The bubble bursts for cavitation in natural rivers: laboratory experiments reveal minor role in bedrock erosion

Paul A. Carling[1*], Mauricio Perillo[2], Jim Best[3,4] & Marcelo Garcia[4]

[1]College of Environment and Planning, Henan University, Kaifeng, Henan Province, 475004, China, [2] Department of Geology, University of Illinois, Natural History Building, 1301 West Green Street Urbana, IL 61801, [3]Departments of Geology, Geography and GIS and Mechanical Science and Engineering, University of Illinois, Natural History Building, 1301 West Green Street Urbana, IL 61801-2938, [4]Civil & Environmental Engineering, Ven Te Chow Hydrosystems Laboratory, University of Illinois, 301 N. Mathews Ave., Urbana, IL 61801.

[*]Corresponding author: P.A.Carling@soton.ac.uk.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/esp.4101

Abstract

The erosion of rock-bedded channels generally is considered a slow process caused mainly by abrasion due to bedload or suspended sediments, but the mechanisms of rapid erosion remain unclear. Cavitation is a clear-fluid erosive process, well known for its effect on engineering structures, when water vapour bubbles collapse and the resultant pressure shocks erode the boundary. However, although the occurrence of cavitation erosion in natural watercourses has long been a matter of debate, as yet there are no incontrovertible examples of cavitation damage to natural river beds. Using flume experiments, we show for the first time that only weakly-cavitating clear-water flows can occur for the range of flow velocities observed in rivers, and these do not erode medium-hardness rocks after 68 hours. During this time period, only a very soft rock featured erosional marks due to dissolution. Thus, our results cast significant doubt on the likelihood of identifying cavitation damage in most rivers, and provide pointers to those river systems that might be investigated further to identify cavitation erosion.

Short title: Cavitation and bedrock erosion

Key words: Cavitation, bedrock channels, bedrock erosion, abrasion, dissolution

Introduction

The mechanical erosion of rock-bedded channels is generally slow (Karlstrom et al., 2008), primarily owing to abrasion by the sediment load and fluid stressing by turbulent flow (Richardson & Carling, 2005). Bedload and suspended sediment may directly impact the rock surfaces causing abrasion (Whipple et al., 2000; Sklar & Dietrich, 2004) or fluid stressing may entrain flakes and blocks from rock surfaces already weakened by other processes (Chatanantavet & Parker, 2009), but the mechanisms of rapid erosion remain unclear (Johnson & Whipple, 2010; Lamb & Fonstad, 2010; Lamb et al., 2015). Flows in such channels are usually high velocity, with field studies of steep bedrock channels recording supercritical flows locally (Froude numbers > 1: *e.g.* Tinkler & Parish, 1998; Turowski & Rickenmann, 2008) and experimental studies have included consideration of flows with Froude numbers up to 3.5 (Wohl & Ikeda, 1997; Johnson & Whipple, 2007; Finnigan et al., 2007, Johnson & Whipple, 2010). As is demonstrated below, in principle supercritical flows are conducive to the development of cavitation, but to date there have been no experimental considerations of the role of cavitation in eroding bedrock channels whilst laboratory studies of cavitation erosion of rock remain few (El-Saie et al., 1980; Auel & Boes, 2012; Momber, 2003, 2004a, b, c). Thus, the role of cavitation generally is regarded as uncertain (Whipple et al., 2000) and it is neglected in bedrock incision models (*e.g*. Johnson & Whipple, 2007; Finnegan, 2013).

Cavitation is the appearance of water vapour bubbles within a high-velocity fluid-flow when the pressure in the fluid falls below the vapour pressure of the liquid. These bubbles collapse and disappear when they are carried by the flow into regions of higher pressure. Although direct evidence is lacking, cavitation often has been cited as causing rapid erosion on natural bedrock surfaces under high-velocity flows, when the bubbles collapse and the resultant pressure shocks erode the boundary. However, whether cavitation occurs in natural water courses has been a matter of debate for more than seventy years (Hjulström, 1935; Embleton & King, 1968; Allen, 1971; Baker, 1973; 1974; Allen, 1982, Vol 1, p. 74; Baker & Costa, 1987; Sato et al., 1987; Wohl, 1992; O'Connor, 1993; Shaw, 1996; Baker & Kale, 1998; Hancock et al., 1998; Tinkler & Wohl, 1998; Gupta et al., 1999; Whipple et al., 2000) and there are no irrefutable examples of cavitation damage to natural river-beds (Allen, 1982, Vol. 1 p. 74; Richardson & Carling, 2005; Whipple et al., 2000). In contrast, cavitation is a well-known erosive high-velocity clear-fluid process on engineering structures (Arndt, 1981; Graham, 1987; Falvey, 1990). In order to address this debate, experiments with a cavitating flow are used herein to replicate a range of natural river flow velocities to determine, for the first time, the nature of any cavitation damage caused by clear water to rock surfaces under representative flood durations. If distinctive erosional features can be identified in experimental cavitating flows, then these could be compared profitably with natural river erosional features to determine if cavitation does erode natural channel boundaries.

In respect of engineering structures, the erodibility of concrete by cavitating or non-cavitating water depends on the binding agents used (May, 1987; Jacobs and Hagmann, 2015) but, as a general guide, 'conventional concrete' (which is the usual facing for dam spillways and bypass tunnels; Dolen et al., 2005), does not erode if the impinging bulk flow velocity U_b < 5ms^{-1}, but incipient erosion of dam spillways may occur for 5ms^{-1} < U_b < 16ms^{-1} (Arndt, 1981; Falvey, 1990). Above 16ms^{-1} erosion is progressive because mass loss increases as U_b^6 (Falvey, 1990).

Importantly, cavitating flows on spillways may also erode by fluid stressing, abrasion and dissolution (Graham, 1987), these being factors that are difficult to distinguished from any cavitation damage in field studies of spillway erosion in cavitating flow (Kells & Smith, 1991). Thus, the engineering literature considering spillways often records the *gross* effects of cavitating-flow on erosion rather than the contribution of cavitation *per se*. In a rare laboratory-study of erosion by *cavitation alone*, significant erosion of a range of rock-types (Momber, 2004a) only occurred for flow velocities > 60ms^{-1}. The US Army Corp of Engineers (1990) do not recommend inspection for erosion of concrete in cavitating flows when U_b < *circa*. 10ms^{-1} and anticipate significant erosion of spillways only when U_b > 30 - 35ms^{-1} is sustained for long periods of time (Novak et al., 2007). As many substrata, especially sedimentary rocks, are softer than concrete, it is logical to expect cavitation erosion of softer rocks in high velocity flows; for example, at the base of spillways where large rock masses can be removed by high discharges (Ribeiro et al., 1976; Cameron et al., 1986; Falvey, 1990; Anton et al., 2015).

Barnes (1956) concluded that stream flow must exceed 7.6ms^{-1} for cavitation to be possible, whilst Baker & Costa (1987) argued that flows need to exceed 10ms^{-1}. However, velocities in alluvial rivers rarely exceed 3ms^{-1} (*e.g.* Jia et al., 2016), with flow in steep bedrock gorges occasionally reaching 8 to 10ms^{-1} (Barnes, 1956; Pielou, 1998; Whipple et al, 2000) and, exceptionally, 16ms^{-1} for local threads in highly-turbulent currents (Tinkler et al., 2005). Baker & Costa (1987) argued that natural channels, potentially subject to cavitation, adjust to preclude cavitation so that velocities do not exceed 10ms^{-1}. In this respect, Allen (1982, Vol. 1 p. 74) concluded that cavitation is absent in rivers except possibly locally under extreme flood conditions. In contrast to river flow, natural dam failures can result in short-duration, high-speed flows (Carling et al., 2010). For instance, hydraulic models of Holocene jökulhlaups (Alho et al., 2005; Carrivick, 2007; Carrivick et al., 2013) produced flows in the range 15 to 19 ms^{-1}, whilst models for Pleistocene megafloods indicate maximum velocities of 40 to 60 ms^{-1} (Carling et al., 2010; Alho et al 2010). Yet these natural flows also carry large sediment loads (*e.g.* < 20% by volume: Carrivick, 2010) that may abrade and efface cavitation damage (Allen, 1982, Vol 1, p. 72), or prevent cavitation erosion due the static cover effect of deposited sediment (Carrivick et al., 2010; Guan et al., 2015) or the dynamic cover effect of high concentrations of moving bedload (Turowski et a., 2007). Thus, it can be hypothesized that cavitation may occur in extreme-velocity natural flows, but it is uncertain if cavitation erosion can be identified in the vast majority of natural river settings. Consequently, the experiments reported herein are for the range of high velocities (5-11ms^{-1}) reported for modern rivers, in order to assess the likelihood and identification of cavitation erosion in most natural channels.

