Winter 2006

Fluvial Response to Intra-Canyon Lava Flows, Owyhee River, Southeastern Oregon

Cooper Cooke Brossy
Central Washington University

FLUVIAL RESPONSE TO INTRA-CANYON LAVA FLOWS,

OWYHEE RIVER, SOUTHEASTERN OREGON

A Thesis

Presented to

The Graduate Faculty

Central Washington University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Geology

---

by

Cooper Cooke Brossy

January 2006

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

We hereby approve the thesis of

Cooper Cooke Brossy

Candidate for the degree of Master of Science

APPROVED FOR THE GRADUTE FACULTY

______________ ______________________________________
Dr. Lisa L. Ely, Committee Chair

______________ ______________________________________
Dr. Wendy Bohrson

______________ ______________________________________
Dr. Paul Hoskin

______________ ______________________________________
Dr. Jim E. O’Connor

______________ ______________________________________
Associate Vice President of Graduate Studies

ABSTRACT

FLUVIAL RESPONSE TO INTRA-CANYON LAVA FLOWS,

OWYHEE RIVER, SOUTHEASTERN OREGON

by

Cooper Cooke Brossy

January 2006

At least six lava flows have entered the Owyhee River Canyon north of Rome, Oregon, since the Pliocene and directly impacted the Owyhee River. The effects on the river of the two youngest lava flows, the West Crater (60–80 ka) and Saddle Butte (> 60–90 ka), are readily apparent. These two lava flows entered a paleo-Owyhee Canyon several kilometers wide via three different tributary drainages. The flows dammed the Owyhee River, created lakes, and effectively confined the river to the opposite side of the valley from the flows' entrance. Lava from these flows filled a paleo-Owyhee Canyon to depths of up to 25 m for distances of at least 12 km. Several minor river channels were incised into these lava flows, but abandoned once the river began to incise into the less-resistant adjacent and underlying geologic units. The Upper AM-PM lava is older than the Saddle Butte lava. It likely represents distal portions of the Clarks Butte lava flow and records a time when the Owyhee River channel was at a higher elevation than today but at a very similar gradient to the modern river for over 26 km.

The Bogus Point, Bogus Rim, and Greeley Bar lava flows are the oldest (up to 2 Ma) and their effects on the river are mostly obscured by younger geologic units. From cosmogenic dating of fluvial features and $^{40}Ar/^{39}Ar$ dating of lava flows, estimates of mean incision rates through and the around the West Crater flow range from 0.27 mm/yr at Airplane Point to 3.3 mm/yr at Dog Leg Bar. No deposits from catastrophic outburst floods resulting from lava dam failure have been found, supporting gradual incision rather than catastrophic failure of the dams. The lava dams were long and low, and the river commonly eroded around the dams, reducing the likelihood of catastrophic lava dam failure. Today, the river flows through a narrow inner gorge often less than 500 m wide within the wider Owyhee Canyon.

ACKNOWLEDGMENTS

I received assistance from many helpful people and organizations while working on this project. Funding was generously provided by National Science Foundation grant EAR-0617234, the CWU Department of Graduate Studies, the Geological Society of America, and the Jack Kleinman Internship for Volcano Research. Thanks go to Rich Bupp, Heidi Buettner, Jamon Frostenson, Fred Brossy, Brian Gray, Lisa Ely, Jim O'Connor, P. Kyle House, Cassandra Fenton, Liz Safran, Gordon Grant, Stephanie Vandal, Ninad Bondre, and Duane Champion for their help in the field. Ninad Bondre and Duane Champion generously provided and discussed the meaning of data on the geochemical and paleomagnetic signatures of the lava flows. Luke, Neely, Tim, and John from Ouzel Outfitters provided safe and convivial transportation down the river. Rich Bupp, Natalie Sudman, Joe O'Neill, Jack Wenderoth, Brent Grasty, and Connie Slusser at the Vale and Denver BLM offices were very helpful with locating air photos, providing GIS data, and offering great field support. Bob Corbari and Ralph Fillmore generously shared their knowledge of the local geography and the use of their shade trees, cabins, and water sources. My committee and many other members of the CWU Department of Geological Sciences, especially Craig Scrivner and Vicki Potts, provided assistance in moments of technical or logistical frustration. I must thank my advisor, Dr. Lisa Ely, for her guidance and patience. I am also indebted to my parents and my fellow graduate students for their support and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

CHAPTER I

INTRODUCTION

This study investigates the effects of Quaternary lava flows on the channel migration and incision history of the Owyhee River in semiarid, southeastern Oregon (Fig. 1). Because this region is semiarid and the lava flows are young, the effects of the lava flows on the river are still readily apparent. The lava flows provide an excellent opportunity to study the response of a river to changes in its slope and the resultant processes of canyon cutting, channel abandonment, and channel migration.

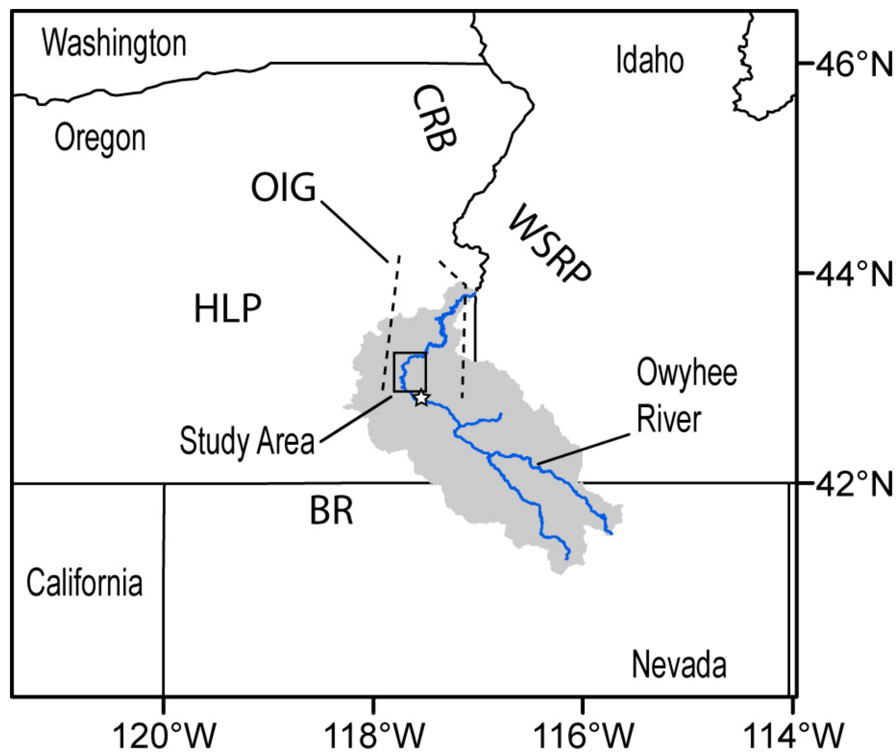

Figure 1. Location map showing the Owyhee River and its drainage area (shaded). The study area is indicated by the small rectangle. The town of Rome, Oregon, which serves as river kilometer 0, is represented by the small star. Dashed lines indicate the approximate location of the Oregon Idaho Graben (OIG) (Cummings et al., 2000). Approximate locations of the Columbia River Basalt feeder dikes (CRB), Western Snake River Plain (WSRP), Basin and Range (BR), and High Lava Plains (HLP) are also shown.

The four main objectives of this study were (1) determine the number of lava flows that have entered the canyon, their ages, and extents; (2) identify how the lava flows have altered the course of the river and what the landscape looked like before the lava flows were emplaced; (3) investigate how the rate of lava effusion into a river interacts with the river's discharge and channel morphology to influence the structure and stability of lava dams; and (4) use the lava flows to calculate rates of river incision.

Significance of Project

This study examines the interaction of lava flows with fluvial systems by refining models of lava dam emplacement and lava dam breaching mechanisms. Lava flows can substantially affect fluvial systems by altering the topography of the valley and by affecting rates of river incision both near and far from the lava incursions themselves. For example, in the Grand Canyon lava flows created dams that raised local base level by tens to hundreds of meters (Fenton et al., 2004) for significant time spans (~20 ka) (Dalrymple and Hamblin, 1998), thereby affecting the entire drainage network. An outburst flood from the catastrophic failure of a lava dam could affect valley morphology for kilometers downstream of the breach by armoring the channel with coarse sediment too large for normal flows to transport (Fenton et al., 2002).

Mapping and dating lava flows within the Owyhee River Canyon provides data on the chronology of volcanic events on the Owyhee Plateau. Shoemaker (2004) proposed that the Owyhee Plateau is a discrete tectonomagmatic entity within the North American Cordillera, and any additional data on the basaltic volcanism of the region will help to understand the significance of the plateau and its relation to previously recognized provinces such as the Snake River Plain and Columbia River Basalts.

Finally, this investigation provides a more complete interpretation of the channel migration, incision rates, and slope of the Owyhee River through time by identifying paleochannels and evaluating the rates of knickpoint retreat and river incision. These data will in turn increase our understanding of the influence that lava flows have on the long-term evolution of rivers in uplifted volcanic plateaus, as well as constrain the rates of bedrock erosion in this type of geomorphic setting. The results could eventually be incorporated into models of landscape evolution of volcanic terrains.

Geologic Setting

The study area lies within the Oregon-Idaho graben, to the southwest of the Western Snake River Plain at the juncture of the High Lava Plains, the Basin and Range, and Columbia River Basalt provinces (Fig. 1). The Oregon-Idaho graben is a 50–60 km wide, 100 km long, north-trending, mostly topographically subdued synvolcanic graben (Cummings et al., 2000). The Oregon-Idaho graben lies adjacent to the inferred western edge of the North American craton between the northern Nevada rift and the dike swarms for the Imnaha and Grande Ronde Formations of the Columbia River Basalt Group (Cummings et al., 2000). Prior to graben development, a large volume of tholeiitic basalt erupted from vents on the nearby Oregon and Columbia plateaus and a substantial volume of rhyolite erupted in the study area between 16.5–15.3 Ma as part of the Lake Owyhee volcanic field. One such middle Miocene rhyolite outcrops within the study area at Iron Point along the Owyhee River and marks the location of a probable caldera (Cummings et al., 2000). Development of the Oregon-Idaho graben occurred in three phases (Cummings et al., 2000). The deposition of fluvial and lacustrine sediments across the basin following intragraben caldera collapse characterized stage 1 (15.3–14.3 Ma). Current indicators show southeast to northwest transport of material across the basin. During stage 2 (14.3–12.6 Ma), calc-alkaline magmatism and associated synvolcanic collapse along intragraben faults split the basin into subbasins. Intragraben sedimentary and volcanic aggradation that exceeded subsidence characterized stage 3 (12.6–10.5 Ma). Subsidence in the Oregon-Idaho graben ceased at 10.5 Ma when extension migrated to the western Snake River Plain (Cummings et al., 2000).

Fluvial and lacustrine sediments and intercalated lava flows are found throughout the study area. Basaltic volcanism on the northern Owyhee Plateau has occurred continuously since the Miocene and a range of compositions from high-alumina olivine tholeiite typical of the Oregon Plateau to olivine tholeiite typical of the Snake River Plain have erupted (Shoemaker, 2004). The oldest sedimentary units include outcrops of the Middle and Late Miocene Deer Butte and Grassy Mountain Formations in the northern portion of the study area near The Hole in the Ground (Cummings, 1991; Plumley, 1986). Some units resemble those associated with Lake Idaho, a Late Tertiary lake that existed in south central and southwestern Idaho (Jenks and Bonnichsen, 1989). Hart and Mertzman (1983) recognized that the ages and lithologies of sediments found in the Owyhee River Canyon at The Hole in the Ground correspond to descriptions and ages of the Pliocene-Pleistocene Glenns Ferry and Upper

Chalk Hills Formations that Malde and Powers (1962) described in the western Snake River Plain. Jenks and Bonnichsen (1989) included the Owyhee River Canyon upstream to Rome in the Lake Idaho Basin based on the postulated high stand of the lake at 3800 ft (1158 m). In the center of the study area, an approximately 150 m thick sequence of mostly tuffaceous siltstone and sandstone exists at Chalk Basin. These lacustrine sediments are late Miocene based on ages applied to vertebrate fossils and interbedded Devine Canyon Ash-flow Tuff (Evans, 1991; Ferns et al., 1993). Some geologic dating ($^{40}Ar/^{39}Ar$) of basalt flows (Hart et al., 1984; Shoemaker, 2004; Shoemaker et al., 2002; and Bondre and Hart, 2004, 2006, and Bondre, 2006) and mapping of bedrock and landslides has been conducted in the study area (Walker and McLeod, 1991; Plumley, 1986; Evans, 1991; Ferns et al., 1993). The Saddle Butte, Upper AM-PM lava flows, and West Crater lava flows are the focus of this study, while several previously unnamed lava flows (the Bogus Point, Bogus Rim, and Greeley Bar flows) are briefly described.

Background on Lava-Water Interaction

Extensive outcrops of pillow lavas and hyaloclastite in some locations of the study area attest to lava-water interaction (Evans, 1991). Fuller (1931) described in detail the interaction of lava flows and standing bodies of water in the Columbia River Basalts. He attributed exposures of volcanic breccias containing foreset bedding, like that found in a river delta, to the advance of a lava flow into water. As lava entered the water, it was chilled rapidly and fractured into vitreous bits and granules of sideromelane (hyaloclastite) that were deposited in beds that dipped down into the water in front of the advancing flow. These deposits were buried by new deposits forming above and up slope. The process was repeated, and beds of hyaloclastite prograded outward, into the body of water as foreset beds (Fig. 2). Fuller (1931) also observed the presence of ellipsoidal masses of lava—lava pillows—of various sizes within the breccias. These too form as water chills an advancing lava flow.

Jones and Nelson (1970) built on the observations of Fuller (1931). The authors described pillow lavas and a breccia of hyaloclastite that were structurally continuous with the overlying subaerially emplaced portion of the lava flow (Jones and Nelson,

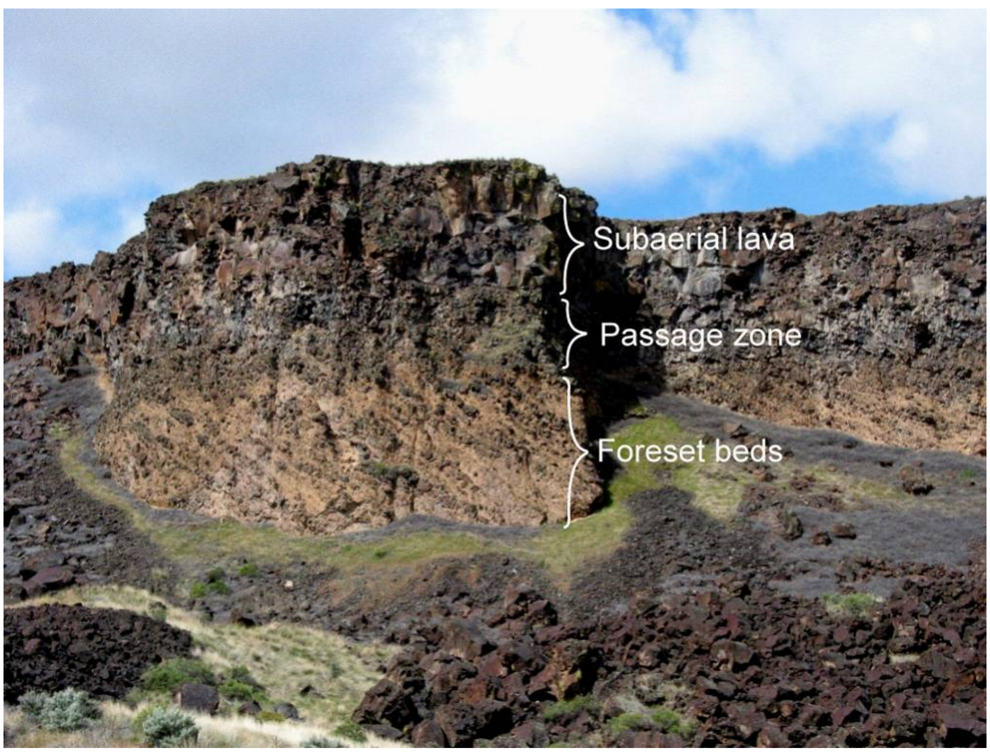

Figure 2. Exposure of the Saddle Butte lava near Read-it-and-Weep rapid (river kilometer 34.25). Exposure shows foreset beds of hyaloclastite and lava pillows, the passage zone, and subaerial lava. The foreset beds of pillow lavas and hyaloclastite dip down to the right, indicating that the lava advanced from left to right into a body of standing water. Much of the hyaloclastite has altered to orange-colored palagonite. The passage zone marks the elevation of the water surface. Above the passage zone, subaerial lava was emplaced. Exposure is ~60 m thick.

1970). The structural continuity of the pillows and breccia with the subaerial lava occurs because subaerial lava enters the water to create lava pillows (Fig. 2). The transition of subaerial lava to lava pillows and breccia is marked by the passage zone (Fig. 2). Pillow lavas and hyaloclastite breccias, along with transitional forms, may occur separately or together in outcrop depending primarily on the lava-to-water ratio, but also the volatile content, viscosity, and temperature of the lava (Batiza and White, 2000; Kokelaar, 1986).

Previous Research on Intra-Canyon Lava Flows

Numerous researchers have documented the interaction of lava flows and fluvial systems at a variety of locations worldwide. Volcanism occurring in Iceland regularly impacts fluvial systems, damming rivers to create large lakes (Pedersen et al., 1998) and re-routing rivers as in the A.D. 1783-1784 Laki eruption (Guilbaud et al., 2005). Bunbury et al. (2001) used intra-canyon lava flows in the Gediz River to determine fault movement history and the timing of graben development in the Kula Volcanic Province in Turkey. Huscroft et al. (2004) used intra-canyon basalt flows in the Yukon River of northwestern Canada to better constrain the age of the Reid Glaciation. Several rivers in California show the effects of volcanism. Wakabayashi et al. (1994) and Wakabayashi and Sawyer (2000) studied intra-canyon lava flows that displaced the ancestral North Fork Feather River to understand the tectonics of the northern Sierra Nevada Mountains. Further to the south, lava flows in Mono Basin closed the spillways of Pleistocene Lake Russell, changing the drainage divide between the hydrologically distinct Lahontan and Owens-Death Valley systems (Reheis et al., 2002). Even further to the south, lava flows near Little Lake repeatedly altered the course of the Owens River during the Pleistocene (Duffield and Smith, 1978). Many authors describe intra-canyon lava flows within the Deschutes River basin in central Oregon (Newcomb, 1969; Russel, 1905; Sherrod et al., 2004; Smith, 1986, 1987, 1991; Stearns, 1931).

Intra-Canyon Lava Flows in Idaho

The rivers of southern Idaho offer several examples of the response of fluvial systems to intra-canyon lava flows. Malde (1991) explained that the Snake River was diverted by canyon-filling lava flows at least five times in locations across southern Idaho from King Hill to Burley. Painter et al. (2005) reported that the Pleistocene Gerrit Basalt episodically dammed the Henrys Fork of the Snake River. Maley and Oberlindacher (1994) described how the Big Wood River was diverted from its original course by eruption of basaltic lava from Black Butte volcano.

Similar to the study presented herein, Howard et al. (1982) utilized K-Ar dating to determine the timing and effects of five episodes of canyon filling lava flows on the incision rates of the South Fork of the Boise River. The authors mapped and described the sources and extents of the flows, the architecture of lava dams, and the response of the river. They correlated intra-canyon lava outcrops based on the stratigraphic and geomorphic positions of the lava outcrops, the magnetic polarity of the lava, the degree of lava preservation, and K-Ar ages of the lavas. The authors identified two styles of lava dam removal: gradual incision and nickpoint retreat. In the first case, the South Fork filled the reservoir behind the Smith Prairie Basalt dam with sediment, then overtopped the dam on its shoulders, and gradually cut through the dam. The river then usually followed the margins of the intra-canyon lava downstream, incising into both the underlying granodiorite and the Smith Prairie Basalt. In the second style of dam removal, removal occurred by the headward retreat of the 30 m high Smith Creek Falls. Here, more resistant subaerial basalt was overlain by less resistant pillow lavas that easily eroded, resulting in a waterfall. Howard et al. (1982) calculated that over the past 2 million years, rates of river incision in the Boise River were 0.05 to 0.10 mm/yr. These long-term rates are lower than the rates the authors calculated for incision through the lava dams: 0.70 mm/yr for the Smith Prairie Basalt and 0.30 mm/yr for the lava dams at Mores Creek. These values provide a comparison to the Owyhee drainage where the river runs through basalt, rhyolite, and sediments and may therefore have different incision rates.

Intra-Canyon Lava Flows in the Colorado River System

Some of the most widely known and extensively studied intra-canyon lava flows occur in the Colorado Plateau region of the southwestern United States. Duffield et al. (2006) used infrared stimulated luminescence, ^{3}He cosmogenic, ^{40}Ar/^{39}Ar, and paleomagnetic dating techniques to better constrain the age of the Grand Falls lava dam on the Little Colorado River. This multi-pronged approach to dating utilizes the strengths of each dating technique to better constrain the ages of young features that can be quite problematic to date accurately with radiometric techniques alone. This approach provides a model for the study of the Owyhee Canyon lava dams.

Many workers have described the intra-canyon lava flows and lava dams found in the Grand Canyon along the Colorado River (Dalrymple and Hamblin, 1998; Fenton et al., 2006; Fenton et al., 2002; Hamblin, 1994; McKee et al., 1968). These researchers have proposed several different catastrophic and noncatastrophic mechanisms for removal of the dams. Hamblin (1994) provides the most complete description of each lava dam, its location, longevity, and possible failure mechanisms. In the 13 major lava dams Hamblin (1994) described, he recognized four general types of dams: single-flow dams, massive dams, dams formed by a sequence of thin flows, and complex dams (Fig. 3). Single-flow lava dams in the Grand Canyon are composed of a very long (≥ 138 km in one instance!) single-flow package 45–185 m thick. These dams were formed by rapid emplacement of 0.125–2 km^3 of lava. In contrast, massive dams are thicker (~240 m thick), shorter (< 30 km long), and contain more lava (2–5 km^3) than single-flow dams. Massive dams formed when one or more flow units of lava were emplaced much faster than the river could overtop it. A third type of dam appears to have been created by a series of thin flows 3–9 m thick (Hamblin, 1994). The river likely immediately overtopped each flow unit and began eroding it so that when the next flow unit was emplaced, the previous flow unit only partially remained. Fluvial sand and gravel were often deposited between each flow unit. These thin flow dams are short (≤ 15 km), low volume (0.25–0.96 km^3) dams characterized by a relatively steep downstream gradient. Hamblin’s (1994) fourth dam type is the complex dam. Complex dams are similar to thin flow dams, but the flow units are much thicker (15–60 m thick) and the surface of the flows is more scoured and eroded by the river. Sometimes the entire upper colonnade is eroded. Fluvial erosion cuts significant channels in the flows, which are filled with gravels, sand, tephra, or other lava flows. Complex dams have a steep

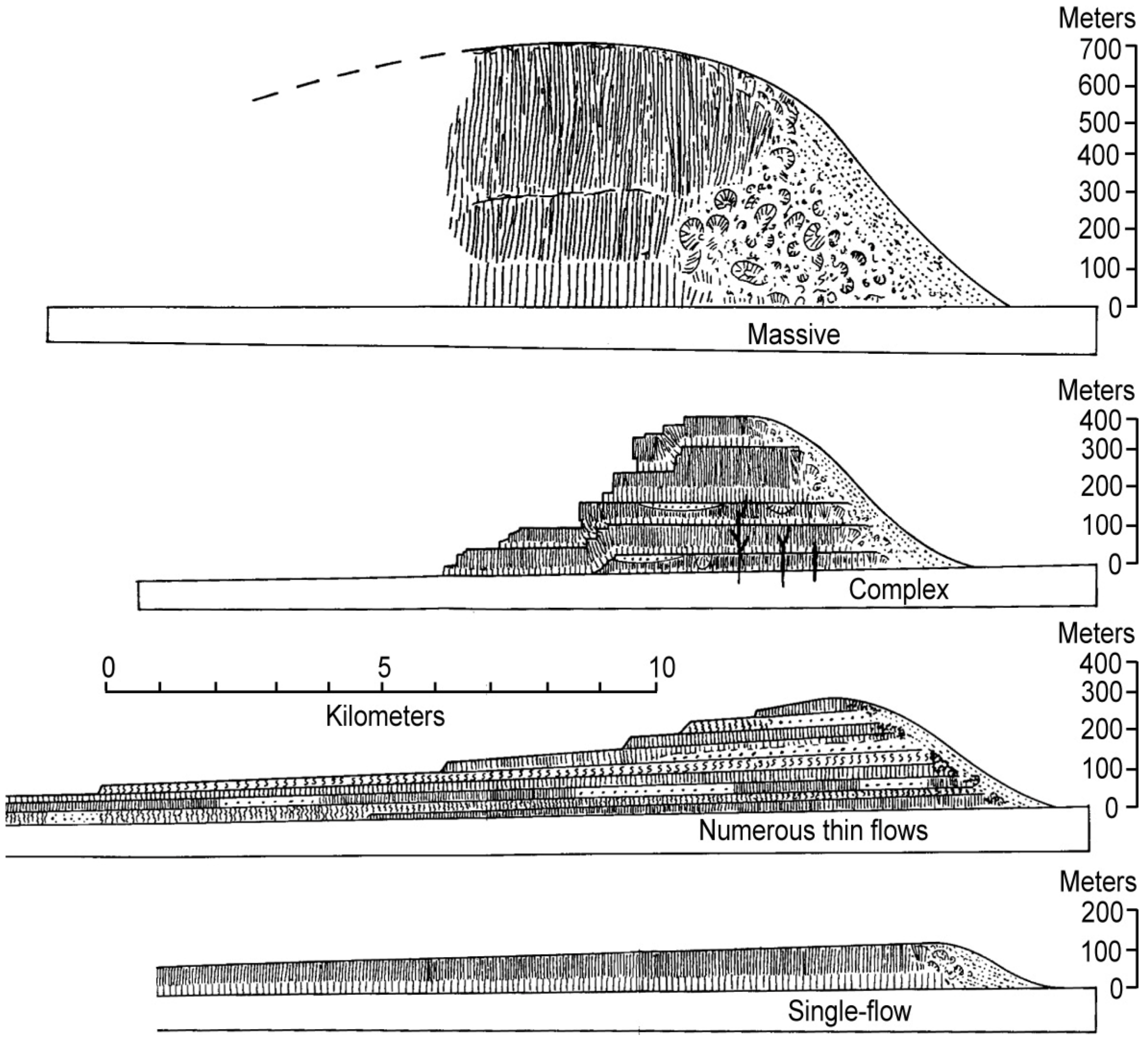

Figure 3. Illustrations of Grand Canyon lava dam types modified from Hamblin (1994). Illustrations of the dams were shortened to fit on the page. The numerous thin flow dams range up to 15 km in length and single-flow dams can be over 100 km long.

downstream gradient because the distal portions of the flow units were eroded away prior to emplacement of later flow units. These dams are very short (15 km) and their fronts may have a stepped surface. In contrast to the Owyhee River Canyon where the source vents of intra-canyon lava flows are many kilometers from the river, most Grand Canyon lava dams formed from eruptions of lava within the canyon (Hamblin, 1994).

