Bedrock cohesion in columnar basalt, and its influence on erosion generated by extreme floods: upper Grand Coulee, WA, USA

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1. Introduction and study area

Many landscapes on Earth have experienced rapid incision by extreme floods (Baker, 2008). Ancient channels, much larger than those on Earth, provide evidence of extensive flood erosion on Mars (e.g., Baker and Milton, 1974). Quantifying the discharges and shear stresses produced by extreme floods is important for understanding the role that rare, extreme floods play in eroding landscapes and shaping planetary surfaces (O'Connor and Baker, 1992; Lamb and Fonstad, 2010; Baynes et al., 2015; Larsen and Lamb, 2016; Garcia-Castellanos and O'Connor, 2018; Goudge and Fassett, 2018). The ability to infer flood sizes from the erosional features they produce can provide important insight into paleoclimatic and geologic conditions of Earth (e.g., Barber et al., 1999; Praetorius et al., 2020) and Mars (Baker et al., 1991). For instance, theory predicts that canyon width scales with flood discharge where columnar-jointed basalt erodes by plucking (Lapotre et al., 2016). However, application of such relationships depend on a robust understanding of the erosion mechanisms, which are influenced by rock mass strength and fracturing. The degree to which properties such as cohesion within fractured rocks limit erosion is poorly constrained, especially for extreme events where observations are limited (Lamb and Dietrich, 2009; Lamb and Fonstad, 2010). Here, we perform 2D hydraulic models of floods on reconstructed pre-incision topography to determine the smallest flood capable of emplacing high-water marks along Grand Coulee, a large flood-carved canyon in the Channeled Scabland of eastern Washington, and assess whether this flood produces shear stresses sufficient to drive canyon incision using a model for toppling (Lamb and Dietrich, 2009; Lehnigk and Larsen, 2022).

