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Pleistocene cataclysmic flooding along the Big Lost River, east central Idaho

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ABSTRACT

Relationships between cataclysmic flood–generated landforms and flood hydraulics were investigated along Box Canyon, an 11 km long bedrock gorge of the lower Big Lost River. Geomorphic mapping along Box Canyon indicates that a cataclysmic flood completely inundated the gorge, resulting in large-scale erosional and depositional features on the adjacent basalt upland. Step–backwater hydraulic modeling indicates that a discharge of 60,000 $m^3 s^{-1}$ was required to produce the geologic paleostage evidence. Maximum stream power per unit area of bed locally attained values of 26,000 W m^{-2} during the peak, ranking the Big Lost River flood third, in terms of power, behind the famous Missoula and Bonneville floods. The spatial distribution of unit stream power indicates that bedrock erosion and boulder deposition on the basalt upland adjacent to Box Canyon were governed primarily by decreasing unit stream power and/or fluctuating unit stream power gradients. A preliminary depositional threshold for the largest flood boulders defines a lower limit of flood power required to sustain boulder transport along this bedrock fluvial system. Ultimately, hydrodynamic controls on Box Canyon flood erosion and deposition derive from the irregular volcanic rift topography of the eastern Snake River Plain. Outburst floods from a glacial lake in headwater regions during the late Pleistocene may have induced the torrential discharges within Box Canyon.

Introduction

Climatic fluctuations and glaciation during the Pleistocene led to widespread fluvial adjustments through changes in water discharge and sediment load. In certain environments, glaciation-induced cataclysmic flooding created spectacular geomorphic features over large tracts of landscape. The effects of such floods have been preserved and described in several areas of the northwestern United States; important examples include the Lake Bonneville and Missoula flows, first noted by Gilbert (1878) and Bretz (1923), respectively, and further studied by Malde (1968), Baker (1973a), and numerous others. Bedrock gorges in the basalt of the Snake River Plain and Columbia Plateau provide ideal opportunities to study the effects of late Pleistocene extreme floods, and in particular, flood forces in rigid-boundary channels.

Distinctive landforms in and adjacent to Box Canyon, an 11 km long bedrock gorge of the Big Lost River (Fig. 1), are rare in the volcanic rift zone topography characteristic of the eastern Snake River Plain. A flood-flow origin for the Box Canyon features was first suggested by Baker (1984, p. 89), and new geomorphic evidence indicates that a flood or floods completely inundated Box Canyon, resulting in substantial flow on the adjacent basalt uplands. The current analysis considers the relationship between erosional and depositional features and the flow conditions during Big Lost River flooding.

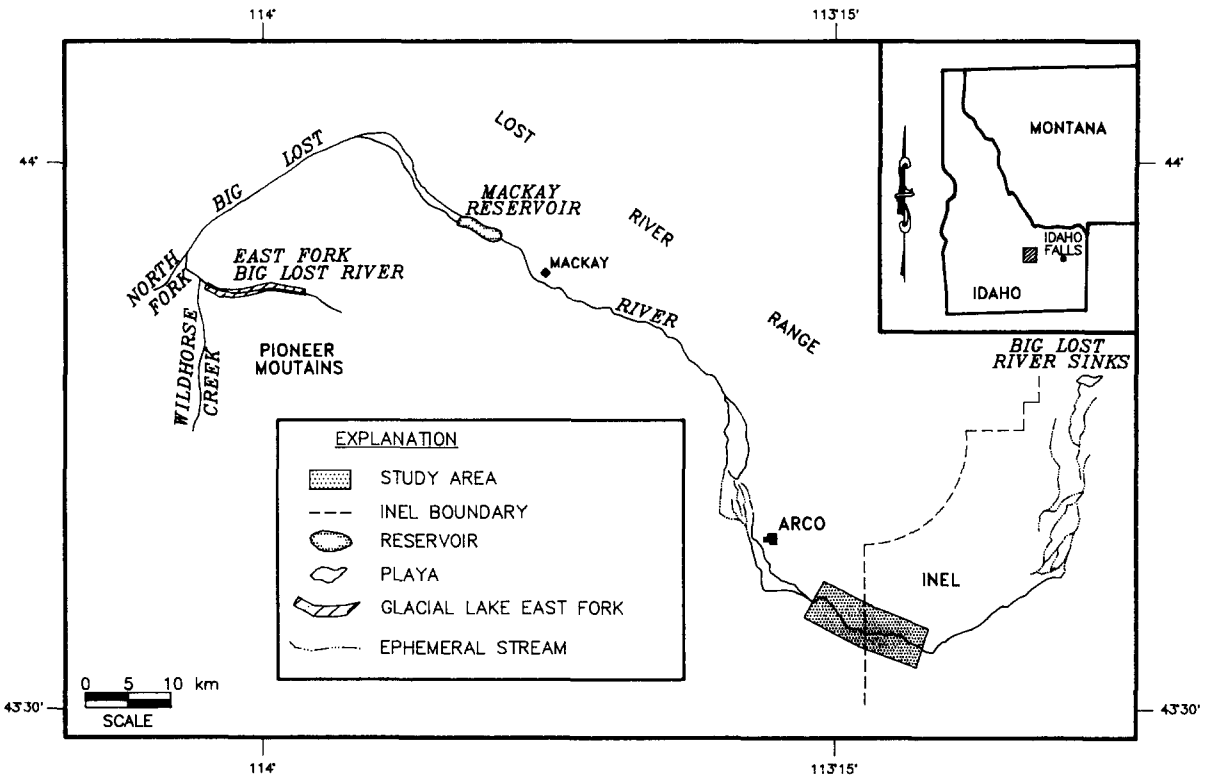


Fig. 1. Location map of the Big Lost River extending from the headwaters in the Pioneer Mountains to the Big Lost River Sinks at the Idaho National Engineering Laboratory (INEL). Box Canyon study reach is shaded.