Five factors primarily contribute to the degree of cavitation erosion: the cavitation number (defined in the Methods), flow velocity, material strength, time and air content. Although suspended sediment particles can provide nucleation surfaces for cavitation bubbles to form at low suspended sediment concentrations (< 3%), suspended sediment at higher concentrations usually is considered to supress cavitation (Gyr & Bewersdorff,1995), there being only limited evidence to the contrary (Toshima et al., 1991; Li, 2006). Sub-microscopic air bubbles, trapped on local surfaces, can constitute nucleation points that aid the inception of cavitation (O'Hern, 1990) and, as the intensity of cavitation increases, bubbles visible to the naked eye often appear close to or on the boundary (Plesset, 1949). Fissures and vugs are the loci for the preferred initiation of cavitation (Mazurkiewicz & Summers, 1982), with erosion propagating from these locations by pitting and mechanical failure of the rock masses (Erdmann et al., 1978). However, in situations where cavitation erosion is already occurring, loss of eroded rock mass decreases as entrained air content increases (Arndt et al., 1993).

Methods

Planar surfaces of sawn-rock were exposed to clear-water flows on the bed of a Kempf & Remmer Type 23™ cavitation tunnel (Fig. 1) located at the Ven Te Chow Hydrosystems Laboratory of the University of Illinois at Urbana, Champaign, with the rock types and hardness values being shown in Table 1. The base of the upper duct was modified to include a steel recessed pan (1.1m long, 0.20m wide and 0.07m deep). Rock test blocks were cut to shape and fixed in the pan such that the upper, plane, rock surface was flush with the steel flume bed. Air content was controlled using a closed water-filled conduit without a free surface (as the tunnel was water-filled) so that there was no air entrainment, such that any cavitation damage should be maximized. The dissolved oxygen content was 2mg L^{-1} at the beginning of runs and 3mg L^{-1} at the end of runs; consequently, air entrainment was negligible (0.002 moles of air per mole of water). The effects of water chemistry and suspended solids content were kept constant by using the city sediment-free water supply. The pH of the water was seven and conductivity was zero. Water temperature was initially 10^{o} C that, after long flume runs, rose to 21 ^{o}C. The maximum discharge was 1 m^3 s^{-1} and as defined below, the flows were weakly-cavitating for velocities between $5ms^{-1}$ and $11ms^{-1}$.

The initial material tested was cast gypsum cement. The reasoning for this choice was that because prolonged exposure to 10ms^{-1} velocity may erode concrete (US Army Corp of Engineers, 1990), there was a reasonable expectation that the gypsum would erode at lower velocities than concrete. The surface of the gypsum possessed a few 1mm-sized vugs due to air bubbles included during casting. Similarly, the saw-cut surface of the travertine locally had a few natural vugs some 2mm deep and 5mm wide. In addition, a natural fissure of similar depth and width ran transversely across the travertine surface approximately two-thirds of the way along the section. These surface roughness defects should induce cavitation (Mazurkiewicz & Summers, 1982) but the other test blocks (slate and very-fine grained sandstone) had smooth sawn surfaces. To introduce further surface roughness to promote cavitation, all the test surfaces were also ornamented with a single protruding steel bolt-head (5mm high; 10mm diameter) centrally placed one-third of the distance along the test section, and a transverse rectangular groove (10mm wide and 10mm deep) cut two-thirds of the way along the section. These artificial defects were included to induce cavitation due to enhanced flow shear by the local fluid velocity (U_l) around bed defects. Barnes (1956) reported acceleration factors (U_l/U_b) of 1.5 to 2.4 for similar size protuberances. The section-averaged flow velocities (U_b) for each test were determined using non-intrusive laser Doppler velocimetry.

The inception of cavitation is understood readily in terms of Bernoulli's principle that the reference fluid pressure (p) is constant along a steady flowline. The reference pressure is equal to the sum of the static pressure (p_s) and the dynamic pressure

($\rho(U_b^2/2)$. Assuming negligible viscous friction and a constant fluid density (ρ), a large increase in the fluid velocity ($U_1 << U_2$) can lead to the pressure falling below the vapour pressure such that cavitation occurs:

$$p = p_s + \frac{\rho(U_1^2 - U_2^2)}{2} \quad \text{Eq 1}$$

To prevent cavitation erosion on the rock surface, $k > k_e$, where k_e is a threshold value of the cavitation number k below which there is the possibility of cavitation erosion:

$$k = \frac{2\,(p - p_v)}{\rho U_b^2} \quad \text{Eq 2}$$

where p_v is the water vapour pressure at 10 ^{o} - 20^{o}C.

The value of k_e ~ 1 discriminates local from widespread cavitation inception and above k_e ~ 3 cavitation is extremely unlikely (Novak et al, 2007). The gypsum was subject to weakly-cavitating flows (k < 3) with a velocity range of 5 — 10.86 ms^{-1}. The Froude number, $F_r = U_b/\sqrt{(gd)} < 6.38$, whilst the flow Reynolds number, $R_e = U_b d/v$, was < 2.86x10^7 for 24 hours for the gypsum and 67.94 hours for the travertine, sandstone and slate (g is acceleration due to gravity, d is flow depth and v is the kinematic viscosity). In the latter three tests, a total run duration of 50.73 hours at 9 ms^{-1} was followed by 16.73 hours at 7 ms^{-1} with three increments to 10.86 ms^{-1} for 0.16 hours on each occasion. This seemingly complex series of flow reductions and increments, totalling some 68 hours, was necessary, as running the flume at full speed for extended periods risked burning out the pump.

The test surfaces were photographed before and after each test. In addition, all the rock surfaces were scanned before and after the test runs using a NextEngine™ model 2020i desktop 3D scanner, mounted at a fixed distance above the test surface, with a resolution of 0.127mm in all dimensions. Scans were beneath artificial lighting but conducted at the same time of day so as to standardize for the direction and intensity of ambient natural lighting. Images were georeferenced by identification of several pixel matches in each run and subsequently a JPG quality 100 image of the original scan was compared with a scan taken after the run using the difference function within Adobe Photoshop CC™. This method looks at the RGB colour information in each channel and subtracts either the blend colour from the base colour or the base colour from the blend colour, depending on which has the greater brightness value.

Results

In all test runs, a small number of cavitation bubbles became visible close to, or on, the test surfaces as the flow velocity was increased such that a cavitating flow state was achieved. Further increases in flow velocity resulted in bubbles coalescing and growing larger until numerous bubbles were shed from the boundary. This shedding process was most common along the interface between the flume base and the upstream edge of a test rock slab, but also from the up-stream lip of the transverse groove. The progressive development and shedding of bubbles from the boundary, as described above, is well-known for cavitating flows (Plesset, 1949). Tests with the gypsum bed were initiated in non-cavitating flows ($k > 3$) at $1.1 ms^{-1}$ and the flow rate was increased at *circa.* $1 ms^{-1}$ increments over 1 hour and yielded similar results. When the non-cavitating flow rate reached $4.25 ms^{-1}$, 0.20m-wide, very shallow, furrows developed one-third of the way along the test block surface in association with incipient flutes (*sensu* Richardson & Carling, 2005) that developed spontaneously across the bed in the distal third of the section. As cavitation did not occur in these flows, the development of the furrows and flutes was associated with dissolution (as has been observed in other non-cavitating flows; Allen, 1982, vol. 2; page 244). In locally-cavitating 6.7ms^{-1} flow, the flutes extended upstream and began to coalesce (Fig. 2). As flutes had appeared on the bed surface in non-cavitating flows, the evolution of the flutes in the weakly-cavitating flow appeared to be a continuation of the dissolution process that began in non-cavitating flow, rather than due to cavitation *per se*. Maintaining the flow at 8.95ms^{-1} resulted in a uniform distribution of conjugate planform V-shaped flutes across the complete test surface (Fig.3).

With respect to the transverse groove in the gypsum test bed, the wall and lip of the backward-facing step, from which cavitation bubbles were seen to be shed, were more heavily ornamented by flutes than the forward-facing step (Fig. 4). Longer test runs resulted in deeper flutes and mutual interference of the flutes results in shortened flutes (Fig. 3). Nevertheless, despite increasing coalescence, the angle of flutes (β) measured from their upstream apices was constant through time (n = 44; $\bar{\beta}$ = 51^{o}; standard error of $\bar{\beta}$ = 2.14^{o}; β_{max}= 80^{o}; β_{min} = 19^{o}). Tests on the travertine, sandstone and slate in cavitating flows (k < 3) did not result in any visible surface erosion after 50 hours, with velocities of 9ms^{-1}, nor for tests after 67.94 hours with velocities of 7 to 10.86 ms^{-1}.