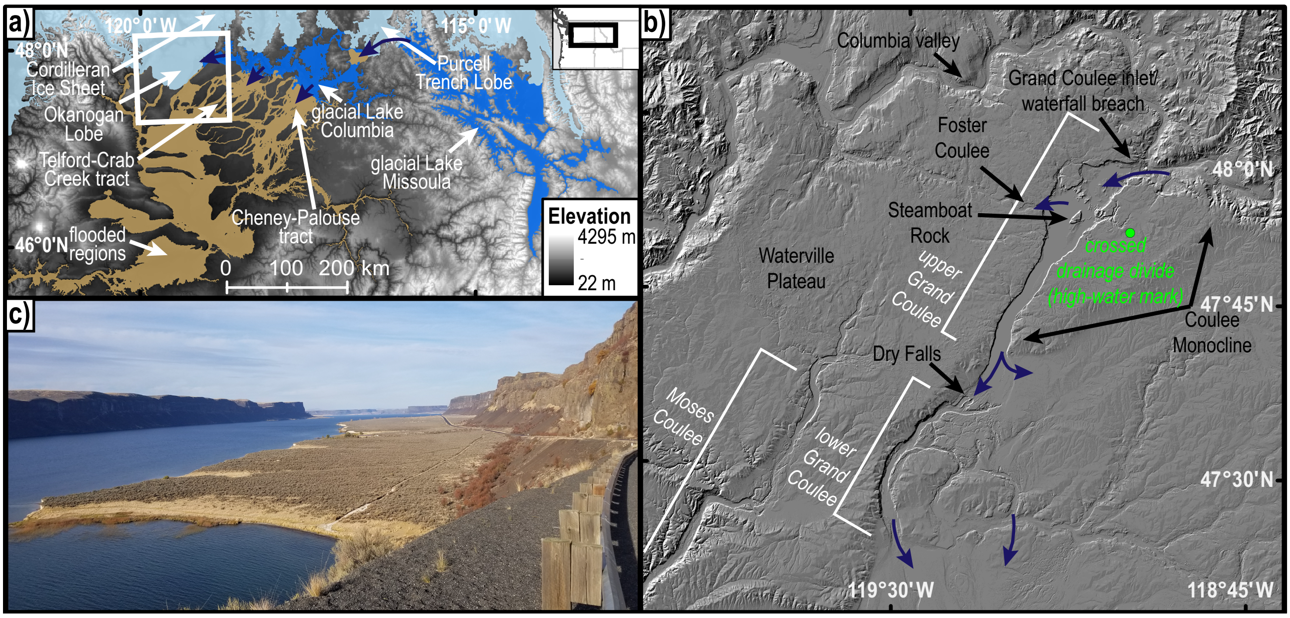

Figure 1. The study area, Grand Coulee in the Channeled Scabland of eastern Washington. a) Locations of ice sheets (light blue), glacial lakes (dark blue), and areas inundated by Missoula floods (brown) during the Last Glacial Maximum (Ehlers et al., 2011). b) Grand Coulee and other geomorphic features in the northwest portion of the Channeled Scabland. Purple arrows show flow directions. c) Photo looking north towards Steamboat Rock from the east side of the center reach of upper Grand Coulee.

The Channeled Scabland of eastern Washington (Figure 1) is a landscape of scoured bedrock, huge boulder bars, dry waterfalls and channels, and streamlined loess hills formed by periodic Pleistocene outburst floods from glacial Lake Missoula (Bretz, 1923, 1932, 1969; Pardee, 1942). Some of these channels are deeply incised canyons in the Miocene-age Columbia River basalt bedrock (Barry et al., 2013), the largest of which is Grand Coulee, a system of two canyons, each of which was incised by headward waterfall retreat driven by the spillover of floodwaters from the Columbia valley (Bretz, 1923, 1932). Floodwaters initially flowed across the low-relief Columbia Plateau until encountering steeper topography at the Coulee Monocline. A waterfall initiated at the monocline, where folding related to regional tectonics had fractured and weakened the basalt (Bretz, 1932). Upper Grand Coulee formed as the waterfall retreated upstream via plucking of jointed basalt until it eroded entirely through the drainage divide separating it from the Columbia valley (Bretz, 1923, 1932). Lower Grand Coulee developed in a similar fashion via headward waterfall retreat (Bretz, 1932), terminating at Dry Falls.

2. Methods and results

Bretz (1923, 1924, 1932, 1969) recognized that erosion in the Channeled Scabland was dominated by plucking of the jointed and fractured Columbia River basalt rather than abrasion, and that a receding waterfall would be especially effective in eroding the horizontal layers of basalt. Field studies in other canyons confirm the dominance of plucking as the primary driver for erosion of fractured bedrock during floods (Lamb et al., 2008; Lamb and Fonstad, 2010; Anton et al., 2015; Baynes et al., 2015; Beer et al., 2017). Many aspects of the mechanistic basis for plucking erosion have been investigated (Lamb and Dietrich, 2009; Lamb et al., 2015; Lapotre et al., 2016; Hurst et al., 2021), though other aspects, such as the role of interlocked joints, require further study (Lamb and Dietrich, 2009). It has been suggested that the waterfalls in fractured basalt maintain vertical faces due to toppling of rock columns made of multiple blocks, which occurs due to the combined influence of shear stress generated by the overflowing water, buoyancy imparted by water in the plunge pool at the base of the waterfall, and gravity (Lamb and Dietrich, 2009). Hence, we assessed whether the shear stresses that were generated on the waterfall brink by the minimum high-water-inundating discharge on topography modified to include a partially incised waterfall would have been high enough to topple rock columns, using the torque balance model of Lamb and Dietrich (2009) modified to include wall cohesion between adjacent columns to solve for the minimum shear stress necessary to topple a column (Lehnigk and Larsen, 2022).

To estimate the wall stress from cohesive forces between adjacent columns, we first use the field measurements of column length and the height of the reconstructed waterfall to identify geometrically unstable column stacks. A column of rock is geometrically unstable if the center of gravity lies outside the base (Hoek and Bray, 1981), and will not topple if the torque due to cohesion is equal to or greater than the torque due to the weight of the column. We therefore find the minimum wall stress to keep the geometrically unstable columns from toppling by balancing the torque due to the weight of the column with the torque due to the wall stress (Lehnigk and Larsen, 2022).

2D hydraulic modeling revealed that a discharge of 2.6 x 10^6 m^3 s^{-1} inundates the high-water mark, a drainage divide that was crossed by floods and has been inferred to be close to the maximum extent of flood inundation (O'Connor et al., 2020), on topography including a reconstructed retreating waterfall (Lehnigk and Larsen, 2022). To estimate toppling thresholds, we measured 50 columns from a basalt flow with large columns near the base of Steamboat Rock along the southeast face and 153 columns across two locations on the summit, and found median horizontal column lengths of 0.91 m at the base and 0.68 m at the top. Cohesion is expected to be greatest in the entablature portions of basalt flows (Baker, 2009). Field observations roughly constrain the entablature thickness to be 20% of the total thickness of basalt stratigraphy at Steamboat Rock. Steamboat Rock is made up of multiple basalt flows, and since the position of the torque arm is unknown, and likely complex, we assume an average position halfway up the column.