Study reach

The Big Lost River drains 3800 km^2 above Arco, Idaho (Fig. 1). The river emerges from the Pioneer Mountains and Big Lost River Valley onto the eastern Snake River Plain as a series of alluvial braided channels. On the Snake River Plain, the river has incised the Box Canyon gorge. Upon exiting the gorge, the river turns north, crossing and ending in thick alluvial deposits on the Idaho National Engineering Laboratory (INEL). Modern streamflow is usually diverted for irrigation or lost by infiltration before reaching Box Canyon. The study area was in the vicinity of Box Canyon, a rectangular bedrock channel incised into columnar-jointed basalt flows of the Snake River Plain. In general, the canyon is sinuous and has a relatively constant channel geometry with an average top width and depth of 40 m and 23 m, respectively, before expanding onto the alluvial deposits near the western boundary of the INEL.

Flood sedimentation and erosion in bedrock river channels

Large floods in bedrock gorges produce a unique fluvial environment where distinctive geomorphic features develop in response to very high relative roughness, flow velocities, and stream power (Baker, 1984). Flood-induced sedimentation in bedrock channels consists of gravel and boulder deposits, at scales not normally associated with fluvial transport. Under certain bedrock flood conditions, boulders may be transported as bedload and even in temporary suspension (Komar, 1988). Large floods in bedrock channels can lead to

intense bedrock erosion as a result of macro-turbulent flow phenomena such as cavitation.

Evidence for cataclysmic flooding of the Big Lost River

Large-scale fluvial landforms were mapped along the study reach using aerial photographic interpretation and field observation. The landforms along Box Canyon provide strong evidence for cataclysmic flooding on the Big Lost River (Fig. 2). Some of the most spectacular flood features are erosional in nature such as cataracts, scabland topography, a loess scarp, and a low, streamlined loess-capped hill. Depositional features are more widespread throughout the study reach, and consist primarily of large bars of basaltic boulders, and small accumulations of exotic rocks known as erratics.

Erosional features

Cataracts

Cataracts are horseshoe-shaped bedrock erosional features that are interpreted as bedrock knickpoints that migrated headward during the flood. Along Box Canyon, the cataracts have vertical faces that range from less than 1 m to more than 9 m high and occur as plucked embayments marginal to the gorge and on the adjacent basalt upland. Lost Moon Cataract (LMC in Figs. 2 and 3) is one of the largest identified cataracts, bounding the northern side of the streamlined hill. Lost Moon Cataract has the typically associated features of plunge-pool, abandoned channel, and boulder accumulations downstream of its vertical face.

Scabland topography

Sizable tracts of scabland topography (basalt surfaces stripped of loess and soil; Bretz, 1923), exist on the uplands adjacent to Box Canyon. Within these scabland areas cataracts are abundant. Cataracts and scabland topography develop simultaneously once plucking and quarrying of the basaltic surface creates an initial cavity (Baker, 1973a)

Loess scarp

A scarp eroded into loess demarcates the edge of the scabland topography along the southern side of the Big Lost River (Fig. 2). The distinct, linear scarp extends for nearly 2 km, and separates thick (> 1m), light-colored loess from flood-scoured basalt bedrock. I interpret the loess scarp to represent the erosional limit of floodwaters. It helped define the flood peak water-surface profile during hydraulic modeling.

Streamlined loess hill

A low, streamlined loess-capped hill exists on the southern side of Box Canyon (SH-L, Fig. 2). Its smoothly tapered downstream tail (Fig. 3) formed as fluid flow split around the resistant upstream prow and rejoined on the downstream end, a shape that minimizes flow resistance (Baker, 1973b; Komar, 1983). Length and width of the streamlined hill are approximately 750 m and 400 m (length/width ratio of nearly 2), dimensions similar to the streamlined hills of the Channeled Scabland left by the Missoula Floods (Baker, 1973a).

Depositional features

Boulder bars

Boulder bars were deposited at sites of flow deceleration, such as on the insides of bends, downstream of cataracts, and on the basalt upland where obstructions caused flow separation. Big Lost River boulder bars are up to 300 m in length and 15 m in width, and those on the upland are shaped similarly to, although smaller than, the longitudinal bars found along the routes of the Missoula and Bonneville floods. Baker (1978b) describes this type of bar formation as requiring a strong longitudinal component of vortex flow over a planar surface.

