The Structural Fabric and Deformation of Channel-Spanning Mountain Logjams: Field Observations and Experimental Analogs

by

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Committee Approval

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Chapter 1: Introduction

Thesis Abstract

Logjams are accumulations of wood in rivers that are found within a spectrum of topologies. Despite wide recognition of the prevalence and importance of logjams in river ecosystems, they defy the force-balance framework that underlies and informs studies of wood transport. Namely, we lack empirical observations of large, channel-spanning logjams and their dynamics. Existing work is conducted on coarse timescales and focuses on individual logs or volumetric fluxes, not the mechanisms and physics of log-log interactions. Here, we report the results of 1) a novel monitoring campaign of a thousand-member, channel-spanning logjam in the mountains of central Idaho and 2) a series of flume experiments inspired by said field observations. Both seek to answer a fundamental question: how do channel-spanning logjams deform?

We find that deformation is accommodated internally via compression, a common mechanism in both field and analog experiments. This is apparent only over significantly long timescales of observation. Over short timescales, logjams in the field and the flume appear rigid and static. Because deformation occurs as many small incremental displacements over long timescales, we suggest that logjams exhibit a creep-like behavior, analogous to that in materials science. This creep is most active when logs are buoyant in the water column and are able to be sheared by moving water from below. As the logjam compresses by reducing interstitial spaces between logs, friction and support from the bed reduces deformation. We integrate insights from the flume and field to construct a conceptual model of logjam initiation and evolution.

1.1 Problem Statement

Logjams are accumulations of wood that aggregate in rivers and whose persistence in the landscape carry implications for stream function and form, as well as for biological actors [*Piégay and Gurnell* 1997]. Therefore, understanding the physics and transport mechanics of large, channel-spanning logjams in mountainous environments is critical for informing river management and restoration best practices, stream rehabilitation efforts and collective understanding of geomorphology and natural phenomena. We are historically blinded by the consequences of Westward expansion, logging practices and the systematic removal of large wood from rivers, rendering us poor in empirical examples to guide studies of logjam dynamics and fundamentally altering river-wood feedbacks in North America [*Wohl* 2014]. Current understanding of wood transport mechanics is rooted in a theoretical model derived from first principles [*Braudrick and Grant* 2000, 2001] that is not adequate to capture the full dynamism of field observations, nor is it designed to account for the kinematics of channel-spanning logjams, composed of an ensemble of individual logs and therefore a complex network of physical interactions. Granular physics is a discipline that deal with precisely these problems: the ensemble kinematic behavior of 'grains'. Workers within this community have casually suggested that logjams are a granular phenomenon, although accompanying field data to support this claim are lacking. This is intriguing, as the namesake 'logjam' also contains a current buzzword in physics: 'jam', which has a precise definition and is an active area of current research. This uniquely poses logjams as an area of research with the potential to bridge very different scientific disciplines by adopting the analytical perspective of one (granular physics), with the intention of advancing collective knowledge and practical application of the other (geomorphology).

1.2 Wood Transport Background

Large wood interacts with flowing water and sediment to produce a suite of geomorphic effects that fall into three general categories: changes in sediment dynamics (storage, routing), channel dynamics and processes (avulsions) and channel morphology (scour, pools) [*Montgomery et al.* 2003]. Logs deposited within rivers support biocomplexity [*Gurnell et al.* 2005]. The accumulation of wood into logjams has been found beneficial to salmonid populations [*Collins et al.* 2011]. We acknowledge the topics above as broader impacts of wood in rivers, but focus in this chapter on outlining the framework of wood transport mechanics, as it is most relevant to the following work. This thesis focuses on logjam deformation, not their influence on channel morphology or ecologic systems.

The definition of 'logjam' is somewhat ambiguous, as workers employ varying definitions of the term in the literature. Logjams are found on gravel bars, meander bends, and on a number of other morphologic features. They can be constituted by tens of logs, or by a single large piece and many smaller members. A taxonomy detailing the variety of logjams can be found in *Abbe and Montgomery* [2003]. None of the logjam types that they document (nor any other type found during our literature search or in conversations with colleagues) accurately describe the feature that we study here. As further explained in Chapter 2, the logjam in Big Creek, Idaho is located in a steep, bedrock-confined reach and is composed of many thousands of large wood pieces. Sources may describe this as a 'log raft'. However, these features are typically defined by the low-lying alluvial reaches in which they are found [*Abbe and Montgomery* 2003, *Kramer and Wohl* 2014*, Boivin et al.* 2015]. In this work, we use the term ‘logjam’ to refer specifically to the example in Big Creek.

Current understanding of wood transport mechanics is rooted in a theoretical model derived from first principles and observations from downscaled physical experiments [*Braudrick et al.* 1997, *Braudrick and Grant* 2000, 2001]. The simplest case, a force balance on a smooth, cylindrical log, interrogates the relationship between wood piece characteristics (density, diameter, rootwad presence and orientation to flow) and the hydrologic parameters (width and depth) required to entrain wood pieces and their subsequent movement (Figure 1.1). The force balance requires a piece of wood to overcome frictional and gravitational forces by either floating or rolling at some threshold floating depth. Refinements to the force balance model indicate that hydrodynamic lift is an important component for determining log entrainment [*Alonso* 2004].

Within this suite of flume experiments, the collective dynamics of wood in transit yield two pertinent observations that relate to logjam formation. The first is that movement can be characterized by three transport regimes: congested, uncongested and semi-congested, which depend on the input rate and flux of wood into the flume *Braudrick et al.* (1997) (Figure 1.2). Logs within the semi-congested and congested regimes were likely to result in deposition and the formation of logjams. However, log-log contacts in the congested regime and during their subsequent deposition as logjams are outside the scope of the force balance model and were not pursued within these studies. Additionally, these logjams were impeded by barforms and meanders, a fundamentally different setting from the logjam we study in this thesis. The second observation indicates that wood aligns preferentially to the flow direction, as a way of minimizing drag. Granular physicists (Chapter 1.3), observe similar dynamics in ensembles of elongate grains and that the evolution of structural fabric and orientational order is a mechanism of reducing bulk friction by 30% *[Börzsönyi* et al. 2012] (Figure 1.3). This idea is further explored by *Shields and Alonso* [2012], who use field-scale experiments to demonstrate that the drag coefficients of submerged logs is reduced by two orders of magnitude when their orientations are parallel to the flow.

The force-balance framework lends itself to collecting data in the field: flow depths and widths are easily measurable hydrologic parameters, as are the dimensions, orientations and locations of individual logs. In field studies, this threshold is typically cast as a dimensionless length, L*, the ratio between the log length and the channel width, following the experiments of *Braudrick and Grant* [2000, 2001]. They find that the longer wood pieces are, the longer their travel distances, and that the transport regimes of wood is dependent on the rate at which they are delivered into the stream. Until recently, transport dynamics of single logs were conducted over coarse, annual timescales [*Wohl and Goode* 2008]. The application of GPS, RFID and video techniques for monitoring wood movement [*Ravazzolo et al.*, 2013, 2015, *Schenk et al.* 2014, *MacVicar et al.* 2009] has enabled a surge in the interest and a wealth of data that detail the mechanics of single log mobility. Transport rates encode signatures of hysteresis [*MacVicar and Piégay*, 2012], are dependent on diverse fluvial process such as ice break-out floods [*Boivin et al.*, 2015], and are highly sensitive to hydrograph shape and timing [*Ruiz-Villanueva et al.* 2016]. However, L* remains a poor explanatory variable, (as is stream power [*Wohl and Goode* 2008]) as there is considerable scatter [Figure 1.4].

Scatter likely sources from the diverse processes listed above and by the ‘perching’ of logs along topographic highs that are inaccessible to flows that are less than those that emplaced the logs. The surge of data and techniques for measuring wood transport have been summarized by *Kramer and Wohl* [2016] and *Ruiz-Villanueva et al.* [2016], both of whom explicitly call for high spatio-temporal measurements of *in-situ* logjam dynamics though do not provide this data.

The mobility of logjams composed of tens of logs and located in low-gradient, gravel-bedded rivers has been explored both in the field and in flume studies. These logjams tend to persist in the same locations in the landscape because of channel constrictions and obstacles [*Curran* 2010, *Bochhiola et al.* 2006]. In steep catchments, small logjams persist by dynamically shedding logs from their front while recruiting wood supplied from upstream and therefore maintaining their location [*Dixon and Sear* 2014]. It should be emphasized that these logjams are on a much smaller scale than the logjam that we address in this study. Flume investigations likewise indicate that logjams are quite stable when deposited, but can become mobile by morphological changes to the bed that undermine logjam stability [*Bertoldi et al.* 2014]. Even randomly recruited logs quickly amalgamate into logjams, and large pieces of wood facilitate the nucleation and stability of these features. In steep mountainous catchments, rivers are confined by bedrock and cannot choose alternative courses of flow or circumvent logjams. While in low-gradient, alluvial settings, logjams may be static because hydrologic forcings are dispersed throughout the floodplain, logjams in steep bedrock sections experience a more intense concentration of fluid shear.

Schematic, conceptual force-balance models (different from the single-log force balance discussed above) and mechanistic models of logjam formation have been proposed [*Wohl* 2011, *Manners and Doyle* 2008]. These models are designed for relatively small logjams composed of tens of logs and smaller pieces of wood, not the channel-spanning features that we study here. Additionally, these approaches are quasi-physically based, because they implicitly assume some stationarity in the time and length scales over which forces are measured. The kinematics of logs themselves are not considered which is again, a primary goal for this study. The monitoring of large-scale log rafts (large accumulations found in low-gradient, meandering sections of rivers) have been examined by *Kramer and Wohl* [2014] and *Boivin et al.* [2015] within the context of watershed wood fluxes. Because log rafts retain wood, they are 'sinks' for mobile wood, and integrate the wood load of the catchment.

