Constriction-Pool-Widening Sequences. An Externally Controlled Morphology or Emergent Property of Bedrock Rivers?

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Introduction

The Big Bar Landslide occurred in late fall of 2018, where a 125 m high rock cliff catastrophically failed into a remote canyon of the Fraser River, located in British Columbia, Canada (Murphy et al., 2020). The rockslide was not discovered until June 23, 2019, at which time, an estimated 5 m high overfall was observed. This overfall acts as a hydraulic barrier to the migration of already endangered salmon populations native to the Upper Fraser Basin. Despite mitigation efforts, at moderate to high flows this barrier persists to this day. It is presently unclear the exact extent of damage and how long salmon populations will take to recover, if at all (Murphy et al., 2020).

Within each of the 42 canyons of the Fraser River, there exists a common channel morphology consisting of deep scour pools, where the river becomes constricted laterally, followed by downstream channel widening. This morphology, first documented by (Curran., 2020), is referred to as a constriction-pool-widening (CPW). CPW morphology usually occurs in sequence within the Fraser Canyons. Within French Bar canyon, there exists two CPW sequences, one of which coincides with the location of the Big Bar Landslide. In the CPW morphology the processes acting to widen the channel downstream of the constriction-pool are a result of side wall undercutting of the channel margins (Venditti et al., 2014). This undercutting is the likely cause of this recent landslide. Rock avalanches like the Big Bar Landslide are common in the Fraser Canyons (Ryder et al., 1990). At least two such events have occured within the last 1000 years, with the most recent occurring in Hells Gate Canyon ~100 years ago. Both these catastrophic rock failures are attributed to undercutting by the Fraser River (Ryder et al., 1990).

It is currently unclear if CPW sequences are an emergent property of canyons (autogenic) or an externally imposed (allogenic) feature of bedrock rivers. It is important we understand how the CPW morphology emerges so we can better predict the locations where future slides are most likely to occur. This is imperative so we may act to mitigate landslide risks that threaten to wipe out the already dwindling salmon populations of the Fraser River Basin.

Morphology of Bedrock Rivers.

Contrary to what the name suggests, bedrock rivers are not always exclusively bedrock bound at the channel bed and margins. More commonly, entirely bedrock-bound reaches are short in length and recurrent (Wipple et al., 2013). At the reach scale, bedrock channel morphology can be described as bedrock-bound, bedrock-constrained (sometimes referred to as mixed bedrock-alluvial) or alluvial (Turowski et al., 2008; Rennie et al., 2018; Venditti et al., 2020). Following Rennie et al., (2018) I use the term "canyon" to indicate reaches that are entirely or mostly bedrock-bound. Canyons may have intermittent and spatially variable sediment cover on the bed (Venditti et al., 2020). Bedrock-constrained reaches can either be confined laterally by bedrock walls with an alluvial bed or a bedrock bed with alluvial banks. Alluvial reaches within otherwise bedrock rivers are characterized as having sediment cover on both their bed and banks, but the alluvial cover is often relatively thin above underlying bedrock (Whipple et al., 2013; Rennie et al., 2018; Venditti et al., 2020). Bedrock rivers undergoing active uplift often alternate between wider alluvial sections characterized by high width-to-depth (w/h) ratios and narrower canyon and bedrock-constrained reaches with comparatively lower w/h ratios (Dolan et al., 1978; Whipple et al., 2013; Rennie et al., 2018; Venditti et al., 2020; Figure 1).

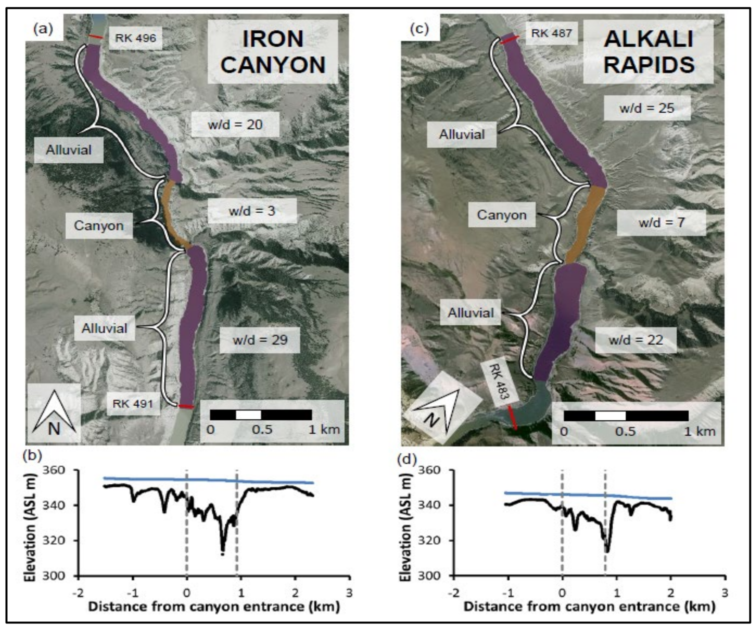

Figure 1. The alluvial-canyon-alluvial alternation observed throughout the canyons of the Fraser River. RK represents river km upstream of ocean. From (Venditti et al., 2020).