Boulders found in flood bars along the Big

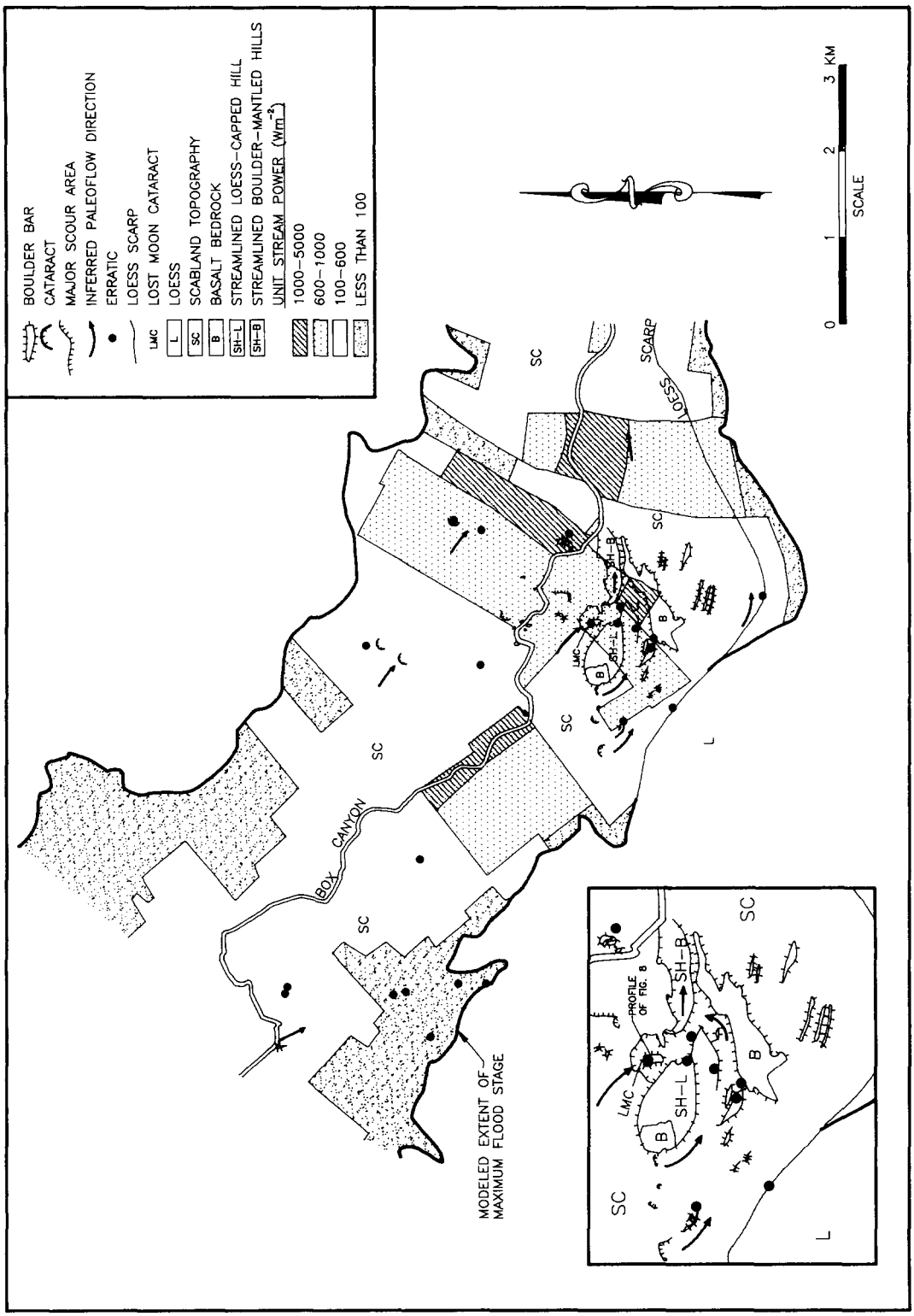


Fig. 2. Geomorphic map of cataclysmic flood features along Box Canyon with unit stream power isopleths during peak discharge superimposed. Mapping units are after Baker (1978a). Isopleths are angular due to modeling output format as subdivisions along a channel cross section. Flow in river from upper left to lower right. Enlargement is of area with most abundant and striking flood features.

Fig. 3. Oblique aerial photograph of the low, streamlined hill on the south side of Box Canyon, Big Lost River (SH-L, Fig. 2). Approximate dimensions of the streamlined feature are 400 m wide by 750 m long. View is upstream (NW) with the Arco Hills in the background. *LMC* denotes Lost Moon Cataract.

Lost River are primarily angular blocks (Fig. 4a), with clast diameters ranging up to 4.5 m in intermediate axis. They were probably introduced into the flow by plucking, a process facilitated by the abundant columnar joint planes within the basalt bedrock. Boulders within the bars are often imbricate (Fig. 4a) and armor the bar surfaces.

Erratics

While locally derived basalt comprises a majority of the boulders within the flood bars, well rounded, erratic clasts of banded augen gneiss and quartz monzonite are also present. The erratics are conspicuous because of their lighter color and great degree of rounding relative to the dark, angular basalt boulders within the bars (Fig. 4b). These erratic rocks are composed of exotic lithologies derived from the igneous and metamorphic terrain of the Pioneer Mountains (Wust and Link, 1988), located 100 km upstream of Box Canyon in the headwaters of the Big Lost River (Fig. 1). I believe the erratics were ice-rafted to their present locations along Box Canyon. Erratic clasts along the Box Canyon flood path are important in reconstructing the high water-surface of the flood. This is similar to the Missoula Flood, where ice-rafted erratics provide another piece of geomorphic evidence for constraining a water-surface profile.

Hydraulic analysis of Big Lost River flooding

Flood discharge

A major emphasis of this study was to evaluate quantitatively the flood in the vicinity of Box Canyon. Most importantly, ice-rafted erratics and scour features allow reconstruction of the water-surface profile at maximum stage. A peak flood discharge can then be estimated,