1.3 Jamming: a Granular Phenomenon

Although the namesake 'logjam' results from vernacular use (which stems from the common perception of logjams as static entities), 'jamming' has a precise meaning for workers in the granular physics community. Granular materials are assemblages of individual particles (grains: sand, rice, corn, balls, nails, rods and so on) whose behaviors do not easily categorize as solid or liquid [*Jaeger and Nagel* 1992]. The canonical sand pile organizes into a stable, solid state around the angle of repose but easily displays flowing, liquid-like movement when this critical angle is exceeded. Because of their ubiquity in nature and industrial settings (corn silos, manufacturing) and their potential to aid in describing phenomena in geomorphology, granular physics invites us to integrate methodologies and paradigms to aid in our pursuit of the question: ‘how do logjams deform?’.

As a granular system transitions from a flowing to rigid state, particle velocities asymptotically approach zero. The assemblage becomes ‘jammed’ (also known as the ‘glass transition’) [*Liu and Nagel* 2010, *Cates et al.* 1998, *Weeks* 2016]. While many of these investigations involve glass spheres [*Charru et al. 2004*, *Corwin et al. 2005*], elongate (shape-anisotropic) particles produce other dynamics. Logjams have explicitly been cited as an articulation of these dynamics [*Börzsönyi and Stannarius* 2013]. While the jamming of elongate, rod-like particles have been studied in granular physics experiments [*Desmond and Franklin* 2006], no field studies to explore the treatment of logs as particles or grains, or to verify that it is appropriate to view logjams as a granular phenomenon exist. The question of how particle shape influences stable states, packing, the character of the glass transition and jamming is also of interest to granular physicists [*Weeks* 2016]. Ensembles of elongate grains encompass greater degrees of freedom than spheres because of the multitude of frictional configurations that hold them stable [*Frette et al.* 1996]. Contrary to current paradigms, *Houssais et al.* [2015] find that over long timescales, sediment deep below a sheared laminar fluid exhibit ‘creep’, infinitesimally small displacements that are only apparent over long observation timescales. If this phenomenon is found to operate in the field, then we must also consider the possibility that other material transport processes also exhibit creep (like logs).

1.4 If a Tree Falls in the Forest…

"If a tree falls in the forest and no one is around to hear it, does it make a sound?"

- philosophical thought experiment

Scientific inquiry carries with it epistemological and ontological implications. Here, the classic thought experiment "If a tree falls in the forest…" raises the basic question of whether natural phenomena exist 'in-itself' [*Kant* 1781], without requiring human perception to verify the Event as such. The modification: "If a logjam moves and no one is around to see it, does it still move?" is especially pertinent to the work outlined here. Creep is the accumulation of infinitesimally small displacements that are apparent only over sufficiently long time-scales of observation, requiring time-interval photography (or similar techniques) to capture, speed up, and replay snapshots of time to observe this phenomena. So then, to answer the question, yes: not only may logjams be creeping, they do so constantly and beyond our perception. While a novel and somewhat difficult concept, this is consistent with scientific materialism, to which all scientists by default subscribe to [*Bunge* 2012]. Scientific materialism is the stance that the truth of the universe lies in material things and that the properties and attributes of these things are knowable and testable.

The popular ontological discourse in philosophy today follows that of workers such as Slavoj Žižek, whose 'dialectical materialism' asserts that the truth of material objects (or subjects, from a psychoanalytic standpoint) which lie in their inherent inconsistencies, antagonisms and indeterminacy [*Žižek* 2009]. However, progressive truth and insight is attainable by assuming a 'Parallax View'; a perspective that juxtaposes the object within an unorthodox frame or vantage point, which exposes further inconstancies and elevates the observer to a new plateau of knowledge or understanding (though not necessarily by the progression of accumulating empirical data) [*Žižek* 2009]. Considering logjams as a granular phenomenon can be considered some articulation of this Parallax, in my view. This process is highly iterative and may never end in an 'Absolute' truth. Workers such as Graham Harman, whose 'Object Oriented Ontology' (OOO) attempts to collapse these relationships onto a flat plane, oppose Žižek. In OOO, buildings, peoples, societies, pens (long lists of random nouns) and so on are no more special than the other, and that the "Truth" about those objects are not accessible by any other object. In this philosophy, the privileged position given to humans and cognition is reduced, in an attempt to equal the playing field and restore some kind of 'natural' balance and remove the anthropomorphic bias and privilege [*Harman* 2011]. Disagreements between Žižek and Harman are outside of the scope of this chapter and my intent, but are likely rooted in Žižek's political projects, of which incorporating Lacanian psychoanalysis (and therefore privileging the status of the subject) is an integral piece. Furthermore, Žižek's position is more aligned with the pursuits of science, whereas Harman assumes a strong anti-science stance in order to make space for the humanities and arts.

Where then, is the truth of logjams to be found? Is a logjam an object in-itself or can we penetrate its truth by juxtaposing it against a rice pile parallax? While there may not be a definitive answer, there is one point I would like to make. This thesis is constituted of field observations during two months of living in the Idaho wilderness and a lengthy, iterative experimental component, also with a demanding timescale of investment. Not included here are the personal accounts and narrative that accompanied and enabled the scientific work to be done although it is integral to it. Nor are the voices or perspectives of those who generously enabled me to conduct this work. In the following text, calculations and graphs are distilled observations and contain a great deal of information about logjams and their material truths but also neglect equally important components of how they were generated. Furthermore, if creep is an important process in shaping the surface of the Earth, it is also worthy to contemplate the ontological and epistemological consequences of the idea ‘everything is moving all the time, we just can’t perceive it.’.

1.5 Field Setting and Observational Tools

To explore the kinematic behavior and deformation of logjams, we take advantage of a natural experiment in the Big Creek watershed. Big Creek is a tributary of the Middle Fork Salmon River and located within the Frank Church River of No Return Wilderness, west-central Idaho. The watershed has experienced multiple episodes of intense wildfire, most recently during the Marble Creek fire in 2003. In March 2014, a rain-on-snow event initiated a series of avalanches in the upper reaches of Big Creek, delivering thousands of burned, standing dead Douglas Fir and Lodgepole pine into the channel. By the late spring, the logs had washed downstream and coalesced into a thousand-member, channel-spanning logjam, impeded by the downstream-most avalanche debris deposit. The size and character of this logjam is inspiring; it seems like a rare occurrence (although as I outline later, they were more common historically and may become more prevalent in the future). For a full description and historical account of Big Creek and its history, see *Whiting* [2015].

1.6 Experimental Design and Methods

Observations and results in Big Creek inspired a suite of exploratory flume experiments to investigate logjam dynamics in a physically controlled setting. Experiments were conducted within a 6 m long, 1.22 m tall auxiliary channel using a flexible but durable plastic as the bank and bed surfaces. We used chopsticks to simulate logs and painted them red, green and blue to aid in distinguishing them in Particle Image Velocimetry (PIV). Five nails were hammered into the bed to inhibit chopsticks and initialize logjam formation. Once an aggregate of chopsticks formed a coherent structure, we photographed the simulated logjam each minute. PIV operated by comparing pixels within a sequence of images, and calculating the difference in color and intensity values from these images to track individual pixels. Velocities were reported in pixels per frame, and were converted to velocities with units length per time, as length-pixel equivalency and frame rate was known. With this set-up, we sampled the structural fabric and deformation field of simulated logjams under two scenarios. Experiment A sampled the velocity field of chopsticks once every minute for 24 hours with a single discharge. Experiment B sampled the logjam velocity field once every minute for 24 hours as discharge alternated between a high and low state every two hours. All experiments were conducted at a fixed slope of 1%.

1.7 Thesis Organization and Objectives

In this thesis, we report on the results of a novel field campaign to measure the kinematic behavior and deformation of a channel-spanning logjam (Chapter 2) and a suite of physical experiments inspired by the field (Chapter 3) to interrogate the basic question: how do channel-spanning, mountain logjams deform? These insights will be valuable in theoretical contexts and in applied river management. In Chapter 4, I will revisit these goals, summarize results and make suggestions for future work.

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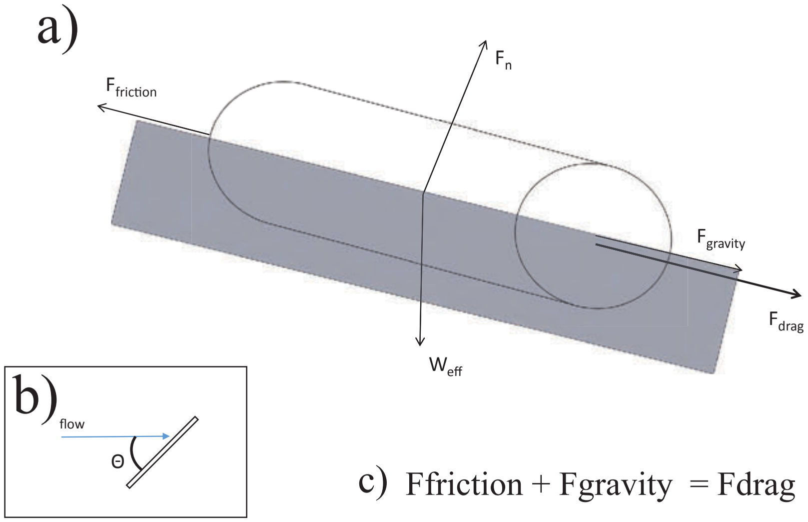


c) Ffriction + Fgravity = Fdrag

Figure 1.1: Schematic free-body diagram which illustrates the force balance on a smooth, cylindrical log Braudrick and Grant [2000]. a) Fn is the normal force, Ffriction is the friction force, Fdrag is the drag force, Fgravity is the gravitational force and Weff is the effective weight. b) the angle between log orientation and the flow direction (Θ), is an important control on log mobility: pieces that are oriented perpendicular to flow are generally less prone to entrainment. c) Force balance equation which indicates that when the drag force overcomes the frictional and gravitational forces, a log is entrained.

