gravel. The lava had to span only 270 m to block the river in this narrow bedrock reach of the canyon. Thick, stacked sequences of pillow lavas, passage zones, and subaerial lavas at different elevations upstream indicate that the lake height rose concurrently with latter stages of dam construction. No fluvial deposits are interbedded within the lava dam, suggesting fairly rapid and continuous dam construction. No significant deposits of pillow lavas or hyaloclastite were found downstream of the Saddle Butte 1 dam, aside from a few lava pillows near Rk 30.8 in the plunge pool of the Sand Spring Creek waterfall, probably resulting from lava interacting with the water in this tributary.

Following the damming by the Saddle Butte 1 lava flow, the Saddle Butte 2 lava flow entered and dammed the river near Hill 3562 at Rk 34 (Fig. 2B). Hyaloclastite and pillow-lava deposits, tens of meters thick at the base of the Saddle Butte 2 lava flow (Fig. 8A), indicate that the river had overtopped the Saddle Butte 1 lava dam and was flowing down the canyon by the time the Saddle Butte 2 lava flow entered the canyon downstream. The absence of similar exposures of hyaloclastite downstream of the Saddle Butte 2 lava dam indicates that this lava flow completely dammed the river. The lava flowed upstream and halted at the Sand Spring drainage, where the blunt and steep upstream face of the dam is well displayed (Rk 30.7; Figs. 2B and 7). The Saddle Butte 2 lava flowed downstream for at least 8 km to near Rk 39, where it is exposed below the younger West Crater lava on the opposite side of the river. Beyond this point, it is obscured by landslides that cover much of the lower canyon walls. The absence of the Saddle Butte lava at the AM-PM site (Rk 49), where the older Clarks Butte and younger West Crater lavas rest on strath terraces, indicates that it did not extend that far downstream. Approximately 5 m of sandy silt, gravel, and rounded river cobbles accumulated on top of the Saddle Butte 1 lava at Sand Springs Wash (Rk 31), immediately upstream of the Saddle Butte 2 dam (Figs. 2B and 7). Rounded boulders on top of the Saddle Butte 1 lava dam at Granite Creek (Rk 28, Fig. 2B) were most likely deposited by the river flowing across the Saddle Butte 1 surface after the emplacement of the Saddle Butte 2 dam. Evidence of the river overtopping the Saddle Butte 2 dam is preserved at White Rock Creek (Rk 31.5, Fig. 2B), where a remnant of the Saddle Butte 2 lava is perched on the eastern canyon wall at the elevation of the

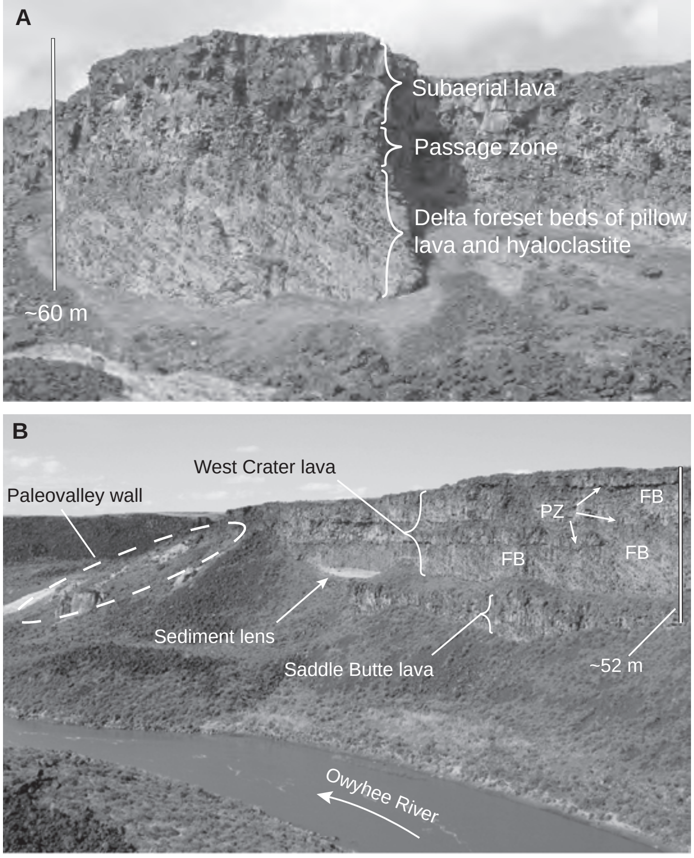

Figure 8. Examples of passage zones and pillow lava–hyaloclastite breccias typical of Owyhee River lava dams. (A) An exposure of the Saddle Butte 2 (SB 2) lava flow near Rk 34.25 clearly illustrating the subaqueous delta foreset beds of hyaloclastite and pillow lavas, passage zone marking the water surface at the time of emplacement, and capping subaerial lava (Jones and Nelson, 1970). (B) An exposure of the West Crater lava dam on the eastern canyon wall (river right) at Rk 39.25, overlying the SB 2 lava. Foreset beds (FB) of pillow lavas and hyaloclastite dip upstream. Three stacked sequences of foreset beds, passage zones (PZ), and subaerial lava indicate that the lake level rose during construction of the WC dam. The dashed ellipse encircles an outcrop of Tertiary sediment that formed the western margin of the valley prior to the filling of the Owyhee channel by the Saddle Butte (SB) lava flow. The lens of sediment in the center of the photo is interpreted to be the former channel of Ryegrass Creek, which would have joined the Owyhee River to the east of the present river canyon prior to the SB lava (Fig. 9). The river subsequently incised the present channel to the west of its former location, cutting through the former valley wall.

dam crest (1044 m). Patches of intact pahoehoe ropes identify the original lava flow surface, but in places the surface has been smoothed by fluvial erosion. The surface is littered with rounded boulders and cobbles of diverse lithologies up to an elevation of 1043 m. Some of the boulders match the lithologic characteristics of the Saddle Butte lavas, indicating erosion of the dam itself (Table DR4 [see footnote 1]).

West Crater Lava Flow

The lava of West Crater (hereafter West Crater lava) is the informal name adopted by Bondre (2006) for lava flows originating from the vent named West Crater (43°0′N, 117°32′W) on the Bogus Bench USGS 7.5′ topographic quadrangle. The youngest lava dam in the study area was formed by the West Crater lava flow (Fig. 2), which traveled 13 km down Bogus Creek into the Owyhee River. A weighted mean age of 69 ± 9 ka (Table 1; rounded to a representative age of 70 ka) was derived from ^{40}Ar/^{39}Ar ages of samples collected near the source and in the canyon (Bondre, 2006; Table DR1 [see footnote 1]). Closely overlapping remanent paleomagnetic signatures from upper and lower flow units of the West Crater lava indicate that the lava was emplaced over a short time interval (Fig. DR2; Table DR3 [see footnote 1]; Champion and Shoemaker, 1977).

The West Crater lava first dammed the river east of the present river channel location at Rk 40–41, from which it flowed 8 km downstream and 3 km upstream (Figs. 2B and 9). The crest of the West Crater lava dam stands at an elevation of 1030 m. The highest overflow gravels lie at an elevation of 1029 m at 39.5 km (Fig. 5B). The base of the West Crater lava sits 8.5 m above the modern river channel in the narrow gorge from Rk 47.75 to 49.5. Thick exposures of pillow lava and hyaloclastite capped by passage zones (Fig. 8B) indicate the advance of the lava flow upstream into a rising lake. No extensive outcrops of pillow lavas or hyaloclastite were observed downstream of the dam, although a 15-m-long, 0.5-m-thick outcrop of hyaloclastite and a few weakly developed lava pillows ~30 m above the river near Rk 43 indicate either minor leaking of the dam or local damming of a tributary. There is also a 1- to 2-m-thick lens of basalt-rich gravel between two West Crater flow units at Rk 45 that might suggest enough time between these units for the river to fill and overtop the initial portion of the dam before it was completed.