According to Hamblin (1994), two general types of erosional processes act on lava dams: incision of the channel bottom by normal traction load and the upstream migration of waterfalls and rapids. Several factors influence these processes and dam removal (Hamblin, 1994). The well-jointed nature of the basalt flows aids in the separation and hydraulic plucking of joint blocks. Jointing might also limit the amount of fluid pore pressure a lava dam could withstand, resulting in catastrophic dam failure. In addition, the presence of unconsolidated sediments or channel deposits underlying the dam might enhance sapping and therefore undercutting by the plunge pool of a waterfall. Hamblin's (1994) conceptual model of lava dam failure is based on headward migration of a waterfall through the dam. Once the waterfall reduces the length of the dam to some key distance, catastrophic failure of the dam may result. Using Niagara Falls as a model, Hamblin (1994) concluded that Grand Canyon lava dams could have been destroyed by headward migration of waterfalls alone in about 40,000 years.

Building on previous work, Fenton et al. (2002) describe a lava dam failure model that differs from Hamblin (1994). Fenton et al. (2002) note that the lava dams were emplaced on unstable talus slopes and poorly sorted alluvium. In addition, the hydrothermally weakened basalt flows added to the instability of the dams such that the dams may not have survived long enough to be overtopped and eroded by waterfall migration. Catastrophic dam failure may therefore result from the unstable nature of the dam foundation and abutments (Fenton et al., 2002).

Fenton et al. (2002, 2004) successfully used major and trace element data and cosmogenic dating (^3He_c) to correlate outburst flood deposits to the failure of specific lava dams in the Grand Canyon. Because the Colorado River drains a variety of diverse lithologies, Fenton et al. (2002) were able to distinguish lava dam outburst flood deposits from meterological flood and debris flow deposits based on the presence of hyaloclastite tuffs and high percentages (82%–98%) of basalt clasts within flood deposits. Once catastrophic outburst flood deposits were conclusively recognized and correlated to a specific dam, Fenton et al. (2006) were able to complete hydrologic modeling on the flood wave. The failure of the 366-m-high Hyaloclastite Dam resulted in an outburst-flood that released 11×10^9 m^3 of water over 31 hr (Fenton et al., 2006). Peak discharge estimates for the flood ranged from 2.3 to 5.3×10^5 m^3/s. These values place the flood in the top 30 floods known worldwide and in the top 10 in North America (Fenton et al., 2006).

CHAPTER II

METHODS

Geologic Mapping

A geologic map illustrating the location of lava flows and fluvial deposits was created to address study objectives one through three. Study of the river-lava flow interface with aerial photographs and fieldwork overland and via raft occurred in 2004, 2005, and 2006. The locations and extents of intra-canyon lava flows, paleochannels of the Owyhee River, strath and fill terraces, and potential outburst flood deposits were compiled in ArcMap 9.1 software (ESRI, 1995) to create geologic maps of the study area.

The Owyhee River Canyon, portions of the Granite Creek and Ryegrass Creek drainages, and the immediately adjacent uplands were mapped in detail. The uplands distant from the river were mapped in a reconnaissance fashion using 1:24,000 scale color stereo aerial photographs and topographic maps. Geographic place names were taken from United States Geological Survey (USGS) 1:24,000 scale maps and the *Owyhee & Bruneau River Systems Boating Guide*, published by the U.S. Department of the Interior, Bureau of Land Management (BLM). Copies of the guide can be purchased from the BLM district offices in Boise and Twin Falls, Idaho as well as Vale, Oregon. The mile markers shown in the boating guide along the lower Owyhee River are inaccurate for discussion of the river corridor geology and are not used for reference herein. Distances along the river were measured by viewing 1:24,000 scale topographic maps and using the measure tool in ArcMap 9.1 (ESRI, 2005). Measurements began at the 1024 m (3360 ft) contour just east of the U.S. Highway 95 bridge at Rome. The distance down the centerline of the river was recorded. Where the river channel was braided, the measured route passed through the widest braid. Where the channels in braided portions were of the same width, the route passed through the center of the braided reach. Due to the methods used and the limits of the measure tool in ArcMap (ESRI, 2005), the uncertainty in river distances is ± 25-50 m. The natural ability of river channels to change location will add additional uncertainty to the stated distances over time.

In some cases, the edges of digital aerial photographs provided by the BLM were misaligned with the digital topographic map by as much as 70 m in ArcMap (ESRI, 2005). This is often a result of poor georectification due to extreme relief, lack of ground control points, or both. When digital aerial photographs and maps were not aligned, additional georectification was not attempted. Instead, features were mapped according to the topographic map. Additional uncertainty in location may result from errors in the contour lines due to the great change in relief (> 300 m) between the canyon rim and river level and the varied topography within the narrowest (< 100 m wide) portions of the canyon.

Distinguishing and Dating Lava Flows

Only intact and coherent sections of lava were mapped; portions of lava flows involved in landslides were not mapped. Individual lava flows were distinguished from one another by their surface morphology, amount of soil cover, hand sample mineralogy, and directions of remanent magnetization. A limited number of isolated outcrops were correlated based on the geochemistry of the lava flows; the rest were correlated based on their stratigraphic relations, geomorphic positions in the canyon, and hand sample mineralogy (Appendix A). Relative ages of the lava flows were established by stratigraphic relations where possible, but elsewhere by their general appearance and surface morphology, amount of soil cover, and extent of weathering and alteration of minerals examined in hand sample. Absolute ages of lava flows were determined by $^{40}Ar/^{39}Ar$ dating, paleomagnetic studies, or by using geochemistry to correlate the flows to vents dated by Hart et al. (1984), Shoemaker et al. (2002), Bondre and Hart (2004), and Bondre (2006).

Nine samples for $^{40}Ar/^{39}Ar$ dating (Appendix B) were collected from the most crystalline sections of individual flow units where the core of the flow was exposed in the center of tumuli or along cliff faces. Samples were field processed into 2- to 5-cm-diameter pieces at the sample location, using large pieces of the sample rock as anvils to minimize contamination. Six samples were sent for analysis to the Nevada Isotope Geochronology Laboratory at University of Nevada, Las Vegas. Results are pending.

Major and trace element analyses of selected samples were completed to determine whether the lava flows had unique geochemical signatures that could be used to identify and correlate isolated lava outcrops to vents whose ages were already known. Geochemical data were used after attempts to use petrography to correlate lava flows proved difficult because the mineral assemblages for the West Crater, Rocky Butte, and Clarks Butte flows were similar. In addition, developing an accurate hand sample description was complicated by the fact that samples of the same lava flow exhibit some natural variability due to local differences in factors such as composition, cooling rate, degree of degassing, and variable crystal settling.

Geochemical analyses and interpretation of data were conducted in collaboration with Dr. Ninad Bondre and Dr. William Hart, Miami University of Ohio, Oxford Ohio. Dr. Ninad Bondre completed major and trace element analyses of samples collected from lava flows and isolated lava outcrops (Bondre, 2006). These new data supplemented existing data collected in ongoing research of the geochemical nature of lava flows on the Owyhee Plateau (Bondre and Hart, 2004, 2006; Hart and Mertzman, 1983; Shoemaker, 2004; Shoemaker and Hart, 2002; and Hart, 1982). Major element analyses were done at Miami University with direct current argon plasma spectroscopy using the methods of Katoh et al. (1999). Trace element analyses were done at Miami University using direct current argon plasma spectroscopy or at Franklin and Marshall College using the x-ray fluorescence techniques of Mertzman (2000).

New analyses were compared to existing data collected by Bondre and Hart (2004, 2006), Hart et al. (1984), Hart and Mertzman (1983), Shoemaker (2004), Shoemaker and Hart (2002), and Hart (1982). In the case of major elements, 22 existing analyses were used to identify fields that characterized 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. Owyhee Butte is a prominent shield volcano to the south of the study area that was not studied extensively. Geochemical data from Bondre (2006) on the Owyhee Butte lava flows was included to ascertain whether Owyhee Butte might be the source of the Bogus Point lava flows. The Clarks Butte and Rocky Butte have been plotted in the same field because they have similar geochemical characteristics. Nine new samples from this study were compared against these fields. Dr. Ninad Bondre (2006) provided 19 existing trace element analyses from samples of the Rocky Butte, West Crater, Bogus Rim, and Owyhee Butte lava flows that were used to define characteristic fields for La, Nb, Rb, Sr, Ba, and Zr. Trace element analyses of five new samples from this study were compared against these fields.

Study of the natural remanent magnetization (NRM) of the intra-canyon lava flows along the Owyhee River may allow distinct directions of magnetizations to be recognized for individual lava flows and provide a tool for dating and correlating isolated lava flow outcrops (Kuntz et al., 1986). Study of the NRM of the lava flows was conducted in collaboration with Dr. Duane Champion, Volcano Hazards Team, USGS Menlo Park, California, in an effort to distinguish the lava flows from each other and create a database of paleomagnetic data for future studies. Directions of remanent magnetization have been used to approximately date and correlate lava flows (Kuntz et al., 1986) because the direction and magnitude of the geomagnetic field of Earth changes with time (Butler, 1992; McElhinny, 1973). Changes that occur on timescales of 1–10^5 years are termed geomagnetic secular variation (Butler, 1992) and can occur at geologically rapid rates (~4°/century) (Champion and Shoemaker, 1977). These changes are not cyclic and should be characterized as a random walk about the mean whose path, because random, can be repeated (Butler, 1992).

Paleomagnetic sample sites were flat, stable areas of the lava flow that had not tilted or been rotated after crystallization. Where possible, sample sites were located where the surface of the flow had been removed by streams or road cuts to reduce the presence of isothermal remanent magnetization resulting from lightning strikes. A water-cooled, gasoline-powered drill was used to take eight independently oriented, 1-in diameter cores at each site. A sun compass was used exclusively to orient the azimuth of the field cores because the magnetic character of black volcanic rock can influence a magnetic compass. A cryogenic magnetometer, under computer control, measured the remanent magnetization of the cores (Appendix C). The mean directions of magnetization for each site were then plotted on an equal-area diagram.

Mapping of Fluvial Deposits

Paleochannels, terraces, and other locations where the river once flowed were identified by the presence of rounded cobbles and boulders of basaltic and exotic compositions, eroded tumuli, and fluvially sculpted basalt surfaces devoid of pahoehoe ropes (Appendix D). Locations where the Owyhee River ponded behind lava dams were recognized by deposits of cobbles, pebbles, and coarse sands. A key piece of evidence for determining locations where the river occupied the surface of the lava flows was the presence of clasts of non-basalt lithology on the surface of the lava flow.

River Incision Analysis

River incision rates were calculated by dividing the ages of river terraces and paleochannels, as determined from cosmogenic exposure dating, by the height of those features above the modern river. Dating strath terraces in particular was useful because strath terraces helped constrain the age of the lava flow they occur in by providing a minimum age for the lava flow. Dating was performed in collaboration with Dr. Cassandra Fenton, GeoForschungsZentrum Potsdam, Potsdam, Germany.

Cosmogenic dating measures the amount of cosmogenic nuclides, in this case ^{3}He, that directly result from the amount of time a surface is exposed to cosmic radiation (Zreda and Phillips, 2000). Cosmogenic ^{3}He ($^{3}He_{c}$) is ideal for dating the exposure time of basalt-rich geomorphic surfaces and young basalt flows (Cerling, 1990; Cerling and Craig, 1994; Cerling et al., 1994; Cerling et al., 1999; Fenton et al., 2002; Gosse and Phillips, 2001; Kurz, 1986), because $^{3}He_{c}$ is produced and retained in olivine and pyroxene phenocrysts (Gosse and Phillips, 2001). $^{3}He_{c}$ is stable and has the highest and most well established production rate of all terrestrial *in situ* cosmogenic nuclides (Cerling, 1990; Cerling and Craig, 1994; Gosse and Phillips, 2001). The $^{3}He_{c}$ system is an appropriate choice for exposure dating in the study area because lava flows along the Owyhee River have abundant olivine phenocrysts.

Cosmic ray flux and $^{3}He_{c}$ production is mainly controlled by elevation, latitude, the geomagnetic field, and solar activity (Cerling, 1990; Cerling and Craig, 1994; Gosse and Phillips, 2001). In general, sample sites at higher elevations and latitudes have higher production rates. Likewise, the waxing and waning of the geomagnetic field causes production rates to be lower and higher, respectively, over geologic time scales (Gosse and Phillips, 2001). Cosmogenic ^{3}He production is also controlled by shielding from topography, burial (e.g., snow or sediments), or self-shielding (Fenton et al., 2002; Gosse and Phillips, 2001). Although production of cosmogenic nuclides decreases with depth, production rates remain essentially constant to depths of 4 cm (Cerling and

Craig, 1994). Therefore, only the top 4 cm of basalt flows and/or basalt boulders was collected from surfaces at the sample sites. Samples for cosmogenic dating were collected according to the methods described by Gosse and Phillips (2001) and Fenton et al. (2002,2004). Olivine was separated from the basalt samples using magnetic and density separation techniques. Pure olivine separates were visually inspected and then loaded in the noble gas mass spectrometer at the University of Rochester or the USGS (Denver). The samples were melted under high vacuum at 1400 °C and the helium isotopes were measured.

The amount of helium in a rock is a result of air contamination, mantle gas contamination, radioactive decay, and cosmic ray influx (Mamyrin and Tolstikhin, 1984). Alteration of target minerals (i.e., olivine to iddingsite) may decrease $^{3}He_{c}$ concentration (Zreda and Phillips, 2000). However, this problem was avoided by treating the olivine separates with dilute HCl and HNO_3 before mass spectrometric analysis; acid treatment dissolves the iddingsite coatings of grains.

In most cases, olivine phenocrysts from Owyhee River basalts have only mantle gas and cosmic contributions, because many of the basalts are young (< 250 ka) and have not had enough time to accumulate radiogenic helium. Cosmogenic ^{3}He dating works best on rocks with young crystallization ages because radiogenic ^{3}He can overwhelm $^{3}He_{c}$ in old rocks that have only recently been exposed to cosmic rays (Gosse and Phillips, 2001). A shielded sample was collected from a cave > 2 m deep in the West Crater lava flow at Dog Leg Bar, and the helium isotopes were used to correct for any mantle contribution. Based on the exponential depth-dependence of cosmogenic isotope production, this shielded sample should have no cosmogenic component.

In addition to the dating of fluvial deposits, a long profile was created to understand how the elevation of the lava flows relates to the modern and paleo-river elevations. Horizontal distances refer to the distance from Rome, Oregon, along the course of the modern river and were measured from digitized 1:24,000 scale topographic maps viewed in ArcMap 9.1 (ESRI, 1995). Elevations of the surfaces of the lava flows and terraces were read from maps or determined with a handheld Global Positioning System (GPS) altimeter. Where exposed, the thicknesses of the lava flows and the elevation of their uppermost surfaces, and the elevations of terraces were measured from water level with a laser rangefinder during a river trip May 7–11, 2006, when the river discharge at Rome, Oregon was 104–122 m^3/s (3680–4340 cfs).

Commonly, the entire lava flow section, or at least the base of the lava flows, is obscured by talus or landslide deposits. In these locations, the entire visible section of lava was measured and included on the long profile. The visible portion of the flow represents the minimum thickness of the flow and places a constraint on the paleotopography at that location at the time of lava flow emplacement. The vertical uncertainty of the long profile is at least ± 6 m (20 ft) because the variable topography of a lava flow that results from tumuli, inflated flow fronts, and collapse features cannot be shown in true detail on a topographic map having a 20-ft (6-m) contour interval. In addition, the great relief (> 300 m) between the canyon rim and modern river and the varied topography within the narrowest (< 100 m wide) portions of the canyon may result in contour lines being inaccurately located on 7.5 minute 1:24,000 scale topographic maps. The horizontal accuracy of the long profile ranges from ± 20–50 m due to the scale and quality of topographic maps displayed in ArcMap.

CHAPTER III

DATA/RESULTS

Seven intra-canyon lava flows spanning approximately 2 million years in age were identified (Fig. 4; Plate 1; Table 1). Figure 4 shows the relative positions of the lava flows to each other. Plate 1 and Table 1 summarize the sources and extents of the

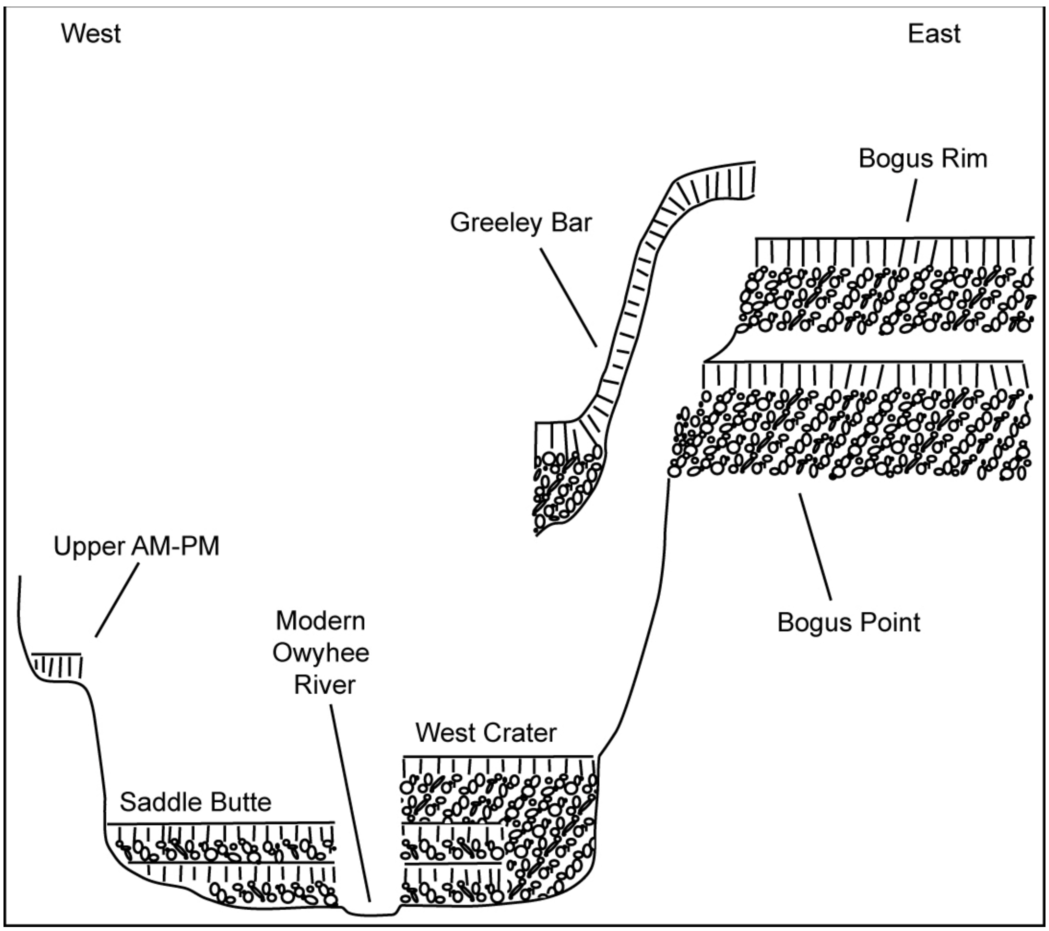

Figure 4. Schematic cartoon illustrating the relative positions of intra-canyon lava flows in the study reach. Short vertical lines represent columnar jointing in the lava flows and dipping beds of pillow lavas and hyaloclastite are indicated by aligned ellipses. Extensive deposits of pillow lavas and hyaloclastite underlie the subaerial portions of all the lava flows at one or more locations except the Upper AM-PM lava. The Greeley Bar Lava is not in contact with any other intra-canyon lava and so only the relative elevation is depicted. Figure is not to scale.

TABLE 1. SUMMARY OF CHRONOLGOCIAL DATA FOR SELECTED LAVA FLOWS ALONG THE OWYHEE RIVER AND NEARBY UPLANDS FROM ROME, OREGON, TO BIRCH CREEK

Vent location	Chronology data			Minimum distance of river influenced (km)
	Age	Method	Source	
Rocky Butte Lava Flow				
Lava Butte/Rocky Butte	0.03 Ma (max)	K-Ar	Hart and Mertzman, 1983	N.D.
West Crater Lava Flow				
West Crater	61 ± 23 ka	$^{40}Ar/^{39}Ar$	Bondre, 2006	12
	86 ± 33 ka	$^{40}Ar/^{39}Ar$	Bondre, 2006	
	88 ± 4 ka	$^{3}He_{c}$ on strath terrace†	This study	
	68 ± 3 ka	$^{3}He_{c}$ on strath terrace†	This study	
Saddle Butte Lava Field				
Sheepshead Mountains	> West Crater	Field relations	This study	12
Clarks Butte Lava Flow				
Clarks Butte satellite vent	0.25 ± 0.05 Ma	K-Ar	Hart and Mertzman, 1983	N.D.
Upper AM-PM lavas				
Clarks Butte satellite vent?	> West Crater, < Greeley Bar	Field relations	This study	26.5
Greeley Bar Lavas				
Hill 4737	> Upper AM-PM, > 250 ka?	Field relations, morphology	This study	12
Bogus Rim Lava				
Bogus Bench vents	~1.92 ± 0.22 Ma	Bondre, $^{40}Ar/^{39}Ar$	Bondre, 2006	15
Bogus Point Lava				
Owyhee Butte?	> Bogus Rim	Field relations	This study	11

Note: N.D.—no data. A question mark indicates uncertainty.
†Provides a minimum age for the lava flow.

lava flows, the ages of the lava flows, and the number of river kilometers influenced by the lava flows.

Attempts to use petrography to correlate isolated lava outcrops proved difficult because the mineral assemblages for the West Crater, Rocky Butte, and Clarks Butte flows were similar. The brief hand sample descriptions listed in Appendix A illustrate the homogenous mineral assemblages of the younger lava flows and the weathered minerals of the older flows. Lava flows were ultimately distinguished from each other by a combination of methods, including hand sample mineralogy, surface morphology, geomorphic position in the canyon, stratigraphy, geochemical data, and paleomagnetic data.

Plate 1 shows that the Bogus Point and Bogus Rim lava flows form an expansive upland that creates much of the modern canyon rim. The Bogus Point lava is not well displayed on the map because it is usually only exposed in vertical outcrops in the canyon rim. The Bogus Rim lava flow is mantled with soil and fluvial deposits in most locations (Ferns et al., 1993). Both the Bogus Point and Bogus Rim lava flows are cut by large landslides (Plate 1). The Greeley Bar lava outcrops intermittently above the modern river in the northeastern part of the study area. The lava outcrops as cliffs above the modern river and likely erupted from hill 4737. The Upper AM-PM lava, first recognized near the AM-PM river camp, exists only as small, isolated outcrops tens of meters in extent very near the modern river. The Clarks Butte lava and Rocky Butte lava occur in the southeastern portion of the study area. While these two lava flows are not intra-canyon flows themselves, the Clarks Butte lava could be the source of the

Upper AM-PM lavas. The Saddle Butte lava outcrops in the southwestern portion of the study area and entered the Owyhee Canyon via both the Granite Creek and Ryegrass Creek tributary valleys. The West Crater lava erupted from West Crater and flowed down Bogus Creek into the Owyhee Canyon.

Field relations where the Rocky Butte lava flow approached the Clarks Butte and West Crater flows are difficult to determine due to the presence of Quaternary playa deposits separating the Rocky Butte and West Crater flows (Plate 1). It is clear though that the Rocky Butte lava flow is younger than the Clarks Butte lava flow based on less soil development on the Rocky Butte lava flow and radiometric ages (Table 1). Because the contact between the Rocky Butte and West Crater lava flows is not visible, the possibility remains that an older Rocky Butte lava flow underlies the West Crater lava flow and entered the Owyhee River Canyon via the Bogus Creek Canyon in the same manner as the West Crater lava flow. However, radiometric ages displayed in Table 1 show that the Rocky Butte lava flow is younger than the West Crater. Field relations do show that the West Crater lava overlies the Clarks Butte lava east of Bogus Lake in the Bogus Creek drainage. No evidence of the Clarks Butte lava exists downstream in the Bogus Creek drainage but the possibility also remains that this lava flow made it down to the Owyhee River too and is simply covered by the younger West Crater and Rocky Butte flows.

Once initial mapping of the lava flows and fluvial deposits was complete, geochemical and paleomagnetic studies and cosmogenic exposure dating were employed to correlate and date the lava flows and isolated lava outcrops. Plots depicting 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 are shown in Figures 5 and 6. Plots showing the concentrations of La, Nb, Rb, Sr, Ba, and Zr for each lava flow are shown in Figures 7–9. The results from study of the natural remanent magnetization of the lava flows are displayed in Figure 10. Results from cosmogenic exposure dating and estimates of mean incision are shown in Table 2.