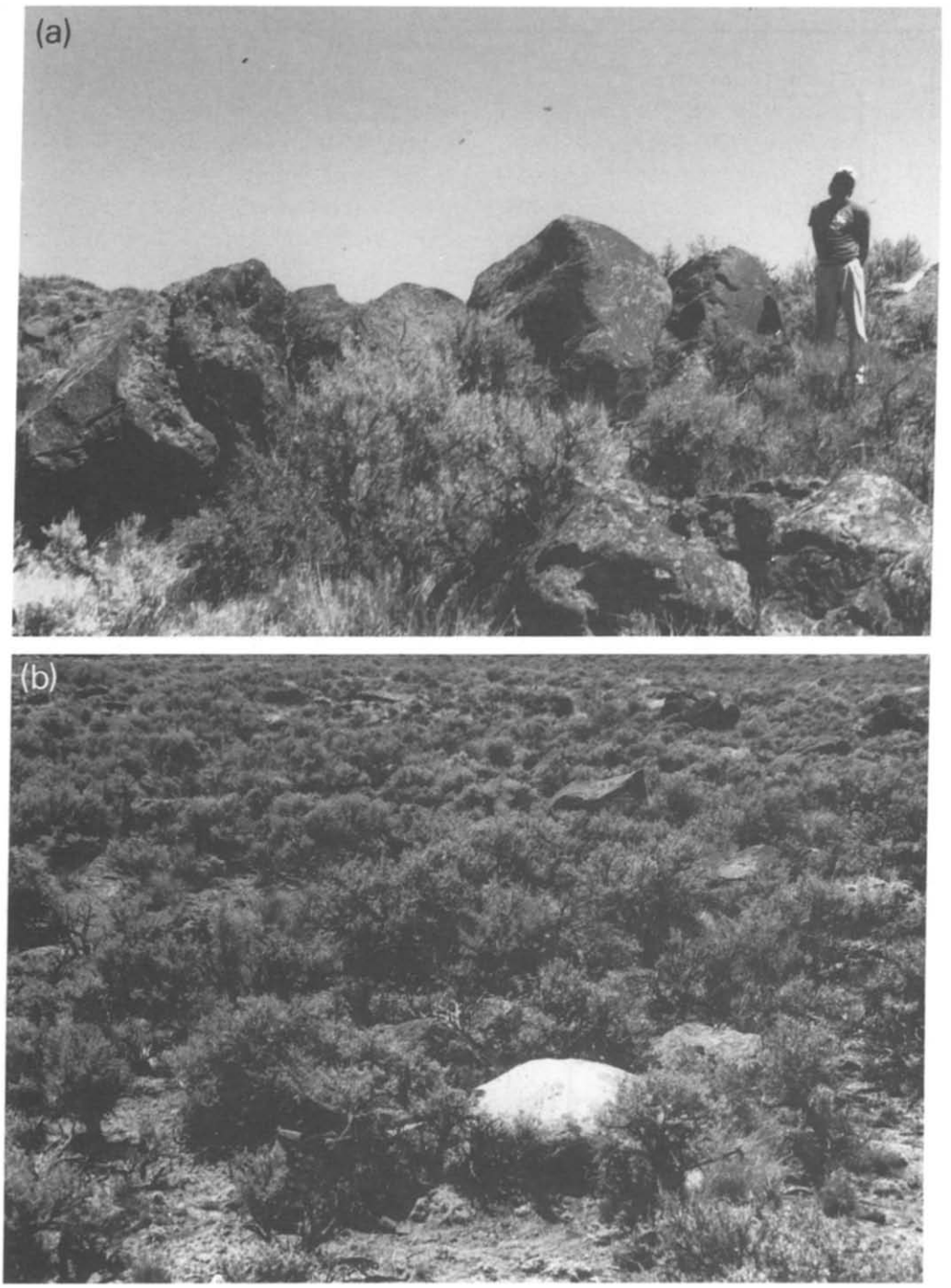


Fig. 4. (a) Basaltic flood boulders deposited in a bar within the abandoned channel of Lost Moon Cataract. The boulders are imbricate and have retained the angular form of columnar jointed basalt. The boulders were transported approximately 50 m after being plucked from the vertical face of Lost Moon Cataract. Person standing near boulder bar is 1.9 m tall. (b) Erratic flood boulder deposited near the boulder bar shown in (a). Note the prominent rounding and lighter color. Its exotic lithology matches igneous and metamorphic rocks in the Pioneer Mountains, located 100 km upstream. Cataclsymic flooding along the Big Lost River ice-rafted the erratics to existing locations along Box Canyon. Intermediate diameter of the erratic boulder is 1.2 m for scale.

along with numerous other hydraulic properties of the flood flow. The most useful evidences of maximum paleostage along Box Canyon are the highest-altitude erratics and the loess scarp. The erratics and loess scarp are minimum indicators of flow depth since some unknown depth of water was required to emplace the erratics and erode the loess scarp.

Peak discharge was calculated by the step-backwater method to compute an energy-balanced water-surface profile (Chow, 1959). A computerized version of this method (HEC, 1985) was applied to calculate the water-surface profiles for several discharges using 31 cross sections measured across Box Canyon and the adjacent uplands. The calculated profiles were compared to the field evidence of maximum stages to obtain an estimate of the peak discharge. This method has been successfully applied to several paleoflood studies within bedrock gorges of the Snake River Plain and Columbia Plateau (Jarrett and Malde, 1987; O'Connor and Baker, 1992), and is described more fully by O'Connor and Webb (1988). Manning's roughness coefficients (n) of 0.05 and 0.1 were assigned for flow within the channel and overbank areas, respectively. These values are consistent with those used by Jarrett and Malde (1987) for the Bonneville Flood, and by O'Connor and Baker (1992) for the largest Missoula Flood in similar joint-controlled basalt gorges. Coefficients of expansion and contraction were assigned 0.3 and 0.1, respectively, as recommended by HEC (1985).

Results of the modeling indicate that a peak discharge of 60,000 $m^3 s^{-1}$ is consistent with the high water indicators along Box Canyon (Fig. 5). For comparison, an estimated 3000 $m^3 s^{-1}$ is necessary to fill Box Canyon completely (Koslow and Van Haaften, 1986), and the maximum gaged flow at Arco, Idaho (2.5 km upstream) is 54 $m^3 s^{-1}$ for the period of record 1947 to 1989. Mean channel velocities during the 60,000 $m^3 s^{-1}$ flood peak ranged between 4 and 12 m s^{-1}, and calculated flow depths ranged from 9 to 31 m. During peak