Isolated outcrops of West Crater lava form ledges perched on bedrock strath terraces within the narrow gorge from Airplane Point (Figs. 2B and 10) to the AM-PM site (Rk 49.5) (Figs. 2B and 6). The upper surfaces of these West Crater lava remnants are sculpted and polished by water and capped with rounded basalt boulders. At Airplane Point, an 18-m-thick remnant of the West Crater lava sits on a strath cut into rhyolite, 8.5 m above river level, and sparse river gravel is present at the base of the lava at this site. The farthest downstream outcrop is at the AM-PM site (Rk 49.5), where a 3-m-thick remnant of West Crater basalt is perched on 1.5 m of imbricated rounded cobbles overlying a strath surface cut into Tertiary sediment 8.5 m above the river. The lava is in turn overlain by ~1 m of rounded cobbles.

Several types of evidence indicate the impoundment of water behind the dam and overflow across the dam surface. Shallow channels across the top of the lava dam from Rk 39 to 45 (Figs. 2B and 9) record flow of the Owyhee River over the surface prior to significant

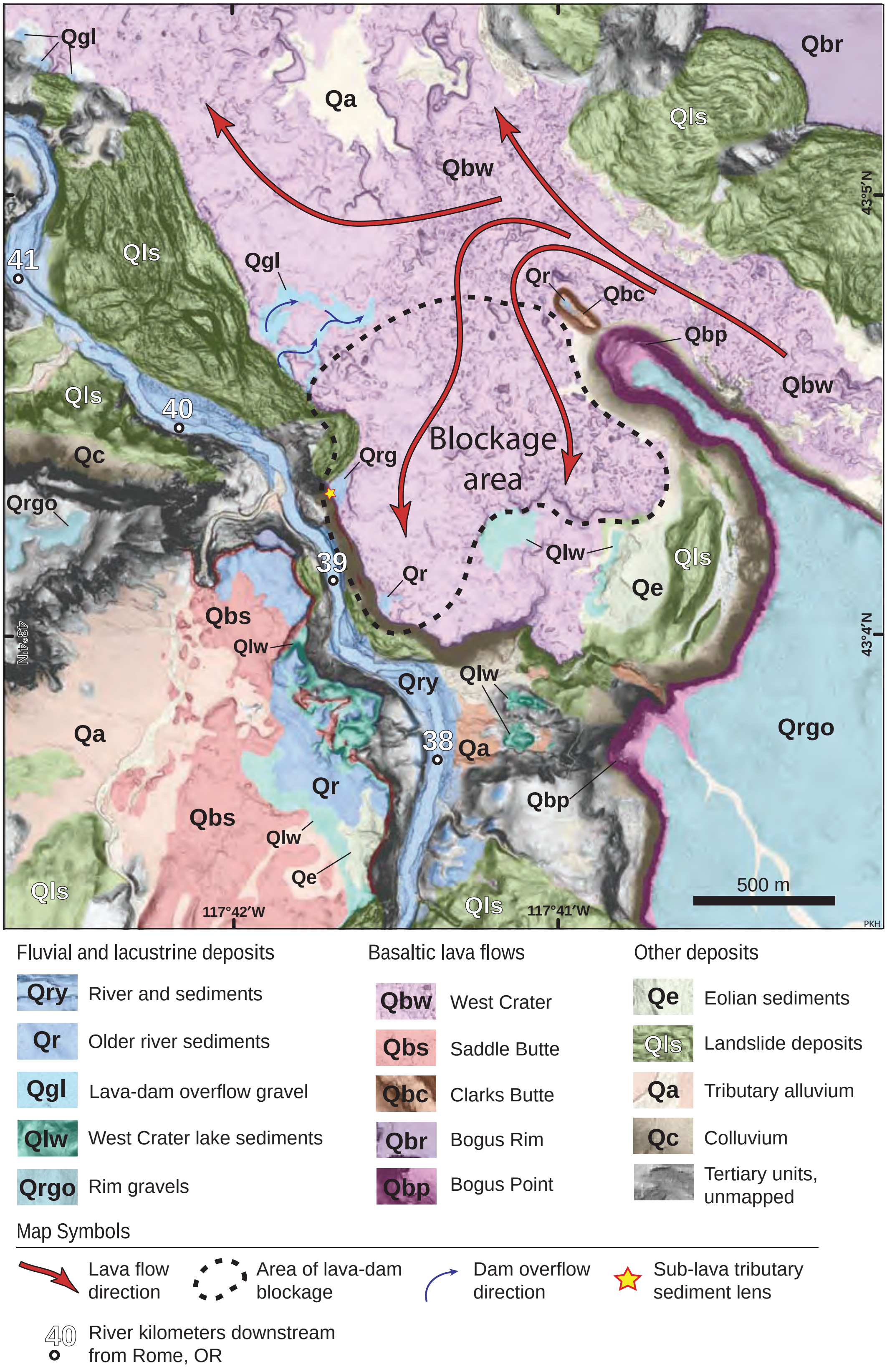

Figure 9. Map of Rk 37.5–39.5 showing the West Crater lava dam, landslides, lacustrine sediment, and fluvial deposits of the Owyhee River. The river flows to the north (up) in this image. The West Crater lava flow entered the Owyhee Canyon from the east down the Bogus Creek canyon (Fig. 2B), and the dam extended ~3 km upstream from its point of entry. Lacustrine sediment (Qlw) later accumulated in the lake behind the West Crater lava dam (Fig. 11). The yellow star marks the location of the sediment lens depicted in Figure 8B.

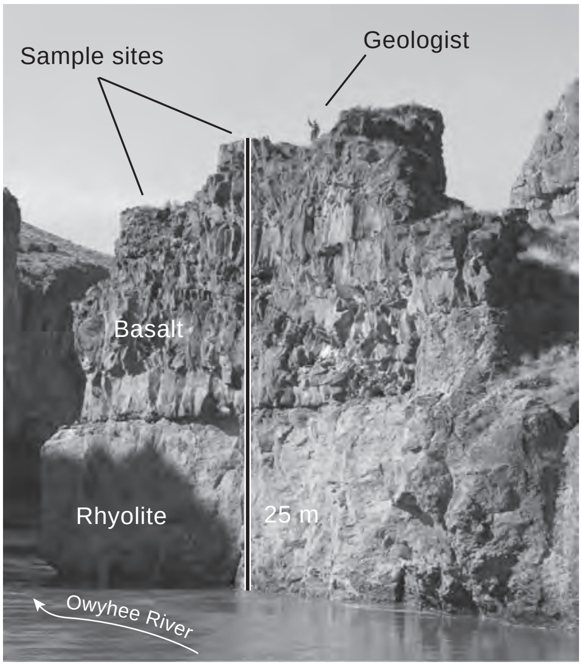

Figure 10. Photograph of a downstream portion of the West Crater lava dam perched on a rhyolite strath surface at Airplane Point (Rk 47.75). The mean cosmogenic ^{3}He surface exposure age of 39 ka on the two fluvially polished upper surfaces of the lava flow helps to constrain the timing of dam overflow prior to the re-incision of the channel (Tables DR1 and DR2 [see text footnote 1]). The confined, bedrock canyon at this location forced the river to incise directly through the basalt lava dam.

incision of the dam. A sample of the numerous rounded basaltic boulders on the surface of the West Crater lava along the rim of the Owyhee canyon in this reach (Fig. 5B) yielded a mean ^{3}He$_c$ exposure age of 62 ± 3 ka (Table 2; Table DR1 [see footnote 1]). Upstream of the dam (Rk 38), deposits of finely bedded lacustrine silts up to 20 m thick and capped with Owyhee River gravel drape the sides of the canyon to an elevation of 1018 m, approaching the height of the dam crest (Fig. 11). Two Mount St. Helens set C tephra layers with ages of ca. 55 and 47 ka (Berger and Busacca, 1995; Negrini et al., 2000) were identified within these lacustrine sections (Orem, 2010; Table DR1 [see footnote 1]).