Difference images of the slate test surface, comparing before and after cavitating flow, showed no change had occurred (not illustrated), whereas the sandstone showed minimal differences with a few scattered, but individually isolated, pixels showing change (Fig. 5). Because the sandstone was fine-grained on the Wentworth (1922) scale with a D_{50} of *circa* 0.125 mm, at the image resolution each pixel may represent a single grain. Thus, changed pixels might represent resolution error or minor grain loss owing to fluid stressing during tests. Consequently, there was effectively no erosion on the harder substrates due to cavitation. As a caveat, this conclusion applies for the scan image resolution and the duration of the test runs. It is conceivable that this erosion of the sandstone could amplify over much longer duration runs. Nevertheless, it is evident that cavitation erosion in these experiments did not occur for velocities in excess of those commonly noted in natural rivers, as defined in the Introduction. Furthermore, cavitation erosion did not occur over the 68 hours of each test run, which period of time can be equivalent to the duration of typical flood events. The duration of flood events, in relation to cavitation developing, is an issue that is addressed within the Discussion.

Discussion

V-shaped flutes of similar form and scale as seen on the gypsum surface have been reported from bedrock surfaces in natural streams that were not subject to cavitation (Richardson & Carling, 2005). It is not known if flutes are unique to any specific flow regime, such as upper or lower regime, cavitating or non-cavitating. Rather, similar bedforms occur for a wide range of flow velocities and flow regimes in both natural channels and in the laboratory, including laboratory cavitating-flow velocities that do not occur in nature (Fig. 6). The cavitating flow experiments of Momber (2004a, b, c), conducted on granite, included glass beads impacting the granite surface at low density concentrations but at high velocities, but Momber (2004a, b, c) did not differentiate the abrasion effects of the impacting grains from the cavitating flow on the surface ornamentation. The flutes detailed by Momber (2004a, b, c) are small-scale, non-conjugate, and have narrow V-angles in contrast to the flutes formed in the present series of experiments on a gypsum surface. It is not known if this difference in scale and shape between the gypsum and granite flutes reflects the flow conditions, the duration of the tests, or the lithology of the substrates. However, there is a general agreement that the size of flutes reduces in inverse proportion to flow velocity and the density of ornament increases with time (Allen, 1971, 1982, Vol. 2, page 242; Richardson & Carling, 2005). Thus, the small, narrow-V flutes of Momber (2004a, b, c) may be indicative of high-velocity flows rather than cavitating flows. Further laboratory work on flute development would be required to ascertain if any distinction can be made between ornament formed by cavitation erosion *per se* and by other erosive processes.

Although the studs and grooves emplaced in the present test blocks did not induce erosion in the harder rocks, it is possible that other obstacles or natural rough surfaces offering a greater amplitude or angle of attack might induce more intense local cavitation and hence erosion. However, given acceleration ratios around obstacles of *circa* 1.5 to 2.4 are reported (Barnes, 1956), it is evident that the surface irregularities in the present experiments were subject for 68 hours to local speeds possibly twice the bulk flow velocities (*i.e*. 14ms^{-1} $\leq U_l \leq$ 22ms^{-1}). In this context, the spontaneous appearance of flutes across the gypsum bed (5ms^{-1} $\leq U_b \leq$ 11ms^{-1}) is interpreted as due to fluid stressing and dissolution rather than necessarily due to cavitation. This interpretation is supported by the fact that cavitation erosion does not develop spontaneously over large areas but rather tends to develop at surface defects (Mazurkiewicz & Summers, 1982) and then spreads progressively (Graham, 1987). Thus, given that gypsum flutes formed readily over large areas and there was no detectible erosion on the harder rocks, this outcome suggests that fluid stressing and dissolution were more important in causing soluble-rock erosion in this range of natural high-velocity, short-duration flows than cavitation. This contention is supported by the results of Mazurkiewicz & Summers (1982) and Erdmann-Jesnitzer et al. (1978) who only observed clear-water cavitation erosion of dolomite and granite for unnatural flow pressures of 5MPa and 50MPa respectively. These high pressures contrast to atmospheric pressure at sea level of 0.1MPa, which is the order of pressure to which natural rivers are subject.

The efficacy of abrasion, in contrast to cavitation, in natural flows is supported by El-saie et al., (1980) and Auel & Boes (2012) who concluded that, for natural river flow velocities, abrasion by sediment was more effective than cavitation in eroding basalt and granite. However, Momber (2003) recorded clear-water cavitation-induced pitting of granite, limestone, marble, rhyolite and schist for a bulk flow speed of $66ms^{-1}$ after three minutes in an experimental apparatus. However, a velocity of $66ms^{-1}$ far exceeds recorded natural flow rates in rivers. Nevertheless, within any natural cavitating flows, fluid stressing and dissolution will also cause erosion, the former being particularly effective on fissured or granular rock and the latter on soluble rocks. It is not clear how these processes can be separated experimentally, although simple approaches (Allen, 1971) can determine the likely occurrence of dissolution and fluid stressing in a fluid.

The observations presented herein prompt the question: what fluvial systems might demonstrate cavitation erosion? Any steep bedrock-chute that has a high, sustained, clear-water discharge, and is thus analogous to a dam spillway, might be a suitable candidate. Such systems largely will be restricted to mountainous regions, although lowland steep cascades are also potential sites. The fact that cavitation damage was not observed during a 68-hour period on the harder rocks has implications for the required duration of a flood, or series of conjugate floods, for cavitation erosion to be significant. Clearly, in natural flows, it cannot be precluded that weakly-cavitating flows of longer duration than observed in these experiments, or of repeated occurrence, may induce visible cavitation damage. Thus, given that the range of velocities that occur in natural rivers did not induce visible cavitation damage, the frequency of cavitating events becomes important and the following text considers this aspect.

Convective rain falls as local showers and most precipitation events in the tropics and the centres of continental masses tend to be convective and of short duration (Henry, 1974; Lumbroso & Gaume, 2012). In the same manner, warm fronts lead to extended periods of light rainfall, whereas cold fronts result in short-duration intense rainfall. Much precipitation in mid-latitude continental margins can be frontal and of short duration. All these short-duration storms can result in flash-flooding, generally of less than 24 hours duration (Gaume et al., 2009). In contrast, the equatorial regions near the Intertropical Convergence Zone are the wettest portions of the continents, such that flood volumes can be large and of extended duration as a result of the cumulative monsoonal rainfall over several months. Thus, it seems that cavitation erosion is more likely to be recorded in low latitude, high altitude, steep streams subject to extended monsoon-rain-induced discharge regimens (Lumbroso & Gaume, 2012) in which sediment loads are small, such that cavitation damage to the river bed is less likely to be effaced by sediment scouring. Theoretical calculations (Hancock et al., 1998) for the Indus River for monsoonal flows, augmented by snowmelt, demonstrated the importance of the steep shallow headwaters, in contrast to deeper low-gradient reaches, as potential sites for cavitation erosion. Thus, the meltwater flow regimens of glacial or snow-covered mountains are also additional candidates due to prolonged high discharges during the spring thaw, but herein sediment abrasion may confound cavitation erosion.