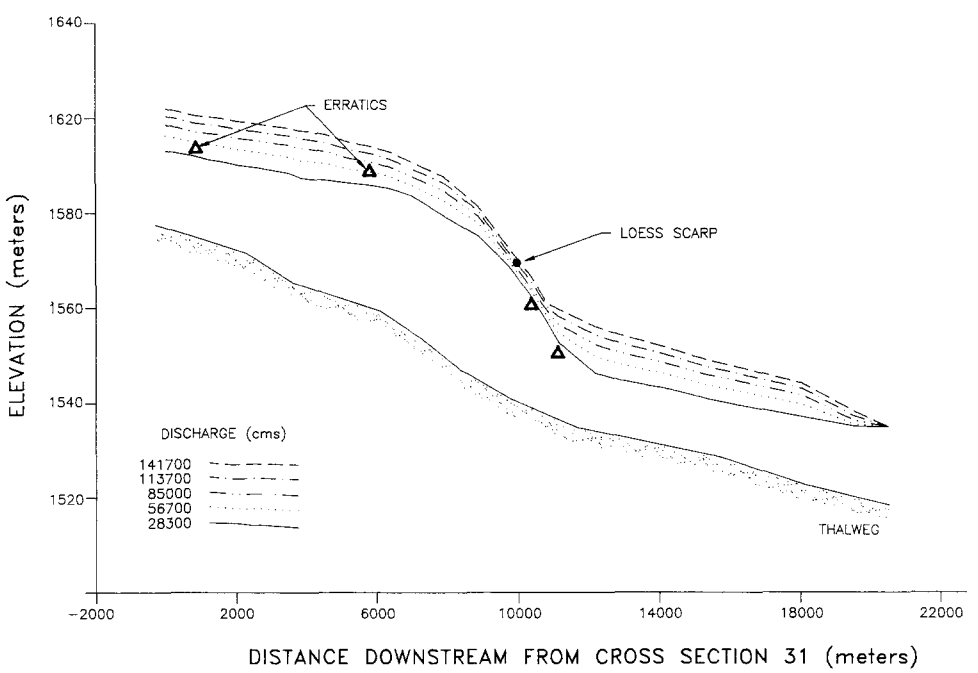


Fig. 5. Box Canyon water surface profiles for five discharge trials using HEC-2 step-backwater computer modeling program. A discharge of approximately 60,000 $m^3 s^{-1}$, constrained between the loess scarp and the highest erratic, generates the most reasonable profile for the Big Lost River cataclysmic flooding.

flooding, the local energy slopes were as high as 0.0093, and the present-day gorge conveyed between 25% and 42% of the total discharge. The present-day gorge acted as an inner channel during flooding with the total flood swath extending for over 2 km on either side of Box Canyon (Fig. 2). Froude numbers during the flood were in the subcritical domain, ranging from 0.5 to 0.9 within the steepest, narrowest section of the gorge. The reach of steepest water-surface gradient (Fig. 5) corresponds to the narrowest and steepest area of flow.

A sensitivity analysis was conducted to quantify the effect of Manning's n and the contraction/expansion coefficients on the computed water-surface profile. Varying n by a factor of $\pm 25\%$ causes only a 1.2% change in discharge, indicating that the roughness coefficient has a minimal effect on modeling results. Likewise, the modeled flow magnitude is relatively insensitive to varied contraction and expansion coefficients, which can be partly attributed to the constant flow width.

Unit stream power estimates

The step-backwater results allow for calculation of unit stream power magnitudes within the study reach. Unit stream power, as defined by Bagnold (1966), is the rate of energy expenditure per unit area of channel boundary. Since the total stream power per unit length scales with the discharge of a river, the stream power per unit area of bed, referred to hereafter as the unit stream power, is a better index of the power of a flood in terms of erosion and transport potential (Baker and Costa, 1987). The unit stream power is expressed as:

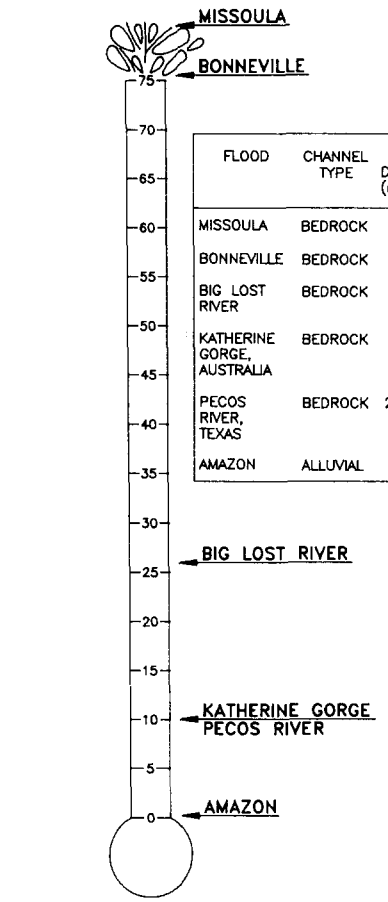
$$\omega = \gamma d S v \qquad (1)$$

in watts per square meter ($\mathrm{W\ m^{-2}}$), where γ is the specific weight of water, d is the flow depth, S is the energy slope, and v is the mean flow velocity.

The maximum unit stream power for Box Canyon gorge is estimated at 26,000 $\mathrm{W\ m^{-2}}$. This value is exceeded only by the two largest known terrestrial floods, the late Pleistocene Missoula and Bonneville floods (Fig. 6). The Big Lost River flow is the third largest known flood, in terms of unit stream power. Although greater depth of flow and flow velocity were attained during historic flooding of Katherine Gorge and the Pecos River, respectively (Fig. 6), the steeper gradient of the Big Lost River through Box Canyon, combined with its depth and velocity, translate into greater flood-derived energy. Unit stream power maximization for a given basin during flooding results from an ideal combination of gradient, flow depth, flow velocity, and the upstream drainage area (Baker and Costa, 1987). Despite the tremendous disparity in drainage areas and peak discharge between the Big Lost River flood and the Missoula/Bonneville floods, the unit stream power of the Big Lost River flooding was comparable, thus explaining the similarities in observed landforms produced as a result of all three floods.