Cobble terraces up to an elevation of 995 m are common in the canyon for at least 5 km upstream of the West Crater dam to Artillery landslide complex at Rk 34 (Fig. 2B). These terraces and the gravel-capped lacustrine silt represent Owyhee River sediment that filled the lake behind the West Crater dam. They were subsequently incised as the river cut through and around the dam. This fluvial and lacustrine sediment also overlies the lower parts of a series of rotational landslides immediately upstream of the lava dam on the eastern canyon wall, indicating that some of the canyon-flanking landslides were older than or contemporaneous with the lava dam. The West Crater lava flow buried the toe of the downstream-most landslide, which is overlain by two tephras in the closed depression at the back of the slide, above the elevation of the West Crater lava dam crest: the Trego Hot Springs tephra (23.2 ka) and the Mazama tephra (7.7 ka) (Table DR1 [see footnote 1]). Neither of these tephra layers was found in the lake sediment behind the West Crater dam.

FORMATION, STABILITY, AND REMOVAL OF LAVA-FLOW DAMS

The six lava dams affecting the Owyhee River corridor over the last ~2 m.y. share basic similarities, supporting generalizations regarding dam emplacement, longevity, and removal.

Lava-Dam Emplacement and Geometry

The basaltic lavas that formed the Quaternary lava dams on the Owyhee River flowed 0.5–30 km from their sources before entering the

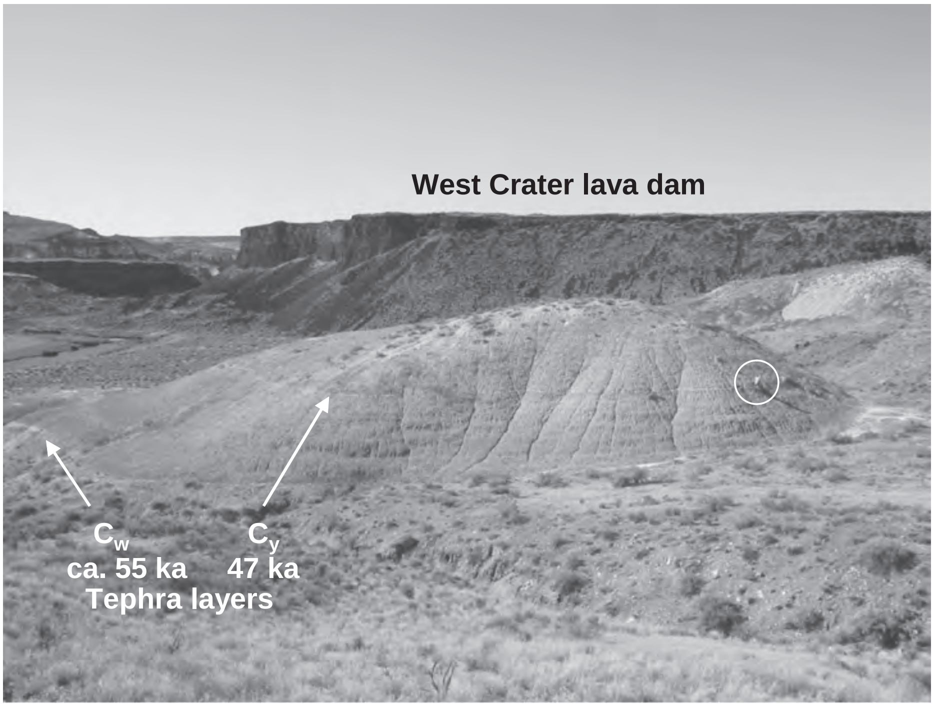

Figure 11. Photograph of silty lacustrine sediment that accumulated behind the West Crater lava dam at Rk 38 (Fig. 9). Arrows denote Mount St. Helens set C_w and C_y tephra layers in the stratigraphy. Circle marks the location of a geologist for scale. The elevation of the top of the pictured deposit is 997 m, but the elevation of the highest preserved section of lacustrine sediment behind the West Crater dam is 1018 m, which approaches the dam crest of 1030 m.

river corridor. As the various lava flows entered the Owyhee River canyon, they flowed both upstream and downstream, and so the topographically highest part of the valley blockage is near the point of entry. Resulting dam crests were many tens of meters above the river channel at the time of dam emplacement (Table 1).

As is the case for most intracanyon lava flows, the geometry of most Owyhee River lava dams is strongly asymmetric. The lava flows extend no more than 3 km upstream from their point of entry. The upstream faces of the best preserved dams form steep, blunt escarpments where lava fronts were quenched by their impounded lakes (Figs. 7, 9, and 12). The lavas flowed many kilometers down valley on a dry channel bed, exemplified by the >30 km down valley extent of the Bogus Rim and Clarks Butte lavas (Fig. 12). These long travel distances of lava flows along river channels are consistent with measurements of lava flows that traveled up to 100 km down valley in other canyon rivers, such as the Boise River in southwestern Idaho (Howard et al., 1982), the Little Colorado River in northeastern Arizona (Duffield et al., 2006), and the Colorado River in Grand Canyon (Hamblin, 1994; Crow et al., 2008).

The characteristics of the lava and the interaction between lava and river water control the structure and competency of the resulting lava dam (Howard et al., 1982; Long and Wood, 1986; Hamblin, 1994; Lyle, 2000; Howard and Fenton, 2004; Crow et al., 2008; Milazzo et al., 2009). In the Owyhee River Canyon, >10-m-thick deltas of hyaloclastite and lava pillows with upstream-dipping foresets (Fig. 8A) reflect up-valley delta progradation into lakes impounded behind growing lava dams. Subaerial lava constitutes 30%–50% of the total thickness in the upstream portions of the lava dams. This ratio of subaerial to subaqueous lava and rising passage zones capped by subaerially emplaced lava indicate that the supply of lava to the dam site exceeded the supply of water (Jones and Nelson, 1970). By contrast, if lava inflow were less than the rate of water inflow into the impoundment, the resulting outcrops would more likely consist of thick sections of hyaloclastite and lava pillows nearly all the way to the top of the dam (Howard et al., 1982). The paucity of clastic fluvial deposits interbedded within the lava flows indicates that the initial blockages formed rapidly during single, discrete episodes, in contrast to some of the Grand Canyon lava dams that contain river sediment deposited during pauses in dam formation (Hamblin, 1994). Subaqueously emplaced lava can create dams that are more susceptible to leakage or failure (Fenton et al., 2002). In the case of the long, low dams on the Owyhee River, however, the combination of subaqueous lava at the upstream end changing to subaerial lava in the long downstream portion of the lava flows appears to have contributed to dam stability and longevity.