Finally, cavitation has been proposed frequently as an erosion agent in Quaternary megafloods due to the very high velocities predicted by flood models. As noted in the Introduction, velocities of <60ms^{-1} have been simulated on steep slopes (Carling et al., 2010; Alho et al., 2005; Alho et al., 2010; Carrivick, 2007) such that, for atmospheric pressure at sea-level and cold clear-water, locally-cavitating flow is possible (Fig. 7) as cavitation numbers could fall below 3.0. Ideally, flows need to be supercritical (Fr > 1; Fig. 7), but whereas this flow regimen is difficult to sustain over time and distance in normal stream flows (Grant, 1997) it may be possible for sustained supercritical flows to occur in megafloods. Specifically, hydraulic modelling of jökulhlaup and lahar flows has demonstrated that, in extreme events, super-critical flows might be sustained for time periods (typically < 2 hours) over distances of several hundred meters (Carrivick, 2007; Carrivick et al., 2009; 2013). In these examples, periods of subcritical flow were repeatedly interspersed with periods of supercritical flows, thus potentially allowing cavitation erosion to occur. Nevertheless, the durations of the large Quaternary megafloods were around 1 to 18 days during which very high sediment loads might suppress cavitation (Gyr & Bewersdorff, 1995). Not only will abrasion remove cavitation marks during non-cavitating flows, but sediment abrasion during cavitating flows is known to efface the evidence of any cavitation erosion (Allen, 1982, Vol. 1, p. 74; Li, 2002) and plucking would do likewise. Concentric fracture patterns and percussion marks on rocks have been associated with possible cavitation (Shaw, 1996; Richardson & Carling, 2005). Similar features have been observed on natural rock samples (Momber, 2004a) during water-drop impact cavitation experiments, but only for drop-impact velocities of 596 to 800ms^{-1}. The velocity at which erosion was observed was reduced when particles impinged on the rock surfaces, but the particle velocity range is still 60ms^{-1} to 200ms^{-1}, depending on rock type (Momber, 2004b). A schist of a hardness (Mohs ~ 3) intermediate to the present non-eroding test samples (Table 1), displayed significant cavitation-induced erosion in clear water only when the velocity exceeded 600ms^{-1} (Momber, 2004c). Thus, although erosion in cavitating flow has been observed on spillway concrete (an aggregate) for relatively low speeds (~ 16ms^{-1}; Falvey, 1990), and these velocities might occur in some exceptional natural floods, the rate of erosion was exceedingly slow and fluid stressing and dissolution also would have occurred (Graham, 1987). Consequently, extended clearwater flood durations are required if extensive cavitation erosion is to be identified in nature on fairly homogeneous rock types such as slate and sandstone. By analogy with concrete (Graham, 1987), it is possible that some natural aggregate rocks may erode due to cavitation in a range of natural streamflows due to preferential erosion of the softer interstitial cement between harder grains (Momber, 2004a, b, c), but this has yet to be demonstrated. For all rock-types, experimental work is required to determine the cavitating clear-water flow conditions during which individual particles are removed due to: (1) dissolution; (2) intergranular failure; and (3) structural failure caused by fracturing of brittle elements within the microstructure (Guiberteau et al., 1994; Bourne & Field, 1995) due to fluid stressing, as well as cavitation itself. The substantial differences in rock-types will mediate erosion mechanisms and thus will dictate the erosion rates as well as the typology of any erosional bedforms, including cavitation-induced forms.

Conclusions

Weakly-cavitating flows, with a velocity range typical of natural rivers, did not induce cavitation erosion of medium resistance bedrock (travertine, slate and sandstone) in an experimental channel despite 68 hours of cavitating flows. A soft gypsum rock was shown to be erodible in weakly-cavitating flows, but this erosion was an extension of dissolution erosion already noted prior in non-cavitating flow. In addition, cavitation erosion may be effaced, or replaced, by bedrock plucking due to clear-water fluid stressing, clear-water dissolution or abrasion by a sediment load. It appears that the range of velocities observed in natural river flows does not induce cavitation erosion over the time-scales of typical individual flood events due to the short duration of rainfall typical of temperate latitudes. Monsoon flow regimens, or flow regimens dominated by extended periods of high velocity discharge due to ice or snow melt (with low sediment loads), are likely environments in which cavitation erosion of bedrock might be identified. In terms of geomorphological implications, cavitation erosion of rock is unlikely to be a major contribution to incision in bedrock fluvial systems and consequently its neglect in incision models is justified.

Acknowledgements

Jose M. Mier and Nicholas Moller (Civil & Environmental Engineering, University of Illinois) are thanked for velocity calibration of the tunnel, and Andy Wartuke provided invaluable laboratory assistance. The use of the cavitation tunnel at the Ven Te Chow Hydrosystems Laboratory was made possible thanks to the generosity of the Chester and Hellen Siess Endowed Professorship in Civil Engineering. Andrew Wilson and Vic Baker provided insightful reviews of an earlier version of the manuscript. The published version benefited from thorough reviews by Jonathan Carrivick and an anonymous reviewer.

References

Alho P, Russell AJ, Carravick JL, Köyhkö J. 2005. Reconstruction of the largest Holocene jökulhlaup within Jökulsá á Fjö llum, NE Iceland. Quaternary Science Reviews 24: 2319–2334

Alho P, Baker VR, Smith LN. 2010. Paleohydraulic reconstruction of the largest Glacial Lake Missoula draining(s). Quaternary Science Reviews 29**:** 3067-3078

Allen JRL. 1971. Transverse erosional marks in mud and rock: their physical basis and geological significance. Sedimentary Geology 5**:** 167-385

Allen, JRL. 1982. Sedimentary Structures: their Character and Physical Basis, Vols 1 & 2, Elsevier, The Netherlands

Anton L, Mather A.E., Stokes M, Muñoz-Martin, De Vicente G. 2015. Exceptional river gorge formation from unexceptional floods. Nature Communications 6:7963, DOI: 10.1038/ncomms8963

Arndt REA. 1981. Cavitation in fluid machinery and hydraulic structures. Annual Reviews of Fluid Mechanics 13: 273-328

Arndt REA, Ellis CR, Paul S. 1993. Preliminary investigation of the use of air injection to mitigate cavitation erosion, In Arndt RE, Billet ML, Blake WK (eds). Proceedings: ASME International Symposium on Bubble Noise and Cavitation Erosion in Fluid Systems, FED-176: 105–116.

Auel C, Boes RM. 2012. Sustainable reservoir management using sediment bypass tunnels. In Proc. ICOLD Symposium, Dams and Reservoirs under Changing Challenges, 80th Annual Meeting, 2-5 June 2012, Kyoto, Japan, Paper Q.92-R.16, 224-241

Baker VR. 1973. Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington. Geological Society of America Special Paper 144

Baker VR. 1974. Erosional forms and processes for the catastrophic Pleistocene Missoula floods in eastern Washington. In Fluvial Geomorphology, Morisawa M (ed), Allen & Unwin, London, 123-148

Baker VR, Costa JE. 1987. Flood power. In Catastrophic Flooding, Mayer L, Nash D (eds), The Binghamton Symposia in Geomorphology International Series 18: 1-21

Baker VR, Kale VS. 1998. The role of extreme floods in shaping bedrock channels. In Rivers Over Rock: Fluvial Processes in Bedrock Channels. Tinkler KJ, Wohl EE (eds). Geophysical Monographs 107. Washington D.C.: American Geophysical Union; 153-165

Barnes HL. 1956. Cavitation as a geological agent. American Journal of Science 254: 493-505

Bourne NK, Field JE. 1995. A highspeed photographic study of cavitation damage. Journal of Applied Physics 78: 4423-4427

Cameron CP, Cato KD, McAneny CC, May JH. 1986. Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels, Technical Report REMR-GT-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS, USA.

Carling PA, Villanueva I, Herget J, Wright N, Borodavko P, Morvan H. 2010. Unsteady 1D and 2D hydraulic models with ice dam break for Quaternary megaflood, Altai Mountains, southern Siberia. Global and Planetary Change 70**:** 24-34

Carrivick JL. 2007. Hydrodynamics and geomorphic work of jökulhlaups (glacial outburst floods) from Kverkfjöll volcano, Iceland. Hydrological Processes 21**:** 725–740

Carrivick JL. 2009. Jökulhlaups from Kverkfjöll volcano, Iceland: modelling transient hydraulic phenomena. In Megaflooding on Earth and Mars, Burr DM, Carling P, Baker VR (eds). Cambridge University Press: Cambridge; 273–289

Carrivick JL, Manville V, Cronin S J. 2009. A fluid dynamics approach to modelling the 18th March 2007 lahar at Mt. Ruapehu, New Zealand. Bulletin of Volcanology 71: 153-169

Jonathan L. Carrivick JL. 2010. Dam break – Outburst flood propagation and transient hydraulics: A geosciences perspective. Journal of Hydrology 380 (2010) 338–355

Carrivick JL, Manville V, Graettinger A, Cronin SJ. 2010. Coupled fluid dynamics-sediment transport modelling of a Crater Lake break-out lahar: Mt. Ruapehu, New Zealand. Journal of Hydrology 388: 399-413

Carrivick JL, Turner AG, Russell AJ, Ingeman-Nielsen T, Yde JC. 2013. Outburst flood evolution at Russell Glacier, western Greenland: effects of a bedrock channel cascade with intermediary lakes. Quaternary Science Reviews 67: 39-58

Chatanantavet P, Parker G. 2009. Physically based modeling of bedrock incision by abrasion, plucking, and macroabrasion. Journal of Geophysical Research 114: F04018, doi:10.1029/2008JF001044.