The median modeled shear stress of the 2.6 x 10^6 m^3 s^{-1} flood (Figure 2a) is 876 Pa with 25th percentile 565 Pa, 75th percentile 1,329 Pa, and 95th percentile 2,345 Pa along the edge of the reconstructed waterfall. We estimate the median wall stress to be 68 and 77 Pa for unstable columns measured at the base and top of Steamboat Rock respectively. Using the median wall stress value of 68 Pa, the shear stress threshold required to topple the median length column at the base of Steamboat Rock was 867 Pa and thresholds for the 25th, 75th, and 95th percentile length columns were 325, 1,893, and 6,558 Pa respectively (using the maximum wall stress value of 154 Pa, thresholds are 1,627 Pa for the median length column and 1,130, 2,604, and 7,160 Pa for the 25th, 75th, and 95th percentile length columns). For columns with lengths of those at the top of Steamboat Rock and the median wall stress value of 77 Pa, a shear stress of 440 Pa is required to topple the median length column, with shear stresses of 266, 805, and 1,718 Pa required to topple the 25th, 75th, and 95th percentile length columns, respectively (using the maximum wall stress value of 197 Pa, thresholds are 1,559 Pa for the median length column and 1,429, 1,878, and 2,725 Pa for the 25th, 75th, and 95th percentile length columns; Figure 2b).

The toppling theory is based on idealized columns and there is considerable uncertainty in the parameter values, especially cohesion. Additionally, turbulent fluctuations likely cause shear stresses to deviate several-fold from the mean value we model (Schmeeckle et al., 2007). Despite these limitations, the agreement between the theory-based toppling shear stress thresholds and the model-based shear stresses indicates that, to a first order, the smallest flood that could have inundated the high-water mark on the eastern rim would have been sufficiently large to sustain waterfall retreat by toppling columns.

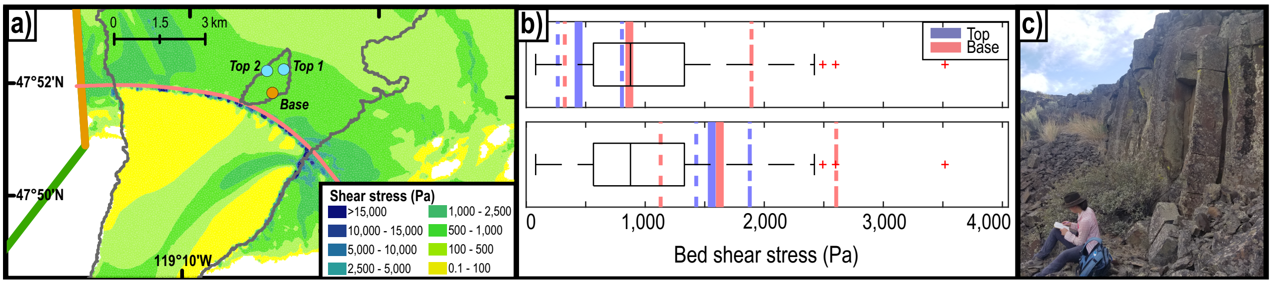

Figure 2. Shear stress. a) Spatial distribution of modeled shear stress for a 2.6 x 10^6 m^3s^{-1} flood with a reconstructed waterfall in upper Grand Coulee. Shear stresses are extracted along the waterfall's edge (pink line) and compared to mechanistic toppling thresholds. b) Distribution of modeled shear stresses along the waterfall's edge (box plots) compared to mechanistic toppling thresholds using cohesion values generated by the median (top) and maximum (bottom) wall stress values from the median (solid lines), 25^{th} (dashed lines), 75^{th} (mixed dash-dot lines), and 95^{th} (dotted lines) percentile lengths of geometrically unstable columns. c) Photograph by Scott David at lower Grand Coulee, depicting wide fractures between columns and talus with dimensions comparable to intact columns.