A. Run 2 (congested)

B. Run 3 (semi-congested)

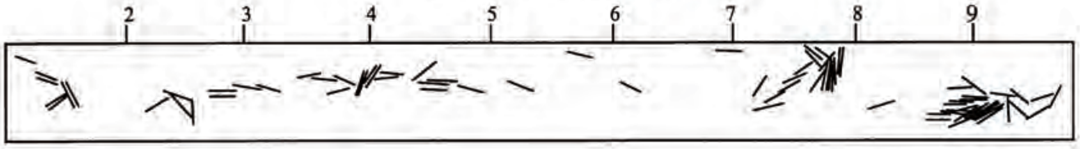


Figure 1.2: Observations of two wood transport regimes from the flume experiments of Braudrick et al. [1997]. Note that experiments are conducted in a flume with a sand-bed with formed channels. A. Run 2 displays logs fed at a high flux rate. In this regime, logs travel as a single mass. B. Run 3 shows logs within the semi-congested regime where some logs move independently and clusters of logs move together. Logs within these two regimes were most likely to form logjams.

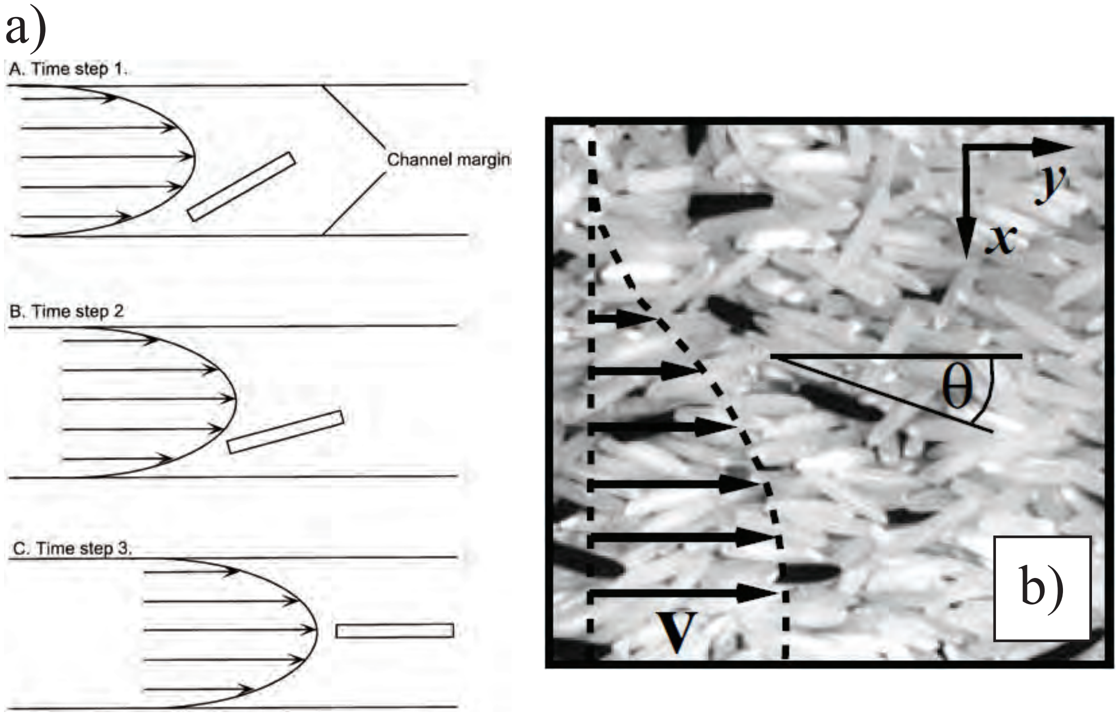


Figure 1.3: a) Conceptual model of Braudrick and Grant [1997], who observe that logs in transit exhibit a preferential orientation to flow. b) A study of sheared rice illustrate that the ensemble of grains also orient parallel to the velocity profile as a mechanism of friction reduction [Borszoyni et al 2012]. Both panels are in map-view.

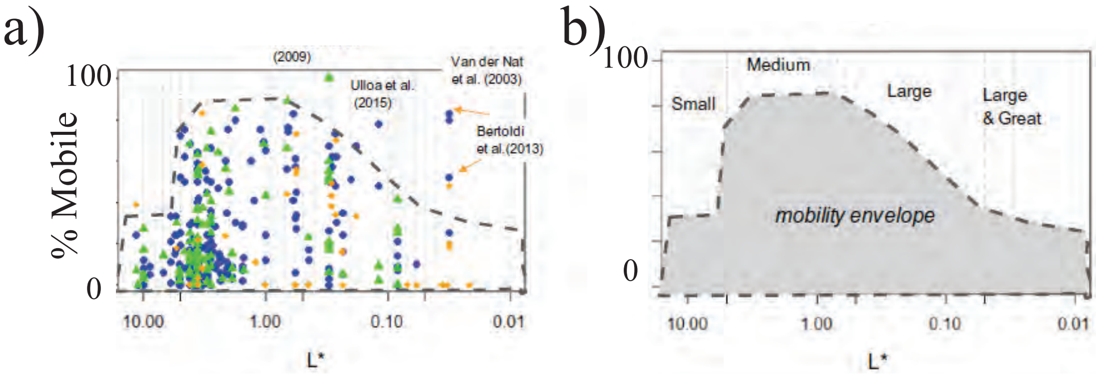
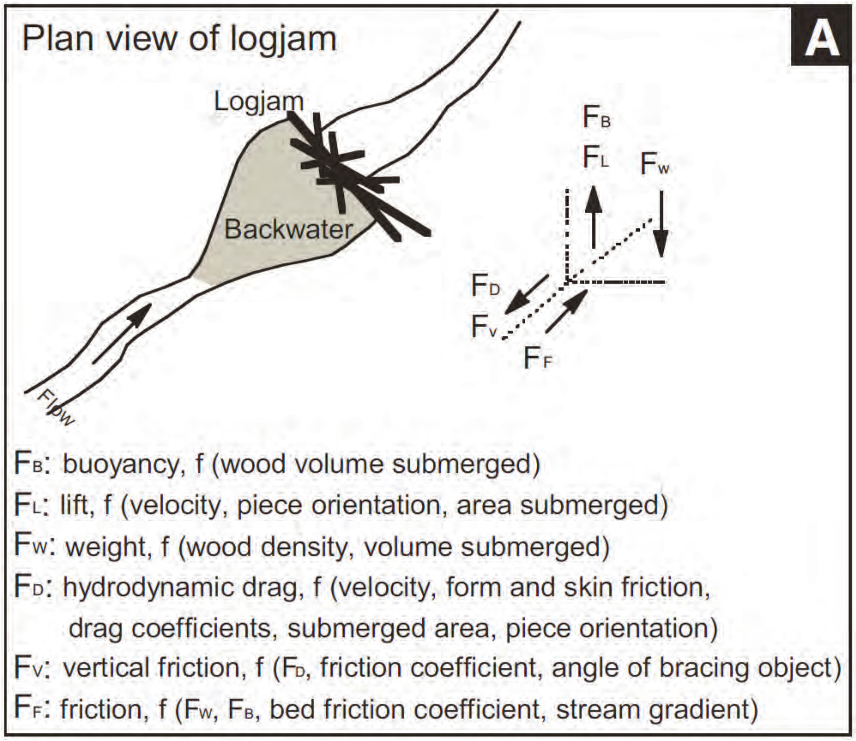


Figure 1.4: Variability in the thresholds of single log mobility, summarized by Kramer and Wohl [2016]. a) is a compilation of field measurements, indicating the fraction of mobile wood within the respective study. Blue circles are remobilized wood, green triangles are redeposited wood and orange stars are repositioned wood. b) is a hypothesized mobility envelope for different size rivers.



F_B: buoyancy, f (wood volume submerged)
F_L: lift, f (velocity, piece orientation, area submerged)
F_W: weight, f (wood density, volume submerged)
F_D: hydrodynamic drag, f (velocity, form and skin friction, drag coefficients, submerged area, piece orientation)
F_V: vertical friction, f (F_D, friction coefficient, angle of bracing object)
F_F: friction, f (F_W, F_B, bed friction coefficient, stream gradient)

Figure 1.5: Conceptual force balance of a channel-spanning logjam, proposed by Wohl [2011]. The indicated body forces are averaged over the entirety of the logjam and do not indicate the individual force balance on each log within the jam.

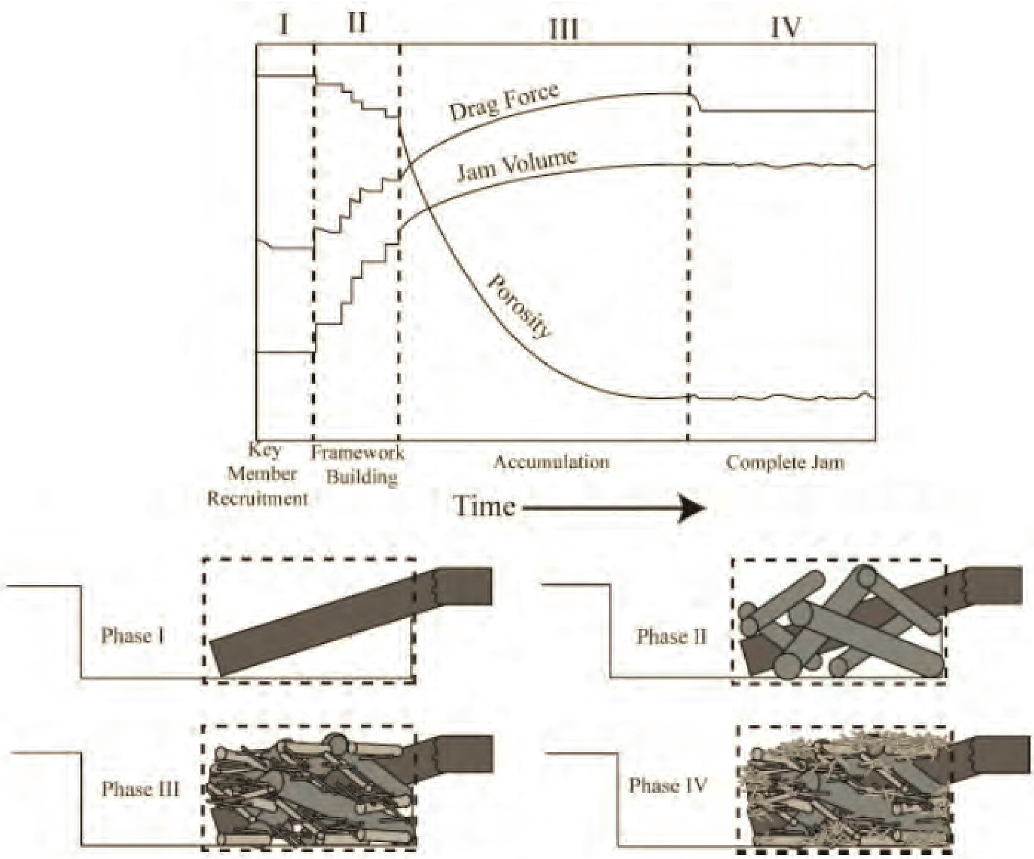


Figure 1.6: Conceptual model of logjam kinematic evolution as proposed by Manners and Doyle [2008]. While instructive, these metrics are difficult to measure in the field, and are designed for logjams that are of a much smaller scale than the Big Creek logjam or large-channel spanning log-rafts.