Relationship of unit stream power to erosion and deposition

Within the reach for which I was able to make estimates, maximum unit stream powers during the flooding were attained within Box Canyon. These maximum values, however, cannot be readily related to erosional and depositional processes responsible for the plethora of out-of-channel features. Only on the uplands, where preserved erosional and depositional features resulted from more localized hydraulic conditions, is it possible to investigate the link between flood processes and local rates of energy expenditure. To help define controls on erosion and deposition associated with the Big Lost River flooding, spatial fluctuations in calculated flood power were superimposed over the geomorphic map of flood features (Fig. 2). The unit stream power was calculated for 8 to 13 lateral subdivisions of each Box Canyon cross section.



FLOOD	CHANNEL TYPE	PEAK DISCHARGE ($m^3 sec^{-1}$)	SLOPE	DEPTH (m)	VELOCITY ($m\ sec^{-1}$)	SHEAR STRESS (Nm^{-2})	FLOOD POWER (Wm^{-2})
MISSOULA	BEDROCK	$5x10^6$	$1x10^{-2}$	100	30	$1x10^4$	$3x10^5$
BONNEVILLE	BEDROCK	$9x10^5$	$4x10^{-3}$	63	26	$2.5x10^3$	$7.5x10^4$
BIG LOST RIVER	BEDROCK	$6x10^4$	$8x10^{-3}$	31	11.5	$2.3x10^3$	$2.6x10^4$
KATHERINE GORGE, AUSTRALIA	BEDROCK	$6x10^3$	$3x10^{-3}$	45	7.5	$1.5x10^3$	$1x10^4$
PECOS RIVER, TEXAS	BEDROCK	$2.7x10^4$	$3x10^{-3}$	30	12	$9x10^2$	$1x10^4$
AMAZON	ALLUVIAL	$3x10^5$	$1x10^{-5}$	60	2	6	12

FLOOD POWER–IMETER
(Watts/m^2) x 10^3

Fig. 6. Flood power–imeter comparing unit stream power values of the Big Lost River to other cataclysmic floods around the world. Maximum unit stream power of 26,000 W m^{-2} during Big Lost River flooding occurred within the Box Canyon gorge. Table modified from Baker and Costa (1987), and Baker and Kochel (1987).

The lower end of Box Canyon near INEL is the most intensely flood-modified portion of the study reach. The downstream end of Box Canyon is also the area of highest unit stream power values. While depositional features of bars and erratics are distributed throughout the length of the study area, erosional features are limited to the downstream portion, and particularly to the south side of Box Canyon. I believe that substantial flood flow exited the gorge at the 90° bend (upstream limit of the modeled river reach; Fig. 2), sculpting the landscape on the south side of Box Canyon.

Erosion

With few exceptions, cataract formation was restricted to areas of unit stream power in excess of 600 W m^{-2} during peak flooding (Fig. 2). Unit stream power of 600–5000 W m^{-2} was apparently sufficient to drive the headward recession of vertical basalt faces, forming the rugged topography and anastomosed scour patterns typically associated with cataracts. Flow modeling indicates that streamlining of the loess-capped hill took place subfluvially, under approximately 3 to 4 m of water and a unit stream power between 600 and 1000

Wm^{-2}. The loess cap present today suggests either post-flood accumulation, or only minimal erosion behind the protective basalt outcrop during flooding. Stripping of loess forming the linear-trending scarp occurred, as expected, at even lower unit stream power, in the 100 to 600 W m^{-2} range. Lithologic and structural characteristics of the Box Canyon region may have enhanced flood erosion so that the pronounced erosional features on the basalt upland, such as Lost Moon Cataract, do not necessarily correspond with the highest unit stream power values.

Boulder deposition

Abundant boulder bars are one of the more striking features of the Big Lost River Flood. They occur in a region where landscape degradation has dominated deposition in creating a bedrock fluvial system. Depositional effects of Box Canyon flooding, in particular, should correlate directly with the hydraulics of the flow, since the non-alluvial nature of the channel means that energy dissipation was probably transferred directly to sediment movement and deposition.

Numerous studies of past flood events have used some measure of maximum particle size within preserved flood deposits to estimate hydraulic properties of the flow, specifically, measures of flow competence such as tractive force or stream power (Birkeland, 1968; Scott and Gravlee, 1968; Baker and Ritter, 1975; Bradley and Mears, 1980; Costa, 1983; Williams, 1983; O'Connor et al., 1986; Wohl, 1992). Studies primarily focusing on hydraulic controls of deposition are few, in spite of the common practice of quantifying flow conditions from depositional features.

Boulder-laden areas within the Box Canyon study reach are generally concentrated where unit stream power conditions were less than 600 W m^{-2}. However, the largest basalt boulders along Box Canyon occur in bars located north of the channel in the narrow strip of highest, non-channel unit stream power (1000–5000 W m^{-2}; Fig. 2). In previous studies, boulder deposition has been shown to occur at sites of stream power minima within bedrock gorges where channel geometry changes reduce coarse sediment transport capabilities (O'Connor et al., 1986; Wohl, 1992). An unusual aspect of boulder deposition reported in this study is that the basalt upland, the locus of abundant deposition and the surface into which Box Canyon gorge is incised, is on average 20 m higher than the gorge, and is not where the deepest, swiftest flow occurred. While site-wide deposition of Big Lost River flood boulders on the uplands may occur at sites corresponding to unit stream power minima, the stream power decrease cannot be attributed to local channel geometry changes. Instead, these abrupt fluctuations in unit stream power were probably induced by local flow phenomena set up by subtle topographic irregularities. Despite the seemingly flat terrain of the eastern Snake River Plain, flow ridges, tumuli, and pressure plateaus, with less than 5 m of relief, were likely sufficient to accelerate and retard flow velocities and transport capabilities over very short distances. At the present scale of the flow reconstructions, these local flow perturbations are below the resolution of the one-dimensional hydraulic modeling, because HEC-2 (HEC, 1985) fixed the Box Canyon cross-section subdivisions, on average, from 600 to 850 m long.