Once the affinity of isolated lava outcrops was established, a river long profile was completed (Fig. 11). Figure 11 shows the position of the Greeley Bar, Upper AM-PM, Saddle Butte, and West Crater lava flows and the position of terraces relative to the modern river. The Greeley Bar lava outcrops high above the modern river and is over 100 m thick at its upstream end. Small remnants of the Upper AM-PM lava consistently outcrop 40–50 m above the modern river for over 26 km (Table 1; Fig. 11). In contrast, the heights and thicknesses of the Saddle Butte and West Crater lava flows are much more variable in outcrops along the modern river. Figure 11 also shows that terraces exist at several different heights and locations between river kilometers 40–50.

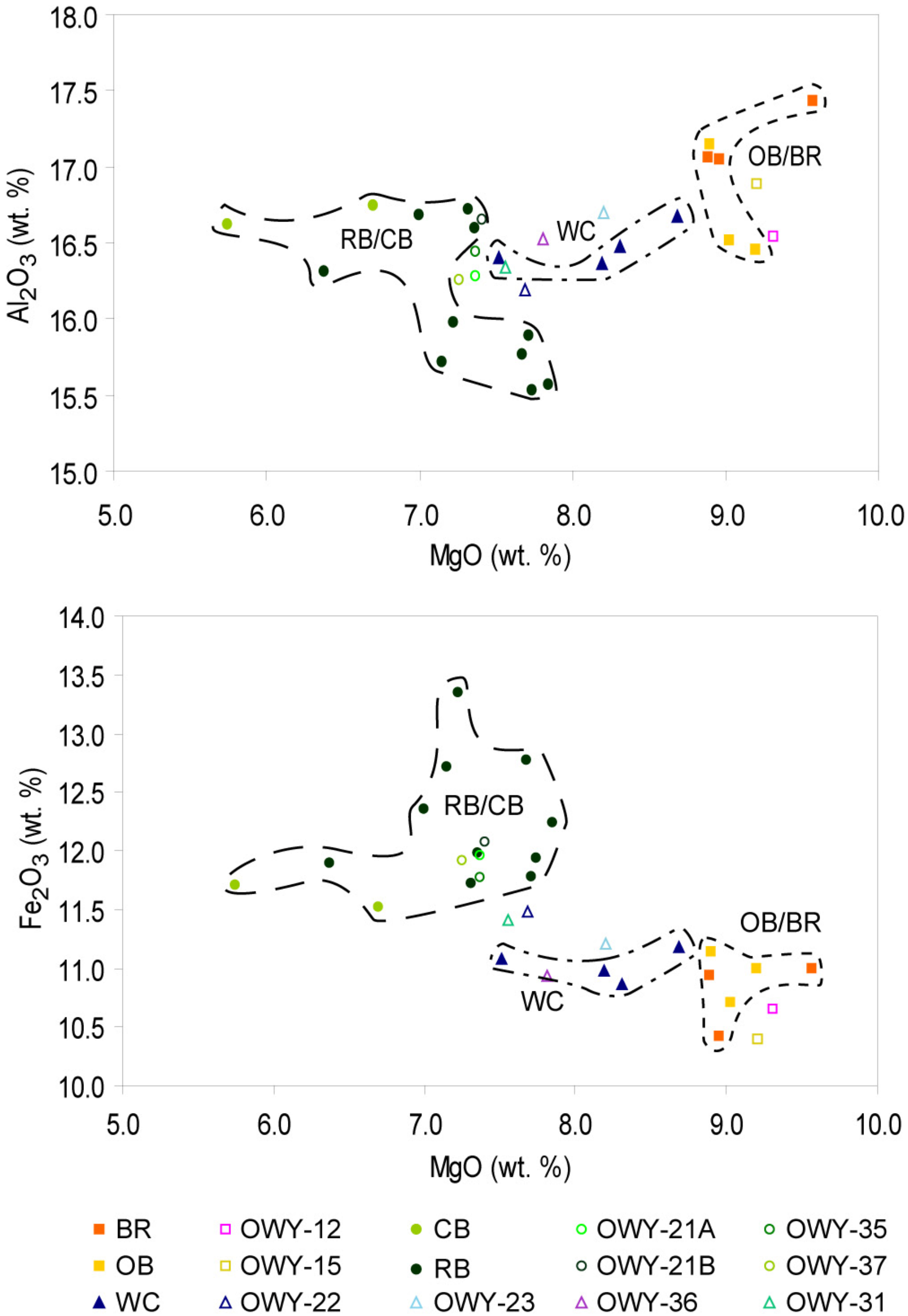

Figure 5. Plots of Al_2O_3 versus MgO and Fe_2O_3 versus MgO. Fields delineated by dashed lines represent the variable geochemical signature of the Rocky Butte (RB) and Clarks Butte (CB), Owyhee Butte (OB) and Bogus Rim (BR), and West Crater (WC) lava flows. Open symbols represent analyses from samples collected for this study and filled symbols are analyses produced from samples collected by Bondre (2006). Fields were defined using only the data from Bondre (2006). All analyses are tabulated in Bondre (2006).

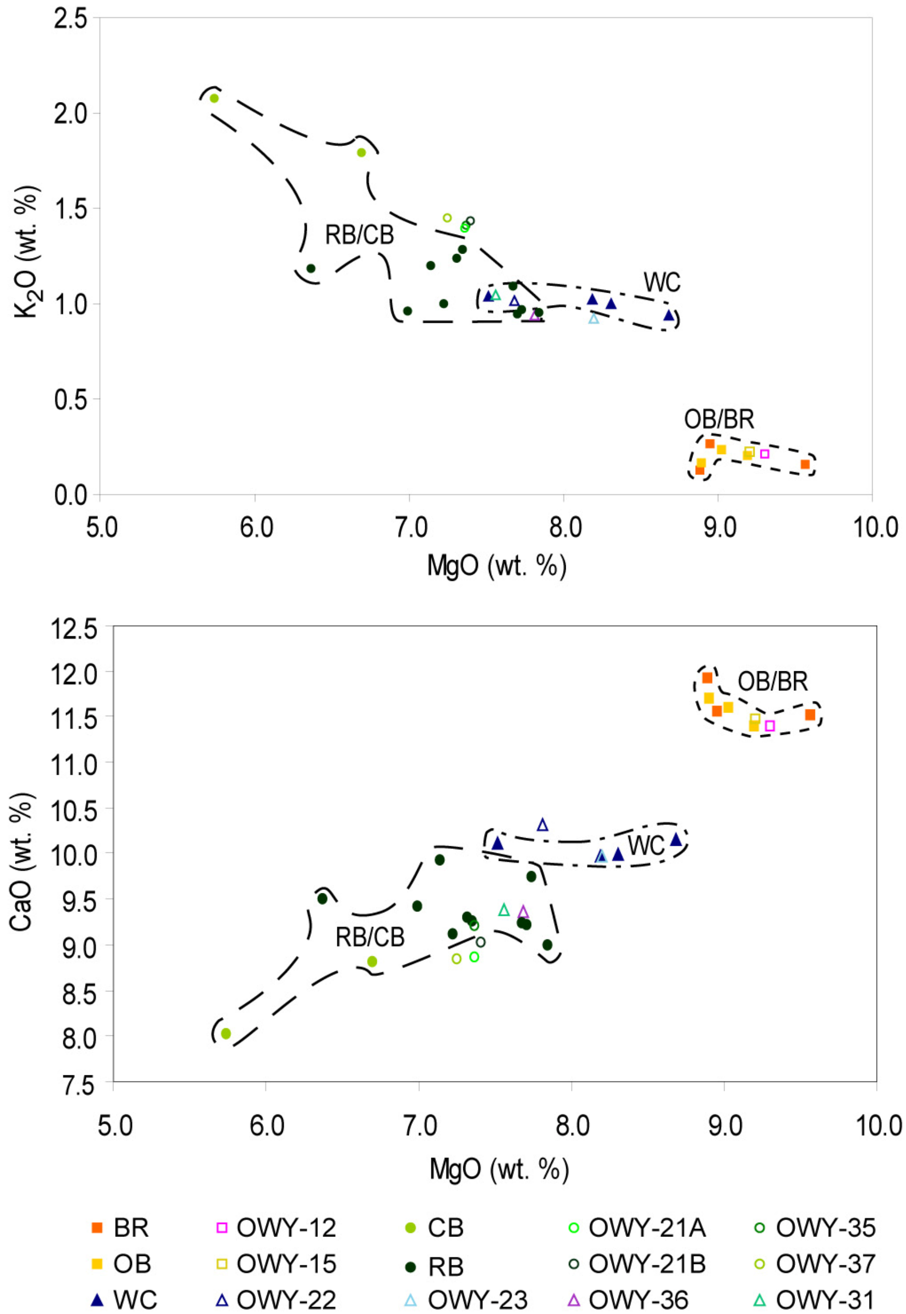

Figure 6. Plots of K_2O versus MgO and CaO versus MgO. Fields delineated by dashed lines represent the variable geochemical signature of the Rocky Butte (RB) and Clarks Butte (CB), Owyhee Butte (OB) and Bogus Rim (BR), and West Crater (WC) lava flows. Open symbols represent analyses from samples collected for this study and filled symbols are analyses produced from samples collected by Bondre (2006). Fields were defined using only the data from Bondre (2006). All analyses are tabulated in Bondre (2006).

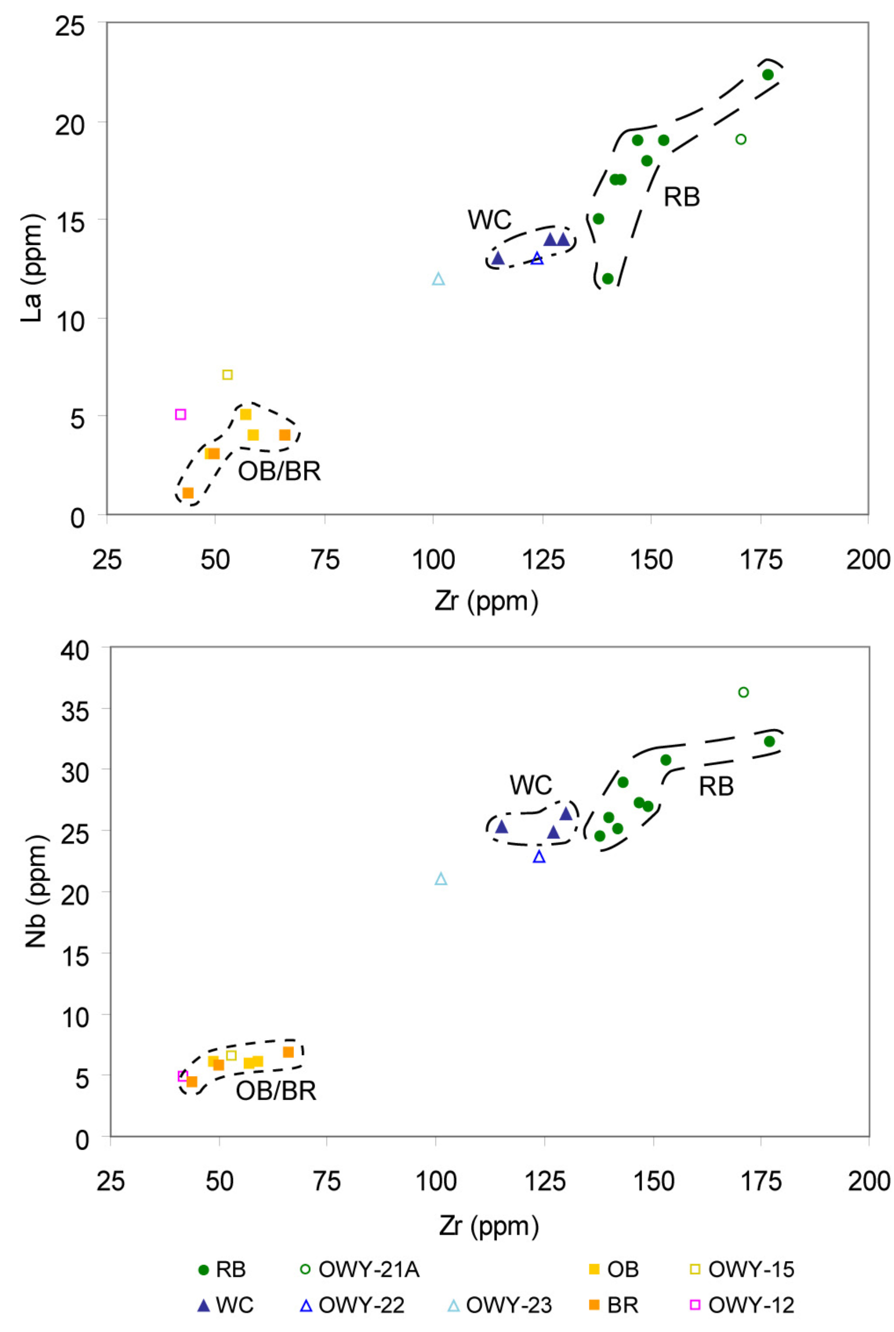

Figure 7. Plots of La versus Zr and Nb versus Zr. Fields delineated by dashed lines represent the variable geochemical signature of the Rocky Butte (RB) and Clarks Butte (CB), Owyhee Butte (OB) and Bogus Rim (BR), and West Crater (WC) lava flows. Open symbols represent analyses from samples collected for this study and filled symbols are analyses produced from samples collected by Bondre (2006). Fields were defined using only the data from Bondre (2006). All analyses are tabulated in Bondre (2006).

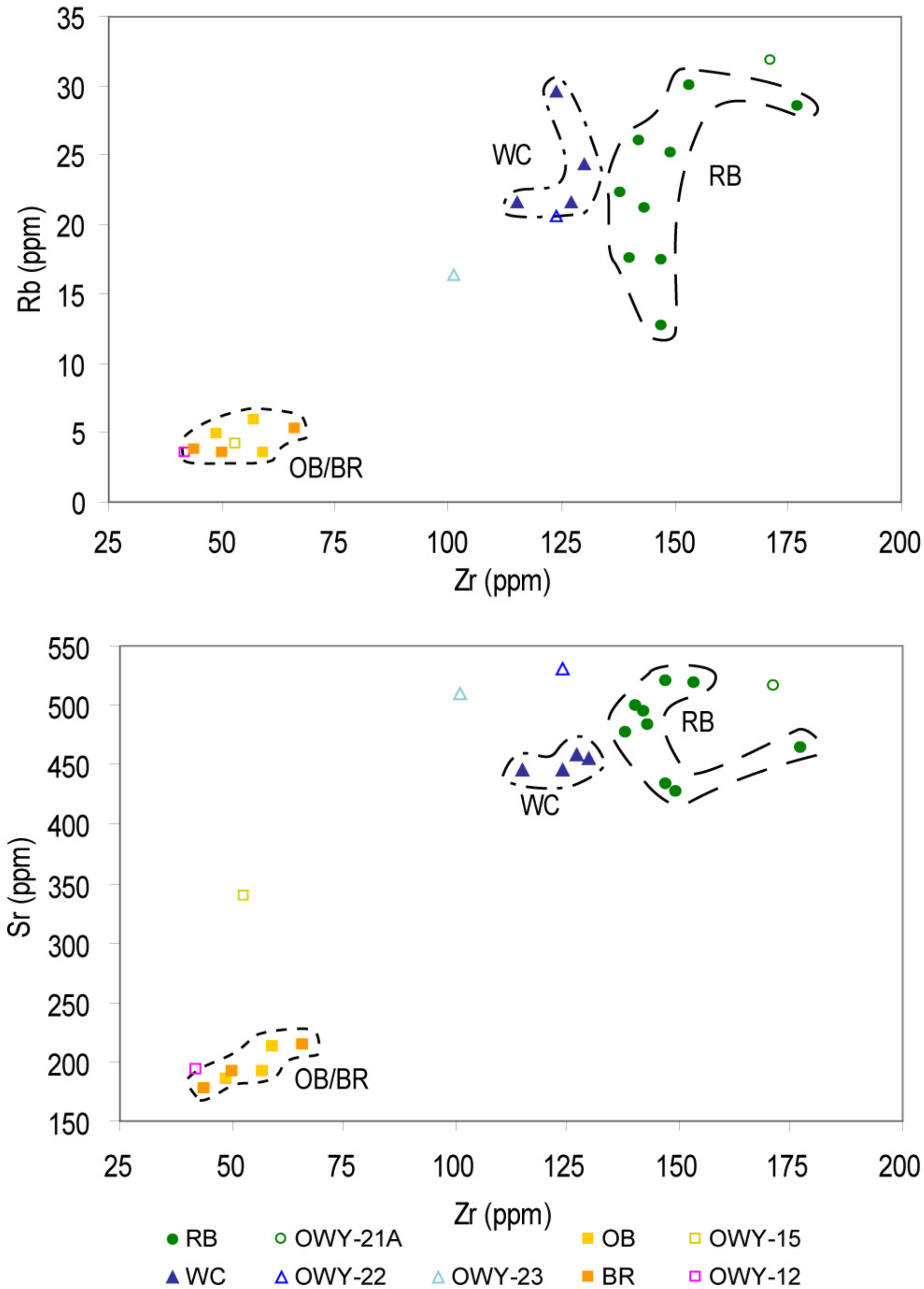

Figure 8. Plots of Rb versus Zr and Sr versus Zr. Fields delineated by dashed lines represent the variable geochemical signature of the Rocky Butte (RB) and Clarks Butte (CB), Owyhee Butte (OB) and Bogus Rim (BR), and West Crater (WC) lava flows. Open symbols represent analyses from samples collected for this study and filled symbols are analyses produced from samples collected by Bondre (2006). Fields were defined using only the data from Bondre (2006). All analyses are tabulated in Bondre (2006).

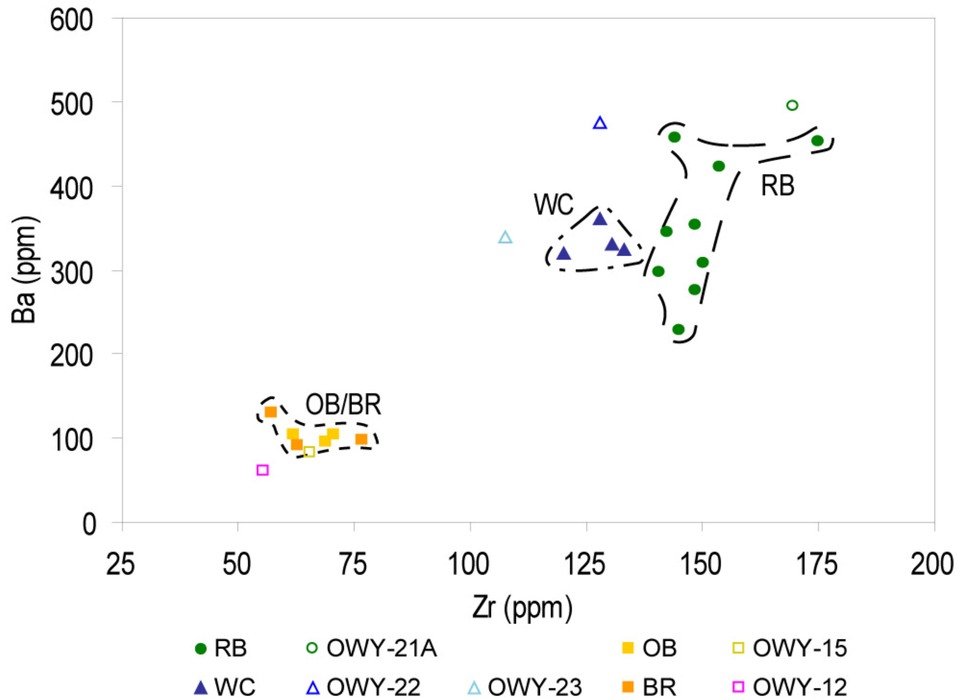

Figure 9. Plot of Ba versus Zr. Fields delineated by dashed lines represent the variable geochemical signature of the Rocky Butte (RB) and Clarks Butte (CB), Owyhee Butte (OB) and Bogus Rim (BR), and West Crater (WC) lava flows. Open symbols represent analyses from samples collected for this study and filled symbols are analyses produced from samples collected by Bondre (2006). Fields were defined using only the data from Bondre (2006). All analyses are tabulated in Bondre (2006).

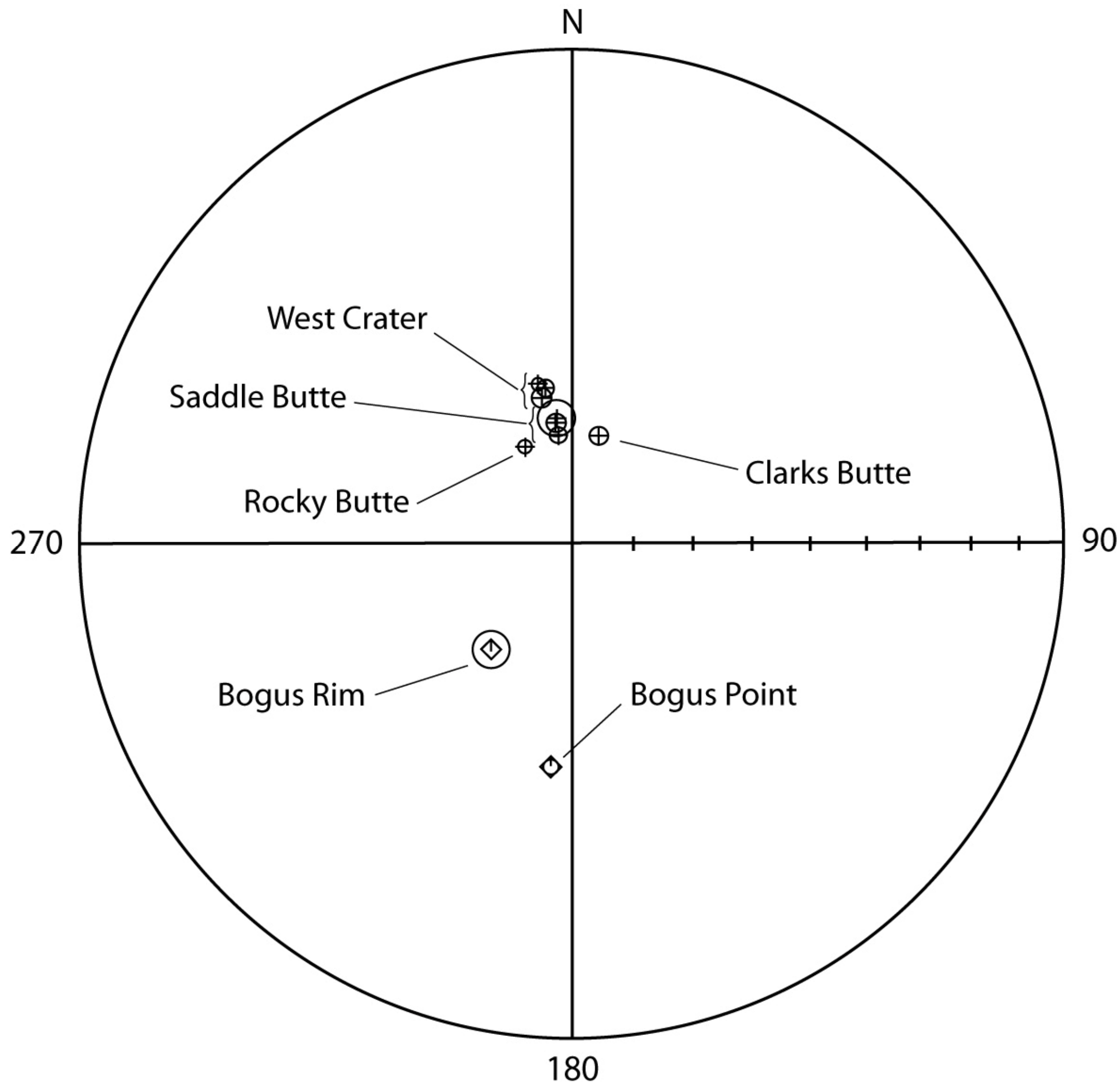

Figure 10. Equal-area diagram of mean directions of remanent magnetization for lava flows near and within the Owyhee River canyon. Directions of magnetization are depicted by the declination east from true north and the inclination (with positive being downwards) from the horizontal (Butler, 1992; McElhinny, 1973). The directions are represented by vectors at the center of a sphere and the location where the vector intersects the sphere is plotted as a point. The sphere is then projected onto the horizontal plane. Three samples each were collected from the West Crater and Saddle Butte lava flows. Samples with large uncertainty were affected by lightning. Data are tabulated in Appendix C.

TABLE 2. ^{3}He COSMOGENIC SURFACE EXPOSURE AGES AND ESTIMATES OF MEAN INCISION

Feature sampled	Sample number	$^{3}He_{c}$ exposure age		Height[‡] (m)	Incision rate[§] (mm/yr)
		Age (ka)	Error (ka)		
West Crater Lava Flow					
Landslide block or landslide covered lava flow	042904-34	37	2	N.A.	N.A.
Intact (?) lava flow but on T5 surface	042904-18	118	6	49.1	0.42
T5 Dogleg bar surface				49.1	1.3
Boulder	042904-20	41			
Boulder	042904-21	38			
Boulder	042904-22	36			
Average		38	3		
T4 Dogleg bar surface				38.6	1.1
Boulder	042904-23	37			
Boulder	042904-24	33			
Average		35	2		
T3 Dogleg bar surface				13.8	0.94
Boulder	042904-26	17			
Boulder	042904-27	15			
Boulder	042904-29	12			
Average		15	1		
T2 Dogleg bar surface				7.30	0.66
Boulder	042904-30	11			
Boulder	042904-31	11			
Boulder	042904-32	11			
Average		11	1		
T1 Dogleg bar surface				4.20	0.28
Boulder	043004-35[†]	78			
Boulder	043004-36	12			
Boulder	043004-38	19			
Average		15	1		
Airplane Point					
Polished basalt surface	090506-17	74	4	25.0	0.34
Polished basalt surface	090506-18	68	3	23.3	0.34
Polished basalt surface	090506-21	88	4	23.3	0.27

Note: N.A.—not applicable.