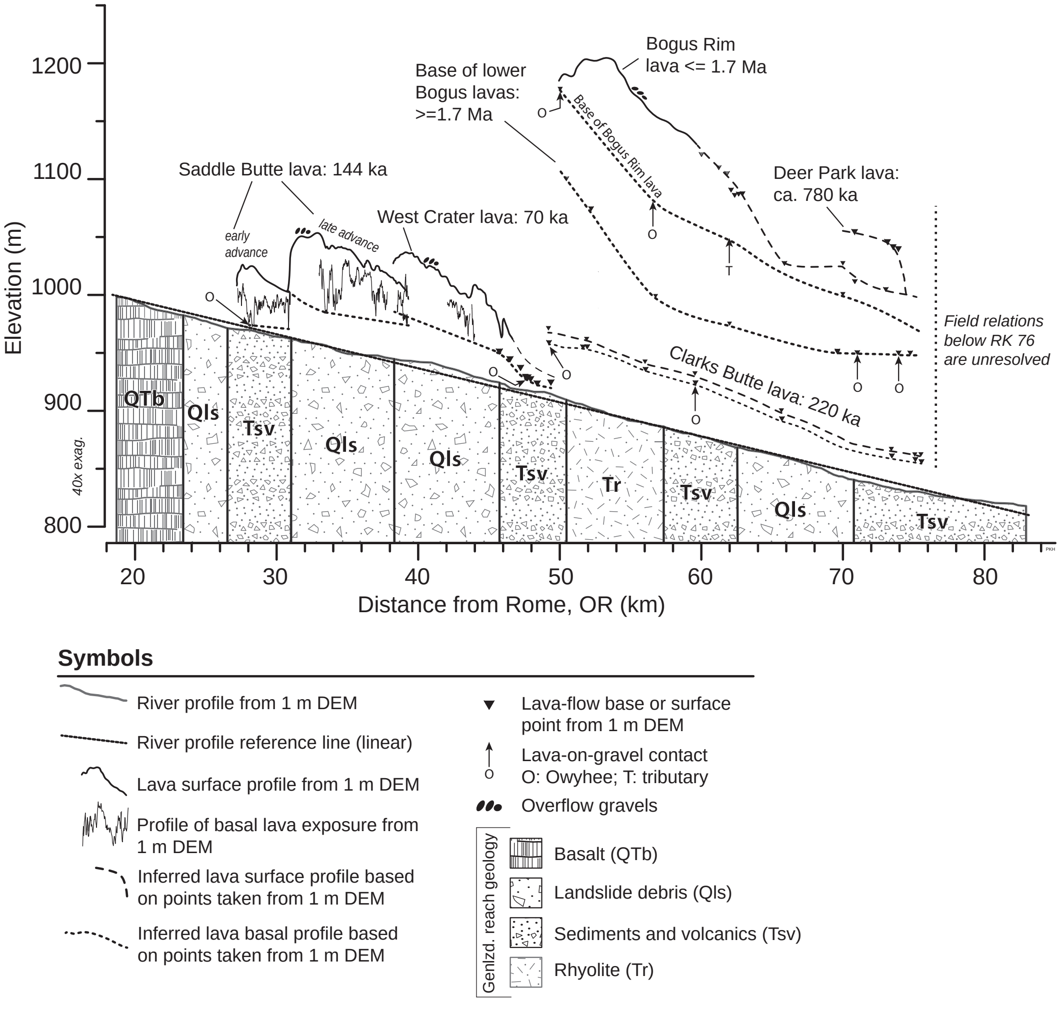

Figure 12. Longitudinal profiles of the Owyhee River and intracanyon lava flows from Rk 19 to 76. The lithologic units at the base of the diagram indicate the geologic units that compose the canyon walls at the river level in each reach. The narrow, bedrock canyon reaches are characterized by basalt (QTb) and rhyolite (Tr) bedrock, and the wider reaches are dominated by sediment interbedded with thin volcanic layers (Tsv) or landslide debris (Qls). The surface of the West Crater flow markedly steepens as it approaches the bedrock gorge at Rk 46. Arrows indicate locations where the lava directly overlies river gravels (O) or tributary gravels (T), which most closely represent the paleo–river channel elevations. The dotted lines approximate the paleovalley gradients based on the basal contacts of the lava flows. The basal profiles of the lower Bogus and Bogus Rim lava flows portray a valley gradient significantly steeper than today through the rhyolite gorge. The paleochannel profile preserved by the strath terraces overlain by remnants of the Clarks Butte lava is only slightly steeper than that of the modern river.

Lava-Dam Stability

Several of the lava flows that entered the Owyhee canyon formed dams that were sufficiently stable and impermeable to allow lakes to fill with water and overflow. The upper surfaces near the crests of the Bogus Rim, Saddle Butte, and West Crater dams contain rounded cobbles and gravel, as well as fluvial erosional features signifying overtopping by impounded lakes (Figs. 5, 9, and 12). Of these, the Bogus Rim lava dam created the largest lake, attaining a maximum elevation of 1210 m with a depth of up to 100 m near the blockage site (the predam river elevation is not known precisely in this reach). Thick deposits of lacustrine sediment and river cobbles occur up to an elevation of 1200 m on the modern canyon rim upstream of the Bogus Rim lava dam (Evans, 1991). Using present topography and a conservative lake-surface elevation of 1200 m, the Bogus Rim lava-dam lake would have inundated ~1170 km^2 and extended more than 60 km upstream. The actual dimensions were probably smaller, as independent evidence shows that the river channel elevation was higher at that time. Nevertheless, a lake of that size would have required decades to fill at the present mean annual river discharge of 25 m^3/s. The smaller lakes (<1 km^3) that formed behind the Saddle Butte flows (maximum lake elevation 1044 m) and the West Crater lava dam (maximum lake elevation 1030 m) were close to 80 m deep at the dams and would have extended 30–40 km upstream, slightly beyond the present location of Rome at Rk 0. These lakes would have been largely contained within the existing narrow canyon, except where the valley widens near Rome (Rk 0–8). They would have taken less than 1 y to fill at the present mean annual river discharge (Orem, 2010). Insufficient preservation of the lava dams and lacustrine or fluvial deposits associated with the Deer Park and Clarks Butte lava dams precludes inferences regarding the stability of those dams.

Lacustrine deposits of varying thicknesses and containing identified tephra units of known ages (Fig. 11) indicate that the lava-dammed lakes were long lasting. Each of the lakes behind the Bogus Rim, Saddle Butte, and West Crater lava dams filled with lacustrine sand, silt, and clay and are capped by fluvial gravel (Orem, 2010). Lacustrine sediment accumulation to elevations approaching the heights of dam spillways has been observed for other lava-dammed lakes within the region as well, such as the Yahoo Clay behind the Pleistocene McKinney Basalt lava dam on the nearby Snake River (Malde, 1987). The thick lacustrine sequence behind the well-documented West Crater lava dam required $>10^4$ yr to accumulate (Orem, 2010). The greater thickness and volume of sediment behind the much larger Bogus Rim lava dam could have taken a proportionately longer time to accumulate, depending on the variations in the sediment yield between 70 ka and ≤1.7 Ma.

Various geochronological data indicate that the lake behind the West Crater lava dam persisted at least 25 k.y. before the initiation of incision. Fluvially rounded boulders in shallow channels near the crest of the West Crater lava dam yielded cosmogenic ages of 58–67 ka (Tables DR1 and DR2 [see footnote 1]), which indicate lake filling and overflow soon after the emplacement of the lava flow at ca. 70 ka (Table 1). Mount St. Helens C_w and C_y tephra layers in the lacustrine sediment behind the dam (Fig. 11) show that the dam and its reservoir were present until after 46 ka. Incision through the dam probably began shortly thereafter, as indicated by the ^3He_c exposure ages of 42–44 ka on the uppermost strath surfaces eroded into the dam surface downstream at Dogleg Bend and Airplane Point (Fig. 2B; Table 2). The absence of the 23 ka Trego Hot Springs tephra (Table DR1 [see footnote 1]) in the lake sediment also suggests that the lake had drained or lowered below the top of the sediment sequence by that time. Less is known about the durations of the lakes behind the other lava dams. The 145 ka Saddle Butte lava dam lasted less than 75 k.y., as the river had re-incised close to its present elevation by the time of the emplacement of the West Crater lava flow at ca. 70 ka.