At-a-bar

I estimated limiting unit stream powers for flood deposition more precisely from point estimates for seven bars containing flood transported boulders (Fig. 7). Ten of the largest boulders in each of the seven Big Lost River boulder deposits were measured for long, intermediate, and short axes and particle roundness (Folk, 1955). The five largest boulders, out of the ten measured, were averaged for analysis. The largest boulders are important because the location of deposition of the larg-

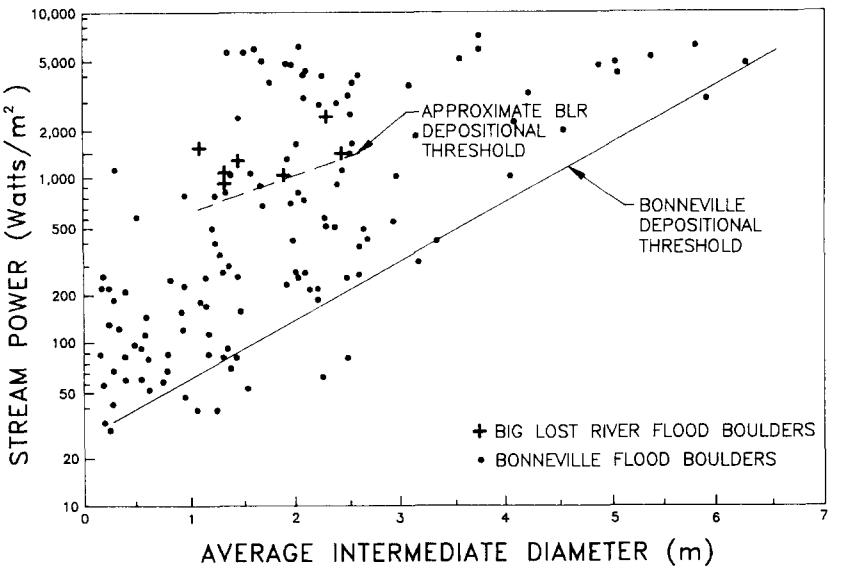


Fig. 7. Approximate depositional threshold for five largest flood boulders from seven boulder bars along Box Canyon, and Lake Bonneville flood boulders. Bonneville boulder data from O'Connor (1993). *BLR* indicates Big Lost River.

est boulders is assumed to better reflect flood power at that site since reentrainment is unlikely. Also, deposition of the largest boulders probably occurs closest to peak discharge, that portion of the hydrograph modeled by HEC-2. Estimates of local unit stream power for the seven flood bars were derived by calculating distance-weighted averages of surrounding unit stream power values for cross-section subdivisions.

Deposition of the Box Canyon flood boulders was associated with unit stream power values between 940 and 2500 W m^{-2} (Fig. 7). These point estimates of unit stream power at particular boulder bars are within range of the unit stream power isopleths (Fig. 2), yet offer more constraints on the conditions of deposition. I fitted a preliminary envelop curve, by eye, to the seven data points from Box Canyon boulder bars. While the Big Lost River data are not sufficient to investigate fully the controls on boulder deposition over the range of entrained clast sizes, an approximate lower limit of flood power required to sustain transport of boulders 1.3 to 2.4 m in size during the flood is defined. Big Lost River flood boulders correspond to sizes on the smaller end of the Bonneville data set of O'Connor (1993), yet are well within the field of deposition. The smaller boulders may be attributed to actual hydrodynamic controls, or perhaps just a limited data set for Big Lost River boulders.

Downstream changes

There are also systematic patterns of deposition at bars in the downstream direction that must relate to local flow conditions too fine to be resolved with the modeling results. To assess changes in boulder size and roundness in the downstream direction, boulders were measured at mid-points of six plots established along the crest of bars formed in the abandoned channel downstream of Lost Moon Cataract (Fig. 8). Again, a minimum of ten of the largest boulders was measured to ensure that five of the largest were included in the analysis. Only the largest boulders were measured, to better bracket limits of transport capability and subsequent deposition.

In the downstream direction, the mean intermediate diameter of the five largest basalt boulders at each site decreases from 2 to 1 m

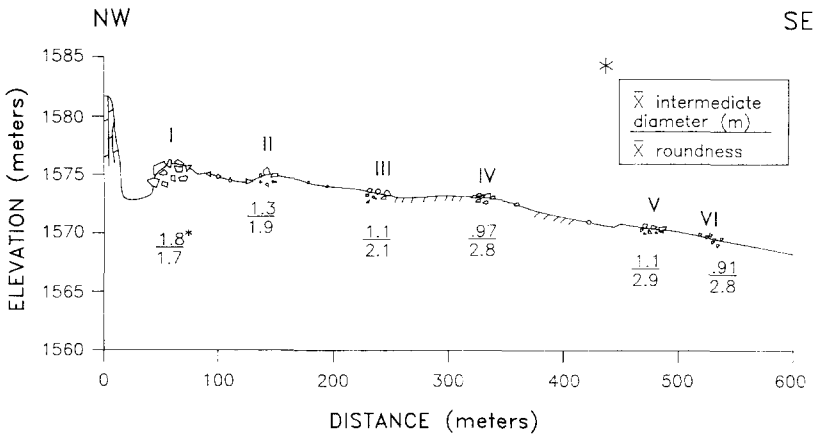


Fig. 8. Long profile of Lost Moon Cataract showing plunge pool and boulder deposition downstream of the cataract face. Roundness and mean intermediate axis were measured within six plots (I–VI) along the length of the abandoned channel. Location of the profile is shown in enlargement of Fig. 2.

in a horizontal distance of 500 m (Fig. 8). Mean boulder roundness increases over the same distance. Acceleration of convergent flow over the jointed face of Lost Moon Cataract probably induced plucking of several of the largest boulders measured within Plot I; their size and angularity indicate minimal transport. Local stream power maxima, such as those associated with the headward recession of a cataract, set up conditions for decreasing unit stream power and diminished particle size downstream as energy is dissipated downstream.