[†]Sample 043004-35 is interpreted to show previous exposure and so was not included in calculations. T1 may not be a terrace but a flood bar that is active at high water levels and contains boulders reworked from higher terraces.

[‡]Height above water surface on April 4, 2004.

[§]Preliminary estimate of mean incision from that surface to water surface on April 4, 2004.

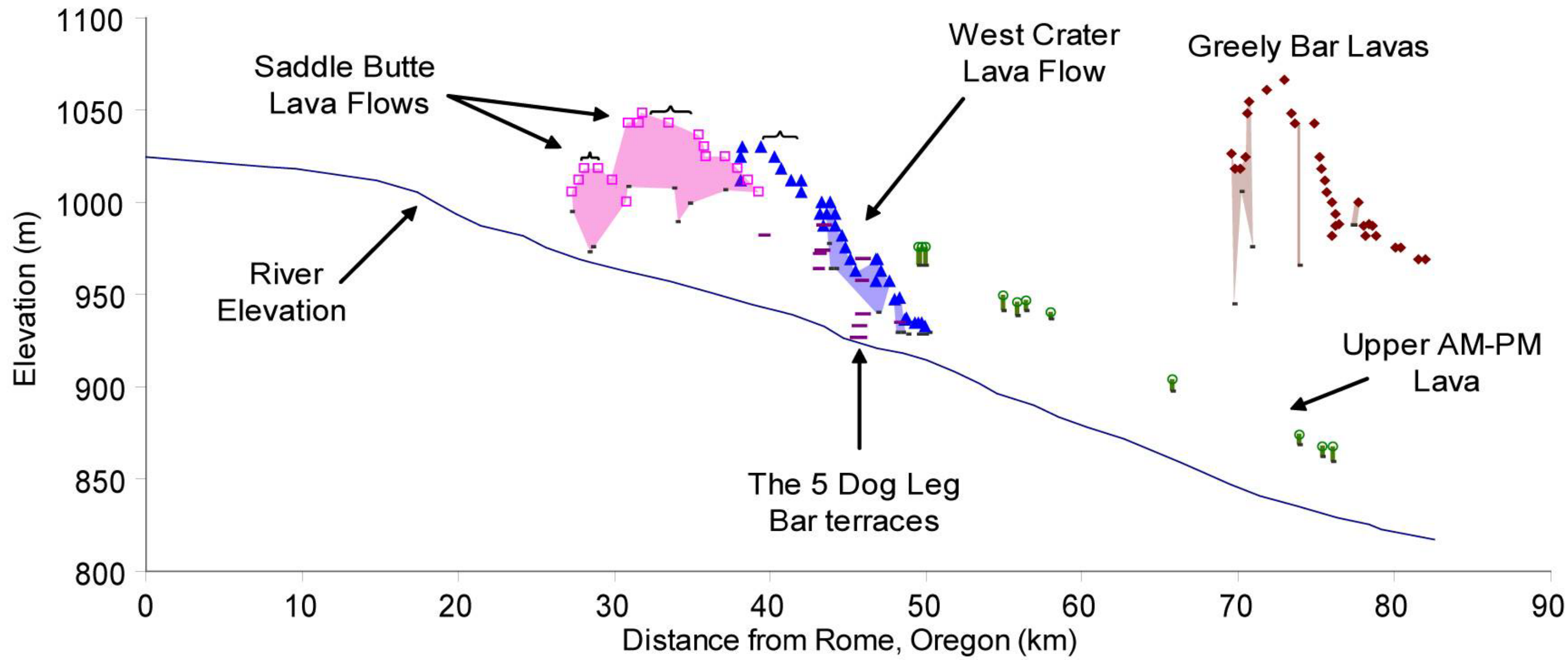

Figure 11. Long profile of Owyhee River from Rome to Birch Creek. The first advance of the Saddle Butte lavas (down Granite Creek) is the lower group of open rectangles and the second advance (down Ryegrass Creek) are the upper open rectangles. The solid triangles are West Crater lava. The green circles are the Upper AM-PM lavas. The brown diamonds are the Greely Bar lavas. Terraces are purple lines. The short black lines are the bases of the lava flows where the flows contact underlying units or, more commonly, where the lava flows are buried by their own talus. The blue line is the elevation of the modern river. Brackets indicate the initial location of damming of the river by the lava flows.

CHAPTER IV

DISCUSSION

This chapter begins with the description of the lava flows in chronological order from oldest to youngest. Then, the results of the geochemical analyses and paleomagnetic studies are discussed. Next, the dams created by the lava flows are discussed. Finally, the history of the Owyhee River is interpreted based on the location of intra-canyon lava flows, the construction of lava dams, and the rates of river incision around and through the dams.

Descriptions of Intra-Canyon Lava Flows

Bogus Point and Bogus Rim Lava Flows

Stratigraphic relations show that the Bogus Point and Bogus Rim lava flows are older than the Saddle Butte and West Crater lava flows. The Bogus Point and Bogus Rim lava flows define the rim of an older, outer canyon into which the Saddle Butte and West Crater lavas flowed (Plate 1; Fig. 4). The Bogus Point lava is only exposed in vertical outcrops in the eastern wall of the Owyhee Canyon (Plate 1; Fig. 4), and because it underlies the Bogus Rim lava, its aerial extent cannot be accurately determined. Only select outcrops were displayed on Plate 1, but the Bogus Point lava is continuous on the east rim of the canyon from river kilometer 38 upstream to at least river kilometer 32. The source of the Bogus Point lava is unknown but could be Owyhee Butte because the geochemical signature of sample OWY-15 shows an affinity to the geochemical signature of Owyhee Butte (Figs. 5–9). Owyhee Butte was dated at

1.86 ± 0.23 Ma (Bondre, 2006). The Bogus Rim lava likely erupted from vents on Bogus Bench, which were dated to 1.92 ± 0.22 Ma (Bondre, 2006).

Greeley Bar Lava Flows

The Greeley Bar lava flows (Plate 1; Fig. 4) were not extensively studied, and their absolute age is unknown. The age and field relations of these outcrops to the other lava flows are difficult to determine due to extensive overlying Quaternary deposits, erosion by minor streams, and the fact the flow is not in contact with any other intra-canyon lava flow. The Greeley Bar lava flows could be distal portions of the Bogus Rim lava flows based only on elevation but this is unlikely for reasons discussed below. The Greeley Bar lava does appear to be older than the West Crater, Rocky Butte, Clarks Butte, and Saddle Butte lava flows based on morphology and geomorphic position.

Previous mapping by Plumley (1986) grouped all the lava flows that outcrop on the uplands surrounding Deer Butte (Plate 1) above approximately the 3400 ft (1036 m) elevation contour. Plumley (1986) explained that lava flows from the uplands appeared to enter the Owyhee River via lava cascades at Deer Park and lava cascades to the west of Deer Park. He also noted that some that some lava flows on the upland erupted from Deer Butte but did not indicate the extent of these flows. The subtle and enigmatic topography of the uplands surrounding Deer Butte and hill 4737 is difficult to interpret but reconnaissance mapping with aerial photographs viewed in stereo and topographic maps suggest that the Greeley Bar lava may have erupted from hill 4737, flowed northward across the already emplaced Deer Butte lava, and entered the canyon (Plate 1). Aerial photographs viewed in stereo show complex topography surrounding Deer

Butte and hill 4737 indicative of weathered lava gutters, distributary tubes, and lava flow fronts emanating from several different topographic highs. Lava flows from several different source vents likely exist in this area and additional field work is needed to determine the extent and number of flows.

Upper AM-PM Lava

The Upper AM-PM lava was recognized based on its distinctive hand sample mineralogy, Rocky Butte-type chemical composition (see discussion of Geochemical Correlation of Isolated Lava Outcrops to Lava Flows below), and consistent outcrop thickness and elevation above the river (Fig. 11). The upstream-most outcrops appear on river left just upstream of the AM-PM camp near Whistling Bird Rapid (river kilometer 49). At this site, the Upper AM-PM lavas form a ledge 400 m long and approximately 10 m high (Plate 1; Fig. 12). The Hoot Owl Spring drainage divides the outcrop into two portions. At this location, the lava overlies approximately 1 m of unweathered fluvial gravels, which in turn overlie a fluted and polished rhyolite surface. At the contact between the lava and cobbles, the very bottom of the lava flow has been chilled by water and a few lava pillows exist. The presence of water at the time of lava flow emplacement was minimal; there are no thick accumulations (> 0.5 m) of lava pillows, nor any significant hyaloclastite deposits. These outcrops support the interpretation that the Upper AM-PM lava was emplaced in a recently active river channel and the outcrops record a time in the past when the Owyhee River was a higher elevation than the modern river but at a very similar slope to the modern river (Fig. 11).

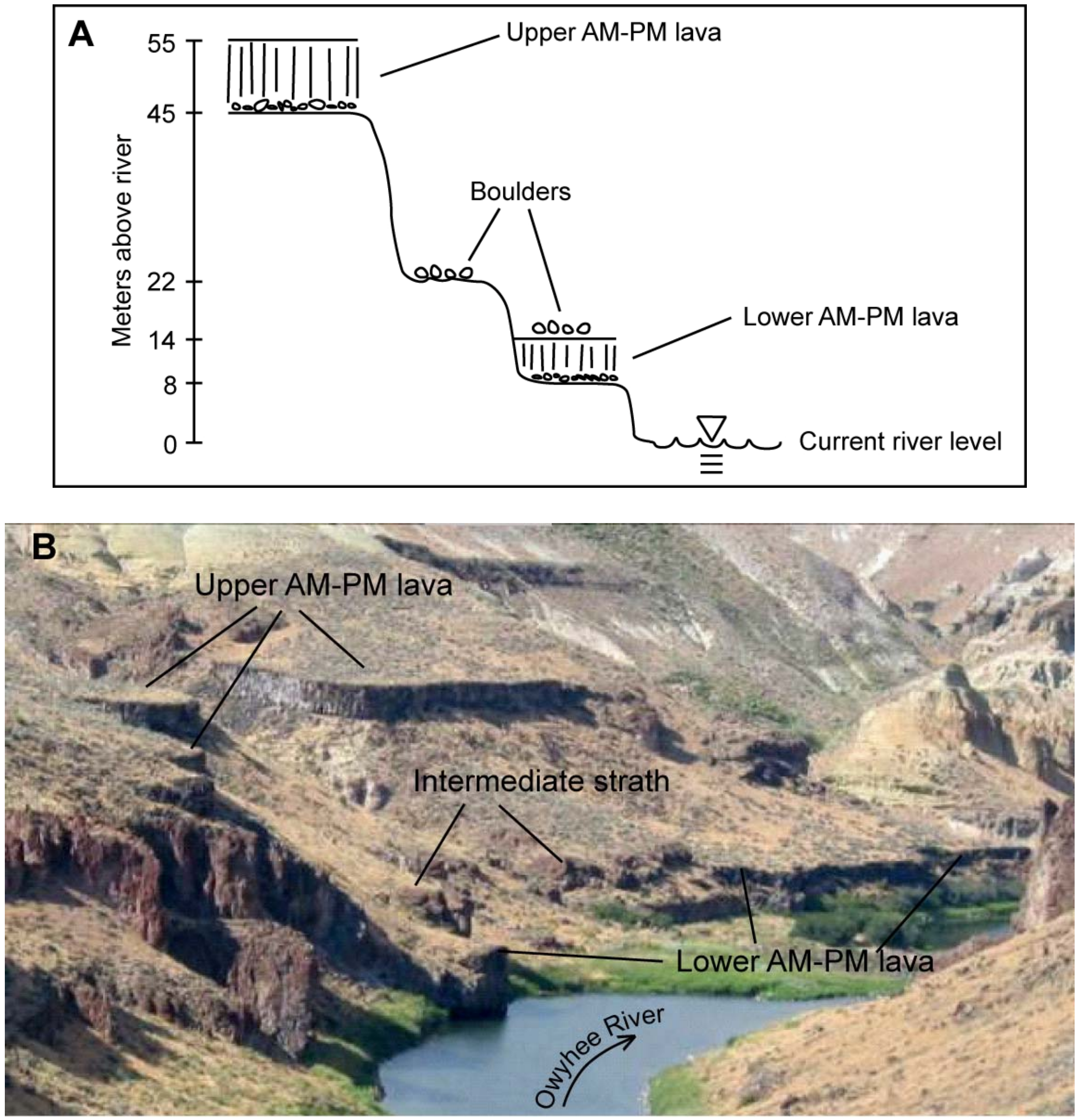

Figure 12. Sketch and photograph of outcrop relations at Whistling Bird rapid, river left at river kilometer 49.25. (A) Sketch (not to horizontal scale) of outcrop relations. The lower AM-PM lava sits on cobbles and gravels that rest on a rhyolite strath surface. Boulders sit on the lower AM-PM lava and the intermediate strath. The Upper AM-PM lava overlies 0.5–1 m of gravel, cobbles, and boulders that rest on a strath surface of polished rhyolite. (B) Photograph of outcrop relations at Whistling Bird rapid, river left at river kilometer 49.25. The drainage headed by Hoot Owl Springs splits the outcrops and has deposited a large debris fan in the river.

Isolated outcrops of the Upper AM-PM lavas occur at a remarkably similar elevation above the river for 26.5 km downstream (Plate 1; Fig. 11). None of these outcrops is thicker than the outcrops at Whistling Bird rapid. All are about 10 m or less thick.

The outcrops at Whistling Bird rapid are significant because two different lava flows occur at different elevations in the same location: the Upper AM-PM lavas and a lower set of lavas (Fig. 12). The hand sample mineralogy and chemistry of the lower lava outcrops are distinct from the Upper AM-PM lava. The geochemical data (sample OWY-36 in Figs. 5–9) and geomorphic position of the lower lava outcrops (Figs. 11–12) appear to match that of the West Crater lava described below. The best explanation for the age relations between the Upper AM-PM lavas and the lower lavas is that the lower lavas are younger. Samples from both the Upper AM-PM lava and the lower lava outcrops at Whistling Bird rapid were collected for $^{40}Ar/^{39}Ar$ dating. Samples were submitted for analysis and results are pending.

Note that no outcrops of Clarks Butte lava were conclusively identified in the Owyhee canyon (Plate 1), but the possibility exists that flows from Clarks Butte reached the Owyhee River via the Bogus Creek canyon. Clarks Butte flows did flow down the upper Bogus Creek drainage, but are buried by the younger West Crater flows east of Bogus Lake. Major and trace element data (Figs. 5–9) show that the Upper AM-PM lavas may be isolated erosional remnants of the Clarks Butte lava flow. (See discussion of Geochemical Correlation of Isolated Lava Outcrops to Lava Flows below.)

Saddle Butte Lava

The Saddle Butte Lava Field is extensive; the source vents lie ~30 km to the southwest of where the lava flows entered the Owyhee Canyon. The Saddle Butte lava first entered the Owyhee Canyon via Granite Creek, flowed upstream for nearly 1 km, and also flowed down the Owyhee Canyon for at least 3 km from this entry point (Plate 1). Further downstream, a second advance of Saddle Butte lava entered the canyon via Ryegrass Creek and flowed over the first advance. The second advance outcrops for at least 9 km along the modern river (Plate 1). These lava flows likely continue down-canyon but are obscured by the younger West Crater lava flow just downstream of Ryegrass Hot Spring near river kilometer 39.

The Saddle Butte lava is likely younger than the Upper AM-PM lava but the Saddle Butte is certainly older than the West Crater lava (discussed below). The Saddle Butte lava is younger than the Upper AM-PM lava because the Saddle Butte lava was deposited closer to the elevation of the modern river. Outcrops between river kilometers 27.25 to 31 show the base of the Saddle Butte lava sits within approximately 5 m of the modern river. In contrast, the base of the Upper AM-PM lava is always approximately 20 to 45 m above the modern river. The Upper AM-PM lava was deposited within the active river channel at the time of its emplacement because rounded boulders, cobbles, and gravel underlie the lava (Fig. 12) and so record a time in the past when the river was at a higher elevation than today. The Saddle Butte lava is older than the West Crater lava flow based on surface weathering, soil development, and stratigraphy (discussed below).

West Crater Lava Flow

The West Crater lava flow erupted from West Crater, about 13 km east of the modern Owyhee River (Plate 1). Lava flowed down the Bogus Creek Canyon and entered the Owyhee Canyon just downstream of Ryegrass Hot Springs (river kilometer 38) to create the spectacular Lambert Rocks area. Cosmogenic surface exposure ages (Table 2) of strath terraces at Airplane Point (river kilometer 47.75; Fig. 13) provide a minimum age for the West Crater lava flow. The lava flow must be older than the age of the erosional surfaces dated at 68 ± 3 ka, 74 ± 4 ka, and 88 ± 4 ka (Table 2). Preliminary results of cosmogenic exposure dating of the West Crater lava flow at Dog Leg Bar indicate the lava flow is between 40–120 ka (Table 2). However, these data require

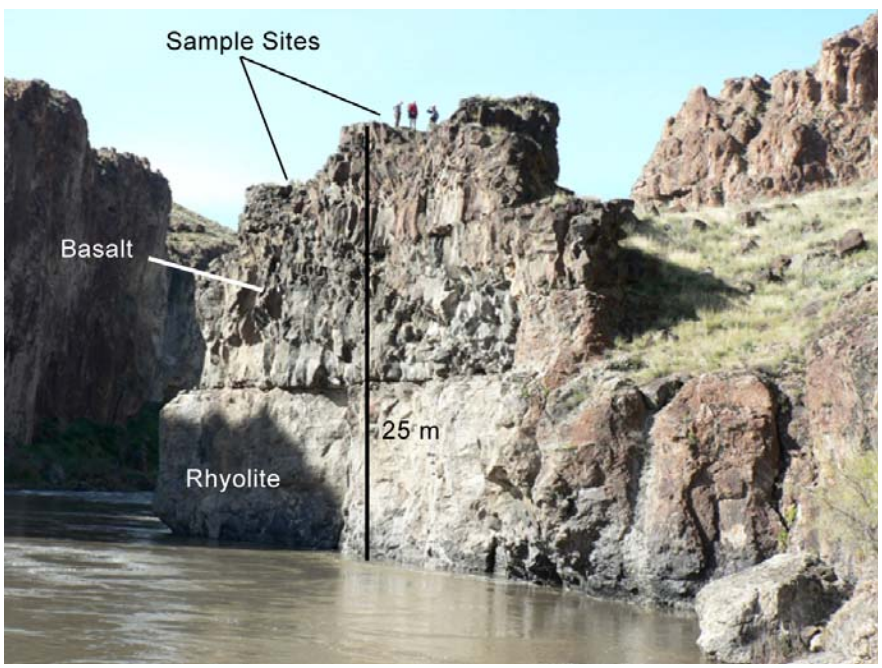

Figure 13. Photograph of Airplane Point near river kilometer 47.75. View is looking downstream on right bank. The basalt sitting on the strath surface is most probably West Crater lava based on hand sample mineralogy and geomorphic position. Cosmogenic sample sites were river polished basalt surfaces on the top of the basalt. Note the three people for scale. Photograph courtesy Gordon Grant (2006).

additional field work to interpret accurately because of the complicated relations between paleochannels, strath terraces, and landslides in this area that may have eroded or buried sample sites some time in the past. Dates for the West Crater flow and vent (86 ± 33 ka and 61 ± 23 ka, respectively; Bondre, 2006) may indicate that the West Crater flow is not much older than the Airplane Point surfaces and therefore, the river began eroding the Airplane Point surfaces soon after the lava flow was emplaced.

The West Crater lava flow is exposed nearly continuously along the river for 9 km from its upstream-most occurrence across the river from Ryegrass Hot Springs (river kilometer 38) downstream to near river kilometer 47.5 (Plate 1; Fig. 11). Figure 11 shows that the elevation of the surface of the West Crater lava flow declines much more rapidly than that of the Saddle Butte. This is not due to erosion because the original emplacement surface of the West Crater lava flow is preserved for 9.5 km until Airplane Point (Fig. 13; river kilometer 47.75) where the river clearly has stripped off the top of the lava flow. Landslides mobilized large portions of the western margin of the West Crater lava flow along river kilometers 39.5–45, and these features were not mapped. Several more isolated outcrops that appear to be West Crater lava based on geomorphic position and hand sample mineralogy exist from Airplane Point/Potter's Cave (Fig. 13) (river kilometer 47.75) downstream to Whistling Bird Rapid/AM-PM camp (river kilometer ~49.75). These outcrops have been heavily eroded by the river, but fluted and sculpted surfaces in the basalt remain (Fig. 13). At Airplane Point, the West Crater lava sits on a well developed strath terrace cut into rhyolite 8.5 m above river level (Fig. 13). Outcrops of West Crater lava at Whistling Bird Rapid on river left are ~8 m above river level and have subrounded to rounded cobbles and boulders underlying and overlying them (Fig. 12). These lavas would have flowed down the river bed after the river had eroded away most of the Upper AM-PM lavas, cut the rhyolite strath at 22 m above current water surface, and incised down to ~8 m above its current position. Samples from boulders on top of the outcrops were collected for cosmogenic exposure dating but results are not yet available. An outcrop of lava immediately below Whistling Bird rapid on river right is strikingly similar to outcrops on river left. Here, a strath surface 8.4 m above the river is overlain by ≤ 1.5 m of well imbricated cobbles, 3 m of basalt, and approximately 1 m of rounded cobbles. Based on geomorphic and mineralogic evidence, this is the downstream-most outcrop of West Crater.

Geochemical Correlation of Isolated Lava Outcrops to Lava Flows

The geochemical data were not particularly useful for conclusively distinguishing the lava flows from each other because some of the lava flows are chemically heterogeneous, the data are sparse, and in some cases only one sample was analyzed from a given lava flow (Figs. 5–9). For major elements, the samples from the Owyhee Butte and Bogus Rim lava flows define the most geochemically distinct field (Figs. 5–6). In contrast, the West Crater and Rocky Butte/Clarks Butte fields are more chemically heterogeneous and their fields even overlap in some cases. Despite the heterogeneity, a few tenuous correlations can be made. Major element analyses from the Saddle Butte (sample OWY-12) and Bogus Point (sample OWY-15) lava flows plot consistently near or within the Owyhee Butte/Bogus Rim field and are clearly chemic-ally distinct from the other flows.

Analyses from the Upper AM-PM lava (sample OWY-35), and samples OWY-37, OWY-21B, and OWY-21A all plot in a tight group (within 0.25 wt. % Mg of each other) within or near the Rocky Butte/Clarks Butte field for all major element plots (Figs. 5–6). These four analyses also plot closest to the Rocky Butte members of the Rocky Butte/Clarks Butte field. These four samples are so chemically homogenous that they could represent a single, unique advance of the Rocky Butte or Clarks Butte lava flow that entered the canyon (N. R., Bondre, personal communication, September 1, 2005). Data collected in the field on the elevation of the outcrops relative to the modern river suggest that these samples belong to their own lava flow distinct from the West Crater lava flow. Given that the West Crater and Rocky Butte/Clarks Butte fields overlap for some elements, samples from outcrops of the Upper AM-PM lava (OWY-35, OWY-37, OWY-21B, and OWY-21A) could be of West Crater origin but are more likely part of either the Rocky Butte or Clarks Butte lava flows. The geochemical data alone tentatively supports correlating these four samples to the Rocky Butte lava flow, but field relations put this correlation into question.

Major element analyses from samples thought to be from the West Crater flow (samples OWY-22, OWY-23, OWY-31, and OWY-36) plot within or near the West Crater field or within or near the Rocky Butte/Clarks Butte field. Sample OWY-22 and OWY-31 were collected from the base of the West Crater lava at Bogus Falls (river kilometer 43.5) and one of the upstream-most flow units of the West Crater near river kilometer 38. These two samples are interpreted to represent the earliest pulses of West Crater to enter the Owyhee Canyon. Alternatively, the two samples could represent an older lava flow (possibly Clarks Butte) that underlies the West Crater but is very similar to the chemical composition of the Rocky Butte lava flow. More data on the chemical composition of the Clarks Butte lava would help determine the affinity of samples OWY-22 and OWY-31. When all the current evidence is considered, the most logical interpretation is that the Upper AM-PM lavas are distal portions of the Clarks Butte lava flow. The Upper AM-PM lavas are high above the modern river and therefore presumably old enough to be contemporaneous with the Clarks Butte lava. In contrast, the Rocky Butte lavas are clearly very young based on morphology and ^{40}K-^{39}Ar dating (Table 1).

Despite only having five analyses, trace element data also allow for some correlation of isolated outcrops to known lava flows (Figs. 7–9). Analyses of trace elements from the Saddle Butte (sample OWY-12) and Bogus Point (sample OWY-15) lava flows plot consistently near or within the Owyhee Butte/Bogus Rim field. Two samples (OWY-22 and OWY-23) collected from suspected West Crater lava flow outcrops usually plot within or nearer the West Crater field than they do the Rocky Butte field. Sample OWY-21A was collected near river kilometer 75.25 and was suspected to be of West Crater origin. However, sample OWY-21A plots closest to the Rocky Butte field and is higher in zirconium than other samples presumed to be, or certain to be, of West Crater origin. No trace element data from the Clarks Butte lava flow were available, but this absence of data does not preclude sample OWY-21A from being of Clarks Butte origin. The trace element data only show that sample OWY-21A has some affinity to the Rocky Butte lava flow.

Paleomagnetic Studies of the Lava Flows

Paleomagnetic techniques were more successful than geochemical techniques in conclusively distinguishing the lava flows from one another. Select outcrops of known origin were sampled in an effort to characterize the directions of NRM of the lava flows. These data provide a baseline to compare with future data collected from isolated lava flow outcrops and potentially correlate these isolated outcrops to known lava flows. Directions of remanent magnetization are displayed in Figure 10.