Dolen T, Hepler T, Mares D, Nuss L, Stanton D, Trojanowski J. 2005. Roller-Compacted Concrete Design and Construction Considerations for Hydraulic Structures. U.S. Department of the Interior, Bureau of Reclamation Technical Service Center Denver, Colorado. 177pp.

El-saie AA, Summers DA, Owen K. 1980. Contrast between sand, water and cavitation erosions of rock. Wear 60**:** 229-236

Embleton C, King CAM. 1968. Glacial and Periglacial Geomorphology, St. Martins Press: New York

Erdmann F, Louis H, Wiedemeier J. 1978. The effect of nozzle configuration on the performance of submerged water jets. In 4th International Symposium on Jet Cutting Technology, 12th - 14th April, 1978, University of Kent, Canterbury, E3-29 to E3-44

Falvey HT. 1990. Cavitation in Chutes and Spillways. Engineering Monograph No. 42, USDI Bureau of Reclamation: Denver

Finnegan NJ, 2013. Interpretation and downward correlation of bedrock river terrace treads created from propagating knickpoints. Journal of Geophysical Research: Earth Surface 118: 54-64.

Grant GE. 1997. Critical flow constrains flow hydraulics in mobile bed streams: a new hypothesis. Water Resources Research 33: 349–358

Gaume E. and 24 other authors. 2009. A collation of data on European flash floods. Journal of Hydrology 367**:** 70-78

Graham JR. Erosion of concrete in hydraulic structures. Report by American Concrete Institute Committee 210, American Concrete Institute, Detroit, USA, 24pp.

Guan M, Wright NG, Sleigh PA, Carrivick JL. 2015. Assessment of hydro-morphodynamic modelling and geomorphological impacts of a sediment-charged jökulhlaup, at Sólheimajökull, Iceland. Journal of Hydrology 530: 336-349

Guiberteau F, Padture NP, Lawn BR. 1994. Effect of grain size on Hertzian contact damage in alumina. Journal of the American Ceramic Society 77: 1825-1831

Gupta A, Kale VS, Rajaguru SN. 1999. The Narmandu River, India, through space and time. In Variety of Fluvial Forms, Miller AJ, Gupta A (eds). Wiley, Chichester: 113-143

Gyr A, Bewersdorff H-W. 1995, Drag Reduction of Turbulent Flows by Additives. Fluid Mechanics and Its Applications, 32, Springer-Science, The Netherlands.

Hancock GS, Anderson RS, Whipple KX. 1998. Beyond power: bedrock river incision process and form. In Rivers Over Rock: Fluvial Processes in Bedrock Channels. K.J. Tinkler KJ, Wohl EE. (eds). Geophysical Monographs 107. American Geophysical Union, Washington D.C: 35-60

Henry WK. 1972. The tropical rainstorm. Monthly Weather Review 102**:** 717-725

Hjulström F. 1935. Studies of the morphological activities of rivers as illustrated by the River Fyris. Uppsala University Geological Institute Bulletin 25**:** 221-527

Jacobs and Hagmann-2015 - Sediment bypass tunnel Runcahez: Invert abrasion 1995-2014; Proc. First International Workshop on Sediment Bypass Tunnels; ETH Zurich, Switzerland: 211-222

Jia Yanhong, Wang Zhaoyin, Zheng Xiangmin, Li Yanfu. 2016. A study on limit velocity andits mechanism and implications for alluvial rivers. International Journal of Sediment Research 31: 205–211

Johnson JPL, Whipple KX. 2007. Feedbacks between erosion and sediment transport in experimental bedrock channels. Earth Surface Processes and Landforms 32: 1048-1062.

Johnson JPL, Whipple KX. 2010. Evaluating the controls of shear stress, sediment supply, alluvial cover, and channel morphology on experimental bedrock incision rates. Journal of Geophysical Research 115, F02018, doi:10.1029/2009JF001335

Karlstrom KE, Crow R, Crossey LJ, Coblentz D, Van Wijk JW. 2008. Model for tectonically driven incision of the younger than 6Myr Grand Canyon. Geology 36**:** 835-838

Kells JA, Smith CD. 1991. Reduction of cavitation on spillways by induced air entrainment. Canadian Journal of Civil Engineering, 18: 358-377

Lamb MP, Fonstad MA. 2010. Rapid formation of a modern bedrock canyon by a single flood event. Nature Geoscience 3**:** 477-481

Lamb MP, Finnegan NJ, Scheingross JS, Sklar JL. 2015. New insights into the mechanics of fluvial bedrock erosion through flume experiments and theory. Geomorphology 244: 33–55

Li S. 2006. Cavitation enhancement of silt erosion – an envisaged model. Wear 260: 1145-1150

Lumbroso D, Gaume E. 2012. Reducing the uncertainty in indirect estimates of extreme flash flood discharges. Journal of Hydrology 414-415: 16-30

May RWP. 1987. Cavitation in Hydraulic Structures: Occurrence and Prevention, Report No. SR 79, Hydraulics Research Ltd, Wallingford, UK, 235pp.

Mazurkiewicz M, Summers DA. 1982. The enhancement of cavitation damage and its use in rock disintegration. In 6th International Symposium on Jet Cutting Technology, 6th - 8th April, 1982, University of Surrey, Guildford, 27- 38

Momber AW. 2003. Cavitation damage to geomaterials in a flowing system. Journal of Materials Science 38: 747-757

Momber AW. 2004a. Wear of rocks by water flow. International Journal of Rock Mechanics & Mining Sciences 41: 51-68

Momber AW. 2004b. Damage to rocks and cementitious materials from solid impact. Rock Mechanics & Rock Engineering 37: 57-82

Momber AW. 2004c. Deformation and fracture of rocks due to high-speed liquid impingement. International Journal of Fracture 130: 683-704

Novak P, Moffat AIB, Nalluri C, Naryanan R. 2007. Hydraulic Structures, 4th Edition, Taylor & Francis, London,

O'Hern TJ. 1990. An experimental investigation of turbulent shear flow cavitation: Journal of Fluid Mechanics 215: 365–391.

Pielou EC. 1998. Fresh Water, University of Chicago Press, Chicago

Plesset MS. 1949. The dynamics of cavitation bubbles. ASME Journal of Applied Mechanics 25: 228-231.

Ribeiro AA, DaCunha VL, DaSilva DP, Lemos FO. 1976. Erosion in concrete and rock due to spillway discharge. In Proceedings of Ninth International Congress on Large Dams, 2**,** International Commission on of Large Dams, Istanbul, 315–31.

Richardson K, Carling PA. 2005. A typology of sculpted forms in open bedrock rivers. Geological Society of America, Special Paper 392**:** 1-108

Sato S, Matsuura H, Mayazaki M. 1987. Potholes in Shikoku, Japan, part 1. Potholes and their hydrodynamics in the Kurokawa River, Ehime. Memoirs of the Faculty of Education of Ehime University, Natural Science 7: 127-190

Shaw J. 1996. A meltwater model for Laurentide subglacial landscapes. In Geomorphology Sans Frontiers, McCann SB, Ford DC (eds), Wiley, Chichester, 181-236

Sklar LS, Dietrich WE. 2004. A mechanistic model for river incision into bedrock by saltating bed load. Water Resources Research 40: W06301, doi:10.1029/2003WR002496

Tinkler K, Bursik M, Renschler CS. 2005. Field Trip Guide, BGS'05, 30th Binghamton Geomorphological Symposium: Geomorphology & Ecosystems, University of Buffalo, Buffalo, New York, October 7-9, 2005, 30pp plus figures.

Tinkler KJ, Wohl EE. 1998. A primer of bedrock channels. In Rivers Over Rock: Fluvial Processes in Bedrock Channels, Tinkler KJ, Wohl EE. (eds.), Geophysical Monographs 107, American Geophysical Union, Washington D.C., 1-18

Toshima M, Okamura, T, Satoh J, Usami K, Tanabe S. 1991. Basic study of coupled damage caused by silt abrasion and cavitation erosion, Journal of the Japanese Society of Mechanical Engineers (B) 57: 20-25.