Chapter 2: The structural fabric and deformation of a mountain logjam: field observations and a conceptual framework

(For submission to *Geophysical Research Letters*)

Abstract

Logjams are widely recognized for their benefits to ecological communities, nutrient routing and the evolution of stream morphology and are thus frequently implemented in stream restoration. However, we lack empirical observations of large, channel-spanning logjams in mountainous settings. This is partly due to historic logging practices that have erased cycles of large wood and to the perception that logjams are static features in the landscape. Using time-lapse photography, repeat total station surveys and water level loggers, we characterize the deformation of 134 logs within a channel-spanning logjam in the mountains of central Idaho.

We find that despite the namesake, logs are not jammed, but compress and collapse in response to the shear of flowing water and fluctuating river stage. Time-lapse photography allows for the qualitative characterization of three modalities of logjam movement: daily vertical oscillations, lateral forward jerks and gravitational collapse. Total station data indicate that during the rising limb and peak of the hydrograph, displacements are highly spatially correlated and of large magnitude. On the falling limb, horizontal displacements are uncorrelated while the center of the logjam collapses as water level recedes. We propose that logjams exhibit a dynamic behavior that we infer as analogous to creep in material science, and that a re-evaluation of wood transport mechanics is needed, as well as the need for physical models that move beyond the classical force balance.

2.1 Introduction

Channel-spanning logjams are rare phenomena within the realm of wood transport, in part due to historic logging practices, which altered ‘natural’ wood-river feedbacks, and contemporary attitudes that regard them as a nuisance [*Wohl*, 2014]. Large wood is a critical agent in facilitating river function and form by means of rich feedbacks with sediment and flow [*Piegay and Gurnell* 1997, *Abbe and Montgomery* 2003], rendering them a popular tool in river rehabilitation efforts [*Abbe et al.* 2003, *Abbe and Brooks* 2011, *Dixon et al.* 2016]. Logjam formation is classically conceived as a feedback between near-bank recruitment and deposition [*Abbe and Montgomery* 2003]. However, episodic bulk delivery of wood into river channels increase the likelihood of logjam formation [*Wohl et al.* 2009, *Ruiz-Villanueva et al.* 2014]. As precipitation phase in the western US shifts [*Klos et al.* 2014], along with changing climate [*Ault et al.* 2013], and fire regimes, [*Westerling et al.* 2006], standing dead trees from wildfire (supply) and weak snowpacks with high avalanche probabilities (mechanism) compel us to anticipate large pulses of wood and the formation of large, channel-spanning logjams to become more frequent.

Transport mechanics of single log pieces have been the subject of ~30 years of research and are undergoing something of a revival in geomorphology [*Kramer and Wohl* 2016, *Ruiz-Villanueva et al.* 2016]. These studies rely on flume experiments and the force balance model developed by *Braudrick and Grant* [2000, 2001], which indicates that a log is mobile when the flow depth is sufficient for floatation. New techniques capable of resolving the travel distances of individual logs and wood fluxes within watersheds via GPS, RFID and video monitoring [*Ravazzolo et al.*, 2015, *Schenk et al.* 2014, *MacVicar* *et al.* 2009] have enabled a renewed interest in these mechanics. These studies reveal that thresholds in the mobility of single wood pieces are highly variable and are complicated by logjam formation. Furthermore, wood flux rates a) encode signatures of hysteresis [*MacVicar and Piégay*, 2012], b) are dependent on diverse fluvial process such as ice break-out floods [*Boivin et al.*, 2015], and c) are highly sensitive to hydrograph shape and timing [*Ruiz-Villanueva et al.* 2016]. This complex behavior requires a more rigorous quantitative framework for wood transport informed by empirical observations of logjams. *In-situ* measurements of logjam dynamics can inform river rehabilitation efforts by incorporating more 'natural' behavior into designs with longer lifespans and increased benefit. Additionally, inconsistencies and gaps in our understanding of wood transport mechanics can be advanced by understanding the endmember behavior of large, channel-spanning logjams.

Although the namesake 'logjam' is the result of colloquial use, 'jamming' has a precise meaning for workers in the granular physics community. As a granular system transitions from a flowing to rigid state, it becomes 'jammed' (also known as the 'glass transition') [*Liu and Nagel* 2010, *Cates et al.* 1998, *Weeks* 2016]. While many of these investigations involve glass spheres [*Charru et al. 2004I, Corwin et al. 2005*], elongate (shape-anisotropic) particles produce other dynamics. Logjams have explicitly been cited as an articulation of these dynamics [*Börzsönyi and Stannarius* 2013]. While the jamming of elongate, rod-like particles have been studied in granular physics experiments [*Desmond and Franklin* 2006], no studies have been completed outside the laboratory. Ensembles of elongate grains encompass greater degrees of freedom in their orientations than spheres because of the multitude of frictional configurations that hold them stable

[*Frette et al.* 1996]. Considering logjams as a granular material opens the possibility of universality across diverse disciplines, research problems and, settings. Inspired by this possibility, we test whether large, channel-spanning logjams are truly jammed by measuring and describing the *in-situ* dynamics of logs within a channel-spanning logjam in the mountains of central Idaho with a novel monitoring campaign.

2.2 Field Setting and Methods

Big Creek is a tributary of the Middle Fork Salmon River, drains 1540 km^2 and spans 1030 to 2900 m in elevation. The watershed has experienced multiple episodes of intense wildfire, most recently during the Marble Creek fire in 2003, which burned 24 km^2 [*Short* 2011]. Big Creek hydrology has been identified as sensitive to snowpack loss [*Tennant et al.* 2015]. In March 2014, a rain-on-snow event initiated a series of avalanches in the upper reaches of Big Creek, delivering thousands of burned, standing dead Douglas Fir and Lodgepole pine into the channel. By the late spring, logs in multiple debris jams had blown out, floated downstream and coalesced into a thousand-member, channel spanning logjam, 80 meters long and 20 meters wide (Figure 2.1). Above the logjam, Big Creek drains 275 km^2. Anecdotal reports from other researchers, USFS employees and backcountry pilots indicate that ~20 such channel-spanning logjams exist within the Salmon River watershed.

Our field survey was conducted between May 8th and June 29th 2016. The tips of 134 log pieces were indexed with numbered aluminum tags. Our sampling scheme sought to capture a representative spatial extent within the logjam and to adhere to the size constraints of a ‘large woody debris’ piece: a diameter >= 10 cm and length >= 1 m [*Wohl et al.* 2010]. Logs were surveyed into a local coordinate system with a Leica total station and rebar stakes pounded into the floodplain as reference control points for subsequent surveys. Not all 134 logs were recovered during each survey; the number and mobility of logs within the logjam made it difficult to locate each one with 100% recovery. In addition to the xyz coordinates of indexed logs, we collected water surface measurements throughout the logjam. Moultrie M-1100i game cameras captured time-lapse photos at 30-minute increments. Cameras were installed in trees upon the hillslope and provided three vantage points of the logjam. A water-pressure transducer was installed within the logjam to measure stage at 15-minute intervals and was barometrically corrected.

Each logjam survey consists of spatial coordinates collected from total station measurements. Coordinates of log tips capture the range of movement that a single log may experience, but are not independent observations of displacement. We therefore used the centroid of each log to calculate the magnitude and direction of a displacement vector for each log between each survey interval. See Table 1 for a complete listing of data collected during surveys. Survey intervals were selected heuristically and not over fixed time intervals. We therefore report displacement per survey interval rather than a rate. Observed mechanisms of deformation operate on varying timescales, so some selection of a representative time step is required. From these vectors, we mapped the distributions of displacement between subsequent survey periods. We analyzed the displacement data in both the xy (horiztontal) and z (vertical) dimension. We constructed spatially continuous maps of displacement by kriging, a geostatistical interpolation tool. Kriging quantifies the spatial autocorrelation between measurements to predict values at unmeasured locations. We fit “stable” models to the semivariogram. Kriging allows us not only to construct these maps but also to assess the degree of spatial correlation between logs.

2.3 Results

2.3.1 Hydrograph

Two long-wavelength snow melt peaks superimposed with a diel daily melt signal reflect an early spring storm with mixed precipitation, resulting in an early peak in stream flow (Figure 2.2). Progressing into the summer, the hydrograph assumed a diel pattern characteristic of a snowmelt-dominated hydrology, as daily peaks occurred in the early evening. The lag results from a delay between the timing of peak snowmelt and when this melt is delivered to the stream. The diel pattern in the hydrograph shape persisted through the duration of the study.