Lava-Dam Removal

Several lines of evidence point toward gradual or episodic removal of long-lived lava dams on the Owyhee River rather than catastrophic failure soon after emplacement. This finding is consistent with scant evidence worldwide of coherent lava-flow dams failing in a manner that produces outburst floods (O'Connor and Beebee, 2009). In the few previous cases where catastrophic failure of lava dams has been proposed, a combination of factors led to potentially less stable dams, such as emplacement on unstable colluvial slopes, hydrothermally weakened or fractured layers within the lava flows, or interbedded accumulations of tephra within the dam (Hamblin, 1994; Fenton et al., 2002, 2004, 2006; Howard and Fenton, 2004; Crow et al., 2008; Kataoka et al., 2008). These characteristics were not present in the Owyhee River lava dams. The Bogus Rim, Saddle Butte, and West Crater lava dams could not have produced sizeable outburst floods, as the impounded lakes had filled completely with sediment prior to incision of the dam. Outburst flood boulders would have been deposited downstream from the dam crests or dam remnants at elevations consistent with the paleoprofile of the channel at the time of the lava incursion. We have found no deposits fitting those criteria that could be traced directly to the failure of the other lava dams, although subsequent landscape changes could have obliterated any such evidence.

The initiation of dam incision was controlled in part by sediment transport in the river, especially substantial gravel transport over the dam. At the three lava dams in the study area for which upstream lacustrine deposits are preserved (Bogus Rim, Saddle Butte 2, and West Crater), there is evidence that the upstream lakes filled with sediment to elevations closely approaching the dam crests. The gravel cap on top of the lacustrine sediment behind the West Crater and Bogus Rim lava dams indicates the transport of Owyhee River bed material to, and presumably over, the dams. No significant incision or lowering of these dam spillways occurred before the dams filled with sediment, supporting the interpretation that gravel transport plays a critical role as an erosional tool (Sklar and Dietrich, 2001; Stock et al., 2005; Pratt-Sitaula et al., 2007; Cowie et al., 2008) in dam removal.

DOES THE RIVER GIVE A DAM?

Influence of Lava-Dam Perturbations on the River Profile

The intracanyon lava flows have influenced the geomorphic evolution of the Owyhee River and its canyon over various spatial and temporal scales. The lava dams represent short-term perturbations in the longitudinal profile of the canyon, superimposed upon regional base-level fall related in part to the drainage integration of the Owyhee, Snake, and Columbia River drainages over the last 4–7 m.y. (Wood and Clemens, 2002; Beranek et al., 2006). The lava flows both document and affect channel incision and valley geomorphology, and have also influenced the style and distribution of mass movements along the valley margins.

The Bogus Rim and lower Bogus lavas are the earliest for which we can trace the course of the lava flows down a fluvial canyon. These voluminous basalt flows established the general course of the modern Owyhee River. The river migrated around the edge of the flows into the more easily eroded sedimentary units or was pinned against the rhyolite bedrock and forced to incise narrow gorges through volcanic rocks. The subsequent lava flows were largely confined to the canyon geometry that was partly shaped by the Bogus Rim and lower Bogus lava flows.

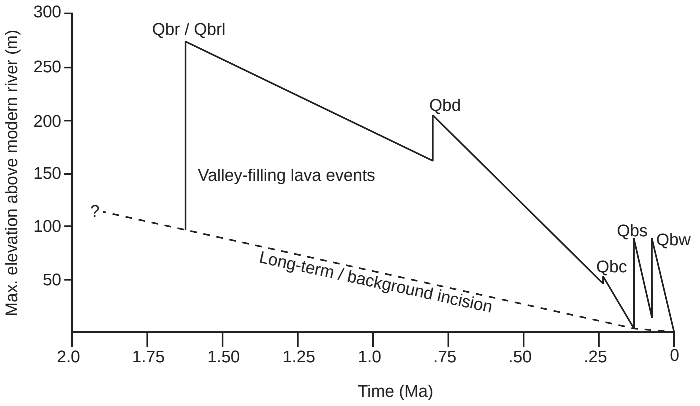

Figure 13. Cumulative incision of the Owyhee Canyon through time. Letter designations represent emplacement of the individual lava dams throughout the study area; not all lava dams occupied the same reach of the canyon. Lava-flow designations: Qbr/Qbrl—Bogus Rim and lower Bogus lavas, Qbd—Deer Park, Qbc—Clarks Butte, Qbs—Saddle Butte 1 and 2, Qbw—West Crater. The valley-filling lava flows in the study reach have superimposed 300–360 m of additional vertical incision upon the background net regional river incision since the emplacement of the Bogus Rim lava dam at 1.7 Ma. The river reached an elevation close to that of the modern river in the upstream portion of the study reach prior to the Saddle Butte 1 flow at 145 ka.

The lava thickness, substrate topography, and bedrock lithology acted together to control the lava-dam longevity and the effects of the dams on the channel and valley morphology. In reaches where the river was confined by rhyolite bedrock or older lava flows, the river was forced to incise through the core of the lava dam itself, leaving lava remnants on either wall, exemplified by remnants of the Saddle Butte 1 lava at Granite Creek (Rk 28), West Crater lava downstream of Airplane Point (Rk 47.75), and Clarks Butte lava from Rk 49 to 60 (Fig. 2B). In wider reaches where the canyon was formed largely in more easily eroded late Tertiary fluviolacustrine and volcaniclastic units, the river incised at the contact between the lava flow and previous valley wall, thereby avoiding direct incision into the lava flow. For example, by the time of the eruption of the West Crater lava at 70 ka, the river had incised a new channel around the margin of the Saddle Butte 2 lava flow (145 ka), up to 1 km east of its earlier position (Fig. 2B). The longitudinal profile of the Owyhee River is affected by many factors, ranging from long-term incision to individual landslides or floods that form localized gradient irregularities (Wood and Clemens, 2002; Carter et al., 2006; Cowie et al., 2008; Safran et al., 2008). Superimposed upon the net decrease in the vertical elevation of the Owyhee channel, there is an additional cumulative 300–350 m of channel incision through the repeated incursion of lava flows that dammed the river over the last 1.7 Ma since the emplacement of the Bogus Rim lava dam (Fig. 13).

Although lava flows temporarily raised the channel bed of the Owyhee River multiple times, they did not have equivalent consequences on the evolution of the river profile. The river took more than 1 m.y. to fully respond to the voluminous, canyon-filling lower Bogus and Bogus Rim lava flows (≥1.7 ka). The channel was still more than 50 m above its pre–lava flow elevation in the Hole-in-the-Ground reach (Rk 73; Fig. 3) by the time of the Deer Park lava flow ca. 780 ka (Fig. 13). The river channel incised close to its modern elevation sometime between the Clarks Butte (215 ka) and Saddle Butte (145 ka) lava flows. The incision subsequent to the later and smaller Clarks Butte, Saddle Butte, and West Crater (70 ka) lava dams was much more rapid than through the earlier Bogus Rim lava dam.

The short-term perturbation of the smaller flows is most clearly shown by the 145 ka Saddle Butte lava dams. At the time of the first of this pair of flows, the Saddle Butte 1 lava dam, the Owyhee River channel elevation was within a few meters of its present elevation at Rk 28.25 (Fig. 12). Despite the massive blockage of Saddle Butte lava filling the valley with as much as 80 m of basalt, and evidence for a sediment-filled lake basin behind it, the river profile resumed a position close to its former elevation before the influx of the West Crater flow at 70 ka. Similarly, the present river profile seems unaffected by the 70 ka West Crater lava flow, which also filled the Owyhee River canyon with more than 80 m of lava at its upstream end and persisted as a dam for at least 25 k.y. Once incision of the West Crater lava flow began, it proceeded to rapidly attain a local longitudinal profile similar to that before emplacement of the lava dam.