Turowski JM, Lague D, Hovius N. 2007. Cover effect in bedrock abrasion: A new derivation and its implications for the modelling of bedrock channel morphology. Journal of Geophysical Research 112: F04406, doi:10.1029/2006JF000697

U.S. Army Corps of Engineers. 1990. Hydraulic Design of Spillways. Engineer Manual 1110-2-1603, Department of the Army, U.S. Army Corps of Engineers, Washington, DC 20314-1000, 170pp

Wentworth CK. 1922. A scale of grade and class terms for clastic sediments, Journal of Geology 30: 377-392

Whipple KX, Handcock GS, Anderson RS. 2000. River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion and cavitation. Geological Society of America Bulletin 112: 490-503

Wohl EE. 1992. Bedrock benches and boulder bars: floods in the Burdekin Gorge of Australia. Geological Society of America Bulletin 104: 770-778

Table 1: Material characteristics of test rock types.

Material	**Mohs hardness (-)**	**Schmidt hardness N mm^{-2}**	**Bulk density kg m^{-3}**
Gypsum Cement	2	6.2	1.585
Travertine	3	11.3	2.425
Slate	4	32	3.00
Fine-Grained Sandstone	5	37.6	2.36

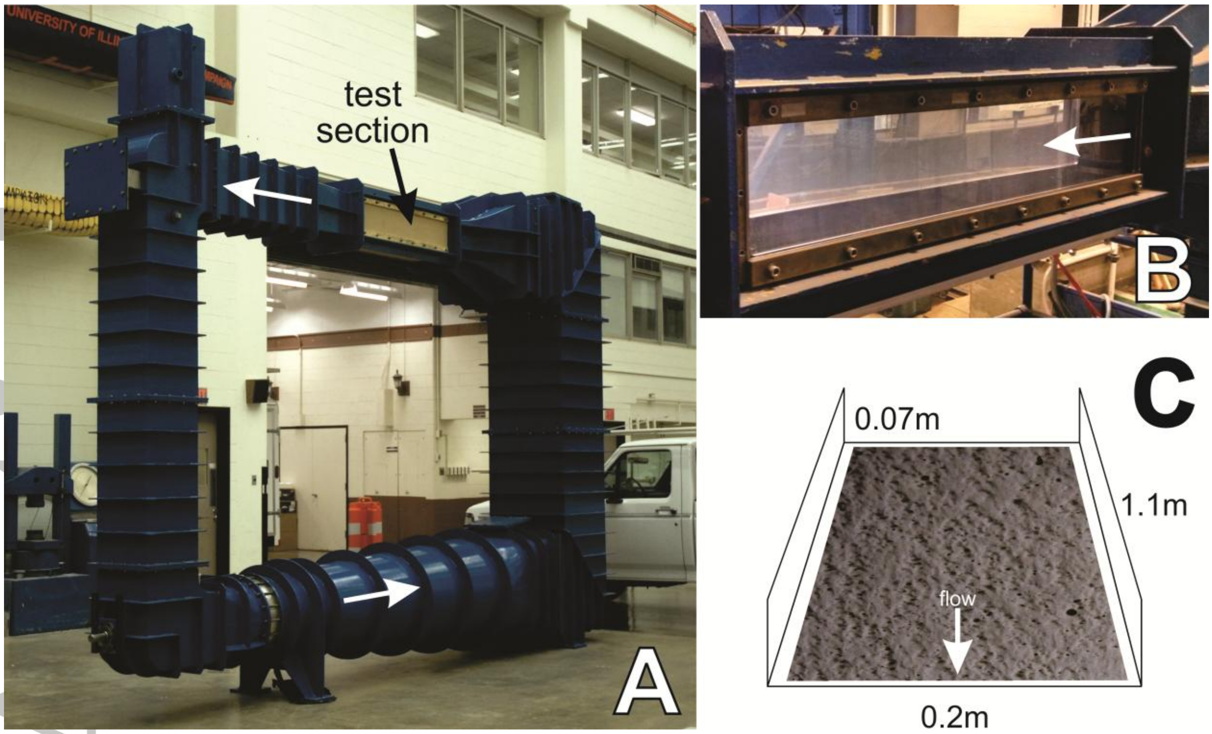

Figure 1: A) The cavitation flume at the Ven Te Chow Hydrosystems Laboratory of the University of Illinois at Urbana, Champaign, consisting of a vertical annulus 2.8m high measured from the centres of the lower and upper ducts. The lateral spacing of the vertical ducts is 4.89m. B) The rectangular test section, 1.1m long by 0.20m high and 0.30m wide, with Plexiglass windows on both sides and on the top. C) Schematic diagram of the sample pan that is recessed into the test section so that the surface of the test rock block is flush with the bed of the test section.

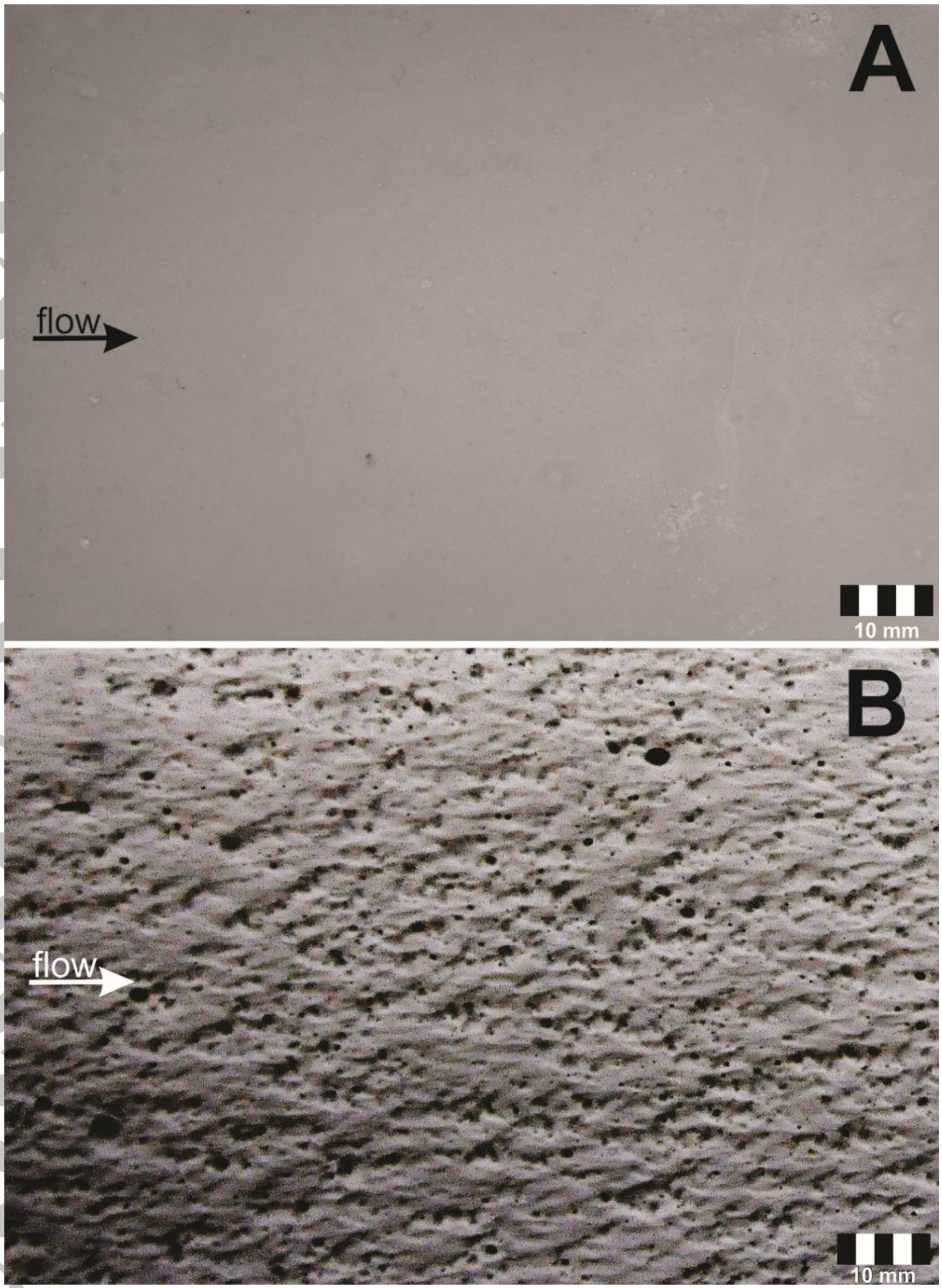

Figure 2: A) Initial planar surface of the gypsum bed before subject to water flow; B) Gypsum surface after 1.66 hours of weakly-cavitating flow at 6.7 ms^{-1}. Note that the V-forms are open in the downflow direction with their apices pointing upstream. The circular pits are vugs (produced during the original casting) revealed once the plane gypsum surface (in A) was eroded away.