The primary NRM of a rock can be due to thermoremanent magnetization (TRM), chemical remanent magnetization (CRM), detrital remanent magnetization (DRM), or some combination of all three (Butler, 1992; McElhinny, 1973). TRM is produced by cooling magnetic materials from above the Curie temperature (the temperature above which a material becomes paramagnetic) in the presence of a magnetic field. The formation of iron oxides at low temperature is an example of CRM and DRM results from the alignment of detrital magnetic particles in a sediment deposit. An example of a secondary NRM that develops after the primary NRM of the rock is isothermal remanent magnetization (IRM) caused by lightning strikes. Lightning produces a strong magnetizing field at a constant temperature that induces an IRM within several meters of the strike. Lightning induced IRM can be a significant problem for determining the primary NRM in areas with frequent thunderstorms (Butler, 1992).

Preliminarily, all the lava flows appear to have their own distinct directions of remanent magnetization (Fig. 10; Appendix C). The West Crater, Rocky Butte, Clarks Butte, and Saddle Butte lava flows do plot close to each other, which suggests the eruptions could have occurred within hundreds of years of age of each another (D. E., Champion, December 1, 2006, personal communication). That the West Crater and Rocky Butte lava flows plot close to one another is not surprising because they both are morphologically very young and, therefore, likely similar in age. That the Saddle Butte and Clarks Butte lava plot close to the West Crater and Rocky Butte lava flow is somewhat surprising because the Saddle Butte and Clarks Butte flows are clearly morphologically older by tens of thousands of years. However, similar directions of remanent magnetization can be attributed to the fact that secular variation is a random walk about the mean direction whose path is sometimes repeated (Butler, 1992; McElhinny, 1973). The Saddle Butte data points appear close to the West Crater points in part because one of the three Saddle Butte sample sites (690B6) was affected by lightning and has a less precise direction (and a large circle depicting this uncertainty). At the time of writing, this sample required additional analyses to precisely determine its direction. Samples 682B6 and 690B6 were collected from the first and second advances of the Saddle Butte lava, respectively. Since these samples plot on top of each other in Figure 10, the two advances of the Saddle Butte lava are likely of the same age. This allows for little time for the river to erode the first lava advance prior to the emplacement of the second lava advance. Likewise, if the three samples collected from the West Crater are characteristic of the paleomagnetic signature of the West Crater lava flow, it too was emplaced over a discrete, short interval of time.

Lava Dam Architecture and River History

In contrast to some Grand Canyon lava dams, Owyhee Canyon lava dams were long and low. The paleo-Owyhee Canyon that was filled by the Saddle Butte and West Crater lava flows was, for the most part, rather wide compared to its depth. The lava flows did not build short, discrete impoundments but rather spread out, filling the valley and are perhaps best termed canyon-filling lava flows rather than lava dams.

None of the Owyhee Canyon lava dams show evidence of being constructed over the large intervals of time needed for the river to erode and deposit fluvial sediments between flow units that make up the dams, as in the case of the dams composed of numerous thin flows and the complex dams of Hamblin (1994). Of the four types of lava dams described by Hamblin (1994) (Fig. 3), the single-flow dam and the massive dam share characteristics with Owyhee Canyon lava dams (Table 3). Single-flow lava dams in the Grand Canyon are composed of a very long, single flow 45–185 m thick. These dams were formed by rapid emplacement of 0.125–2 km^3 of lava. In contrast, massive dams are thicker (~240 m thick), shorter (< 30 km long), and contain more lava (2–5 km^3) than single-flow dams. Massive dams formed when one or more flow units of lava were emplaced much faster than the river could overtop it.

Careful attention must be paid to the terminology used to discuss the structure of the lava dams to clarify the difference between a single-flow dam and a single flow unit. Hamblin (1994) uses the terms single-flow unit, single flow, and single-flow when describing single-flow dams, and this can lead to some confusion. For example, Plate III in Hamblin (1994) appears to show that single-flow dams are constructed by one lava

TABLE 3. CHARACTERISTICS OF SELECTED LAVA DAMS

Name	Dam location	Age[†]	Length (km)	Minimum thickness (m)	Elevation of dam crest (m)	[‡]Type
West Crater	Lambert Rocks	60–90 ka	~12	36	1036	Single-flow
Saddle Butte	Granite Creek/Ryegrass Valley	> West Crater, < Upper AM-PM	> 12	73	1048	Massive/complex hybrid
Upper AM-PM	Adjacent to modern river kilometers 39–40	0.25 ± 0.05 Ma	> 26.5	10	> 969	Single-flow?
Greeley Bar	The Hole in the Ground/Greeley Bar	> Upper AM-PM	> 12	110	1054	Massive/complex hybrid

[†]Lava dams are listed in chronological order. For more complete discussion of ages see Table 1.
[‡]Terminology from Hamblin (1994) (see Fig. 3). A question mark indicates uncertainty.

flow having only one flow unit composed of a basal colonnade, entablature, and upper colonnade, but the use of the term single-flow dam does not preclude several different flow units from constructing the dam. A distinction must be made between the flow units that make up an individual lava flow and individual incursions a single lava flow can make into a river. Lava flow structure and emplacement are summarized below from Cas and Wright (1987) and Kilburn (2000). A single eruptive episode at a vent may produce several lava flows. A single lava flow can make several different incursions into the river canyon. Each individual incursion may result in several flow units (surges or advances) of the same flow being emplaced, but each incursion and each flow unit is still part of the same single lava flow. Multiple flow units within the same lava flow occur when low silica pahoehoe flows advance as a series of overlapping lobes that inflate (Kilburn, 2000). These overlapping lobes may coalesce to form one or more flow units separated in time by minutes to days. The more time that passes between flow units being emplaced, the easier the different flow units are distinguished from one another because significant cooling occurs at their tops and bottoms. These cooling breaks define the individual flow units.

In all the outcrops of upstream portions of lava dams, the amount of subaerially emplaced lava is often one third to one half the total outcrop thickness. This provides evidence for at least two scenarios at the time of damming. Scenario A is that the supply of lava to the dam site greatly exceeded the supply of water; the lava flows effectively dammed the river and were not immediately overtopped by the river. If the river had flowed over the lava dams as they formed, little subaerial lava would exist (Howard et al., 1982). Instead, the entire outcrop would be a thick section of hyaloclastite and lava pillows nearly all the way to the top of the dam overlain by only a thin subaerial lava section. Fluvial deposits such as sand, gravel, cobbles, and boulders might also be found intercalated within the dam architecture (Hamblin, 1994). Scenario B is that enough water leaked through the dam, or around it, for the lake level to stabilize below the top of the dam. The dam could grow by the addition of new lava even though the supply of river water could have exceeded the supply of lava to the growing dam. In this case, if leakage around or through the dam was comparable to the discharge of the river, extensive deposits of pillow lavas, hyaloclastite, or other chilled basalt forms should exist in downstream portions of the dam. However, extensive deposits of pillow lavas or hyaloclastite were not found downstream of the initial damming locations in any of the dams.

The Bogus Point and Bogus Rim lava flows are so obscured by younger geologic units that their interaction with the river is largely unknown. Consequently, the effectiveness of these two lava flows in damming the river is unknown. However, data collected in the field on the Greeley Bar, Upper AM-PM, Saddle Butte, and West Crater lava flows support scenario A (effective damming) more than scenario B (ineffective damming) for the dams these lava flows created. A more detailed discussion of each lava dam follows.

Bogus Point and Bogus Rim Lava Flows

The detailed effects of the Bogus Point and Bogus Rim lava flows on the river are obscured by younger geologic units. The initial locations of damming are uncertain, but the presence of pillow lavas and hyaloclastite at the base of the Bogus Rim and Bogus Point lava flows show that each lava flow entered a lake or river that was continuous for at least 10 km and at times many tens of meters deep. The Bogus Rim lava forms an expansive upland on the eastern side of the modern Owyhee Canyon that may represent a paleofloodplain or paleocanyon of the river (Plate 1). The very narrow section of the modern Owyhee Canyon from river kilometers 51 to 63 may be a result of incision following the filling of the paleocanyon by the Bogus Rim lava.

Greeley Bar Lava Dam

The Greeley Bar lava was not studied in detail, but it may have effectively dammed the river (scenario A) based on the thick sections of hyaloclastite in the upstream sections of the dam (river kilometers 70–71) and the fact that no hyaloclastite was observed in the downstream portions (river kilometers 73–81). Reconnaissance field work of the Greeley Bar lava indicates that the dam shares characteristics of both the massive and complex dam types of Hamblin (1994). Two very thick advances of lava were made into the canyon near Greeley Bar between river kilometers 70 and 71 (Plate 1; Fig. 14). Each advance contains multiple flow units of subaerial lava and a thick section of pillow lavas and hyaloclastite at its base. Apparently, enough time passed between the two advances for the river to overtop the first advance because the second advance contains a thick section of hyaloclastite indicating the lava flowed into standing water. This construction differs slightly from the massive dam of Hamblin (1994), but no fluvial deposits were recognized intercalated within the dam and the dam was not visibly eroded by the river between the first and second advances as is the case

Figure 14. Photograph of Greeley Bar lava dam near river kilometer 71. Two thick sequences of lava make up the dam. A thick section of pillow lavas and hyaloclastite exist in the upper sequence. The cliffs of lava are at least 60 m tall in this photograph. Photograph courtesy Gordon Grant (2006).

with the complex and numerous thin flow dams of Hamblin (1994) (Fig. 3). Additional field work is needed to fully understand the construction of the dam.

At the time of damming, the river elevation was approximately 944 m (3100 ft) based on limited reconnaissance of the units underlying the dam near river kilometer 70. Fluvial deposits under the base of the Greeley Bar lava flows that outcrop at an elevation of 965 m (3167 ft) were surveyed with a laser rangefinder near river kilometer 73. The elevation of the dam crest was at least 1054 m (3460 ft).

The Greeley Bar lava is notable because it may be oldest lava to fill the modern canyon. If the lava did enter the Owyhee Canyon on the eastern margin of The Hole in the Ground via lava cascades, the lava may constrain the age and location of landslides and earthflows exposed on the eastern margin of The Hole in the Ground. Additional fieldwork may reveal that the Greeley Bar lava overlies mass movement deposits, were cut by mass movement events, or both. In any of these cases, an absolute age on the lava may help date mass movement deposits in The Hole in the Ground.

Outcrops of the Greeley Bar lava show that the river was close to its present horizontal position but not present elevation at the time the lava flowed into the canyon. Outcrops of the lava exist in the modern canyon but the base of the lava sits on rounded cobbles and gravels typical of active river channels about 124 m above the modern river near river kilometer 74 (Plate 1). The base of the lava sits on similar deposits at similar elevations both above and below river kilometer 74. The elevation of the tops of these outcrops is approximately 1042 m (3420 ft) and was determined using topographic maps because the tops of the outcrops were out of the range of the laser rangefinder. If the river flowed over the tops of these outcrops at ~1042 m after the lava flow was emplaced, the river has incised approximately 200 m since the emplacement of the Greeley Bar lava.

Upper AM-PM Lava Dam

The lack of lava pillows and hyaloclastite greater than 1 m thick underlying the Upper AM-PM lava at Whistling Bird rapid (river kilometer 49.25) indicates that the Upper AM-PM lava flow probably effectively dammed the river (damming scenario A) somewhere upstream of Whistling Bird rapid. If the Upper AM-PM lava flows are a distal portion of the Clarks Butte lava flows, the lava would have entered the canyon via the Bogus Creek drainage and dammed the river somewhere to the east of river kilometers 39–41, much like the West Crater lava flow did. A thorough analysis of the dam is not possible because the exact dam location is unknown and the dam is likely buried by the West Crater lava flow. However, based on the erosional remnants remaining in what would have been the tail of the dam, the single-flow unit dam is the most likely dam type (Table 3). Only 1 or 2 flow units were recognized in the outcrops from river kilometers 49 to 76. The relatively constant thickness (4–10 m) and outcrop height of the Upper AM-PM lava flow suggests that only a few flow units were originally emplaced in the long tail of the dam. Additional field work is needed to determine whether more flow units once existed and were eroded away.

The outcrops of Upper AM-PM lava at Whistling Bird rapid are significant because two different lava flows occur at different elevations in the same location: the Upper AM-PM lavas and a lower set of lavas (Fig. 12). The vertical distance separating the two lava outcrops, the presence of a strath terrace between the lava outcrops that is not covered by a lava flow, and the fact that rounded cobbles underlie both lava flow outcrops suggest that significant time separates the emplacement of the two lava outcrops. The presence of rounded cobbles and boulders and a few lava pillows underneath the Upper AM-PM lava suggests the lava flow was emplaced on, or near, an active river channel. The river then must have occupied the surface of the lava flow and subsequently incised 33 m down to the elevation of the intermediate strath terrace. This surface has no intact basalt flow sitting on it but does host a few rounded boulders. The river then incised 14 m further to the elevation of several strath terrace remnants at 8 m above the modern river. The lower AM-PM lava, which is likely the West Crater lava flow discussed below, was then emplaced on this surface. The lower lava was overtopped by the river and the river continued incising down to its present position. Absolute ages for the Upper and lower AM-PM lavas are not yet known. Samples from each outcrop have been submitted for $^{40}Ar/^{39}Ar$ dating and results are pending. Stratigraphic position (Figs. 11–12), hand sample mineralogy (Appendix A), and geochemical data (Figs. 5–9) indicate that the Upper AM-PM lava is most likely a distal portion of the Clarks Butte lava and the lower AM-PM lava outcrops are portions of the West Crater lava flow (discussed below).

Saddle Butte Lava Dam

The preponderance of landslides along river kilometers 31–47 obscures much of the interface between the lava dams and bedrock. Often, a nearly impassable block field lies adjacent to the Saddle Butte and West Crater lava flows, limiting access to the outcrops. As a result, only a few outcrops that displayed the architecture of the lava dams at their initial damming points (i.e., Granite Creek and near Ryegrass Hot Springs) were visible.

At Granite Creek, several pieces of evidence support damming scenario A (effective river damming) for the Saddle Butte lava dam. The first advance of the lava entered the canyon via Granite Creek and appears to have dammed the river fairly successfully at that location. Downstream of the confluence of Granite Creek and the Owyhee River, the Saddle Butte lava flowed onto river cobbles, gravel, and sand at the Weeping Wall (river kilometer 28.25), but no significant deposits of pillow lavas or hyaloclastite formed. (A few lava pillows do exist near river km 30.8 in the plunge pool of the Sand Spring drainage waterfall but could be attributed to the Sand Spring drainage rewatering the river downstream of the dam.) If the dam had leaked significantly, extensive deposits of pillow lavas would have likely formed downstream. In addition, the gradient of the river and the canyon architecture at Granite Creek could have facilitated the construction of an effective dam. The narrow bedrock-confined canyon provided ready-made dam abutments and the lava only had to fill a short span of about 270 m to block the river. Furthermore, the gradient of the modern river in this reach is flat enough that even a short initial dam height of 10 m would create a reservoir stretching upstream for 2 km. While little can be said about the exact river discharge at the time of dam construction, such a reservoir might have been large enough to contain the river long enough for a ~270 m wide plug of lava to grow and effectively dam the river. Subaerial lavas and passage zones at several different heights indicate that the reservoir height did change at Granite Creek during later stages of dam construction but no fluvial deposits are intercalated within the flow units making up the dam.

The impoundment created by the second Saddle Butte advance also appears to have dammed the river effectively (damming scenario A) due to the lack of pillow lavas and hyaloclastite for 750 m downstream of hill 3563. The total dam height created by the two advances was at least 73 m. Relative to the path of the modern river, the Saddle Butte lava dam occupied over 12 km of river. The downstream-most extent is likely obscured by the younger West Crater lava flow.

As described above, each of the two advances of the Saddle Butte lava flow formed its own distinct and significant dam. However, little time apparently separated the advances because no fluvial deposits were found intercalated between the lava flows. In addition, no evidence that the first advance was eroded prior to the emplacement of the second advance was found either. Paleomagnetic studies show that the two advances of Saddle Butte lava into the canyon are indistinguishable in age (Fig. 10 and section on Paleomagnetic Studies of the Lava Flows discussed previously). So in the context of river incision, little time likely passed between the two Saddle Butte lava advances. The presence of hyaloclastite and pillow lava deposits tens of meters thick in the second advance shows there was enough time between the advances for the lava dam at Granite Creek to be overtopped by the river or for tributaries to re-water the river. This amount of time is on the order of days, months, or years but certainly not the thousands of years needed for significant fluvial erosion to occur. For these reasons, the two Saddle Butte lava advances are best treated as one dam that shares qualities of both the massive and complex dams of Hamblin (1994) (Table 3).

The area currently overlain by the Saddle Butte lava flows at the confluence of the Ryegrass Valley and the Owyhee Canyon (to the west of river kilometers 31–38) was likely a wide flood plain occupied by the Owyhee River prior to the existence of the lava. The topography under the lava flows here is difficult to interpret, but the presence of several kipukas consisting of Tertiary sediments and lava flows suggests that occasional islands of relief rose above an otherwise relatively flat plain. These kipukas, west of river kilometers 34–35, are hills that rise up to 42 m above the lava plain that completely surrounds them (Plate 1). Ryegrass Creek and the Owyhee River probably worked in concert to erode and isolate these hills from the neighboring Tertiary sediment outcrops to the west. When the second Saddle Butte lava advance entered the Owyhee Canyon via Ryegrass Creek, it confined Ryegrass Creek to the western side of the Owyhee Canyon, pushing it up against the sediments of Chalk Basin where it flows today. By filling the wide floodplain, the second advance restricted the river flow to the eastern side of the valley. The long east-west-trending kipuka, hill 3562 (Plate 1), apparently directed lava to the east where the river was initially dammed by this second advance. Upstream of hill 3562 thick sequences of hyaloclastite and subaerial lava indicate the presence of a lake, but downstream no significant exposures of hyaloclastite occur for about 750 m, suggesting that the lava flow initially advanced over a dry valley floor at this location. After damming the river east of hill 3562, the lava flow advanced upstream, into the lake it created and eventually halted at the Sand Springs drainage. Along the left bank of the Sand Springs drainage, the steep flow front of the second Saddle Butte Lava advance is almost entirely a thick section of lava pillows and hyaloclastite capped by only a few meters of subaerial basalt. The surface elevation of the lava dam here is 1042 m (3420 ft). If a lake behind the lava dam filled to this elevation, it would have occupied the area of the Sand Spring drainage and continued upstream for over 30 km to a point upstream of the town of Rome. The approximately 5 m thick deposits of sand, gravel, and rounded cobbles and boulders that exist just upstream of the Sand Springs drainage would have been deposited in the forebay of the dam (Plate 1). The presence of fluvial boulders on top of the first Saddle Butte lava advance at Granite Creek shows that the river occupied that surface at one time or another; whether it was before or after the second advance entered the canyon cannot be conclusively determined with data presently available. However, the fluvial boulders on top of the Saddle Butte lava at Granite Creek are most likely related to the incision accomplished by the river after the second Saddle Butte advance. Any boulders deposited at Granite Creek in the brief time period between the first and second advances would have been buried in the lake created by the second advance, exhumed, and then remobilized as the river cut through the dam and drained the lake.

More evidence for the fluvial overtopping of the second Saddle Butte advance comes from White Rock Creek (river kilometer 31.5) (Plate 1). Here, a lava remnant sits perched above the river in the mouth of White Rock Creek at the same elevation (3420 ft or 1042 m) as the known Saddle Butte lava to the west. The similar elevation and hand sample mineralogy of this outcrop and the known Saddle Butte lava flow suggest that this outcrop is an erosional remnant of the Saddle Butte lava flow. The surface of the perched lava outcrop is littered with fluvial boulders and cobbles of basaltic and exotic compositions, some of which were sutured together. In some places, intact pahoehoe ropes exist but in other areas, the ropes have been eroded and a smooth surface remains. White Rock Creek could be a source of some of the boulders, but many have hand sample mineralogy that matches Saddle Butte lava, suggesting that the Owyhee River occupied this surface.

West Crater Lava Dam

While damming of the Owyhee River by the West Crater lava flow may have initially occurred at the confluence of a paleo-Owyhee River and Bogus Creek, the lava flow apparently was able to fill the paleocanyon sufficiently to flow upstream to its current position, placing the head of the dam adjacent to Ryegrass Hot Springs. Tumuli, inflated flow surfaces, and flow fronts all show that the lava flowed southwestward, around Bogus Point, and headed upstream (Fig. 15). Like the Saddle Butte lava flows, significant exposures of pillow lavas and hyaloclastite are exposed in the West Crater lava at its upstream most occurrence (river kilometer 38) (Fig. 16). This is the site of the last damming of the river before the supply of new lava to the dam ceased. The architecture of the dam is displayed in cliffs adjacent to the modern river from river

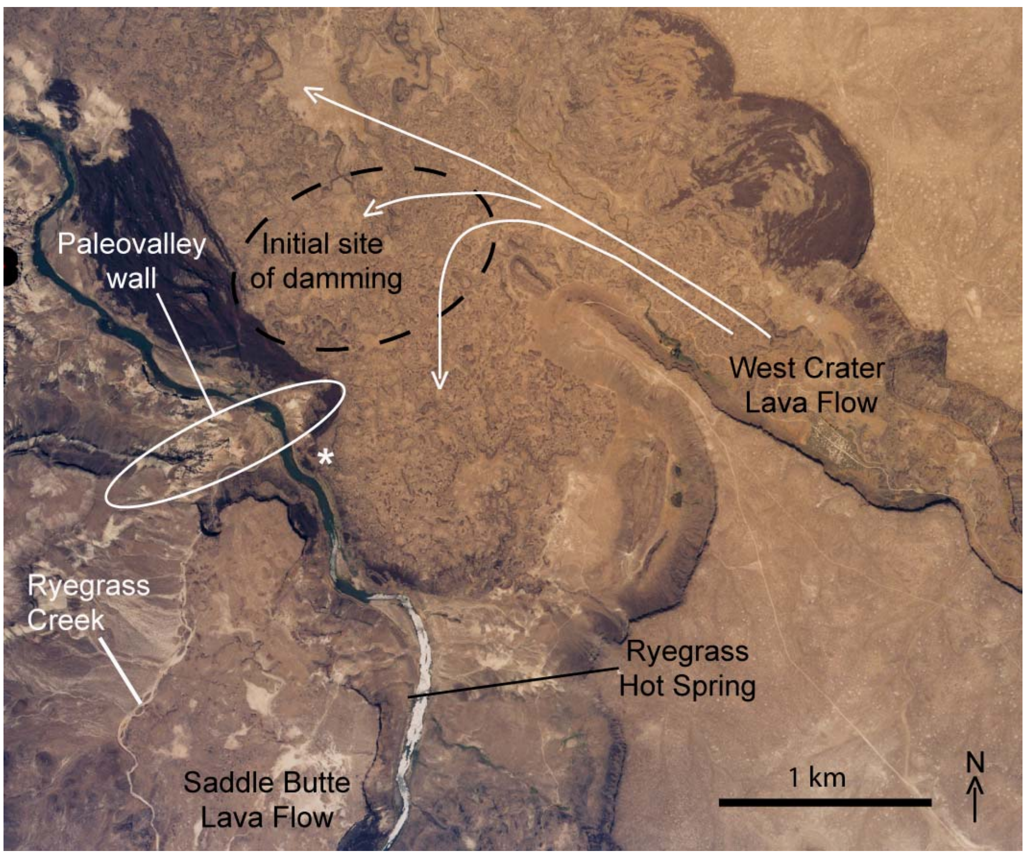

Figure 15. Aerial photograph of river kilometers 37.5–39.5 showing presumed initial location of West Crater lava dam. The Owyhee River flows to the north in this image. The asterisk denotes the location of the sediment lens depicted in Figure 16. Ryegrass Creek defines the western edge of the Saddle Butte lava flow. The West Crater lava flow entered the Owyhee Canyon by flowing down the Bogus Creek canyon. Enough lava was supplied to the Owyhee Canyon that the dam was able to grow upstream towards Ryegrass Hot Spring.