3. Discussion and conclusions

Rather than using toppling thresholds to estimate paleo-discharge, as done by Larsen and Lamb (2016), we assess whether the paleo-discharge constrained by field-based high-water evidence generated shear stresses that were high enough to topple columns and sustain headward waterfall retreat. The smallest flood to cross the drainage divide on the east rim of upper Grand Coulee on the reconstructed topography produces a shear stress distribution that overlaps closely with our estimated range of toppling thresholds. The good agreement between shear stresses reinforces previous work suggesting that erosion thresholds may be more reliable indicators of flood size in flood-carved canyons than high-water indicators because erosion causes the water surface and topography to coevolve (Larsen and Lamb, 2016).

To estimate erosion thresholds, several physical parameters relating to the bedrock structure must be constrained, including the cohesion, its distribution along the block surface, and the range of block dimensions. Columnar basalt has a more regular structure than most crystalline rocks, but it is not homogenous, and approximating the failure limits of columnar basalt for practical purposes is still a matter of ongoing research (e.g., Schultz, 1995). The Hoek-Brown strength criteria is often used to estimate failure thresholds for fractured rock, which predicts cohesion values on the order of 10-100 kPa for columnar basalt (Hoek and Bray, 1981; Hoek and Brown, 1997). However, the Hoek-Brown method may not provide reliable estimates for columnar basalt due to the presence of structural planes of weakness between successive basalt flows (Hoek and Brown, 1997) and simplifying assumptions about column geometry (Lorig and Varona, 2001; Alejano et al., 2015). Even floods which filled the canyons entirely would not produce shear stresses above ~10 kPa, (Larsen and Lamb, 2016), yet field evidence (specifically, the vertical walls of the canyon and Steamboat Rock; Figure 1c) indicate erosion via retreat of a vertical, ~100 m tall waterfall (Bretz, 1932). Observations of toppled columns in post-flood talus deposits (Figure 2c) also indicate that failure can occur at stresses caused by near-surface weathering, without additional torque from flooding, which also suggests cohesive stresses are modest. The single flood of pluvial Lake Bonneville, also during the late Pleistocene, drove km-scale retreat of waterfalls up to ~100 m tall through well-jointed volcanic rock with discharges of 10^3–10^4 m^3 s^{-1} (O'Connor, 1993), additionally implying that moderate shear stresses are capable of eroding large volumes of bedrock where fracture patterns are favorable.

Cohesion typically varies with age or depth in an outcrop as well, with weathering and unloading lowering cohesion near the surface (Hoek and Brown, 1997). Given that all the Missoula floods likely occurred within a few thousand years, and that floods in Grand Coulee are constrained to have occurred in an even shorter interval (Balbas et al., 2017), we conclude that it is unlikely that a weathering mechanism sets the pace of flood erosion in Grand Coulee. For weathering to influence canyon incision by creating a reservoir of low-cohesion rock, the weathering zone would have to influence strengths at the base of the rock column. Observations of >300 m of drill core (Larsen et al., 2021) do not indicate weathering at depth (or substantial weathering between lava flows). If the time rocks resided at the surface was an integral predictor of basalt erosion, we might expect to see very different erosional forms in the Miocene-age Columbia River basalts in the Channeled Scabland versus the Quaternary-age basalts in the Snake River Plain that were eroded by the Bonneville flood, which is not the case. Although the residence time may be relevant for waterfall erosion in "normal" rivers, there isn't empirical evidence for such an influence in basalt landscapes shaped predominantly by large floods.

While our findings indicate that a waterfall could propagate to erode upper Grand Coulee, we have not attempted to estimate the shear stress necessary to initially create the waterfall at the Coulee Monocline. For a waterfall to initiate, the block dimensions and/or hydraulic properties must permit local removal of bedrock, while remaining below the threshold for plucking in other parts of the canyon (Lamb et al., 2015). A prominent canyon was eroded by Missoula floods at Moses

Coulee as well, where floods crossed the Badger Mountain anticline. Yet other flood pathways, such as Wilson Creek and the Cheney-Palouse tract, failed to develop large canyons, despite similar discharges in Moses Coulee and Wilson Creek (Lehnigk et al., in prep.). Tectonically generated relief and rock fracturing may therefore play a determining role in the degree of landscape change from extreme floods—whether or not a canyon will develop, and if so, how large it can be.

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