Source and age of Big Lost River flooding

Episodes of alpine glaciation in the pioneer mountains created glacier-dammed lakes along the East Fork Big Lost River (Fig. 1; Evenson et al., 1982). Westward drainage of the East Fork was apparently blocked by an ice lobe emerging from Wildhorse Canyon, creating Glacial Lake East Fork. Evenson et al. (1982) documented two high stands of Glacial Lake East Fork during alpine glaciation, one described as being during Bull Lake-equivalent glaciation (~140,000 yr BP), and again during the Pinedale-equivalent glacial advance (~20,000 yr BP), suggesting the possibility of multiple lake fillings and corresponding releases.

Light-colored boulders of migmatitic gneiss occur along the valley hillslopes of the East Fork Big Lost River. The only known source of these boulders is an exposure at the head of Wildhorse Creek (Fig. 1). Therefore, the hillside boulders were glacially transported down the valley of Wildhorse Creek and then ice-rafted to their present positions on blocks of ice that calved off Wildhorse glacier into Glacial Lake East Fork. The erratics defining the upper limits of flooding along Box Canyon are rock types similar to those found on the hillslopes of the East Fork Valley. I postulate that the catastrophic emptying of Glacial Lake East Fork emplaced the Box Canyon erratic boulders some 100 km downstream from source terrains in the Pioneer Mountains.

Glacial Lake East Fork outburst discharge

An outburst discharge for Glacial Lake East Fork was calculated using regression equations relating lake volume to maximum discharge for historic jökulhlaups (Clague and Mathews, 1973; Beget, 1986; Costa, 1988). Based on the elevation of hillslope erratics, I estimate the total impounded volume of water for Glacial

Lake East Fork to have been 6.3 km^3, yielding an outburst discharge ranging from 26,000 to 38,000 $m^3 s^{-1}$. The small size of Glacial Lake East Fork approaches that for which the regression equations were derived. Assuming that the discharge estimate for Box Canyon (60,000 $m^3 s^{-1}$) is approximately correct, a large disparity between discharge estimates for Box Canyon and Glacial Lake East Fork exists. It is possible that water contributions from additional source areas, hydraulic ponding of outburst floodwaters within the Big Lost River Valley re-released catastrophically, or some other mechanism increased the peak discharge prior to entering Box Canyon.

Age of flooding

Cataclysmic flooding of the Big Lost River seems to be late Pleistocene in age based on three relative age indicators:

(1) Weathering rinds on basalt boulders within the flood bars are well developed.

(2) Erratic boulders are largely buried by loess indicating post-flood burial.

(3) The flooding is presumed coincident with the most recent existence of Glacial Lake East Fork in the headwaters of the Big Lost River, or approximately 20,000 yr BP, during Potholes Glaciation described by Evenson et al. (1982).

More precise dating work using cosmogenic ^3He and ^{21}Ne in olivine and plagioclase minerals within Box Canyon flood boulders and scoured bedrock is currently in progress (T. Cerling, pers. commun., 1993). Cosmogenic isotopes measured in eroded boulders and bedrock scour features provide a useful method of dating Quaternary surfaces, and have subsequently been applied to further establish the timing of the Bonneville flood (Cerling, 1990).

Conclusions

The assemblage of distinctive landforms along Box Canyon in the lower Big Lost River is the product of torrential discharge(s) during the late Pleistocene. The Big Lost River flooding, although generated in a much smaller drainage basin and under discharges one to two orders of magnitude lower, produced landforms comparable to the famous Missoula and Bonneville flows, spectacular examples of terrestrial flooding. The maximum unit stream power is estimated at 26,000 W m^{-2} for a peak discharge of 60,000 $m^3 s^{-1}$ within Box Canyon, ranking it the third most powerful flood yet reported. The unit stream power during flooding was sufficient to erode bedrock and to entrain, transport, and deposit boulders up to 4.5 m in diameter. These Pleistocene-age features have remained essentially pristine and unmodified for at least the last 10,000 years, indicating that large floods were a dominant influence on landscape evolution along the lower Big Lost River. The paleoflooding along Box Canyon may in part, although probably not solely, be attributed to outbursts from a glacial lake in the headwaters.

The areal distribution of unit stream power during peak flow indicates that decreasing unit stream power and/or fluctuating flood power gradients were largely responsible for flood-induced landscape formation. An approximate depositional threshold for the largest flood boulders defines a lower limit of the hydrodynamic controls on bar formation under cataclysmic flood conditions. Despite the seemingly flat terrain of the eastern Snake River Plain, the less than 5 m of relief generated significant flow perturbations that locally accelerated and retarded flow velocities and transport capabilities. Local topographic relief appears to be the dominant control on the removal and accumulation of flood boulders along Box Canyon, consistent with Baker's (1978a, p. 86) findings in the Channeled Scabland, "...it is mainly structural irregularity of the rock that provides defects which then perturb the flow hydrodynamics to create distinctive bed forms". The unit stream power is recognized as an important indicator of cata-

clysmic fluvial processes producing geomorphological impacts. Future studies of landform change induced by extreme floods in bedrock systems need to explore models that can more finely resolve the large scale erosional and depositional features.

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