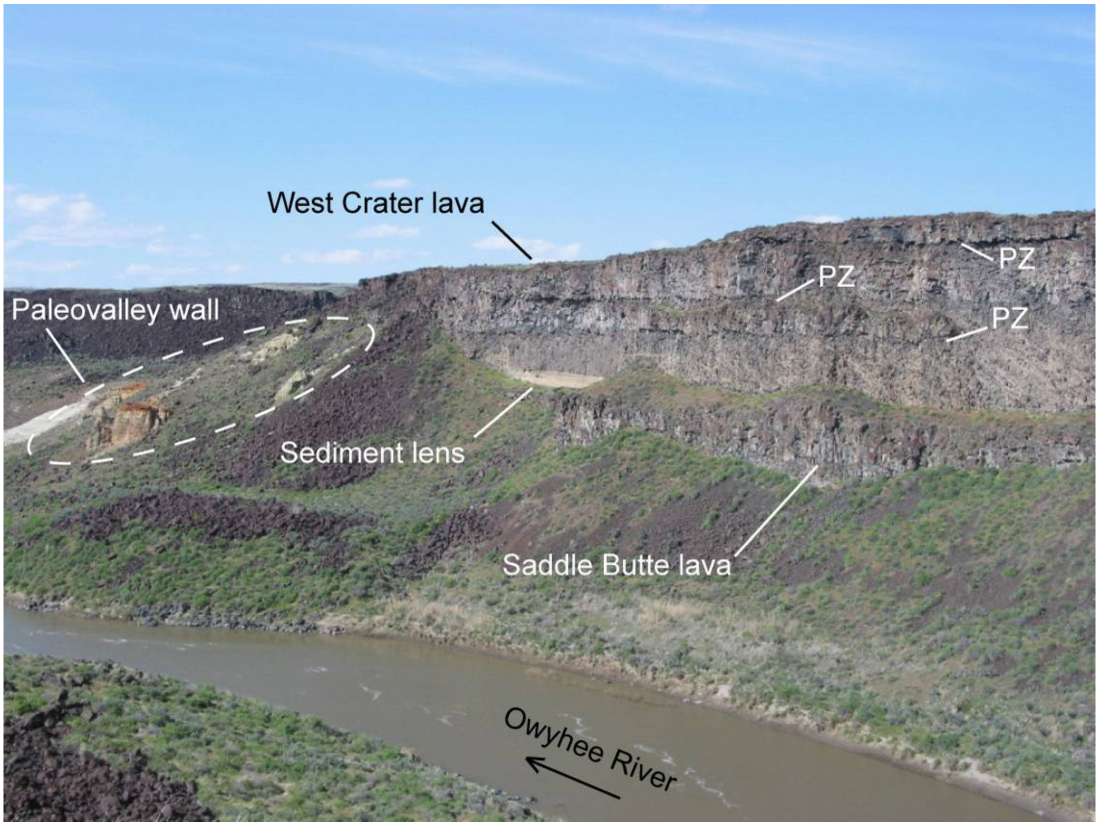

Figure 16. Photograph of outcrop relations at river kilometer 39.25. The Saddle Butte lava appears to underlie the sediment lens in the center of the photograph. The head of the West Crater lava dam overlies the sediment lens and the Saddle Butte lava. Foreset beds of pillow lavas and hyaloclastite dip down to the right in this image. Several different passage zones (indicated by PZ) indicate the lake level rose during construction of the dam. The location of the paleovalley wall discussed in Figure 15 is indicated by a dashed ellipse. The lens of sediment interpreted to be paleo-Ryegrass Creek is visible in the center of the photograph.

kilometers 38–39.25, just downstream of Ryegrass Hot Spring. Thick accumulations of talus exist at the base of the cliffs, obscuring the base of the dam. Where the bottom of the West Crater dam is exposed, it sits on an older lava flow, which may be Saddle Butte lava. The cliffs expose several layers of subaerial lava that interfinger with beds of pillow lava that dip upstream (Fig. 16). These alternating layers of pillow lavas and subaerial lava show that the reservoir level rose during the building of the dam.

The West Crater lava also probably dammed the river effectively (damming scenario A). No extensive outcrops of pillow lavas or hyaloclastite were observed downstream of the dam. The only evidence for lava and water interaction found downstream of the head of the West Crater lava dam exists near river kilometer 42.25 where a small, 15-m-long outcrop of water-quenched lava and a few weakly developed lava pillows occur. Such an outcrop could be the result of a leaky dam upstream or local damming of a tributary. The base of the West Crater lava dam is poorly exposed so evidence of incomplete damming in the initial stages of dam construction may be obscured. Several different heights of subaerial lavas and passage zones are exposed within the head of the West Crater lava dam (Fig. 16), indicating that the reservoir level did rise during construction of the dam. However, in all outcrops studied, no fluvial deposits were found intercalated between the flow units that compose the dam.

The West Crater lava dam was formed by a single lava flow composed of several flow units (Fig. 16). The dam resembles a massive dam because the dam appears to have been constructed faster than the river could overtop it but also resembles the single-flow dam of Hamblin (1994) because of its smaller proportions and volume (Fig. 3; Table 3). Between river kilometer 38 and river kilometer 39.75, the West Crater lava dam is at least 36 m (120 ft) and perhaps up to 67 m (220 ft) thick. Remnants of the dam extend 12 km downstream to the AM-PM camp (river km 49.5).

The surface of the Saddle Butte lava at its downstream-most exposure near Ryegrass Hot Springs was overtopped by the river when the West Crater lava dammed the river, if not before. Evidence for the river occupying this area exists in the form of fluvial gravels, deposits of coarse sands, fluvially worked boulders of basaltic and exotic (meta-sedimentary) compositions, and sculpted and plucked tumuli. This area would have served as the reservoir behind the West Crater lava dam. The top of the West Crater lava dam is at 1030 m (3380 ft). If the river ponded behind a dam of this height, a reservoir would have flooded the surface of the Saddle Butte lava for about 3.5 km upstream to the area south and west of Rustler's Cabin (river kilometer 35.5). This may explain why the surface topography of the Saddle Butte lava appears more subdued in this area compared to locations upstream; the normally jagged tumuli and flow fronts of the lava flow are partly concealed under sediments impounded behind the West Crater lava dam. Two small outcrops of fluvial boulders near the edge of the Saddle Butte lava located just east of Rustler's Cabin corroborate the presence of water on top of the Saddle Butte lava flow in this area at one time (Plate 1; Appendix D).

Another lava flow, probably the Saddle Butte lava, underlies the West Crater intermittently near river kilometer 39 and is approximately 12 m thick (Fig. 16). Talus obscures the base of this older lava flow. At Pruitt's Castle (river kilometer 39.5), a ridge of Tertiary sediment slopes down to the west bank of the river (Figs. 15–16). This ridge is just downstream of the confluence of Ryegrass Creek and the Owyhee River. Adjacent to the ridge, on the east bank of the river, the lower (probably Saddle Butte) lava flow disappears, and the West Crater flow laps up onto Tertiary sediments and pinches out. These outcrops constrain the location of the western wall of the paleovalley prior to the existence of the West Crater lava flow and suggest that the Tertiary sediments extended farther eastward out into the valley prior to the emplacement of the West Crater lava flow.

At river kilometer 39.25, a lens of sediment lies between the Saddle Butte lava and the overlying West Crater lava (Figs. 16–17). Based on the location of the modern

Figure 17. Lens of sediment interpreted to be paleo-Ryegrass Creek. Outcrop is near river kilometer 39.25. Person for scale. Note the excellent exposure of West Crater pillow lavas and hyaloclastite that overlies the lens. Lens is at least 3.5 m thick. Talus cover obscures at least 1.5 m of the base of the exposure. Bedding > 10 cm dominates. Occasional burrows 1–1.5 cm wide exist. Bedding at bottom of exposure is thicker and consists mostly of silts and sands. Coarse sand and granules dominate the middle 1 meter. Basalt and chert clasts are angular to subrounded. Angular platy chert clasts 1–3 cm in diameter are common in upper half of exposure. The top ~1 m contains more clasts up to ~40 cm than lower 2.5 m of outcrop. The basalt and platy chert clasts could be easily sourced nearby in the eastern slopes of the Chalk Basin sediments. Based on the location of the modern Ryegrass Creek and the lithologies of sediment found in the lens, the lens likely represents a paleo-Ryegrass Creek.

Ryegrass Creek and the platy lithologies found in the sediment lens, the lens likely represents a paleochannel of Ryegrass Creek which flowed over the Saddle Butte lava prior to the emplacement of the West Crater lava. This evidence, in combination with the thick section of West Crater lava beginning to the east at river kilometer 38.5, indicates that the Owyhee River was farther to the east near river kilometer 39 at the time of emplacement of the West Crater lava. After the emplacement of the West Crater lava flow, the river eroded around the lava flow on the western edge of the lava flow, incising through Tertiary sediments that composed the western wall of the paleovalley.

Continuing downriver, the West Crater lava flow is generally thin (~10 m) from river kilometers 39.5 to 42 adjacent to Chalk Basin. In this area, the margin of the lava flow is landsliding down to the river and is largely broken up into a field of disaggregated blocks of various sizes. Some of the lava flow remains intact and tall towers of basalt in the center of the landslide demonstrate the variability in the thickness of the lava. These thick sections of basalt may be explained by the presence of a deep tributary valley cut into the Tertiary sediments on the western bank of the river. This valley may have extended eastward out into a paleo-Owyhee Valley at the time of the West Crater lava flow. When the West Crater lava flow was emplaced, it flowed up this tributary, filling it. Since then, erosion of the Tertiary sediments by the river and the tributary stream has enlarged the tributary valley, and landslides have exposed the thick section of basalt that likely represents the location of the paleovalley.

From river kilometer 42 to Bogus Creek Falls (river kilometer 43.5), the basalt often consists only of one 10 m thick flow unit that overlies Tertiary sediments. The lava is thin here because it lapped onto an east-dipping slope cut into Tertiary sediments, demonstrating that this reach was the margin of the paleovalley at the time that the West Crater lava was emplaced. At Bogus Creek Falls, the lava is > 28 m thick. The contact between the West Crater lava and the underlying units is exposed in an alcove approximately 100 m upstream of Bogus Creek Falls, but basalt boulders at the plunge pool of the falls bury the contact between the basalt and any underlying units. This thick section of basalt and the thick section at its upstream-most outcrop adjacent to Ryegrass Hot Springs (river kilometer 38.25), provide two certain tie points through which a paleo-Owyhee River channel likely flowed. In the past, the Owyhee River channel was located further to the east, somewhere under the middle of the West Crater lava flow. It is also likely that the river flowed on both the eastern and western sides of the kipuka, hill 3443 (Plate 1). Without fluvial erosion on both sides of hill 3443, it is unlikely that the hill could have become an isolated topographic high in the middle of a wide canyon.

The fact that West Crater lava exists at Dog Leg Bar (river kilometers 45–46.25) shows that a bend in the Owyhee River or an embayment cut in the paleo-valley wall by the tributary Bull Creek existed at the time of emplacement. Before the emplacement of the West Crater lava, the large landslides and earthflows entering the Owyhee Canyon from Bogus Rim to the east could have pushed the Owyhee River into the western wall of the canyon near where it is today. Thick sections of basalt along river kilometers 43.5–47 support the existence of a deep canyon there prior to the West Crater lava flow.

The base of the West Crater lava can be examined in relation to current river level at exposures downstream of Dog Leg Bar at river kilometer 47 and at Bogus Creek Falls (river kilometer 43.5). The contact of the West Crater lava and underlying units is commonly obscured by talus at these locations. The elevation of the contact between talus and the intact lava flow is the maximum elevation of the paleo-Owyhee river at that location prior to the West Crater flow. At Bogus Falls, the top of the talus is 31 m above the modern water surface. At river kilometer 47, the top of the talus and lowest exposed lava flow is approximately 20 m above the modern water surface. These values are greater than the modern water surface in part because these locations are probably off the axis of the paleovalley and west of the deepest part of the paleovalley that underlies the middle of the lava flow. Nonetheless, these outcrops show that the elevation of the modern river is within a few tens of meters of the paleo-Owyhee River at the time of emplacement of the West Crater lava.

Deposits of sub-rounded to well-rounded basaltic and exotic boulders along the western edge of the West Crater lava flow from river kilometers 39.75 to 43.25 show that the river occupied the surface of the lava flow (Plate 1). A weakly developed paleochannel exists in the upstream portion of the lava flow adjacent to river kilometer 39 (Plate 1). At this location, little sculpting of basalt has occurred, but the lower portions of tumuli were eroded and blocks were plucked from the surface of the lava flow. At river kilometer 43.25 a much better developed paleochannel exists. Here, in addition to eroded and plucked tumuli, sub-rounded boulders and polished basalt surfaces occur in a channel 1–2 m deep and 5–10 m wide (Fig. 18). These well

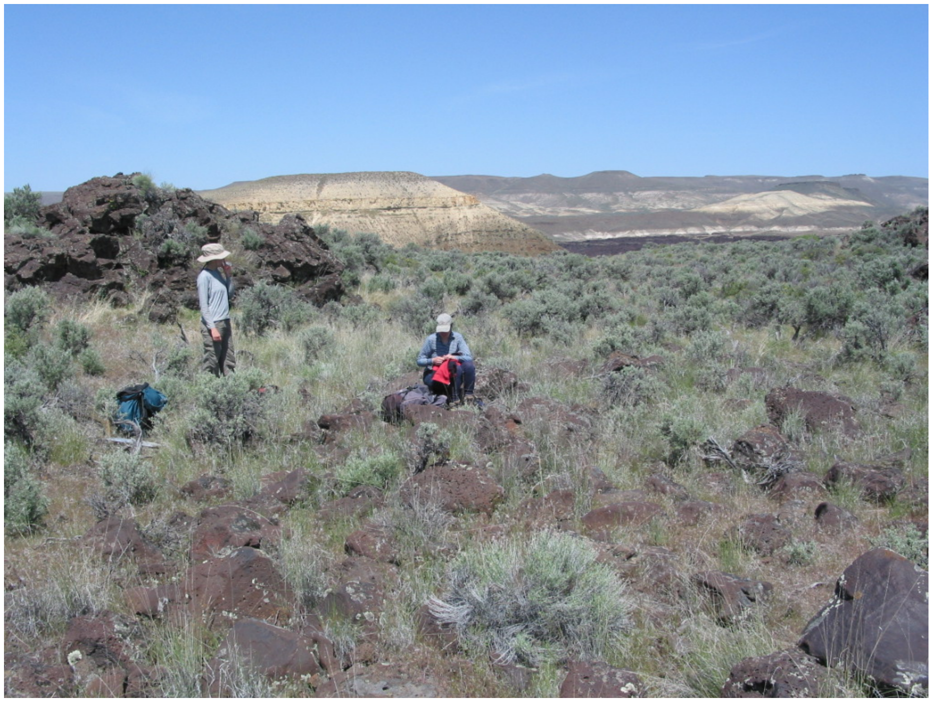

Figure 18. Photograph showing paleochannel cut in the West Crater lava adjacent to river kilometers 41.75–43.25. Blocks of lava from the base and sides of the tumuli behind the standing person have been plucked by fluvial erosion. The other person is sitting amongst sub-angular to sub-rounded boulders in the channel bottom.

developed features suggest that the Owyhee River occupied the surface of the lava flow for a significant amount of time at this location. Samples of the largest boulders were collected for cosmogenic exposure dating to determine the age of abandonment of the channel. Results are pending.

Outburst Floods in the Owyhee River

Mass movement is common in the Owyhee Canyon (Ferns et al., 1993; Evans 1991) and provides a mechanism for the generation of outburst floods. Landslides and earthflows up to several square kilometers in area transported lava flows and the underlying sediments from the canyon rim down to the river (Ferns et al., 1993; Evans

1991). Boulder bars containing clasts with b-axis diameters of 2–4 m often exist immediately downstream of landslides. The extent of these deposits and the large size of clasts within the deposits would require high river discharges to be emplaced. While none of these deposits has been conclusively tied to a landslide source, the breach of an upstream landslide dam and the resulting outburst flooding is the most likely scenario for their genesis.

At least one Late Pleistocene outburst flood from pluvial lakes Alvord and Coyote entered the Owyhee River upstream of the study area via Crooked Creek (Carter, 2005; Carter et al., 2006). Deposits of this outburst flood have not been recognized in the study area. Evidence demonstrating the passage of the flood likely exists but has not yet been distinguished from the many large boulder bars resulting from the failure of landslide dams and the response of the river to impediments created by intra-canyon lava flows.

There are reaches of the Owyhee River that may provide the necessary conditions for catastrophic lava dam failure and the generation of outburst floods. In narrow, bedrock confined reaches of the river, the processes of dam removal could resemble the conceptual model of Hamblin (1994) where nickpoint retreat proceeds upstream until the head of the dam fails catastrophically. Because the river cannot easily erode around the lava dams in reaches where the river is confined by bedrock, the lava dam must be eroded directly. In these settings, the well-jointed nature of lava flows in the Owyhee Canyon could facilitate rapid dam removal. Because little of the Upper

AM-PM lava exists today, it may have been removed by nickpoint retreat. Additional study of the Upper AM-PM lava is needed to fully evaluate the viability of this model.

At least three pieces of extant evidence point toward gradual removal of the Upper AM-PM, Saddle Butte, and West Crater lava dams rather than catastrophic failure. First, compared to the underlying and adjacent sedimentary units, especially the Tertiary sediments exposed at Chalk Basin, the subaerially emplaced portions of the lava flows are much more resistant to incision by the river. As a result, the river has commonly avoided the lava flows altogether where possible and has incised a new channel around the Saddle Butte and West Crater dams in the adjacent geologic units. The lava dams have been left largely intact (with the exception of the Upper AM-PM lavas) and show no evidence of large-scale instantaneous failure.

Second, no deposits from an outburst flood generated from catastrophic lava dam failure have been identified and conclusively linked to a lava dam. Deposits of large boulders do exist in the canyon, and while some boulder deposits cannot be directly linked to any obvious source, many are directly downstream of landslides and appear to be related to landslide dam failure. Clasts transported by the Owyhee River are dominantly rhyolitic or basaltic in composition. Consequently, outburst flood deposits from the failure of a lava dam would be difficult to distinguish from outburst flood deposits generated by other mechanisms without analytical techniques that relate flood deposits to specific lava flows.

Third, the fact that several different terrace heights in several different locations exist adjacent to outcrops of the West Crater lava suggests that the river incised gradually, or perhaps episodically, through that lava flow. If river incision had been at a rapid and constant rate in all areas, as it might following a catastrophic dam failure of the entire dam, no terraces would have been preserved. A more detailed discussion of the incision history and river terraces occurs below.

Lava Dam Longevity and Rates of River Incision

Compared to the underlying and adjacent sedimentary units, especially the Tertiary sediments exposed at Chalk Basin, the subaerially emplaced portions of the lava flows are more resistant to incision by the river. As a result, the river has commonly avoided the lava flows altogether where possible and has incised a new channel around the dams in the adjacent geologic unit.

The thickness of lava, the topography underlying the dam, and the geologic unit underlying the Owyhee Canyon lava dams appear to work in concert to control the lava flow stability and therefore lava dam longevity, channel widening, and valley development. Field mapping uncovered that where the West Crater and Saddle Butte lava flows are thin, or were emplaced on a slope or paleovalley wall comprised of Tertiary sediments, the lava flows have often been incorporated into large landslides after incision by the river (river kilometers 31–45). Thick lava sections, or sections that were emplaced on top of other, subhorizontal volcanic rocks, appear to be the most stable and therefore most durable sections of the lava dams because at least some portions of the lavas remain intact today. Locations exhibiting these geologic conditions occur in reaches of the river confined by rhyolite or older lava flows such as at the

Weeping Wall (river kilometer 28.25) or where well developed rhyolite strath surfaces support the lavas such as at Airplane Point (river kilometer 47.75) (Figs. 11–12).

The river has incised completely around or through the Saddle Butte and West Crater flows in most locations and now flows over older volcanic units or sediments. At the scale displayed, Figure 11 shows the slope of the river is fairly constant throughout the study area with only subtle variations, and the lava flows do not appear to individually influence the slope of the river. The reach of the river containing the lava flows (river kilometers 17–80) does appear steeper than the reach near Rome (river kilometers 0–17); whether this is due to the presence of the lava flows as a group, bedrock control by rhyolite or older basalt flows, or other factors remains to be determined.

Many deposits resembling terraces exist in the study reach and are not discussed in detail for the deposits are of unknown genesis. These deposits may represent flood bars created by the passage of glacial outburst floods, the failure of landslide dams, or possibly even lava dam failures. Potential flood bars/terraces exist at elevations very near the modern river near river kilometers 39, 44.5, 45, and 47. Regardless of their genesis, these deposits do record the elevation of the river at certain times in the past and if studied in detail, may provide data on the incision history of the river.

Once the reservoir behind a lava dam was full, the Owyhee River had to flow over the tops of the lava flow creating the dam, or at similar elevations adjacent to the lava flow. Several terraces at different elevations were created upstream of Bogus Falls, from river kilometers 39 to 47, by this process (Plate 1; Figs. 11 and 19). These terraces

Figure 19. Photographs of terraces near Chalk Basin. (A) Photograph showing two of the several terraces cut into Tertiary sediments at Chalk Basin near river kilometer 42.75. (B) Photograph of upper terrace shown in part (A) above. Person for scale. The terrace deposit is composed nearly entirely of basalt boulders and cobbles.

are often cut into the Tertiary sediments exposed at Chalk Basin, the West Crater lava flow, or inset against older volcanic units that underlie the Tertiary sediments (Fig. 19). Some terraces are at elevations that match the elevation of the West Crater lava and may record the time following the emplacement of the lava flow when the river was shifting laterally, searching for an easier course. Other terraces are at lower elevations and likely represent periods of stalled incision as the river tried to regain its pre-West Crater profile.

Downstream of river kilometer 45, five terraces exist on the inside of a sharp right bend in the river upstream of Dog Leg rapid (Figs. 11 and 20). Cosmogenic exposure dating of the terraces shows that since approximately 38 ka the river underwent periods of episodic incision (Table 2). The average age of boulders from the T5 surface is 38 ka. Based on this age, a long-term minimum incision rate to the present elevation of the river is 1.3 mm/yr (Table 2; Fig. 20). Incision from the T4 surface (35 ka) to present river level is 1.1 mm/yr. In contrast, incision from the T5 to T4 surface was much more rapid: 3.3 mm/yr.

Several uncertainties affect the incision rates. Incision rates calculated between terraces are likely more certain than incision rates that include the modern river because the time when the river reached its current position is unknown. An incision rate that includes the modern river is a minimum rate. For example, the river could have reached its current elevation 10 ka ago and ceased downcutting. Such a scenario would result in much more rapid incision rates. In addition, the uncertainty in the elevation of the terraces is small but notable. For example, instead of the channel bottom, the water

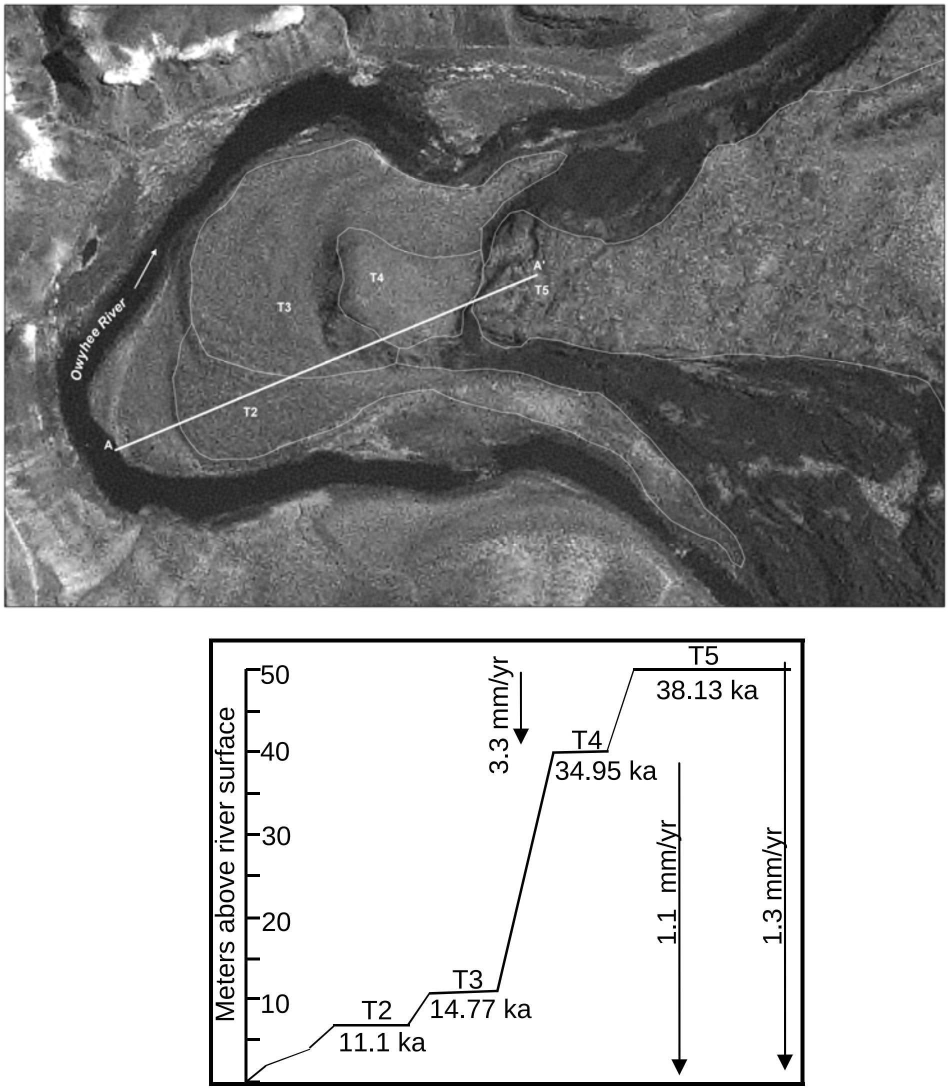

Figure 20. Aerial photograph of Dog Leg Bar terraces and corresponding elevation profile. Vertical arrows show preliminary estimates of mean incision.

surface elevation of the modern river was used as the base elevation. The water surface elevation could be as much as 5 m higher than the channel bottom, depending on location. This means that any incision rate from a terrace surface to the modern river will be a minimum. At Dogleg Bar, elevations were measured on April 4, 2004, by hand level and compared with GPS altimeter by J. O’Connor and P. K. House. The water surface elevation was measured by GPS altimeter at the beginning and end of the transect. At the end of the transect, the water surface elevation was 3.3 m lower. These 3.3 m represent a 6.8% uncertainty in the relative differences in elevation of the terraces. At Airplane Point, elevations were measured relative to the water surface on May 5, 2006, using a laser rangefinder. Uncertainties in elevation at Airplane Point are likely less than those at Dogleg Bar because the instrument used was more accurate. However, the water surface elevation that day was different from April 4, 2004.

Additional uncertainty lies in the cosmogenic exposure dating. The ages reflect the date when significant erosion of the boulders on the surface ceased. In the case of fill terraces, or fill that drapes strath terraces, burial and exhumation of the boulders could affect the exposure of the boulders to cosmic rays and therefore the ages of the boulders. Depending on the exact morphology of the surface, the ages and resulting incision rates may indicate different processes were at work. The T1 surface may contain boulders that experienced previous exposure based on the one anomalously old age (78 ka, Table 2). In addition, its low elevation relative to the modern river allows it to be occupied in modern high water events. The T1 surface may be an inactive river deposit or flood bar containing boulders from other terraces. The T2 and T3 surfaces represent either fill terraces or flood bars. The T4 surface is a strath terrace where several meters of fill drape a basalt surface cut into the West Crater lava flow. The T5 surface is a strath terrace with only scattered boulders and cobbles resting on it.