2.3.2 Game Cameras

Time lapse photography allowed for the qualitative characterization of three modalities of logjam movement: daily vertical oscillations, lateral forward displacements and collapse. Diel peaks in stage occurred during the evening hours and are followed by falling stage during the day. Lateral displacements occurred during the peaks of the diel cycles. At the peaks of both the early spring storm and of the spring snowmelt, the logjam jerked laterally in the evening hours, ~6-9pm. During these events (May 18th and June 5th), logs moved *en masse*; there was no structural re-organization of the feathered ‘v’ structure, no log rotation and no autonomous ‘islands’ of logs that deformed differently than their neighbors. As stage fell, logs within the logjam visibly decreased in elevation, and collapsed. The rear perspective of the logjam shows how interstitial spaces between logs were occupied by water, which persisted for the duration of the survey. In the middle and front of the logjam, no such spaces were visible. Spaces did not open and close. We did not observe a sizable addition of logs in the rear of the logjam, nor a loss of logs from the snout.

2.3.3 Total Station and Stage Hydrograph

Distributions and magnitudes of mean squared displacements supported the qualitative observations from the time-lapse photographs. The interval 'C' brackets the largest magnitude displacement event, which occurred between June 4th and June 9th, at the peak of the hydrograph (Figure 2.2a). Inspection of the game camera data indicated that most of this displacement occurred in the evening hours of June 5th and 6th, and that the distributions of displacements during this interval were broad. On the falling limb of the hydrograph, intervals D, E and F displayed less displacement. Vertical displacements did not display preferences in the shapes of their distributions on either the rising or falling limb of the hydrograph, but rather on the change in water level. Displacements range from -0.690 meters to 0.272 meters. Net increases in log elevations typically corresponded to rising stage, as the absolute change in stage plots within the population of vertical displacements for a given measurement interval (Figure 2.2b).

2.3.4 Water Surface Profiles

Though fluctuating in absolute height, water surface profiles within the logjam retained a fixed geometry during the measurement intervals, with a pronounced inflection where the water surface drops ~0.5 m at the downstream end (Figure 2.3a). This inflection persisted throughout the field campaign; its magnitude and position does not change markedly. Note that water surface measurements were collected within the logjam and that this surface profile does not represent water levels upstream or downstream of the logjam.

2.3.5 Vertical and Horizontal Displacement

Longitudinal profiles of displacement illustrate the heterogeneity in log velocities. Horizontal displacements decay linearly with downstream distance For intervals A, B and C, illustrating that logs in the rear of the logjam moved three times faster than logs in the snout of the logjam (Figure 2.3b). This line is steepest for measurement interval 'C', on the rising limb and peak of the hydrograph. Vertical displacements show that the center of the logjam is most sensitive to rising and falling water level, while the snout and rear appear to be pinned (Figure 2.3c). Note that breaks in water surface and displacement profiles were all located at about 50 m of downstream distance within the logjam (Figure 2.3 a,b,c).

2.3.6 Kriging

Coherent maps of horizontal displacement from kriging could only be produced for surveys on the rising limb of the hydrograph. Maps elucidate the spatial distributions of deformation within the logjam for a given survey interval, while also providing an indication of the length scale of spatial auto correlation. They illustrate a coherent signal in the magnitudes and directions of displacement vectors during measurement intervals A, B and C, where displacements were greatest in the rear of the logjam and decrease on approach to the front. Displacement during these three intervals were focused stream-parallel and were on the order of 0.5 to 1.5 meters (Figure 2.4). This is consistent with observations of the longitudinal velocity profiles (Figure 2.3). Kriging failed for the later three survey intervals as there was not a well-constrained correlation function to describe spatial variability, so the mean was applied to the entire domain (i.e. a 'pure nugget' effect [*Curran* 1998]). The directions of displacements on the falling limb were also widely distributed, unfocused and of low magnitudes. Note that interval A captured the falling limb of the first peak and the initial rise of the second (Figure 2.2a) and thus encoded information from two separate hydrologic periods.

Vertical displacement maps (Figure 2.4) illustrate increases and decreases in logjam elevation which were focused in the center of the logjam and was the dominant pattern of deformation. Kriging again failed for the final survey interval, where there was insufficient spatial correlation. For measurement interval C, the logjam displayed an 'uplift' in the center of the logjam on the order of ~15 cm. Semi-variograms and spatial autocorrelation are further discussed in Appendix A.

2.4 Discussion and Conclusions

In order to account for the heterogeneity of horizontal displacements between the rear and front of the logjam (and the accommodation space problem it presents), compression must be invoked as an explanatory mechanism. Two mechanisms can accommodate compression: increasing the density of the logjam (closer packing) or by 'thickening' (increasing elevation without increasing density). Because no logs shed themselves from the front and the logjam does not move significantly downstream, we suggest that the logjam accommodates strain by deforming internally and compressing. Vertical deformation is a function of stage rise and fall. Logs buoyantly respond to increases to increasing stage. As water level lowers, so do the logs (gravitational settling) until some critical depth where logs re-establish contact with the bed. The logs are no longer acting buoyantly but are supported by the bed, banks and each other. 'Uplift' in the front indicates that deformation must be accommodated internally; this uplift is a 'stacking' response. A conceptual model of these modes of deformation are presented in Figure 2.5.

The persistence of an inflected water surface profile also suggests that despite this rearrangement, it is not sufficient to change the hydraulic permeability conditions within the logjam. Internal deformation is accomplished via creep during diel cycles and at the rising and peak of the hydrograph. Consequently, the idea that the logjam strengthens and therefore exhibits some memory effects. Applied stress enhances the stability of the logjam and its resistance. It remains to be seen if the logjam ever reaches a completely static, and therefore jammed, state. The geometry of the water surface profile may carry significant implications of the force that the logjam experiences. *Kirchner and Manga* [2000] develop a model for calculating the drag force that large wood extracts on the channel. While this model was not designed for logjams, the persistence of inflection point shows that the energetics of the water remain relatively fixed. Logjam is under constant forcing via shear from the flow, but high water levels allow it to lift and respond to the hydraulic forcing.

During the installations of game cameras and water level loggers, we observed a displacement event that was not captured within our measurements. A log in the front of the jam shifted and fell from its position. The logjam responded by an acoustic readjustment that propagated upstream. As the logjam compresses, logs become more connected and perhaps more resistant to subsequent forcing from behind. We infer that log-log contacts increase downstream. If frictional connections resist the effects of shear and buoyant lift, then as logs compress, they become more resistant to applied force i.e. they approach jamming.

Our measurements demonstrate that logjams are not jammed, but instead creep. These results complicate the task of developing thresholds for logjam break up, as precisely determine thresholds for movement is memory-dependent and time-varying. That said, our observations lead us to speculate about the mechanisms of break-up: a) destroy obstruction, b) over-ride obstruction, c) circumvent obstruction. Long-term data from the logjam in Big Creek are needed to describe the full ‘life trajectory’ of wood and to study break out dynamics and downstream dispersal of wood. Nevertheless, we have demonstrated here a first step in documenting the deformation of a mountain logjam.

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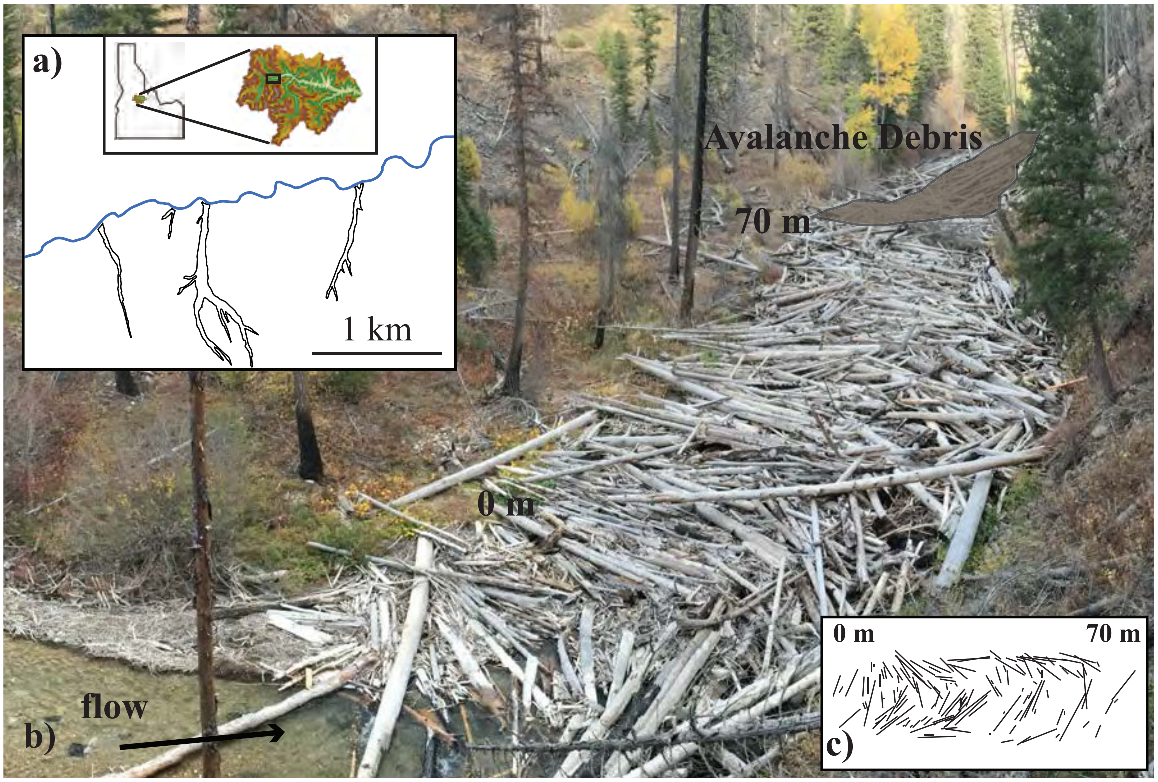

Figure 2.1: a) Location of the logjam and avalanche chutes along Big Creek, Idaho. b) Spatial extent of the logjam, avalanche debris and measurement domain. c) plan-view map of surveyed logs.