Constriction-Pool-Widening Sequences

Within canyon reaches, there is a CPW sequence made up of deep scour pools formed because the river is constricted laterally, focusing bed erosion. The canyon then widens until another lateral constriction initiates the sequence again or it widens into the next alluvial reach downstream (Venditti et al., 2014; Figure 2). Within the Fraser Canyons a series of scour pools are commonly found which can be as deep as the channel is wide. Such pools form because a lateral channel constriction accelerates flow, causing a plunging flow, creating a high velocity core at the bed (Hunt et al., 2017). This directs fast moving water and sediment towards the bed resulting in bed scour (Cao., 2018). Following the plunging flow, the high velocity core diverges at the bed causing water and sediment to be directed into the channel side walls resulting in undercutting (Venditti et al., 2014). Moving downstream and out of the pool, sediment builds up on the bed providing deflectors (Venditti et al., 2014). This enhances the lateral erosion rate by increasing the number of particle impacts with the side walls causing further undercutting (Fuller et al., 2016). Undercutting acts to make the channel wider especially where joints have vertical or sub-vertical orientations (Curran., 2020).

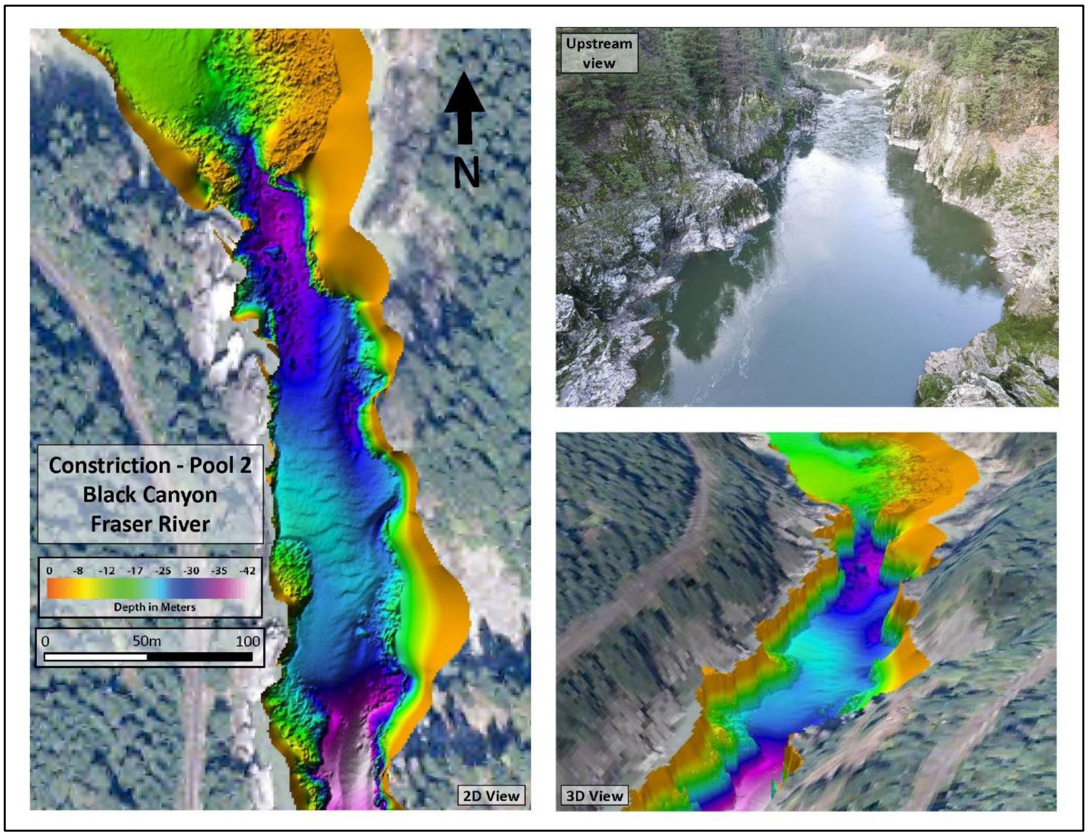

Figure 2. An example of a constriction-pool-widening sequence in Black Canyon of the Fraser river. Flow direction is top down in each image. From (Curran., 2020).