These different rates of incision, plus the fact that the terraces exist in the first place, show that incision has not been constant in this reach of the river. Several variables could influence the incision rate, such as climate and river discharge, river-damming landslides, changes in regional base level, the passage of glacial outburst floods, and the bedrock geology of the Dog Leg Bar area. For example, a fault at the mouth of Bull Creek on the opposite bank of the river from the five terraces vertically offsets several different Miocene lava flows, the Devine Canyon Ash-flow Tuff, and late Miocene lake sediments. The exact displacement on the fault is currently unknown but is enough (many tens of meters) to place the Miocene lava flows, Devine Canyon Ash-flow Tuff, and the Miocene lake sediments at similar elevations to the T4 and T5 surfaces. The variety of geologic units having contrasting resistance to erosion at this location likely contributed to the construction and preservation of the terraces and the differential rates of river incision through time.

Near Potter's Cave, at Airplane Point (Fig. 9), outcrops of West Crater lava flow have been heavily eroded by the river, but fluted and sculpted basalt surfaces remain. At this location, the West Crater lava sits on a well-developed strath terrace cut into rhyolite 8.5 m above river level. The surface exposure ages at Airplane Point (68 ± 3 ka, 74 ± 4 ka, and 88 ± 4 ka) and the $^{40}Ar/^{39}Ar$ dates from Bondre (2006) (61 ± 23 ka, 86 ± 33 ka) indicate that the West Crater lava flow is 60–90 ka. Within the resolution of the data, the Airplane Point surfaces could have been occupied by the river and then abandoned immediately after the lava flow was emplaced.

The surface exposure ages at Airplane Point are all older than the ages of boulders on the five Dog Leg terraces (Table 2). This difference in surface exposure age might be explained by the location of the Airplane Point site. In this location, the river is confined between towers of rhyolite bedrock on each bank and could not avoid the lava. The river had to flow over the basalt at Airplane Point immediately after the river overtopped the lava dam. For this reason, the basalt and rhyolite at Airplane Point may have experienced incision by the river before other locations. Because the river could not shift laterally to leave a terrace at Airplane Point, there is no intermediate time marker between the Airplane Point surfaces and the modern river level. The river may have reached its current elevation long ago after a period of rapid incision responding to the raise in local base level by the canyon filling basalt.

An additional explanation for the differences in age of the Airplane Point and Dog Leg Bar surfaces is that a nickpoint retreated through that portion of the canyon. Fluvial erosion by plucking of joint blocks from the lava flow could conceivably erode the lava flow quite rapidly. After the West Crater lava flow filled the canyon, the river flowed over the top of the lava at Airplane Point because the high rhyolite canyon walls confined the river. The river then began to erode the lava flow and perhaps a nickpoint developed at a location downstream. The nickpoint could have passed through the Airplane Point area between 68 ± 3 ka and 88 ± 4 ka (Table 2), causing the Airplane Point surfaces to be abandoned, and proceeded upstream arriving at the Dog Leg Bar area sometime near 38 ka years ago. Dating additional terrace surfaces and sculpted basalt surfaces near Dog Leg Bar and downstream of Airplane Point may provide enough data to evaluate the retreating nickpoint scenario.

Howard et al. (1982) calculated that over the past 2 million years, rates of river incision in the Boise River were 0.05 to 0.10 mm/yr. These long-term rates are lower than the rates the authors calculate for incision through the lava dams. The lava dam created by the Smith Prairie Basalt was incised at 0.70 mm/yr and the Mores Creek basalt was incised at 0.30 mm/yr (Howard et al., 1982). Compared to these values, preliminary estimates of mean incision on the Owyhee River at Dog Leg Bar (0.66–1.3 mm/yr) are greater. Estimates of mean incision at Airplane Point (0.27–0.34 mm/yr) are similar to those (Howard et al., 1982) calculated for the Mores Creek basalt. Due to the confined nature of the river channel at Airplane Point, the incision rates at Airplane Point may record the long term rate of incision through the West Crater lava flows and the underlying rhyolite.

In summary, the Dog Leg Bar area was being actively eroded by the river well after (at least 30 ka after) the river had abandoned the Airplane Point surfaces. This upstream-younging age of abandonment may support the retreating nickpoint model of dam removal/failure. Somewhat in contrast, the existence of several terraces of different elevations may support individual flow units of basalt being sequentially eroded one by one in a stair-step fashion in which the nickpoint only need be 2–3 m tall. This scenario more resembles gradual dam removal processes rather than catastrophic failure. Radiometric and surface exposure dating of the Upper and Lower AM-PM lavas and additional dating of surfaces at Airplane Point and Dog Leg Bar is pending and once complete will shed light on the complicated incision history of this reach of the river.

Paleotopography

The potential for the topography and the course of the river to have changed over time is highest in the reach of the Owyhee Canyon from Sand Spring (river kilometer 31), through the Ryegrass and Lambert Rocks areas, to Airplane Point (river kilometer 47.75). In these areas, the outcrops of the Saddle Butte and West Crater lava show that the river could have occupied a canyon at least 1.6 km wide at the time of each of their emplacements. In contrast, upstream of Sand Spring (river kilometer 31 and downstream of Airplane Point (river kilometer 47.75), rhyolite and basalt bedrock have confined the river in a narrow canyon sometimes only a few hundred meters wide for much of the Quaternary. Outcrops of the Upper AM-PM lava and the Greeley Bar lava demonstrate this; the river was nearly in its present position lateral position at the time of their emplacements. The Greeley Bar lava may also indicate the location of the downstream portion of the Hole in the Ground landslide and earthflow complex. Several million years ago, the Deer Butte and other lava flows from unknown sources appear to have flowed over a relatively continuous surface tens of kilometers square in area, creating a obstacle for the river approximately 500 ft (152 m) high. The uplands surrounding Deer Butte serve as a plateau that creates the narrow, confined canyon. The presence of pillow lavas and hyaloclastite beds in both the Bogus Rim and Bogus Point lava flows shows that each lava flow entered a lake or river that was continuous for at least 10 km and at times many tens of meters deep.

Future Work

Much of the modern Owyhee River flows adjacent to large landslides and the uncertainties imparted on the present study by landslides must be addressed. These landslides mobilize ample coarse grained debris from both intra- and extra-canyon lava flows and deliver the debris to the river. For this reason, an outburst flood deposit resulting from the failure of a landslide dam is difficult to distinguish from outburst flood deposits related to lava dam failure. In addition, landslides have altered the margin of the lava flows where the river has incised through the flows, obscuring many potentially informative outcrops. Incision rates may also be affected by the landslides if landslides fill the river channel with debris too large to mobilize in all but the most extreme discharge events. Thorough mapping of the landslides, the dams they likely created, and investigation of the causes and timing of landslides would all benefit the understanding of how the lava flows have controlled the development of the modern Owyhee Canyon.

Investigation of coarse and fine grained deposits behind the West Crater lava dam at the Ryegrass Hot Spring area (river kilometer 38) and the Saddle Butte lava dam near the Sand Spring drainage (river kilometer 31) might offer clues to the paleo-discharge of the river, the paleo-sediment load, the timing and duration of dam construction, and the longevity of the dams. Additional detailed mapping and dating of terraces and boulder bars to improve the incision history might indicate how and when the lava dams were removed. More work to conclusively correlate isolated outcrops of lava flows (i.e., the Upper AM-PM lavas, sample OWY-18, and OWY-34) will help determine the extent of the lava flows and the magnitude of landscape change during the existence of the lava flows. Additional investigation of the age, elevations, and thicknesses of the Greeley Bar lavas, and potential fluvial deposits overlying the Greeley Bar lavas, might provide important data on the mass-movement history of The Hole in the Ground and the incision history of the Owyhee River.

CHAPTER V

CONCLUSIONS

In the last 2 million years, at least six lava flows entered the Owyhee River canyon and interacted with the river for distances of up to 26.5 km. The Bogus Point, Bogus Rim, and Greeley Bar lava flows range between several hundred thousand and 2 million years old. Details of the interactions of these three lava flows with the river are largely unknown. The Bogus Point lava flow is overlain by the Bogus Rim lava flow (~ 2 Ma). The Greeley Bar lavas are likely younger than the Bogus Point and Bogus Rim lava flows based on morphology and position relative to the modern river.

The Clarks Butte (250 ka), Saddle Butte, West Crater (60–90 ka), and Rocky (or Lava) Butte (~30 ka) lava flows are younger and their extents and interactions with the Owyhee River are more apparent. The Clarks Butte lava flow flowed down the Bogus Creek drainage and appears to underlie the West Crater lava flow east of Bogus Lake. These field relations and the age of the Clarks Butte lava flow indicate the Clarks Butte lava flow is the most likely source for the Upper AM-PM lava that appears as isolated lava flow remnants in the Owyhee River Canyon. Even though the geochemistry of the Rocky Butte lava flow may match that of the Upper AM-PM lava, the young age of the Rocky Butte lava flow and unclear field relations do not support the Rocky Butte lava flow being the source of the AM-PM lava. The Saddle Butte lava entered the canyon via the Granite and Ryegrass Creek drainages and is older than the West Crater lava flow, and probably younger than the Upper AM-PM lavas, based on morphology and stratigraphic relations. The West Crater lava flow (60–90 ka) is the youngest lava flow to reach the Owyhee River channel in the study area.

The Saddle Butte and West Crater lava flows dammed the river, creating lakes in which pillow lavas and hyaloclastite were deposited. After the lakes filled, the river occupied the surface of the lava flows briefly and then eroded around the dams on the opposite side of the valley from the initial lava incursion. In the case of the West Crater lava dam, the less resistant adjacent sedimentary units facilitated incision around the dam. The dams are largely still intact; the river avoided them wherever possible. Numerous terraces at several different elevations remain from the process of incision around the dams.

Before the Saddle Butte and West Crater lava flows filled the canyon, the river likely flowed through a canyon approximately 2 km wide in the reach from Sand Spring (river kilometer 31) to Potter's Cave (river kilometer 47.75). Today, the river flows through a narrow inner gorge sometimes only a few hundred meters wide. The rate of effusion of the lava flows into the canyon appears to have well exceeded the water available to chill the lava flow because the lava flows created stable dams that effectively dammed the river. The most stable portions of lava dams appear to be those that are thick and sit on other subhorizontal volcanic rocks. The least stable portions of the dams are thin and were emplaced on a slope or paleovalley wall comprised of sediments.

Based on the lack of conclusive outburst flood deposits, the more easily erodable adjacent units, the presence of terraces, and the fact that the dams were long and low, the dams were likely lowered gradually and did not fail catastrophically. However, landslide deposits and outburst floods from landslide dam failure do exist in the study area and could be confused with lava dam outburst flood deposits.

Preliminary estimates of mean river incision through and around the lava dams (0.27–1.3 mm/yr) match or exceed calculated rates of incision through lava dams that occur in the South Fork of the Boise River. Additional work to refine the ages of the lava flows and date and correlate river terraces will refine the calculated incision rates and increase our understanding of the influence of lava flows on the evolution of the Owyhee River canyon.

REFERENCES

Batiza, R., and White, J. D. L., 2000, Submarine lavas and hyaloclastite, *in* Sigurdsson, H., ed., Encyclopedia of volcanoes: San Diego, Academic Press, p. 361-381.

Bondre, N. R., September 1, 2005, personnel communication.

Bondre, N. R., 2006, Field and geochemical investigation of basaltic magmatism in the western United States and western India [Ph.D. thesis]: Oxford, Miami University, 263 p.

Bondre, N. R., and Hart, W. K., 2006, Source and process effects on basaltic volcanism in the Jordan Valley Volcanic Field, southeastern Oregon: Abstracts with Programs Geological Society of America, v. 38, no. 7, p. 446.

Bondre, N. R., and Hart, W. K., 2004, Flow chemistry and vent alignments from the Jordan Valley volcanic field, Oregon; insights into the evolution of monogenetic volcano fields: Abstracts with Programs Geological Society of America, v. 36, no. 4, p. 75.

Bunbury, J. M., Hall, L., Anderson, G. J., and Stannard, A., 2001, The determination of fault movement history from the interaction of local drainage with volcanic episodes: Geological Magazine, v. 138, no. 2, p. 185-192.

Butler, R. F., 1992, Paleomagnetism: Magnetic domains to geologic terranes: Boston, Blackwell Scientific Publications, 319 p.

Carter, D. T., 2005, A large Late-Pleistocene outburst flood from pluvial Lakes Alvord and Coyote into the Owyhee river, Oregon [M.S. thesis]: Ellensburg, Central Washington University, 83 p.

Carter, D. T., Ely, L. L., O'Connor, J. E., and Fenton, C. R., 2006, Late Pleistocene outburst flooding from pluvial Lake Alvord into the Owyhee River, Oregon: Geomorphology, v. 75, no. 3-4, p. 346-367.

Cas, R. A. F., and Wright, J. V., 1987, Volcanic successions modern and ancient: London, Allen and Unwin, 528 p.

Cerling, T. E., 1990, Dating geomorphologic surfaces using cosmogenic ^{3}He: Quaternary Research, v. 33, p. 148.

Cerling, T. E., and Craig, H., 1994, Geomorphology and in-situ cosmogenic isotopes: Annual Review of Earth & Planetary Sciences, v. 22, p. 273-317.

Cerling, T. E., Poreda, R. J., and Rathburn, S. L., 1994, Cosmogenic ^{3}He and ^{21}Ne age of the Big Lost River flood, Snake River Plain, Idaho: Geology, v. 22, p. 227.

Cerling, T. E., Webb, R. H., Poreda, R. J., Rigby, A. D., and Melis, T. S., 1999, Cosmogenic ^{3}He ages and frequency of late Holocene debris flows from Prospect Canyon, Grand Canyon, USA: Geomorphology, v. 27, p. 93.

Champion, D. E., December 1, 2006, personal communication.

Champion, D. E., and Shoemaker, E. M., 1977, Paleomagnetic evidence for episodic volcanism on the Snake River Plain, National Aeronautics and Space Administration Technical Memorandum, p. 7-9.

Cummings, M. L., 1991, Geology of the Deer Butte Formation, Malheur County, Oregon; faulting, sedimentation and volcanism in a post-caldera setting: Sedimentary Geology, v. 74, p. 345-362.

Cummings, M. L., Evans, J. G., Ferns, M. L., and Lees, K. R., 2000, Stratigraphic and structural evolution of the middle Miocene synvolcanic Oregon-Idaho graben: Bulletin of the Geological Society of America, v. 112, no. 5, p. 668-682.

Dalrymple, G. B., and Hamblin, W. K., 1998, K-Ar ages of Pleistocene lava dams in the Grand Canyon in Arizona: Proceedings of the National Academy of Sciences of the United States of America, v. 95, no. 17, p. 9744-9749.

Duffield, W., Riggs, N., Kaufman, D., Champion, D., Fenton, C., Forman, S., McIntosh, W., Hereford, R., Plescia, J., and Ort, M., 2006, Multiple constraints on the age of a Pleistocene lava dam across the Little Colorado River at Grand Falls, Arizona: Geological Society of America Bulletin, v. 118, no. 3-4, p. 421-429.

Duffield, W. A., and Smith, G. I., 1978, Pleistocene history of volcanism and the Owens River near Little Lake, California: U.S. Geological Survey Journal of Research, v. 6, no. 3, p. 395-408.

Environmental Systems Research Institute, 2005, ArcMap 9.1, [computer software]: Redlands, Ca, Environmental Systems Research Institute.

Evans, J. G., 1991, Geologic map of the Lower Owyhee Canyon Wilderness Study Area, Malheur County, Oregon: U.S. Geological Survey Miscellaneous Field Studies Map MF-2167, scale 1:48,000, 1 sheet.

Fenton, C. R., Webb, R. H., Cerling, T. E., Poreda, R. J., and Nash, B. P., 2002, Cosmogenic He ages and geochemical discrimination of lava-dam outburst-flood deposits in western Grand Canyon, Arizona, *in* House, P. K., Webb, R. H., Baker, R. V., and Levish, D. R., eds., Ancient floods and modern hazards: Principles and applications of paleoflood hydrogeology, AGU Water and Science Applications no. 5: Washington, D.C., American Geophysical Union, p. 191-215.

Fenton, C. R., Cerling, T. E., Poreda, R. J., Nash, B. P., and Webb, R. H., 2004, Geochemical discrimination of five Pleistocene lava-dam outburst-flood deposits, western Grand Canyon, Arizona: Journal of Geology, v. 112, no. 1, p. 91-110.

Fenton, C. R., Webb, R. H., and Cerling, T. E., 2006, Peak discharge of a Pleistocene lava-dam outburst flood in Grand Canyon, Arizona, USA: Quaternary Research, v. 65, no. 2, p. 324-335.

Ferns, M. L., Evans, J. G., and Cummings, M. L., 1993, Geologic map of the Mahogany Mountain 30 x 60 Minute Quadrangle, Malheur County, Oregon, and Owyhee County, Idaho: Oregon Department of Mineral Industries Geological Map Series GMS-78, scale 1:100,000, 1 sheet, 12 p. text.

Fuller, R. E., 1931, The aqueous chilling of basaltic lava on the Columbia River Plateau: American Journal of Science, v. XXI, no. 124, p. 281-300.

Gosse, J. C., and Phillips, F. M., 2001, Terrestrial in situ cosmogenic nuclides: Theory and application: Quaternary Science Reviews, v. 20, no. 14, p. 1475-1560.

Grant, G. E., June 2006, Personal communication.

Guilbaud, M., Self, S., Thordarson, T., and Blake, S., 2005, Morphology, surface structures, and emplacement of lavas produced by Laki, A.D. 1783-1784, *in* Manga, M., and Ventura, G., eds., Kinematics and dynamics of lava flows: Geological Society of America Special Paper 396: Boulder, Colorado, Geological Society of America, p. 81-102.

Hamblin, W. K., 1994, Late Cenozoic lava dams in the western Grand Canyon, Geological Society of America Memoir 183, 139 p.

Hart, W. K., 1982, Geochemical, geochronologic and isotopic significance of low K, high-alumina olivine tholeiite in the northwestern Great Basin, U.S.A. [Ph.D. thesis]: Cleveland, Ohio, Case Western Reserve University, 410 p.

Hart, W. K., Aronson, J. L., and Mertzman, S. A., 1984, Areal distribution and age of low-K, high-alumina olivine tholeiite magmatism in the northwestern Great Basin: Geological Society of America Bulletin v. 95, p. 186-195.

Hart, W. K., and Mertzman, S. A., 1983, Late Cenezoic volcanic stratigraphy of the Jordan Valley area, southeastern Oregon: Oregon Geology, v. 45, no. 2, p. 15-19.

Howard, K. A., Shervais, J. W., and McKee, E. H., 1982, Canyon-filling lavas and lava dams on the Boise River, Idaho, and their significance for evaluating downcutting during the last two million years, *in* Bonnichsen, B., and Breckenridge, R. M., eds., Cenozoic Geology of Idaho: Moscow, Idaho Bureau of Mines and Geology, p. 629-644.

Huscroft, C. A., Ward, B. C., Barendregt, R. W., Jackson Jr., L. E., and Opdyke, N. D., 2004, Pleistocene volcanic damming of Yukon River and the maximum age of the Reid Glaciation, west-central Yukon: Canadian Journal of Earth Sciences, v. 41, no. 2, p. 151-164.

Jenks, M. D., and Bonnichsen, B., 1989, Subaqueous basalt eruptions into Pliocene Lake Idaho, Snake River Plain, Idaho, *in* Chamberlain, V. E., Breckenridge, R. M., and Bonnichsen, B., eds., Guidebook to the geology of Northern and Western Idaho and surrounding area: Moscow, Idaho Geological Survey Bulletin 28, p. 17-34.

Jones, J. G., and Nelson, P. H. H., 1970, The flow of basalt lava from air into water—its structural expression and stratigraphic significance: Geological Magazine, v. 107, no. 1, p. 13-19.

Katoh, S., Danhara, T., Hart, W. K., and WoldeGabriel, G., 1999, Use of sodium polytungstate solution in the purification of volcanic glass shards for bulk chemical analysis: Nature and Human Activities, v. 4, p. 45-54.

Kilburn, C. R., 2000, Lava Flows and Flow Fields, *in* Sigurdsson, H., Houghton, B., McNutt, S. R., Rymer, H., and Stix, J., eds., Encyclopedia of volcanoes: San Diego, Academic Press, p. 291-305.

Kokelaar, P., 1986, Magma-water interactions in subaqueous and emergent basaltic volcanism: Bulletin of Volcanology, v. 48, no. 5, p. 275-289.

Kuntz, M. A., Champion, D. E., Spiker, E. C., and Lefebvre, R. H., 1986, Contrasting magma types and steady-state, volume-predictable, basaltic volcanism along the Great Rift, Idaho: Geological Society of America Bulletin, v. 97, p. 579-594.

Kurz, M. M., 1986, In situ production of terrestrial cosmogenic helium and some applications to geochronology: Geochimica et Cosmochimica Acta, v. 50, p. 2855.

Malde, H. E., 1991, Quaternary geology and structural history of the Snake River Plain, Idaho and Oregon, *in* Morrison, R. B., ed., Quaternary nonglacial geology: Conterminous U.S.: The Geology of North America: Boulder, Geological Society of America, p. 251-282.

Malde, H. E., and Powers, H. A., 1962, Upper Cenezoic stratigraphy of western Snake River Plain, Idaho: Geological Society of America Bulletin, v. 73, p. 1197-1220.

Maley, T. S., and Oberlindacher, P., 1994, Rocks and potholes of the Big Wood River, South-Central Idaho, Idaho Geologic Survey Information Circular 54: Moscow, Idaho Geologic Survey, 41 p.

Mamyrin, B. A., and Tolstikhin, L. N., 1984, Helium isotopes in nature: Amsterdam, Elsevier, 273 p.

McElhinny, M. W., 1973, Palaeomagnetism and plate tectonics, Cambridge Earth Science Series: London, Cambridge University Press, 358 p.

McKee, E. D., Hamblin, W. K., and Damon, P. E., 1968, K-Ar Age of lava dam in Grand Canyon: Geological Society of America Bulletin, v. 79, p. 133-136.

Mertzman, S. A., 2000, K-Ar results from the southern Oregon-northern California Cascade Range: Oregon Geology, v. 62, no. 4, p. 99-122.

Newcomb, R. C., 1969, Effect of tectonic structure on the occurrence of ground water in the basalt of the Columbia River Group of The Dalles area Oregon and Washington, U.S. Geological Survey Professional Paper, p. 33.

Painter, C. S., Little, W. W., and Embree, G. F., 2005, Inverted valley development and geomorphic response of the Henry's Fork of the Snake River to episodic basalt damming, Mesa Falls Recreation Area, Caribou-Targhee National Forest, Idaho: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 463.

Pedersen, G. K., Larsen, L. M., Pedersen, A. K., and Hjortkjær, B. F., 1998, The syn-volcanic Naajaat lake, Paleocene of West Greenland: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 140, no. 1-4, p. 271-287.

Plumley, P. S., 1986, Volcanic stratigraphy of The Hole in the Ground area, Owyhee Plateau, southeastern Oregon [M.S. thesis]: Moscow, University of Idaho, 161 p.

Reheis, M. C., Stine, S., and Sarna-Wojcicki, A. M., 2002, Drainage reversals in Mono Basin during the late Pliocene and Pleistocene: Geological Society of America Bulletin, v. 114, no. 8, p. 991-1006.

Russel, I. C., 1905, Preliminary report on the geology and water resources of central Oregon: U.S. Geological Survey Bulletin 252, p. 138.

Sherrod, D. R., Taylor, E. M., Ferns, M. L., Scott, W. E., Conrey, R. M., and Smith, G. A., 2004, Geologic map of the Bend 30- × 60-minute quadrangle, central Oregon: U.S. Geological Survey Geologic Investigations Series Map I-2683, scale 1:100,000, 2 sheets, 49 p. text.

Shoemaker, K. A., 2004, The tectonomagmatic evolution of the Late Cenezoic Owyhee Plateau, northwestern United States [Ph.D. thesis]: Oxford, Miami University, 288 p.

Shoemaker, K. A., and Hart, W. K., 2002, Temporal controls on basalt genesis and evolution on the Owyhee Plateau, Idaho and Oregon *in* Bonnichsen, B., White, C. M., and McCurry, M., eds., Tectonic and Magmatic Evolution of the Snake River Plain Province: Idaho Geological Survey Bulletin 30, p. 313-328.

Smith, G. A., 1986, Stratigraphy, sedimentology, and petrology of Neogene rocks in the Deschutes basin, central Oregon: A record of continental-margin volcanism and its influence on fluvial sedimentation in an arc-adjacent basin [Ph.D. thesis]: Corvallis, Oregon State University, 464 p.

Smith, G. A., 1987, Geologic map of the Seekseequa Junction and a portion of the Metolius Bench quadrangles, Jefferson County, Oregon: Oregon Dept. of Geology and Mineral Industries, scale 1:24,000.

Smith, G. A., 1991, A field guide to depositional processes and facies geometry of Neogene continental volcaniclastic rocks: Oregon Geology, v. 53, no. 1, p. 3-20.

Stearns, H. T., 1931, Geology and water resources of the middle Deschutes River basin, Oregon: U.S. Geological Survey Water-Supply Paper 637-D, p. 125-220.

U.S. Department of the Interior, Bureau of Land Management, Lower Snake River District, Owyhee & Bruneau River systems guide, 65 p.

Wakabayashi, J., Page, W. D., Renne, P. R., Sharp, W. D., and Becker, T. A., 1994, Plio-Pleistocene volcanic rocks and incision of the North Fork Feather River, California: Tectonic implications, *in* Eighth International Conference of Geochronology, Cosmochronology, and Isotope Geology. Abstracts., p. 345.