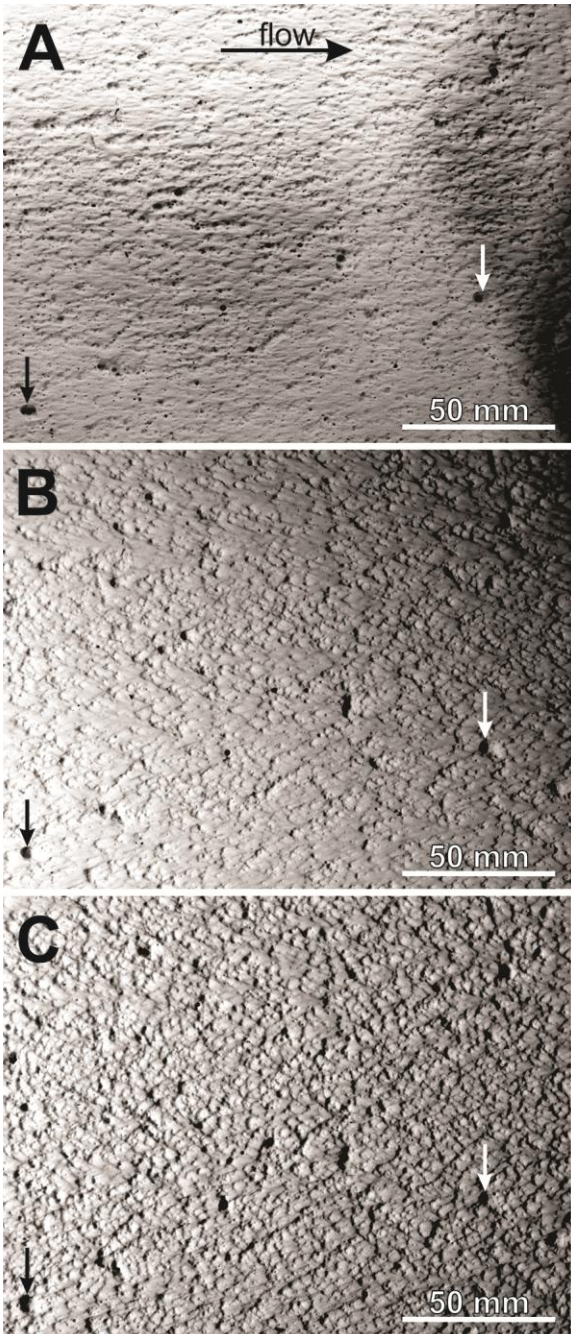

Figure 3: Sequential evolution of flutes on gypsum surface. Flow left to right. (A) After 1 hr in non-cavitating flow at 4.25m s^{-1} flutes are not conjugate; (B) After 1.66 hrs in weakly-cavitating flow at 6.7m s^{-1} flutes begin to conjugate and shorten; (C) After several hours of weakly-cavitating flow at 8.95m s^{-1} flutes are conjugate and short. Arrows point to the same features at each time increment for reference.

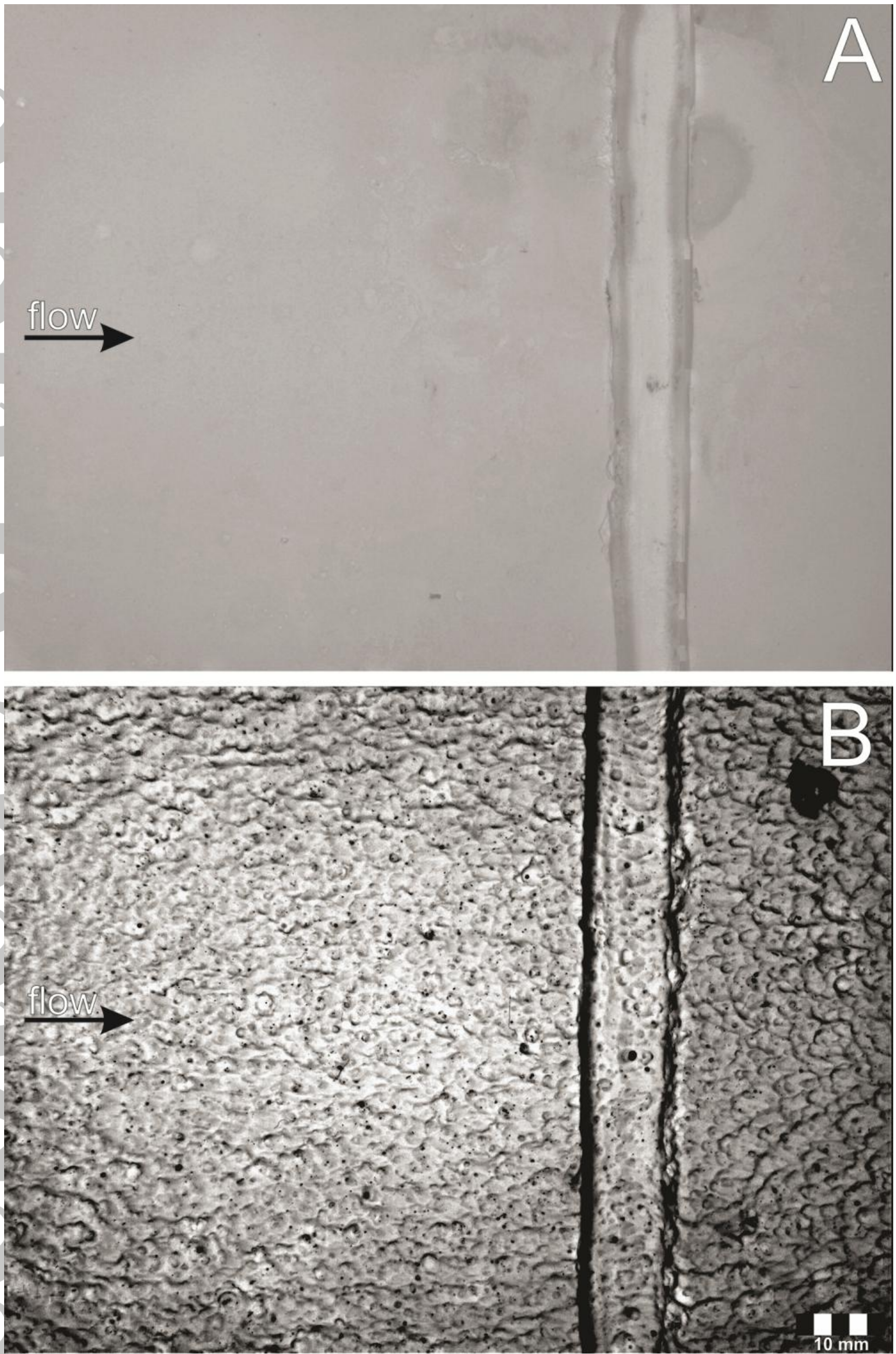

Figure 4: A) Initial planar surface of the gypsum bed with the uneroded transverse groove showing slightly irregular edges from the original casting; B) After several hours of weakly-cavitating flow at 8.95m s^{-1}, conjugate flutes ornament the sides and base of the transverse groove in the gypsum bed as well as the previously planar

surface. Note that fluting is more pronounced on the downstream lip of the groove than on the upstream lip, which remains relatively sharp.