Hydrograph and displacement distributions

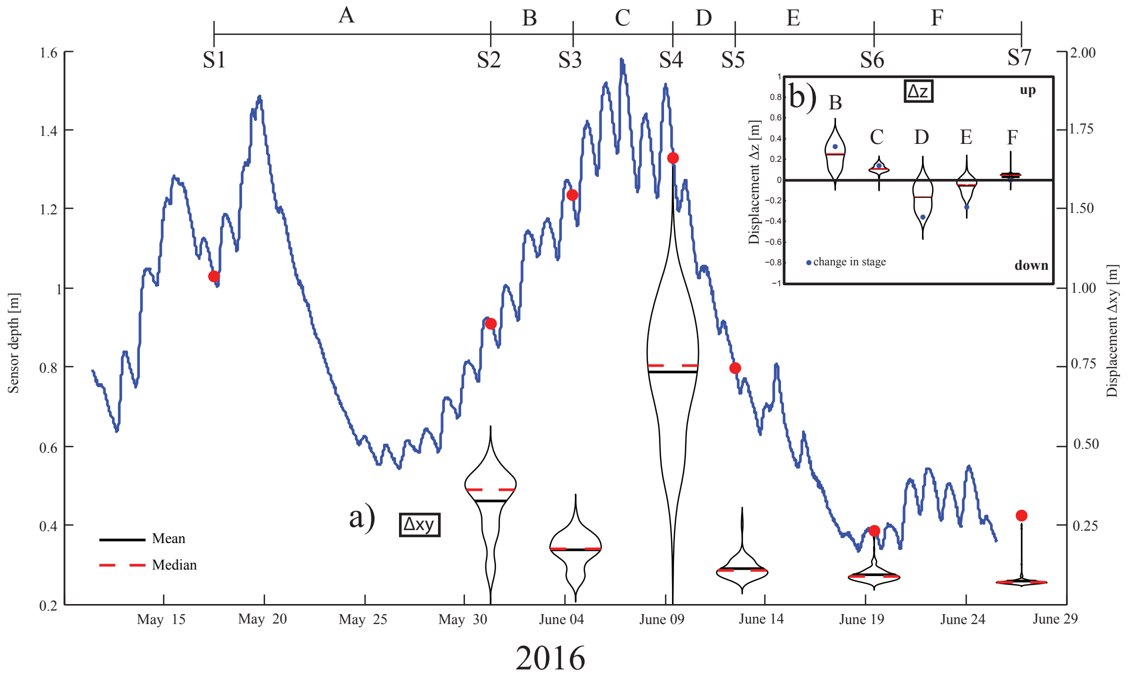

Figure 2.2: Variations in stage during the field campaign in Big Creek, Idaho alongside probability distribution functions of: a) horizontal displacement and b) vertical displacement with the absolute change in stage plotted within the population of displacements. Distributions are measured displacements of log centers. Separate surveys (red circles) are unevenly spaced and prohibit us from reporting log trajectories as physically meaningful rates. Therefore, we analyze each measurement interval (A-F), composed of survey dates (S1-S7).

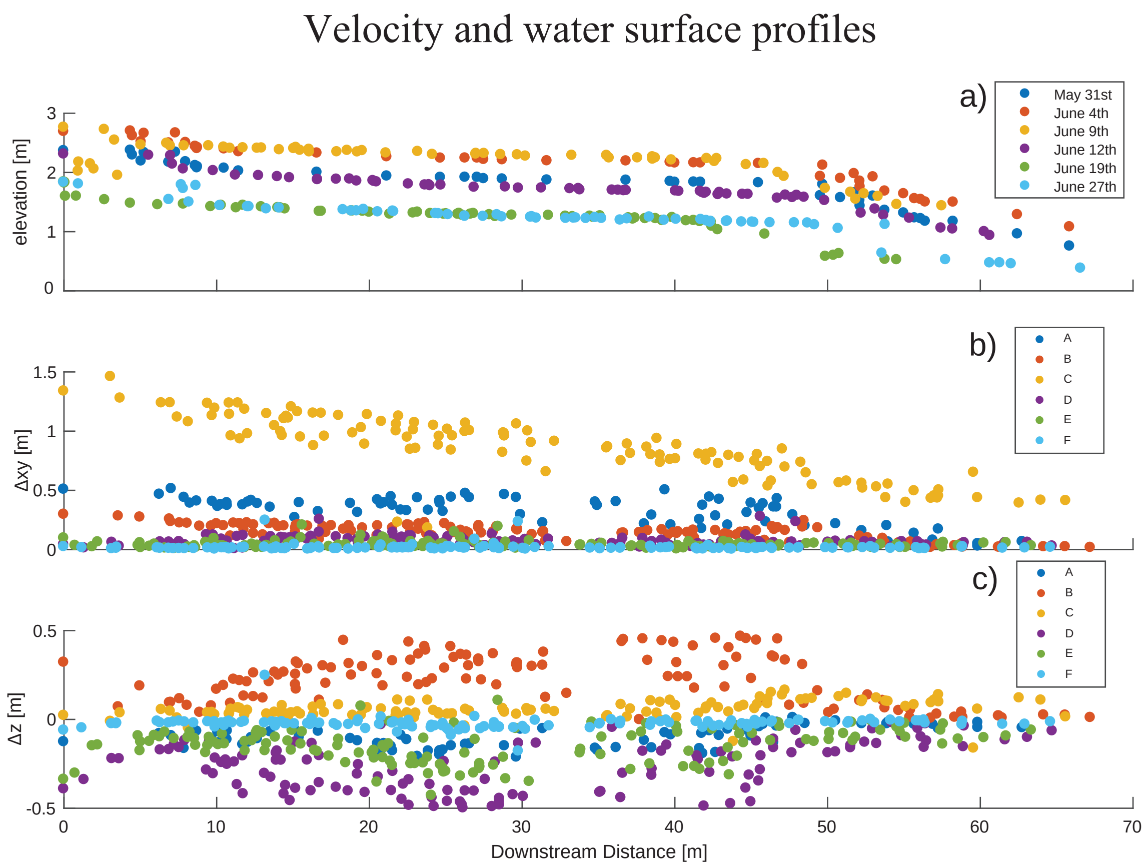

Figure 2.3: Longitudinal profiles of a) water surface points, b) horizontal displacement and c) vertical displacement for survey intervals A-F against downstream distance. a) The geometry of the water surface persists for the duration of the field study and maintains an inflection of 0.5 meters. b) Horizontal displacements are greatest in the rear of the logjam and decay linearly on approach to the front. c) The middle of the logjam is the most sensitive to changes in stage; it ‘flexes’ in concert with changes in water level.

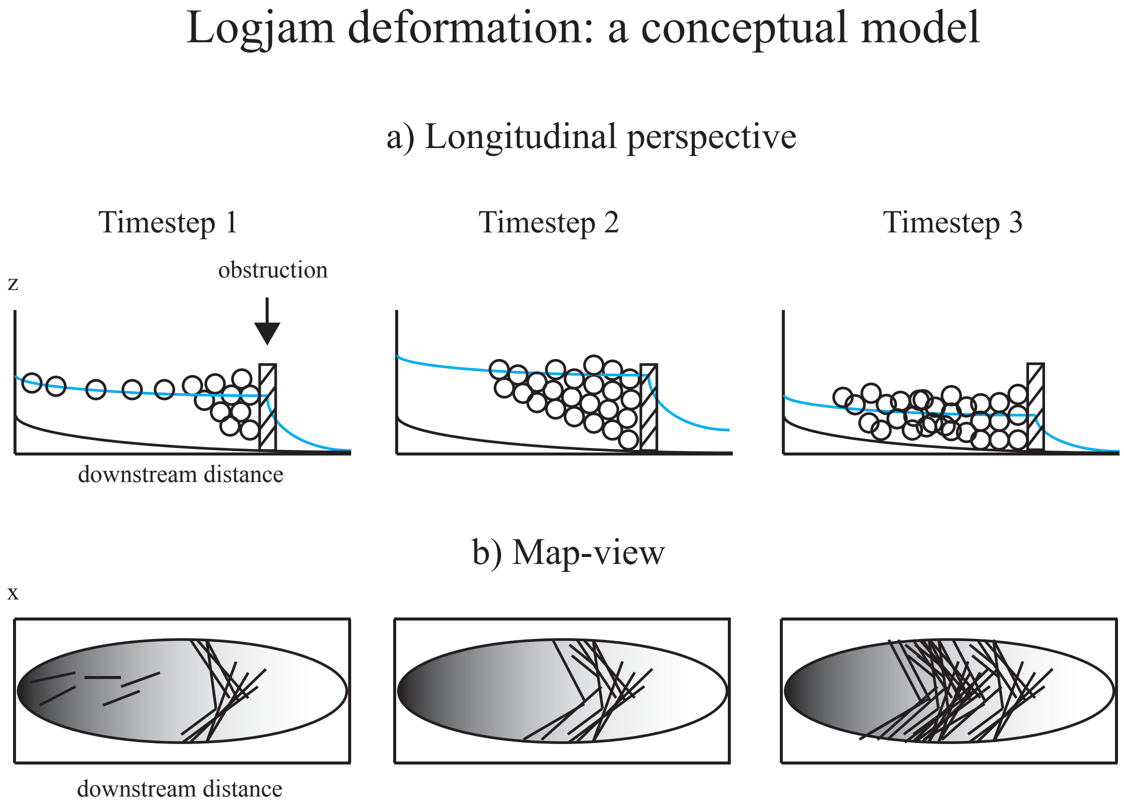

Figure 2.5:
Conceptual model illustrating a) Longitudinal and b) Map-view perspective of logjam deformation at three time steps. As a logjam is initialized, logs are packed in a somewhat haphazard configuration. As flows increase, logs pack and the logjam compresses. As water level falls, the logjam collapses.

Table 2.1. Table of field data from Big Creek, Idaho.