Several factors could be responsible for the much greater time for the river to resume its former profile following the emplacement of the Bogus Rim lava dam than following the younger lava flows. Some of the difference can be explained by characteristics of the lava dams and local river canyon. The much greater volume of lava and length of the Bogus Rim lava flow down the canyon were larger impediments to the river than the later, smaller lava flows. This dam also created an immense lake that would have taken much longer to fill with sediment than the reservoirs behind the later, smaller lava dams. The fully sediment-laden Owyhee River is a more effective agent of erosion than a spilling lake outlet that has access only to sediment entrained from the dam and the abutments. Thus, removal of the larger dams with larger reservoirs requires more time.

Another contributing factor could be the erodibility of the particular reach of the river that was filled by each lava flow. At least half the length of the Bogus Rim lava flow within the Owyhee canyon, from Rk 50 to 63 (Figs. 2B and 3), was within a narrow gorge confined by Tertiary rhyolite and basalt. The river would have been forced to incise directly through the lava flow or the resistant bedrock in this reach. In contrast, the Saddle Butte lava largely filled a wider reach of the river where a Tertiary basalt cap overlies more easily eroded fluviolacustrine sediment. However, the majority of the Clarks Butte lava flow (49.5–63 Rk) and the downstream 2 km of the West Crater flow were also within a bedrock gorge (Figs. 2B and 3), so erodibility does not completely explain the differences in the river response.

Regional factors such as changes in climate and relative base-level could have affected the rate of removal of the older and younger lava dams. Variations in river discharge and sediment load related to regional climate change could have affected the time required to fill the reservoirs with sediment and initiate incision. Several other major rivers in the western United States incised deep canyons sometime after 600 ka (Dethier, 2001). This increased rate of bedrock canyon incision in the middle to late Pleistocene has been proposed to reflect some aspect of regional climate change, such as extended periods of increased discharge related to snowmelt (Dethier, 2001). The older and younger lava dams on the Owyhee span the time of this regional change, and thus incision through the dams might be affected by the same regional climatic factors. The rate and timing of ongoing base-level lowering on the Snake River after 4 Ma (Wood and Clemens, 2002) also could have influenced timing of headward migration of incision up the Owyhee Canyon.

The profile formed by the perched remnants of the Clarks Butte lava on strath terraces from Rk 47.75 to Rk 75 and the basal profile of the lower Bogus lava document changes in the river gradient over time (Figs. 6 and 12). The Clarks Butte remnants trace the river bed ca. 215 ka, when it was slightly steeper and 23–46 m higher than present. The basal contact of the lower Bogus lavas (≥1.7 Ma) on older Tertiary lava units or sediment also indicates a significantly steeper valley gradient than today in the bedrock gorge from Rk 50 to 60 (Fig. 12). This steep gradient persisted through the time of the Bogus Rim lava after 1.7 ka. The specific driving mechanisms responsible for the change in the Owyhee channel gradient have not been confirmed. The age of the Bogus lavas closely follows the draining of Lake Idaho in the Snake River Plain between ca. 3.8 and 2 Ma (Malde and Powers, 1962; Othberg, 1994; Wood and Clemens, 2002). This timing suggests the possibility that the steeper channel gradient preceding the Bogus lavas could represent headward migration of a knickpoint up the Owyhee canyon in response to a falling base level in the Snake River. However, the gradient could also indicate regional uplift within the Owyhee Plateau itself. The river continued to incise into the rhyolite bedrock following the emplacement of the Clarks Butte, and later the West Crater lavas, on successively lower strath surfaces. A strath surface covered by rounded boulders but no overlying lava flow is present at an intermediate elevation between them (Fig. 6). The vertical profile continued to respond to the fall in the regional base level with little apparent lasting effect of these two lava dams in this reach. The river elevation in this reach during the time of the Saddle Butte lava dam cannot be assessed, as the remnants of that dam are farther upstream.

Incision Rates

Most of the lava dams have not had a significant long-term effect on regional incision rates. We were able to isolate and quantify the incision rates between dated control points within and between individual lava flows (Table 2). In most cases, the calculated incision rates are approximate values, because the amount of time that the channel bed spent at the endpoint elevations preceding or following incision is not known.

Estimates of the average long-term incision rate of the Owyhee River from ≥1.7 Ma to the present range from 0.06 to 0.16 mm/yr, based on the maximum and minimum elevations and age estimates of the basal exposure of the lower Bogus lava flows (Table 2; Fig. 12). This long-term rate estimate is within the ranges of calculated average incision rates of other rivers that have experienced damming by lava flows, for example, the Boise River (0.05–0.10 mm/yr), which is a nearby tributary of the Snake River (Howard et al., 1982), and Grand Canyon (0.05–0.175 mm/yr; Pederson et al., 2002; Karlstrom et al., 2007). The incision rate values are consistent with the average 0.12 mm/yr lowering of Lake Idaho due to the incision of the Snake River through Hells Canyon over the last 4 m.y. (Wood and Clemens, 2002), which ultimately controls the Owyhee River base level. Pleistocene incision rates of 0.02–0.3 mm/yr for rivers across western North America also encompass the same range (Dethier, 2001).

Minimum incision rates from the lava-dam crests to the modern river range from 0.18 to 1.2 mm/yr (Table 2). The greater incision rates for successively younger lava dams does not necessarily imply a change in the long-term rates over time but is more likely a result of incrementally shorter periods over which the measurements are averaged. Over the longer time periods, the river would have experienced multiple blockages from lava flows and landslides, and thus more cumulative work expended on incision (Fig. 13). There is also no means to assess the amount of time that the river channel remained at stable elevations within the longer time periods.

A few locations provide data to determine incision rates for shorter time periods or through individual lava flows. For example, the rhyolite strath terraces that underlie the Clarks Butte and West Crater lava remnants in the narrow canyon at the AM-PM site (Rk 49.5) and the Dogleg Bend terraces (Figs. 2B and 14) mark specific elevations of the river just before the lavas were emplaced (Fig. 6). Using the 70 ka date and elevation of the pre–West Crater channel as the younger endpoint increases the calculated incision rates for the Clarks Butte flow (0.33 mm/yr) and the Saddle Butte 2 flow (1.0 mm/yr) (Table 2).

Incision through the West Crater lava dam is well documented by ^3He_c geochronology on five terraces cut into the dam at Dogleg Bend (Rk 45–47, Figs. 2B and 14; Table 2; Tables DR1 and DR2 [see footnote 1]). At this site, the West Crater lava flow consists of multiple units of subaerially emplaced lava. The river has incised vertically through the upper few lava-flow units, and then around the edge of the West Crater lava flow into the Tertiary fluviolacustrine sediment that forms the canyon wall (Fig. 14). Dogleg Bend is immediately upstream of the narrow, rhyolite gorge at Airplane Point (Rk 47.75, Fig. 2B) where West Crater lava remnants are preserved on both sides of the canyon. The incision into and around the margin of the West Crater lava flow at Dogleg Bend was therefore controlled by the rate at which the river could cut directly through the basalt that filled the gorge downstream (Rk 47.75; Fig. 2B). The mean ^3He_c age of boulders on the uppermost strath terrace at Dogleg Bend (terrace T5, 42 ka) is very close to the mean age of the fluvially eroded surface of the West Crater lava at Airplane Point (44 ka; Fig. 10), indicating that the river began incising through the lava flow approximately simultaneously at both sites. By ca. 10 ka, the river reached its predam elevation between Dogleg terraces T2 (12 ka) and T1 (9 ka; Fig. 14B).