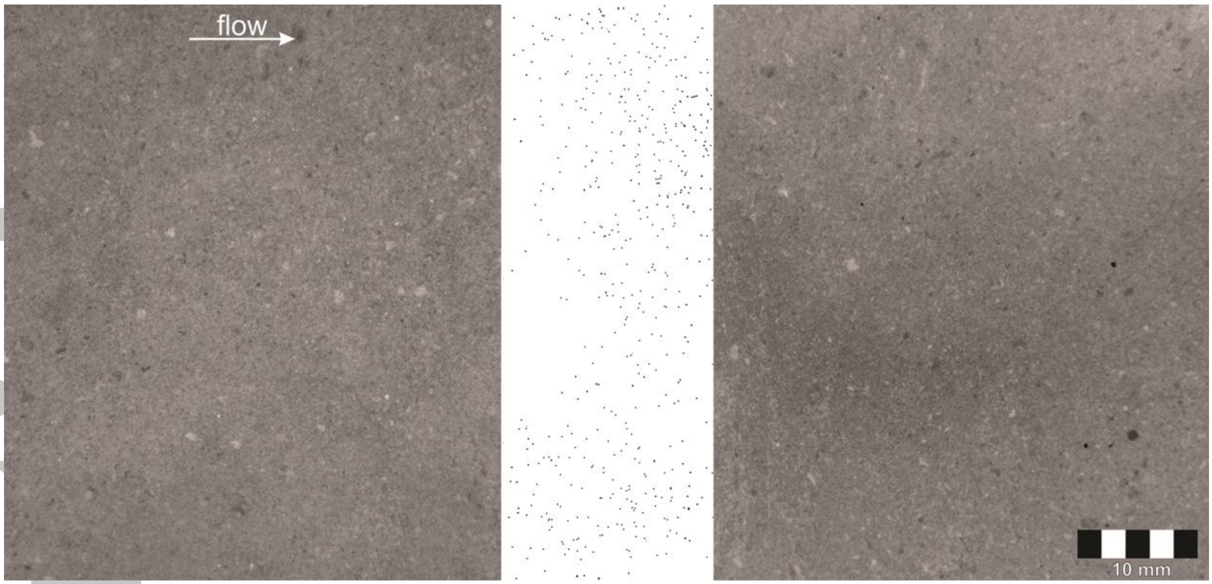

Figure 5: Differenced photograph of sandstone test surface after 67.45 hours exposure to velocities of 7 to 10.86ms^{-1}. Upstream surface to the left and the downstream surface to the right. The two scanned surfaces are over-lapped by 27% in the central (white) area with points of difference in the overlap area shown as black dots.

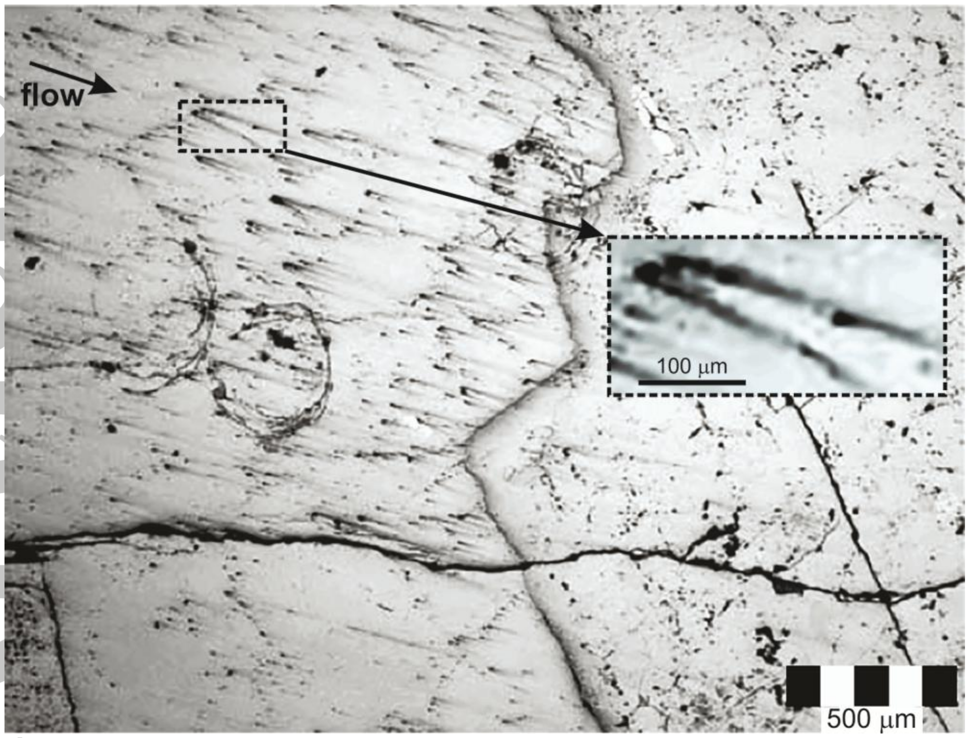

Figure 6: Illustration after Momber (2004b)', his Fig. 16b, showing the effect of glass bead impacts on granite in cavitating flow at a fluid velocity of 80ms^{-1}.

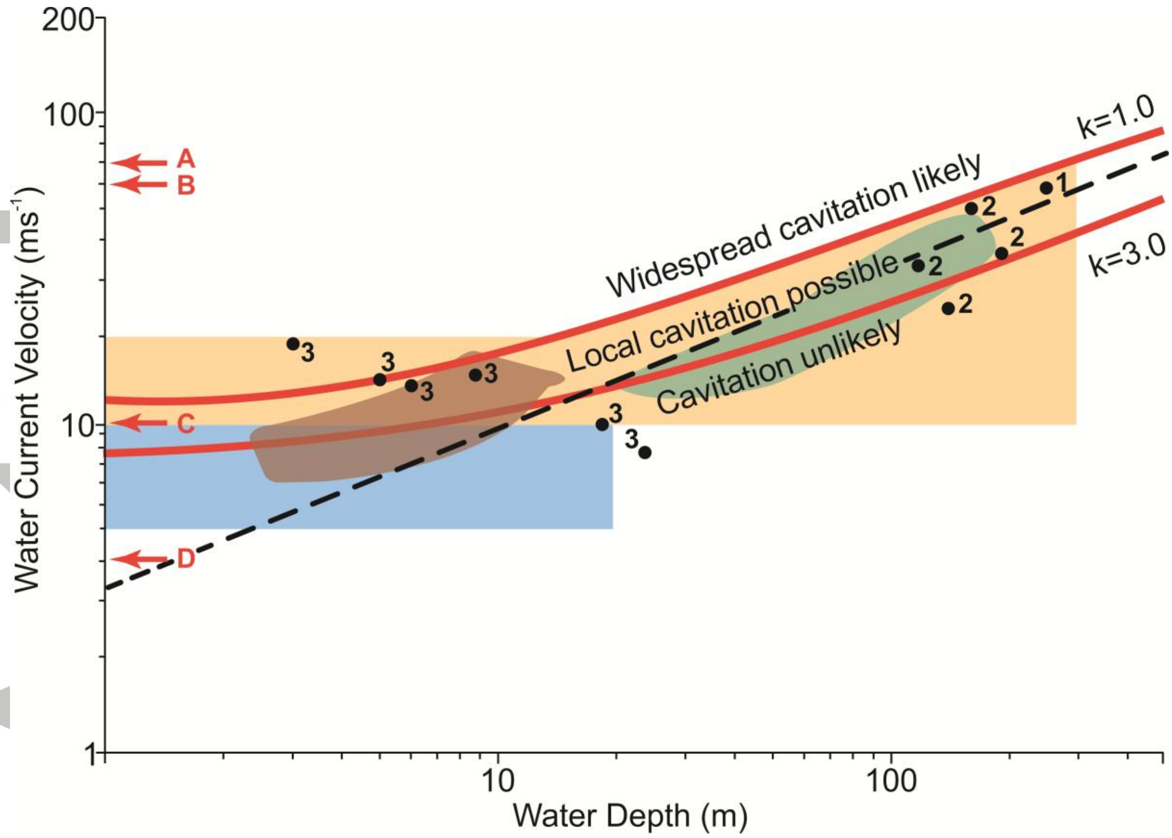

Figure 7: Estimate of likelihood of cavitation occurring for given bulk velocity, $U_b = \left(\frac{2g}{k}\right)^{\frac{1}{2}} [d]^{\frac{1}{2}}$, similar to Barnes (1956), with *d* corrected for vapour pressure and atmospheric pressure at sea level (curve *k* = 1.0). Uncertainty in the occurrence of cavitation is addressed by defining a local maximum speed up to twice the mean bulk flow speed (curve *k* = 3.0). The light blue region defines the usual range of maximum flow velocities in rivers, whilst the beige area defines the modelled range of palaeoflood flow velocities (Carrivick, 2007). The orange area defines the data range for Icelandic Holocene floods (Carrivick, 2007) and the green area defines range of most estimated Bonneville Quaternary megafloods (Carrivick, 2007). Numbered megaflood symbols represent well-constrained hydraulic model estimates: 1: Altai; 2: various Missoula sites; 3: various Iceland floods. A = lowest flow velocity for significant cavitation erosion in: granite, limestone, marble, rhyolite, schist; B = highest palaeoflood velocity; C = significant erosion of gypsum in

cavitating flow; D = lowest recorded cavitating-flow erosion of concrete. Broken line is Froude = 1.0, with subcritical flow occurring when *Fr* < 1 and supercritical flow occurring when *Fr* > 1. Data sources: Alho et al., 2005; Alho et al., 2010; Momber, 2003; Carrivick, 2007.