Dates	# logs	change in stage [m]	mean dxy [m]	std. dev [m]	mean dz [m]	std. dev [m]	dxy azimuthal distributions [degrees]	aziumuthal std. dev [degrees]
(S1) May 17th to (S2) May 31st	73	-0.119	0.329	0.119	-0.101	0.059	364.716	14.603
(S2) May 31st to (S3) June 4th	122	0.325	0.147	0.063	0.231	0.135	368.943	32.915
(S3) May June 4th to (S4) June 9th	119	0.093	0.859	0.258	0.055	0.048	365.473	11.922
(S4) May June 9th to (S5) June 12th	130	-0.532	0.067	0.042	-0.290	0.150	306.965	75.015
(S5) May June 12th to (S6) June 19th	134	-0.411	0.042	0.030	-0.153	0.094	257.997	78.007
(S6) May June 19th to (S7) June 27th	131	n/a	0.016	0.030	-0.025	0.032	277.653	93.853

Chapter 3: Deformation in mountain logjams: experimental analogs with varying flow

(For submission to *Geomorphology*)

Abstract

To explore the formation, kinematics and deformation of channel-spanning logjams, we performed flume experiments to observe the response of a simulated logjam to two flow conditions: a constant discharge, and a series of step increases and decreases in discharge. Using chopsticks to simulate logs, we use Particle Image Velocimetry (PIV) to sample the velocity field of logs within the logjam every minute for 24 hours. Under constant flow, the logjam compressed by 46% while under time-varying flow the logjam compressed by 80%. In both experiments, the displacement time series were initially rapid and slow to a steady compression. This compression was accomplished through both stick-slip events for ensembles and individual log displacements. Over 24 hours, displacements slow, but never reached zero. Our experimental results demonstrate that internal compression is a key mechanism in logjam kinematics. Compression and the character of the deformation is qualitatively similar to an investigation of logjam dynamics in the mountains of central Idaho. Our results contribute and support a working conceptual model that outlines the inception and evolution of channel-spanning logjams.

3.1 Introduction

Logjams enhance biocomplexity [*Gurnell et al.* 2005], are vital for fish habitat [*Collins et al.* 2002], facilitate carbon storage [*Wohl et al.* 2012], and are responsible for a suite of geomorphic effects and influences on channel morphology and behavior [*Piegay and Gurnell* 1997, *Abbe and Montgomery* 2003]. For this reason, logjams and wood retention structures are being engineered, manufactured and installed into rivers at accelerated rates, as they are popular tools in river restoration and rehabilitation efforts [*Abbe et al.* 2003, *Abbe and Brooks* 2011]. The stability of these features have not been observed over long enough timescales to successfully assess their strength [*Pess et al.* 2012, *Whiteway et al* 2010] or to understand their kinematics. These structures are being designed and implemented without empirical observations of naturally occurring logjams nor flume experiments that attempt to characterize these dynamics.

Current understanding of wood transport mechanics is rooted in a theoretical model derived from first principles and observations from physical experiments [*Braudrick et al.* 1997, *Braudrick and Grant* 2000, 2001]. The simplest case, a force balance on a smooth, cylindrical log, interrogates the relationship between wood piece characteristics (density, diameter, rootwad presence and orientation to flow) and the hydrologic parameters (width and depth) required to entrain wood pieces. The force balance requires a piece of wood to overcome frictional and gravitational forces by either floating or rolling at some threshold floating depth. Refinements to the force balance indicate that hydrodynamic lift is an important mechanism for determining log entrainment [*Alonso* 2004]. The approach is analogous to that of *Wiberg and Smith* [1987], who approach the problem of calculating the critical Shields stress for incipient motion of sediment grains by a force balance. However, phenomena such armoring and equal mobility [*Parker and Toro-Escobar* 2002], render the force balance model insufficient for describing the ensemble kinematics of sediment. Likewise, the multitude of log-log contacts within a logjam are problematic within a simple force balance framework. Therefore, an analytic perspective that accounts for the ensemble kinematics of logs within a logjam are required.

Although initial studies of wood transport dynamics were conducted on coarse time and spatial scales [*Wohl and Goode* 2008], new techniques capable of resolving the travel distances of individual logs and wood fluxes within watersheds via GPS, RFID and video monitoring [*Ravazzolo et al.*, 2015, *Schenk et al.* 2014, *MacVicar et al.* 2009] enables a renewed interest in these mechanics. These studies reveal that thresholds in the mobility of single wood pieces are highly variable and are confounded by propensity of logjam formation. Furthermore, wood flux rates a) encode signatures of hysteresis [*MacVicar and Piégay*, 2012], (b) are dependent on diverse fluvial process such as ice break-out floods [*Boivin et al.*, 2015], and c) are highly sensitive to hydrograph shape and timing [*Ruiz-Villanueva et al.* 2016]. This complex behavior requires a more rigorous quantitative framework for wood transport, informed by empirical observations of logjams. *In-situ* measurements of logjam dynamics can inform river rehabilitation efforts by incorporating 'natural' behavior into designs with longer lifespans and increased benefit. Additionally, inconsistencies and gaps in our understanding of wood transport mechanics can be advanced by understanding the endmember behavior of large, channel-spanning logjams.

Logging industry practices and the systematic removal of wood from rivers [*Wohl* 2014] has impaired our ability to make empirical observations of large, channel-spanning logjams or wood rafts. This gap is readily acknowledged by *Kramer and Wohl* [2016] and *Ruiz-Villanueva* [2016], who explicitly call for high-resolution measurements to resolve wood dynamics on fine spatial and temporal scales. Logjams in low-gradient, gravel-bedded rivers have been found to be relatively stable in field and flume studies, either by resisting remobilization [*Bertoldi et al.* 2014, *Davidson* 2015] or by persistence facilitated by channel constrictions or the immobility of 'key logs' that trap smaller pieces [*Curran* 2010]. In these systems, hydrodynamic forces are dispersed through floodplains and gravel bars, whereas in steep, bedrock reaches, logjams persist in the channel [*Wohl* 2011].

Field studies of real-time wood transport during floods [*MacVicar and Piegay* 2012] have verified a key component of *Braudrick and Grant*'s [2000] experiments and conceptual model: that logs have preferential orientations while in transit. This idea is further verified by *Shields and Alonso* [2012], who use field-scale experiments to demonstrate that the drag force exerted on logs is reduced when its orientation is parallel to the flow. Log-log interactions render the theoretical predictions of how wood moves much more complex. However, granular physicists have found in experiments that shear ensembles of elongate grains that the orientations of grains also display preferential orientations that facilitates bulk friction reduction [*Börzsönyi et al.* 2012]. This suggests that ensembles of logs within logjams attain structural fabrics that optimize the frictional connections between logs. Additionally, it has been suggested that bed sediments creep and that transport is a continuum, limited by the observation timescale of movement

[*Houssais et al.* 2015]. This is in opposition to jamming, which assumes that particles are in a kinematic deadlock whereby no changes in position occur, regardless of the observation timescale. The 'static layer' of the bed that is inhibited from movement.

Here, we explore the patterns and rates of deformation of an experimental logjam, inspired by the example in Big Creek. Using nails as obstructions, we sampled the velocity field at 1 minute intervals and compiled a time series of deformation. We measured the change in position of 150 chopsticks in a flume as it experienced two discharge conditions.

3.2 Experimental Design

3.2.1 Apparatus

Experiments were conducted within a 6 m long, 40 cm deep, concave channel with 30 degree banks (Figure 3.1). Five vertical nails hammered at the downstream end of the channel obstructed chopsticks while not significantly obstructing flow. We used bamboo chopsticks .4 cm wide and 22 cm long to simulate logs. Chopsticks were painted red, green, and blue to aid pixel change detection tools used to calculate movement during the experiment. For each experiment, 150 chopsticks were delivered individually at an angle parallel to the flow direction for five minutes. Some chopsticks bypassed the nail obstructions and were not reintroduced. Using an overhead camera and an intervalometer, we sampled the structural fabric of the deformation field under two discharge scenarios. Experiment A sampled the velocity field in of chopsticks each minute for 24 hours with a constant discharge of 0.73 liters/second (Figure 3.1b). Experiment B sampled the velocity field in the logjam each minute for 24 hours with discharge alternating between 0.73 liters/second and 1.31 liters/second every two hours.

All experiments were conducted at a fixed slope of 1%. Precise velocity and depth measurements were not possible to collect without disturbing the logjam. Both experimental logjams created minor backwaters.

3.2.2 Time-lapse and PIV Analysis

Photos were collected with a Canon EOS 6D SLR camera at 1 minute increments. Images are stacked into time lapse videos to support qualitative observations (Appendix B). Chopstick trajectories are measured within PIVLab, a Particle Image Velocimetry (PIV) tool for MATLAB [*Thielicke and Stamhuis* 2014]. The logjams are 10 cells by 68 cells and 12 cells by 68 cells for Experiments A and B, respectively. We select a 1.5 x 5 m region of interest within the frame and a 300 x 150 pixel interrogation window for the first pass of change detection and a 150 x 75 pixel interrogation window for the second (Figure 3.2). One pixel in the image is ~ 0.0003m on the surface of the logjam. PIV returns an output field of velocity vectors by differencing between two consecutive frames. Velocity vectors are averaged within 9 cm cells. Image analysis operates by comparing pixels within a sequence of images and calculating the difference in color and intensity values to track individual pixels. Velocities are reported in pixels per frame, and can easily be converted to velocities with units length per time. Vectors are then converted from pixel to length space and erroneous vectors caused by the water reflections or large displacements are filtered out. Vector fields for each minute of the two experiments are then summed over 15 minute intervals, reducing noise.

3.3 Results

3.3.1 Experiment A

As flow enters the channel, a backwater created by the nails quickly widened, deepened and slowed flow. Chopsticks aggregated into a structure that was ~1.5 meters in length (Figure 3.3a). Although chopsticks were introduced parallel to the flow direction, ~5 members became situated perpendicular the flow direction. Near the nail obstructions, chopsticks were less ordered than those in the upstream backwater who had a highly developed ‘v’ herringbone structure.