Wakabayashi, J., and Sawyer, T. L., 2000, Neotectonics of the Sierra Nevada and the Sierra Nevada-Basin and Range Transition, California, with field trip stop descriptions for the northeastern Sierra Nevada, *in* Brooks, E. R., and Dida, L.

T., eds., Field guide to the geology and tectonics of the northern Sierra Nevada, California Division of Mines and Geology Special Publication 122, p. 173-212.

Walker, G. W., and McLeod, N. S., 1991, Geologic Map of Oregon: U.S. Geological Survey, scale 1:500,000, 2 sheets.

Zreda, M. C., and Phillips, F. M., 2000, Cosmogenic nuclide buildup in surficial materials, *in* Noeller, J. S., Sowers, J. M., and Lettis, W. R., eds., Quaternary geochronology: Methods and applications: Washington, D.C., American Geophysical Union, p. 61-76.

APPENDICES

Appendix A

Descriptions of Selected Hand Samples

Bogus Point Lava

OWY-15
Sample is a grey, fine grained rock having a groundmass of dark grey and white crystals < 0.75 mm in diameter. Rare ~1.5 mm euhedral pale green olivine phenocrysts make up < 1% of the rock.

OWY-20
Sample is a black, fine grained rock with orange secondary crystals in interstices and has burgundy-red crystals < 0.5 mm. (Sample is difficult to describe because it is small and coated with rock saw dust.)

OWY-38
Sample is a light grey, fine grained rock with white crystals that are ~0.5 mm and black crystals that are < 0.5 mm. Orange secondary crystals < 0.5 mm exist where weathered. Olive, light green, yellow, and orange crystals are ~0.5 mm in length.

Bogus Rim Lava

OWY-39
Sample is a grey, fine grained rock with a felty texture having a few subhedral to anhedral phenocrysts of plagioclase. Plagioclase phenocrysts 0.3–0.5 mm in length make up ~1% of the rock. Olivine phenocrysts are also ~1% of the rock and are light pale green, commonly < 0.4 mm, and rarely ~1 mm in diameter.

OWY-30
Sample is a grey, fine grained rock with a felty texture having a few subhedral to anhedral phenocrysts of plagioclase. Plagioclase crystals are < 3% of the rock, are usually < 0.5 mm, and rarely occur as ~1 mm long platy crystals. Olivine also constitutes < 3% of the rock and occurs as pale green crystals < 0.5 mm in length.

Clarks Butte Lava

OWY-26
Sample is a dark grey rock having a fine grained groundmass and vesicles that are partly to completely filled with white and tan secondary minerals. Plagioclase phenocrysts constitute < 3% of the rock and occur as laths ≤ 0.5 mm in length. Rare euhedral laths of plagioclase are 1 mm long. Olivine phenocrysts are tan-olive to brown

to red-brown in color and are usually < 1 mm in diameter. Rare 2 mm phenocrysts do exist. Olivine phenocrysts appear to make up < 10% of the rock but could exist in much greater abundance due to the crystals' dark color making them difficult to recognize.

OWY-27
Sample has a fine grained, dark grey groundmass. Olivine phenocrysts are light pale green to brown to red and most commonly red and are usually < 1 mm in diameter but occasionally 2–2.5 mm. Olivine phenocrysts vary in abundance from ~5–15% depending on location within the sample. Most plagioclase phenocrysts occur as subhedral to euhedral crystals < 1 mm in diameter but occasional 2–3 mm laths and plates exist. Plagioclase phenocrysts make up < 5% of the rock.

Upper AM-PM Lava

OWY-21A
Sample is a fine grained, grey rock. Euhedral plagioclase phenocrysts that are 1.5 mm in diameter make up < 5% of the rock. Pale green to red anhedral phenocrysts of olivine that are < 1 mm in diameter constitute ~15% of the rock.

OWY-35
Sample is a dark grey, fine grained rock. Subhedral to anhedral ~1 mm plagioclase pehocrysts constitute ~10% or less of the rock. Subhedral olivine phenocrysts are usually < 1 mm, but sometimes ~1.5 mm, and make up 10-15% of the rock

OWY-37
Sample is a dark grey fine grained rock with abundant subhedral 1.5–2 mm pale green to yellow olivine phenocrysts that make up 20–30% of the rock. Platy and shiny plagioclase phenocrysts are ~1 mm long, show good cleavage, and are ~10–20% of the rock.

Saddle Butte Lava

OWY-12
Sample is a medium grey, fine grained rock. White crystals < 0.5 mm in diameter are common. Subhedral very pale light green to yellow (olivine?) phenocrysts are rare (< 2% of the rock) and are < 0.5 mm in diameter.

OWY-13
Sample is a medium grey, fine grained rock. Nearly all the yellow to olive brown olivine phenocrysts are < 0.3 mm in diameter but rare (< 1% of the rock) subhedral 1 mm phenocrysts do exist.

OWY-16
Sample is a medium grey, fine grained rock having white crystals < 0.5 mm in diameter. Many pale green crystals are < 0.5 mm and some ~0.5 mm in diameter appear to be olivine crystals.

OWY-34
Sample is a fine grained, grey rock (having a felty looking texture?) with a groundmass of white, grey, and olive green crystals < 0.25 mm in diameter. Occasional bright green phenocrysts of olivine are 1.5–2 mm in diameter make up < 1% of the rock.

West Crater Lava

OWY-14
Sample is a dark grey, fine grained rock with abundant fresh phenocrysts of plagioclase and slightly altered olivine. Plagioclase phenocrysts are 25–35% of the rock while olivine phenocrysts constitute < 10%. Euhedral plagioclase laths show twinning and range up to 1 by 10 mm in size, though are more commonly ~0.5 by 3–4 mm. Anhedral to subhedral tabular plagioclase crystals are up to 4 by 5 mm in size, though more commonly are 2 by 3 mm. Olivine occurs as olive to brown anhedral crystals up to ~3–4 mm but more commonly 2–3 mm in diameter. Orange and tan secondary minerals occupy space in vesicles.

OWY-22
Sample is a medium grey, fine grained rock with abundant fresh phenocrysts of olivine and plagioclase and a diktytaxitic texture. Brilliant pale green anhedral phenocrysts of olivine range up to 6 mm in diameter but are more commonly 4 mm. Olivine phenocrysts make up ~20% of the rock. Euhedral to subhedral phenocrysts of plagioclase occur as laths up to 0.5 by 4 mm in size and tabular crystals up to 3 by 4 mm. Tabular crystals can show striations and laths show twinning. The rock is ~15% plagioclase phenocrysts.

OWY-23
Sample is a medium grey, fine grained diktytaxitic rock with abundant fresh phenocrysts of olivine and plagioclase. Olivine occurs as brilliant pale green, subhedral to anhedral crystals up to 5 by 6 mm in size. Olivine phenocrysts constitute 20% of the rock. Tabular plagioclase crystals are up to 5 mm in diameter and laths are 0.5 by 4 mm in size. Tabular crystals show striations and laths show twinning. Plagioclase phenocrysts make up 10–15% of the rock.

OWY-31
Sample is a dark grey, fine grained rock that has black prismatic crystals that cluster around and project into vesicles. Olivine phenocrysts make up 15% of the rock, are 1–4 mm in diameter, and yellow-green to yellow in color. Plagioclase comprises 10–15% of

the rock and occurs as tabular crystals up to 3 by 4 mm or laths 0.5 by 3 mm. Tabular crystals dominate.

Appendix B

Samples Collected

Sample number	Site number[†]	Sample type	UTM coordinates[‡] East (m)	UTM coordinates[‡] North (m)	Elevation (ft)	Lava flow	Location, sample, or site description
OWY-1	7-28-05-2-1	H	11443475	4768813	N.D.	BP?	Piece of grey boulder red sediments under paleochannel sediment lens
OWY-2	7-28-05-2-2	H, x	11443475	4768813	N.D.	SB	Presumed SB under paleochannel sediment lens
OWY-3	7-29-05-1-1	H, x	11442543	4771679	N.D.	WC	2nd flow unit from top of WC at Bogus Falls
OWY-4	7-29-05-3-1	H, x	11442880	4772924	N.D.	BR?	Sample of boulder near edge of presumed landslide
OWY-5A	7-29-05-4-1	H	11441582	4773232	N.D.	?	Upper of two flow units of black, aphyric basalt at river level downstream of Dog Leg Bar
OWY-5B	7-29-05-4-2	H	11441582	4773232	N.D.	?	Lower of two flow units of black, aphyric basalt at river level downstream of Dog Leg Bar
OWY-6	7-31-05-1-1	H, x	11440623	4760406	N.D.	SB	Waterfall over SB at confluence of Granite Creek and river
OWY-7	7-31-05-1-2	H	11440380	4760326	N.D.	SB	SB tumulus in north fork of Granite Creek
OWY-8	7-31-05-2-1	H	11438847	4759466	N.D.	SB	SB tumulus on west side of Tub Springs road near trough
OWY-9	8-16-05-1-1	H, x	11440592	4763834	3558	BP?	Grey “car flow” on the way to Sand Spring
OWY-10	8-16-05-2-1	H	11441563	4765061	3613	?	“Knob flow” on the top of round vent-like kipuka in 2nd SB advance
OWY-11	8-16-05-3-1	H, x	11442234	4764477	3559	?	Sample of lava pillows in top of Hill 3562
OWY-12	8-16-05-4-1	H, x, Ar	11441534	4762229	N.D.	SB	Lower of two flow units of 1st SB flow which underlies 2nd advance, location from GIS not GPS
OWY-13	8-16-05-5-1	H, x, Ar	11441458	4762257	3379	SB	2nd SB advance
OWY-14	8-17-05-1-1	H, x, Ar	11444927	4769569	3495	WC	WC “tin can site”
OWY-15	8-17-05-2-1	H, x	11444712	4769326	3554	BP	Grey flow of Bogus Grade south of parking spot
OWY-16	9-9-05-1-1	H, x	11443316	4768607	3218	SB	Lowest flow unit of 2nd SB at downstream most point, across from paleochannel sed lens
OWY-17	9-10-05-1-1	H, x	11442272	4762253	3375	SB	Fluvially overtopped SB(?) on river right at mouth of White Rock Creek

Sample number	Site number†	Sample type	UTM coordinates‡ East (m)	UTM coordinates‡ North (m)	Elevation (ft)	Lava flow	Location, sample, or site description
OWY-18	9-12-05-1-1	H, x	11442135	4773255	3211	?	Odd spine that sticks up above surrounding overwashed bench just down from Dog Leg area
OWY-19	9-23-05-1-1	H, x	11441889	4772277	3226	WC?	Perched lava remnant in paleodrainage on river left, downstream from Bogus Falls, location from GIS not GPS
OWY-20	9-25-05-1-1	H, x	11443584	4774360	3659	BP	Grey lava with pillows rimrock on east side of canyon upslope from Airplane Point
OWY-21A	9-26-05-1-1	H, x	11458417	4784246	2975	CB?	First intra-canyon lava upstream from Birch Creek on river right
OWY-21B	9-26-05-2-1	H, x	11457463	4782980	2825	CB?	Third intra-canyon lava upstream from Birch Creek on river right
OWY-22	9-28-05-1-1	H, x, Ar	11442379	4771320	3247	WC	Uppermost WC flow unit just upstream (on river) of Bogus Falls
OWY-23	9-28-05-2-1	H, x, Ar	11442501	4771642	3236	WC	Base of Bogus Falls at Owyhee River
OWY-24	9-29-05-1-1	H, x	11442825	4775620	N.D.	SB	Highest intra-canyon lava on river left at Whistling Bird rapid, river left on Hoot Owl Spring drainage, location from GIS not GPS
OWY-25	11-11-05-1-1	H, x	11453622	4767501	4382	?	Southern edge of Bogus Rim north of Bogus Lake, location from GIS not GPS
OWY-26	11-11-05-2-1	H, x	11454129	4767313	4179	CB	Tumulus (of CB?) on south side of road below Bogus Rim
OWY-27	11-11-05-3-1	H, x	11456266	4767119	4220	CB	Large eleongate north-south tumulus (of CB?) that road splits
OWY-28	11-11-05-4-1	H	11453140	4766703	4120	?	Lava that makes a bench south of Bogus Lake
OWY-29	11-11-05-5-1	H	11452762	4767216	4109	?	Lava bench at same elevation across road to north of OWY-28
OWY-30	11-11-05-6-1	H, x, Ar	11450788	4766458	4109	BR	Basalt at (Bogus?) rim where road reaches cattle guard at rim top above Bogus Creek

Sample number	Site number†	Sample type	UTM coordinates‡ East (m)	UTM coordinates‡ North (m)	Elevation (ft)	Lava flow	Location, sample, or site description
OWY-31	11-12-05-1-1	H, x, Ar	11444361	4768220	3320	WC	WC at upstream most exposure, near Bed Springs Gate and trail to river
N.D.	05-07-06-01-1	H	11441589	4760018	3333	N.A.	River right, just upstream of 1st SB advance, possible sediments impounded in front of SB dam
OWY-32	05-07-06-02-1	H	11442262	4762242	3403	SB	Four pieces of SB lava at mouth of White Rock Creek
N.D.	N.A.	H	11442941	4763117	3328	N.A.	Sample of fine seds exposed in east valley wall across from Virgin Bar Camp
OWY-33	05-08-06-3-1	H	11443498	4767943	3313	SB	Discontinuous outcrops of (SB?) lava in apparent kipuka of Tertiary sediments
OWY-34	5-9-6-1-1	H	11442617	4768461	3216	SB	River right, downstream of Goslings Leap camp, near paleochannel sediment lens
OWY-35	05-10-06-1-1	H, Ar	11442847	4775644	3178	CB?	Upper lava outcrop at Whistling Bird rapid, downstream side of Hoot Owl Spring drainage
OWY-36	05-10-06-1-2	H, Ar	11443022	4775740	3023	WC	Lower lava at Whistling Bird rapid, downstream side of Hoot Owl Spring drainage
OWY-37	N.A.	H	N.D.	N.D.	N.D.	CB?	Jim's Hole in the Ground Lava, collected 5/10/2006, ~100 ft above river, river left, just downstream from ranch house; T 27S R42E Sect 21 SW1/4
OWY-38	8-16-06-3-1	H	11444753	4769471	3700	BP	Grey lava of Bogus Point at top of grade, broken p-mag cores and weathering rind of blocks exposed in road cut
OWY-39	8-17-06-3-1	H	11450881	4766071	3779	BR	Bogus Rim where Bogus Creek spills over BR lava, 2 p-mag cores drilled, very fresh and solid rock
650B6	8-16-06-1	P-mag	1144559	4770177	3315	WC	Bed of Bogus Creek, surface has been eroded by creek but not polished, 20 × 8 m flat, stable surface, no pahoehoe ropes

Sample number	Site number[†]	Sample type	UTM coordinates[‡] East (m)	UTM coordinates[‡] North (m)	Elevation (ft)	Lava flow	Location, sample, or site description
658B6	8-16-06-2	P-mag	11444800	4769575	3551	WC	Road downvalley from Bogus Creek Cabin and near Tin Can site
666B6	8-16-06-3	P-mag	11444753	4769471	3700	BP	In road cut at Bogus Point, also collected OWY-38 here
674B6	8-16-06-4	P-mag	11450202	4766453	3964	WC	Airstrip road as it crosses WC lava, 1/4 mi from grade that climbs up onto Bogus Rim
682B6	8-17-06-1	P-mag	11430902	4758892	3729	SB	Bench Mark 3681 along Tub Springs Road
690B6	8-17-06-2	P-mag	11439756	4765110	3629	SB	Tub Springs road at Ryegrass Creek
698B6	8-17-06-3	P-mag	11450881	4766071	3779	BR	Bogus Rim where Bogus Creek falls spills over Bogus Rim lava
706B6	8-17-06-4	P-mag	11457991	4768480	4150	CB	~45 m east of road 7304-0-BO, east of Bogus Bench
090506-17	N.A.	CE	11442702	4774036	3078	WC	River polished lava dam (Plane Viewing Point)
060506-18	N.A.	CE	11442695	4774058	3072	WC	River polished lava dam (Plane Viewing Point)
060506-19	N.A.	CE	11442702	4774058	3072	WC	River polished lava dam (Plane Viewing Point)
060506-20	N.A.	CE	11442702	4774036	3078	WC	River polished lava dam (Plane Viewing Point)
060506-21	N.A.	CE	11442702	4774058	3072	WC	River polished lava dam (Plane Viewing Point)
042904-17	N.A.	CE	N.D.	N.D.	N.D.	WC	T5 WC lava flow (Lambert flow)
042904-18	N.A.	CE	N.D.	N.D.	N.D.	WC	T5 WC lava flow (Lambert flow)
042904-19	N.A.	CE	N.D.	N.D.	N.D.	WC	T5 WC lava flow (Lambert flow)
042904-20	N.A.	CE	11441579	4773034	N.D.	WC	T5 WC lava flow (Lambert flow)
042904-21	N.A.	CE	11441579	4773034	N.D.	WC	T5 WC lava flow (Lambert flow)
042904-22	N.A.	CE	11441579	4773034	N.D.	WC	T5 WC lava flow (Lambert flow)
042904-23	N.A.	CE	11441448	4773103	N.D.	N.A.	T4 Dogleg Bar
042904-24	N.A.	CE	11441448	4773103	N.D.	N.A.	T4 Dogleg Bar
042904-25	N.A.	CE	11441448	4773103	N.D.	N.A.	T4 Dogleg Bar
042904-26	N.A.	CE	11441335	4773092	N.D.	N.A.	T3 Dogleg Bar
042904-27	N.A.	CE	11441335	4773092	N.D.	N.A.	T3 Dogleg Bar
042904-28	N.A.	CE	11441335	4773092	N.D.	N.A.	T3 Dogleg Bar

Sample number	Site number†	Sample type	UTM coordinates‡		Elevation (ft)	Lava flow	Location, sample, or site description
			East (m)	North (m)			
042904-29	N.A.	CE	11441335	4773092	N.D.	N.A.	T3 Dogleg Bar
042904-30	N.A.	CE	11441366	4772937	N.D.	N.A.	T2 Dogleg Bar
042904-31	N.A.	CE	11441366	4772937	N.D.	N.A.	T2 Dogleg Bar
042904-32	N.A.	CE	11441366	4772937	N.D.	N.A.	T2 Dogleg Bar
042904-33	N.A.	CE	11442148	4772952	N.D.	WC/BR?	WC lava flow (Lambert flow), or Qls overlying?
042904-34	N.A.	CE	11442148	4772952	N.D.	WC/BR?	WC lava flow (Lambert flow), or Qls overlying?
043004-35	N.A.	CE	11441593	4772880	N.D.	N.A.	T1 Dogleg Bar
043004-36	N.A.	CE	11441593	4772880	N.D.	N.A.	T1 Dogleg Bar
043004-37	N.A.	CE	11441593	4772880	N.D.	N.A.	T1 Dogleg Bar
043004-38	N.A.	CE	11441593	4772880	N.D.	N.A.	T1 Dogleg Bar

Note: N.D.—no data. N.A.—not applicable. Abbreviations for type of sample: H—hand sample; x—thin section; Ar—^{40}Ar-^{39}Ar sample; P-mag—sample for paleomagnetic studies; CE—cosmogenic exposure dating sample. Abbreviations for lava flows: BP—Bogus Point; SB—Saddle Butte; WC—West Crater; CB—Clarks Butte; BR—Bogus Rim; RB—Rocky Butte, a question mark symbol indicates uncertainty. GIS—Geographic information system; GPS—Global positioning system; T5 through T1 refer to terrace level five through one at Dog Leg Bar; Qls—Quaternary landslide.

†Site number is specific to field notes of Brossy and refers to date (in day-month-year format), site visited, and sample taken at that site.

‡Geographic coordinates are in UTM NAD 27 zone 11.

Appendix C

Paleomagnetic Data from the Jordan Valley Area

Unit name	Sample no.	Lat. (°N)	Long. (°W)	N/No	Exp.	I (°)	D (°)	α95 (°)	k	R	Plat. (°)	Plong. (°)
<u>Clarks Butte lava field</u>												
West rootless vent	706B6	43.070	242.484	8/8	20	71.6	13.7	1.5	1411	7.99504	74.1	271.1
<u>West Crater lava field</u>												
In Bogus Creek	650B6	43.084	242.319	8/8	20	65.3	348.5	1.6	1184	7.99409	80.8	184.6
Near Bogus Point	658B6	43.079	242.322	8/8	20	63.8	350.5	1.3	1701	7.99589	82.8	174.5
On Airstrip Road	674B6	43.051	242.389	8/8	20	62.8	348.2	1.0	3175	7.99780	81.4	164.4
<u>Saddle Butte lava field</u>												
On Hwy 78	428B4	42.957	241.951	7/8	20	71.8	353.0	1.3	2016	6.99702	75.6	226.3
BM 3681 on Tub Springs Road	682B6	42.982	242.253	8/8	20	69.8	352.4	1.5	1314	7.99467	78.2	219.7
Ryegrass Creek	690B6	43.038	242.260	PSP	PSP	~69	~353	PSP	PSP	PSP	PSP	PSP
<u>Rocky Butte (Lava Butte) lava field</u>												
North side of canal	436B4	42.913	242.594	10/10	20	72.2	334.5	1.1	1942	9.99537	68.5	203.3
<u>Bogus Point lava flow</u>												
Bogus Point	666B6	43.078	242.321	8/8	15	−52.6	185.4	1.2	2150	7.99674	−79.2	217.4
<u>Bogus Rim lava flow</u>												
Near Bogus Falls	698B6	43.048	242.397	PSP	PSP	~−68	217	PSP	PSP	PSP	PSP	PSP

Note: Sample no.—alphanumeric site identifier used by Duane Champion; Lat. and Long.—the latitude and longitude of the site locations in decimal degrees; N/No—the number of cores used compared with the number of cores originally collected at the site; Exp.—the strength of peak cleaning field in milliTeslas; I—remanent inclination; D—remanent declination; α95—95% confidence limit about the mean direction; k—the estimate of the Fisherian precision parameter; R—the length of resulting vector; Plat. and Plong. —°N and °W in decimal degrees of virtual geomagnetic pole calculated from site mean direction; BM—benchmark; PSP—planes solution was pending at time of writing.

Appendix D

Evidence of Fluvial Overtopping of Lava Flows

Site or location	UTM coordinates†		Elevation‡ (ft)	Clast size	Comments
	North (m)	East (m)			
7-18-05-1	4761813	440501	N.D.	Boulders, cobbles	Deposit very near the cliff edge
7-18-05-3	4760357	440720	N.D.	≤ 1.5 m	Deposit very near the cliff edge
7-28-05-4	4770547	442631	N.D.	0.5–1.3 m	Deposit is ~100 m^2 in area
7-28-05-4b	4770628	442546	N.D.	0.3–0.9 m	Deposit is ~20 m^2 in area
7-28-05-4c	4770746	442570	3308	N.A.	Deposit is ~45 m^2 in area, 1-2 cm chips of orange silicic material from Tertiary sediments here
7-29-05-2	4771698	442742	N.D.	Cantaloupe	Not certain of this deposit, could be *in situ* basalt in the Tertiary sediments
9-8-05-2	4763063	440997	N.D.	< 0.5 m	Boulders probably weathering out of a buried terrace that is exposed at break in slope
9-8-05-4	4765848	443062	3375	Watermelon, gravel	Deposit is ~15 m^2 in area
9-9-05-2	4766249	443080	3344	Watermelon	Only a few clasts here
9-10-05-1	4762253	442272	3375	~1 m	Lots of well rounded-subrounded boulders and cobbles here, some chert cobbles
9-26-05-1	4784246	458417	2975	Boulders	Approximately 2 m of fluvial boulders on top of lava flow
9-8-05-3	4762844	441855	N.D.	~0.3 m Blocks, sand	Angular blocks, could be from frost wedging and frost heave
9-8-05-3	4762788	441896	N.D.	~0.3 m Blocks, sand	Angular blocks, could be from frost wedging and frost heave
Near Lisa's paleochannel	4770630	442549	3323	< 0.75 m	Deposit is ~300 m^2 in area, most boulders are ~0.5 m diameter
Lisa's paleochannel	4770965	442550	3275	0.3–1 m	Channel begins near river km 41.5
River kilometer 43	4771095	442211	3283	Cobbles	Chips of Tertiary sediments and cobbles of Tertiary on top of lava
East of Bogus Falls	4771661	442771	3272	N.A.	Chips of Tertiary sediments
North of Bogus Falls	4771798	442620	3295	N.A.	Chips of Tertiary sediments that could be of colluvial origin
Granite Creek	4760550	440516	N.D.	Boulders	Deposit very near the cliff edge
East of Pruitt's Castle	4769288	443356	N.D.	Boulders	Rounded to subrounded

Site or location	UTM coordinates†		Elevation‡ (ft)	Clast size	Comments
	North (m)	East (m)			
East of Pruitt's Castle	4769232	443519	N.D.	Boulders	Rounded to subrounded
Above Dog Leg Bar	4773256	442301	N.D.	Cobbles, boulders	Rounded clasts; deposit possibly landslide related?
Airplane point, RL	4773916	442576	N.D.	~1.5 m	1.5 m thick deposit, being covered by colluvium and talus
Airplane point, RR	4774207	442717	N.D.	Boulders	A few boulders near cliff edge
Airplane point, RR	4774061	442713	N.D.	N.A.	Fluted and sculpted basalt
Airplane point, RR	4774012	442744	N.D.	N.A.	Fluted and sculpted basalt
Whistling Bird rapid, RL	4775674	442966	N.D.	Boulders	Boulders on surface of flow
Whistling Bird rapid, RL	4775606	442941	N.D.	Boulders	Boulders on surface of flow
AM-PM camp, RR	4775748	443205	N.D.	Boulders, cobbles	Boulders, cobbles on surface of flow

Note: N.D.—no data; N.A.—not applicable; RL—river left; RR—river right.

†Coordinates are UTM NAD 27 zone 11 and were obtained via global positioning system or digitized 1:24,000 scale topographic maps viewed in ArcMap software.

‡Elevation was obtained via global positioning system.