Constriction-Pool-Widening sequences, Autogenic or Allogenic?

It is currently unclear if CPW sequences are an externally forced (allogenic) or an emergent (autogenic) character of bedrock rivers. In many cases the width variations in bedrock rivers associated with CPW sequences can be explained by an external forcing (Dolan et al., 1978; Curran., 2020; Venditti et al., 2020), but where no apparent external controls exist, the cause of width variation is not obvious. The idea that CPW sequences are autogenic is supported by morphological similarities to other autogenic features found in fluvial systems (Keller & Melhorn., 1978; Clifford., 1993; Cao., 2018; Chartrand et al., 2018; Scheingross et al., 2019).

In a study of the Colorado River, Dolan et al., (1978) found that the location and spacing of nearly all constriction pools found within the Grand Canyon could be attributed to external controls such as lithology, deposits from debris fans or bedrock fracture spacing, although in a few cases there was no clear allogenic control. More recent observations from the Fraser River also suggest CPW sequences may be allogenic, where channel width is controlled by the orientation of joint sets (Curran., 2020). Curran., (2020) observed that channel constrictions typically occur where joints are horizonal and widenings occur where joints are close to vertical. This provides a conceptual model for the formation of the CPW morphology that is dependent on rock structure in otherwise homogeneous rock.

The idea that CPW is autogenic, is supported by an analysis of the spacing of pools in bedrock and alluvial streams. Keller and Melhorn., (1978) studied 4 bedrock and 7 alluvial channels and found no significant difference between the spacing of pools, (measured in channel widths) suggesting that the development of pools and riffles is a fundamental characteristic of streams that is independent of the type of material in the channel bed and banks (Keller and Melhorn., 1978). In gravel-bedded rivers the formation of these riffle pool sequences has been shown to be an autogenic process (Clifford., 1993). Pool-riffles found in gravel bed streams have also been shown to emerge in response to variations in channel width and velocity, with pools emerging where the channel narrows, a result of higher velocities and riffles forming when velocities decrease in the wider channel sections (Chartrand et al., 2018). This bears a striking morphologic similarity to the CPW sequence that characteristically develops deep scour pools where the channel narrows that widen into shallower sections.

Recent flume experiments also suggest that CPW is autogenic. Cao (2018) conducted an experiment to investigate how a constriction in a channel influences patterns of erosion. It was shown that a lateral constriction associated with the transition from an alluvial to canyon reach could initiate the formation of a scour pool that propagates due to sediment dynamics. These results suggest autogenic and allogenic processes may work together to create CPW sequences.

In this case an externally forced perturbation, a channel constriction, creates an initial scour pool that allows a downstream autogenic pool to form. In this experiment the canyon walls were not erodible and as a result channel widening was not possible. A different flume experiment, conducted by Scheingross et al., (2019) to study the development of bedrock waterfalls, shows that a series of equally spaced constrictions and widenings can form under steady state conditions from an initially flat bed and walls through feedbacks between flow and sediment transport. This result suggests that if the canyon walls of the Cao., (2018) experiments were erodible that channel widening may have occurred, creating a CPW sequence.

Conclusion

Based on the Scheingross et al., (2019) and Cao (2018) flume experiments, and the morphologic similarities to pool-riffles in alluvial rivers, it seems likely that CPW sequences are an emergent property in bedrock rivers. Although, observations from the Fraser River have shown that canyon width variation is correlated with bedrock jointing orientation, suggesting an allogenic control (Curran., 2020). This result does not necessarily contradict the former, if CPW is autogenic then flow hydraulics will compete with external controls such as bedrock structure. In such a case CPW sequences would have a first order autogenic control, a result of flow hydraulics. To explain the observations of Curran., (2020) it may be that this first order control is easily overprinted by external forcings such as rock structure. Ultimately more studies are required to determine whether CPW sequences are autogenic or allogenic. Due to nearly unavoidable influence from external controls in natural bedrock rivers and considering that yearly to decadal changes in erosion are often only on the order of mm to cm (Lamb et al., 2015) it would be impractical to study CPW sequences in natural rivers. Therefore, to uncover if CPW sequences are autogenic researchers should focus on developing flume experiments, with faster eroding materials, where external forcing's can be controlled for.

It is important we determine whether this is a self formed or forced morphology. If the CPW sequence is autogenic then general pool spacing, and locations of channel wall undercutting should be able to be predicted within a canyon. This is important as we can then focus resources to these locations to identify external controls such as rock structure to create more accurate landslide risk assessments.

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