Dogleg Bend terrace T5 is an eroded strath surface and channel on the top of the West Crater flow. It is close to the height of the unaltered flow top and is mantled with scattered rounded, basalt boulders. Terrace T4 is a strath terrace cut into the West Crater flow and covered with up to 5 m of Owyhee River gravels and locally derived, large basalt boulders. Terraces T3 and T2 are large boulder bars, with clasts up to 3 m in diameter. The boulders at the upstream end of T3 consist of slightly rounded basalt columns that were entrained from the adjacent West Crater lava exposed in the T4 terrace riser. The boulders are preserved in all stages of removal, including columns that are only partially separated from the wall, and are increasingly rounded with distance from the source. These boulders close to the bedrock source were good candidates for ^3He_c exposure ages, because of the reduced likelihood of error introduced by previous surface exposure (Fenton et al., 2006). The T2 boulders could not be directly traced to their source, but they still yielded a tight cluster of exposure ages (Table DR1 [see footnote 1]). T1 is also a boulder bar, but the flotsam lines from recent floods in 1993 and 2006 demonstrate that this surface is intermittently inundated by the river. Cosmogenic ages of boulders from T1 were widely scattered, indicating that some are reworked from older deposits. This terrace was thus omitted from incision rate calculations.

Rates between intervening pairs of terraces range from 0.9 mm/yr to 1.8 mm/yr (Table 2). Although these episodic incision rates are the highest calculated for the Owyhee River, they are still minimum rates, because the bedrock base of the river channel would have been at least several meters below the T2 and T3

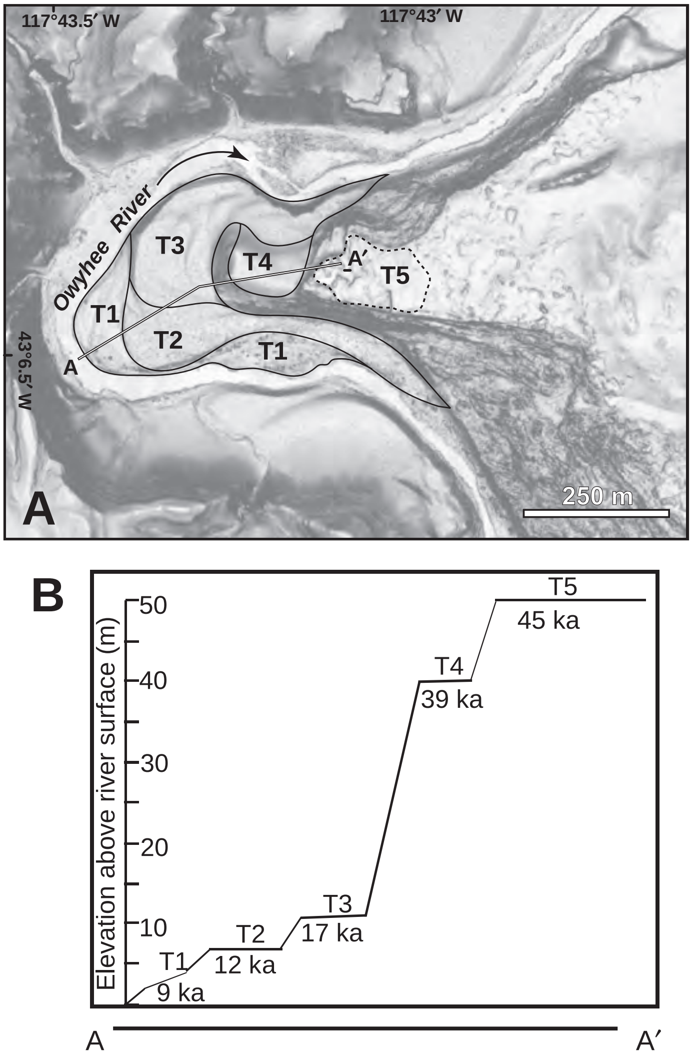

Figure 14. (A) Light detection and ranging (LiDAR) slope-shade image of the terraces at Dogleg Bend associated with the incision of the Owyhee River through the West Crater lava dam. T5 is a fluvially eroded strath surface on top of the West Crater dam; T4 is a bedrock strath carved into the West Crater lava, covered by up to 5 m of Owyhee River cobbles; T2 and T3 are boulder bars, possibly underlain by West Crater lava; T1 is a boulder bar that is inundated by modern Owyhee River floods. (B) Schematic elevation profile of the Dogleg terraces; horizontal axis not to scale.

boulder bars. The incision rate of 1.8 mm/yr between strath terraces T5 and T4 probably most closely approaches the actual episodic incision rate, because these two terraces have the best age and elevation controls. Rapid incision rates of >1 mm/yr through individual lava flows are consistent with previous studies showing that bedrock incision rates around natural dams (Cheng et al., 2006; Pratt-Sitaula et al., 2007) or in fractured bedrock susceptible to plucking (Lamb and Fonstad, 2010) can increase by orders of magnitude above long-term rates.

The greater incision rate through the West Crater flow at the dam crest (>1 mm/yr) than downstream at Airplane Point (0.66 mm/yr; Fig. 2B) is probably largely due to the bedrock composition in the two reaches. In the confined canyon at Airplane Point, the river was forced to incise directly through the basalt or rhyolite bedrock (Fig. 10). At the dam crest, the river incised around the margin of the lava flow into the more easily eroded Tertiary sediment and weathered volcaniclastic units. However, even in this reach, incision did not begin until the reservoir filled with sediment at least 25 k.y. after the dam was emplaced. In the final stages of dam removal, the incision rate at the downstream bedrock gorge (Rk 47.5–49.5) would have controlled the maximum rate of incision through the remaining thickness of the lava dam upstream of that point (Rk 38.5–47.5; Fig. 2B).

Effects on Valley Geomorphology

The river and canyon morphology retains different geomorphic imprints from the various Pleistocene intracanyon lava flows. The Bogus Rim, Saddle Butte 2, and West Crater flows form steep escarpments that mark the interface between the lava flows and the lakes they created upstream (Figs. 2B, 7, and 9). Especially in the case of the Bogus Rim lava flow, the prominent, sharp escarpment that stretches across much of the valley reorganized local tributary drainage. It funneled the subsequent Clarks Butte and West Crater lava flows to entrance points around its upstream periphery and into the new gorge that had incised along its outer margin. Hence, the most extensive lava flows not only shifted the river channel laterally, but redirected subsequent lava flows to different parts of the valley. Examination of other lava flows within the plateau region encompassed by the Owyhee River watershed (Fig. 1) surrounding the study reach indicates that the volcanic/geomorphic association of the source vent(s), down-valley extents of flow complexes, and up-valley–facing escarpments is a common landscape element that has influenced the geomorphic evolution of this region during much of the late Cenozoic.

With its great longitudinal extent down the river canyon (>30 km), the Bogus Rim flow has significantly influenced the position and width of much of the subsequent course of the river canyon (Figs. 2B and 3). As one of the largest and earliest intracanyon lava flows along the modern river course, the Bogus Rim flow established the position of the modern, deeply incised Owyhee canyon. Prior to the eruption of the Bogus Rim lava flow, the canyon was wider, and the channel was 100–200 m above the present river. By the time of the eruptions of the much younger Clarks Butte, Saddle Butte, and West Crater intracanyon lava flows, the river had incised a narrow, deep canyon between the edge of the Bogus Rim lava and the rhyolite-dominated bedrock.

Lateral shifting of the river channel by the lava flows has induced lasting effects on the river canyon geomorphology. Multiple paleochannel positions are most apparent in the reach from Rk 30 to 47, where the river was moved eastward more than 1 km by the Saddle Butte flows, then later back to the west by the West Crater flow below Rk 38 (Figs. 2B and 9). The sequential influx of large volumes of lava from alternating sides of the valley has resulted in a distinct valley morphology characterized by relatively flat, broad basalt shelves bounded by steep cliffs that are the loci of landslides and otherwise locally persistent additions of very large sediment to the river. Re-incision of the river around the margins of the lava dams created fresh exposures of basalt-capped Tertiary lacustrine and volcaniclastic sediment. This stratigraphic combination is highly susceptible to failure in large, rotational slump blocks and earth flows that introduce great quantities of sediment into the river channel, including numerous large basalt blocks (Othus, 2008; Safran et al., 2011; Fig. 15).

The widespread landslides spawned in the wake of the intracanyon lava flows could produce one of the more lasting impacts of the lava flows on the canyon geomorphology. Like the lava flows, the largest landslides also shift the river channel laterally (Figs. 2B, 3, and 15). The consequent incision of a similar stratigraphic sequence on the opposite canyon wall can induce additional landslides. Large boulder bars immediately downstream of many landslides indicate that many of the landslides dammed the river and failed catastrophically (Othus, 2008). Through the ongoing process of landsliding, the intracanyon lava flows thus indirectly continue to impact the channel morphology and local bed load 10^4–10^6 yr beyond the lifetime of the lava dams.

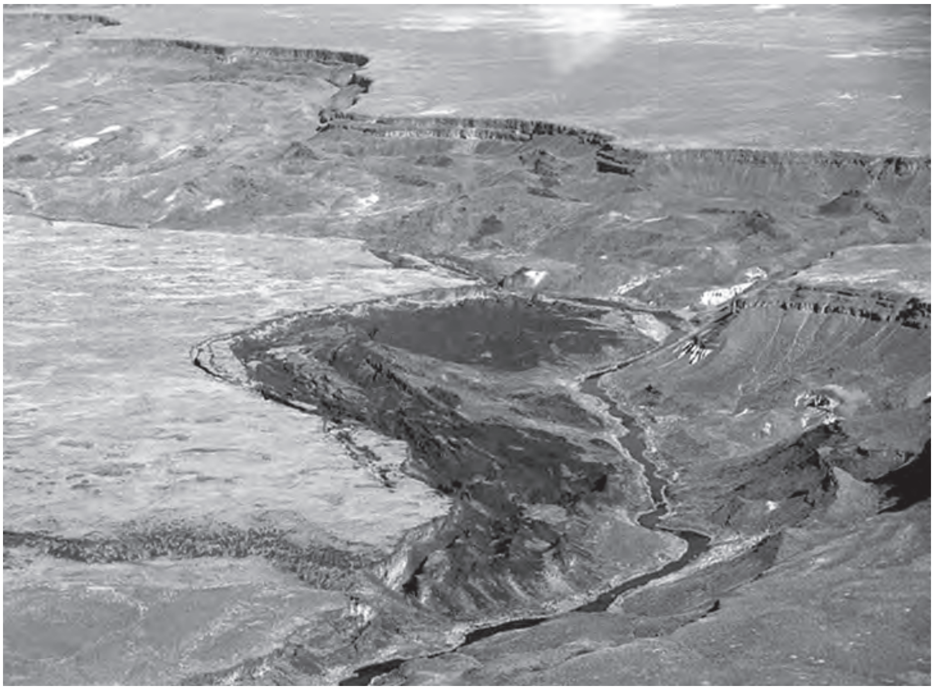

Figure 15. Mass wasting of lava flows (Rk 31–36) typical of the process by which the river canyon has migrated laterally and gradually widened after incising around the intracanyon lava flows. Flow direction in the river is toward the top of the photo (north). The Saddle Butte 2 flow on the left bank of the river is failing by slumps and cantilevered blocks. On the right bank, the combination of the Tertiary basalt cap rock overlying lacustrine sediment generates landslide complexes indicating multiple mobilization events. These mass movement events hold the potential for repeated damming of the river.

CONCLUSIONS

At least six sets of lava flows entered and dammed the Owyhee River between ca. 2 Ma and 70 ka, creating various temporal and spatial impacts on the river channel profile, rates of vertical incision, and valley geomorphology. The variety of geochronological and geomorphic evidence of the emplacement, duration, and removal of the lava dams in the Owyhee River provides an exceptional opportunity to quantify the persistence of lava dams in a fluvial system. The lava dams were stable for periods of >10^4 yr and were sufficiently impermeable for lakes to form and subsequently fill with lacustrine sediment to elevations approaching the dam crests.

Removal of the lava dams was episodic, but none shows evidence of catastrophic failure. After a period of initial stability, the dams were ultimately incised by increased fluvial erosion related to the culmination of sediment accumulation in the reservoirs. The most recent lava dam, formed by the West Crater lava flow ca. 70 ka, persisted for at least 25 k.y. before incision began, and the dam was largely removed within another 35 k.y. The initiation of this episode of relatively rapid incision was synchronous with the increased transport of fluvial sand and gravel across the dam surface once the lake filled with sediment. Thick accumulations of river gravels upstream of the other lava dams that are still well-exposed on the landscape, e.g., at the Saddle Butte and Bogus Rim dams, support the conclusion that the transport of coarse bed-load sediment over the lava dams was an essential factor in dam removal. In reaches where the dams abutted Tertiary sediment, the river carved a new path around, rather than through, the dams.

Most of the intracanyon lava flows do not appear to have exerted a lasting impact on the river valley profile at time scales >10^6 yr, despite repeatedly filling the valley bottom and blocking the river. Net average long-term incision of the Owyhee River canyon since the emplacement of the Bogus Rim lava flow (≤1.7 Ma) is 0.18 mm/yr; and episodic incision rates through individual lava flows are up to an order of magnitude greater. However, the lava dams did produce direct and varied consequences on the river channel and regional geomorphology, some of which have persisted to today or generated secondary effects. The early, most voluminous lower Bogus and Bogus Rim lava flows created a perturbation in the vertical profile of the river that lasted ~10^6 yr, whereas the later, smaller lava flows caused profile perturbations on time frames of 10^4 yr. Lava volume and dam size almost certainly influenced the duration of the lava dams in the river system. Additional unquantified factors such as the time required to fill the reservoir with sediment and changes in relative base level, climate, sediment supply to the reservoir, and valley geometry probably contributed to the river's response to individual lava dams as well.

One of the broadest regional geomorphic effects of the lava flows has been to redirect the river and subsequent lava flows to different parts of the canyon. The most extensive lava flow, Bogus Rim, produced a prominent, up-valley–facing escarpment across the valley that reorganized tributary drainages and funneled subsequent lava flows to entrance points around its periphery. The association of gradually sloping, down-valley flows and blunt, up-valley–facing escarpments is a common landscape element that has influenced the geomorphology of the Owyhee region during much of the late Cenozoic.

The influx of large volumes of lava into the valley shifted the river position laterally multiple times. This process created a distinct valley morphology characterized by relatively flat, broad basalt shelves bounded by steep cliffs, which are the loci of landslides and otherwise locally persistent additions of large sediment blocks to the river. The steep canyon walls of Tertiary sediment capped by basalt lava are particularly prone to rotational slumps, earth flows and rockfalls, some of which have also dammed the river. The intracanyon lava flows thus indirectly continue to impact channel morphology and local bed load 10^4–10^6 yr beyond the duration of the lava dams, through the ongoing landslides spawned in their wake. This tandem effect could produce one of the more lasting impacts on the channel morphology.

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