Chopstick displacements occurred as three categories of movement: 1) discrete plate-like movements that propagated downstream as ‘v’-shaped shear planes, 2) *en-masse* logjam-wide adjustments in response to the change in position of a key member, and 3) independent logs that either slipped underneath the logjam or oscillated in the less confined, upstream end. Vector fields and magnitude maps captured the spatial evolution of the downstream-propagating shear front (Figure 3.6). These capture the ensemble field characteristics, but do not describe the trajectories of individual chopsticks, which are best visualized by the time-lapse (Appendix B). The stick-slip plate movements, although intermittent, were common during the first 4 hours of the experiment. As time progressed, the zones of adjustment became more diffuse in length and magnitude (Figure 3.6). The displayed time-steps illustrate that the most intense velocities, 0.6 cm/min, occurred in the center of the flow and in the upstream-most area of the logjam. Two minutes later, the greatest intensities were 0.4 cm/min, but occurred over a larger spatial extent throughout the logjam. Some hours later, the adjustment zone was longer still, and of lower magnitude: 0.2 cm/min. Note that although the intensities of displacement were largest in the center of the logjam (location of the thalweg), the directions were quite diverse as logs were pushed on top of their neighbors.

Chopsticks accomplish 64 cm of displacement during the experiment, and the logjam compressed 46%. Displacements were most intense during the first 4 hours of the experiment. Because logs were not shed from the front or added from upstream, fluid shear under the floating chopsticks drove compression. Chopsticks moved closer together, reducing open water between. Chopsticks rolled or slid on top of or under each other to accomplish compression. 50% of total displacement is realized during the first 9 hours (Figure 3.4) Subsequent displacement events are 0.5 to 1 cm in magnitude and did not cease over the 24 hour run. The time series does not qualitatively display any periodicity; it appears noisy and jerky (Figure 3.4).

In the later time steps of the experiment, the under-thrusting of individual chopsticks became the dominant mode of deformation and log movement. One particular chopstick that spans the channel was caught on the banks inhibiting the progression of the v-front. It is possible that if we ran the experiment for a longer time period, this log would become loose and prompt adjustment and further compression. While the logs upstream of the channel-spanning member were highly compressed, with little to no spaces between logs and a qualitatively narrower ‘v’, the logs downstream of the key member appear considerably less compressed or organized in their geometries and configurations. Deviant members inhibit compression, as they probably experienced greater stresses from upstream logs until they slip.

3.3.2 Experiment B

Though the start of Experiment B was the same as Experiment A in terms of flow rate and chopstick introduction, there were differences in the initial configurations of chopsticks, apparent from the early minutes of the experiment. No members were perpendicular to the flow direction and although interstitial spaces exist, they were not as large as in Experiment A. Shear planes were active as the herringbone/'v' structures develop.

Initially, low flow conditions accomplished 6 cm of displacement (Figure 3.5). At two hours, when discharge roughly doubled, the logjam deformed at a faster rate. The initial change instigated 30 cm of compression, which had to be approximated visually, as such a large displacement overwhelmed the PIV tracking. Total compression for Experiment B was 80%. As the first high flow period ends, the logjam collapsed back into the more narrow channel, indicating inward collapse, though there was no downstream displacement. During low-flow periods, displacements were minor, with events that were often less than 0.5 cm in magnitude. With each subsequent increase in flow, the magnitude of the compressional response diminished.

Similarly to Experiment A, deformation was accomplished by the same three mechanisms: 1) discrete shear fronts, 2) *en-masse* logjam-wide adjustments and 3) independent log movement. The temporal evolution of the deformation field transitioned from an elongate, logjam-wide front to a narrow, tightly angled v-front (Figure 3.7). These patterns reflect the absence of channel-spanning logs as obstructions, which inhibit the initial deformation front as well as the large increase in discharge, which quickly compressed the chopsticks, confining them to the downstream reaches. The directions of displacement vectors for time steps t = 133 and t = 593 show that chopsticks deformed around more stable neighbors (Figure 3.7). From the time-lapse, it is clear that they circumvented these obstructions by traveling around their neighbors and the nails. Higher fluid stresses and deeper flow enabled the large degree of compression observed after the first discharge increase. It is more efficient to float and stack logs than to shear past or override each other. Even at this compressed state, logs were more compressed and resistant than their neighbors. The shear plane propagated outward as chopsticks became progressively more compacted and resistant.

3.4 Discussion

3.4.1 Logjam Initiation

Despite identical experimental protocols, the configurations of chopsticks were markedly different for both runs: Experiment A was visibly less ordered in the orientations and packing of chopsticks in comparison with Experiment B. However, both experiments were overall less ordered closer to the nail obstructions than in the upstream, backwater section. We suggest that the backwater is critical in facilitating a more ordered state, as logs carry less momentum in a deeper, slower flow and are able to more favorably arrange and pack in amongst neighbors. As both experiments progressed, orientational order matures via fluid shear and the deformation mechanisms listed below.

3.4.2 Compression Mechanisms

Logjams in both experiments compressed and increased packing amongst chopsticks via three mechanisms: 1) discrete plate-like movements that propagated downstream as ‘v’-shaped fronts/shear planes, 2) *en-masse* logjam-wide adjustments in response to the change in position of a key member and 3) independent logs that either slipped underneath the logjam or oscillated in the less confined upstream end. Magnitudes of compression were different for the experiments, in part due to channel-spanning chopsticks that impeded the downstream progression of the shear plane and because of the difference in hydrologic forcing. In Experiment B, the progression of the shear front was accelerated by the increase of discharge. When large-scale displacements decay in the later hours of Experiment A, movement was accommodated by millimeter scale slip along the bank. In the later hours of Experiment B, compression only occurred during high-flow periods, enabled by more energetic flow, fluid shear and greater 'accommodation space' beneath the logjam.

3.4.3 Approach to jamming

Displacements significantly decreased with time for both experiments and never reach zero. We acknowledge that as each experiment progressed, the magnitudes of deformation converge on the error in PIV and our signal to noise ratio approaches 1. We used PIV to track rod-shaped particles, which is outside of its designed purpose. Nevertheless, we are confident that displacements never truly reach zero, as time-lapse videos indicate that slip is still occurring. Because displacements never reach zero, we suggest that the logjam creeps and is on approach to jamming. That is, over increasingly long timescales of observation, displacement does not completely stop. This is because a constant force is being applied to the logjam and a perfectly static state cannot be attained.

3.4.4 Limitations and future considerations

The difficulty in preserving scaling relationships render our experimental results inappropriate when applied to real-world analogues. However, some similarities between these experiments and the field example of the Big Creek logjam exist. Both structures 1) collapse during lowering flow, 2) are embedded with herringbone v-ing texture, which is more mature in the backwater, 3) experience the most displacement at the upstream end and 4) accommodate changes to the front by propagating a response upstream. However, exact flow parameters, hydrograph shapes, log size distributions and evolutionary state are different in both examples. The degree of compression at the end of our experiments are qualitatively similar to the dense, packed state of the Big Creek logjam, suggesting that this field analog may be the continuation of where our flume experiments end.

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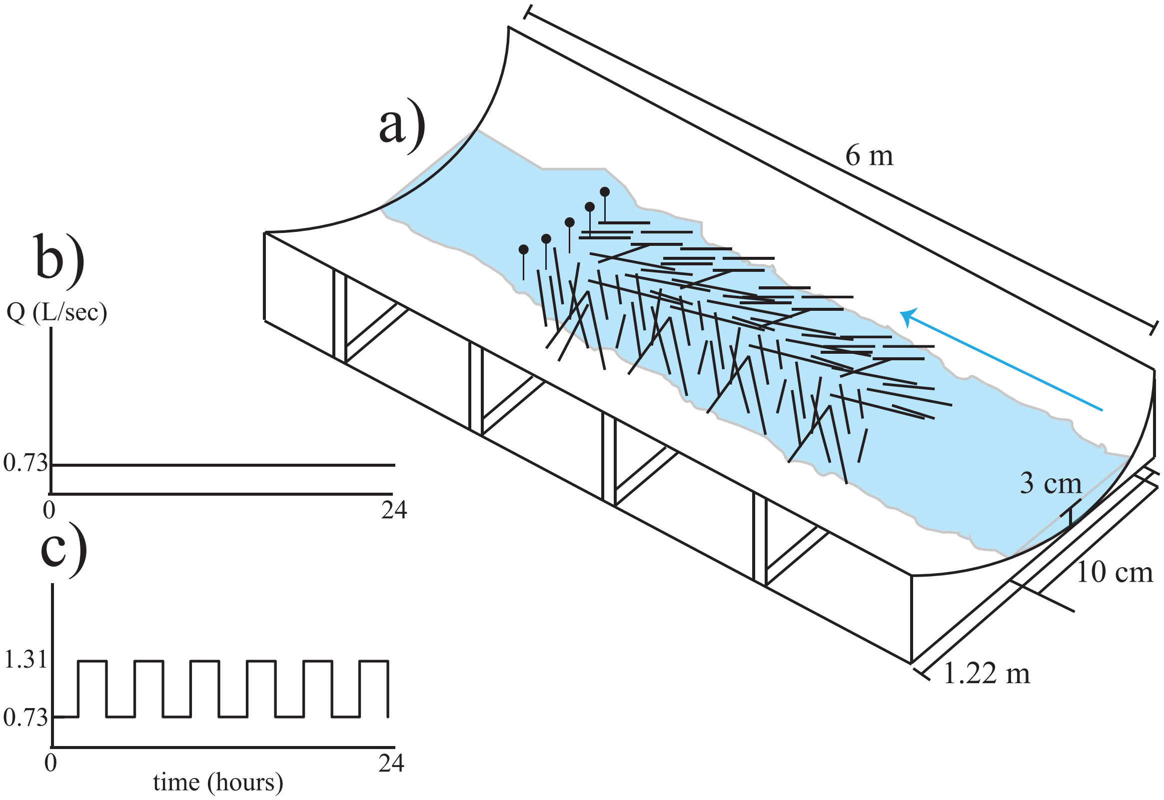

Figure 3.1: a) Experimental apparatus and dimensions. Hydrographs for b) Experiment A and c) Experiment B. Experiment A sampled the velocity field of chopsticks each minute for 24 hours with a constant discharge of 0.73 liters/second. Experiment B sampled the velocity field in the logjam each minute for 24 hours with discharge alternating between 0.73 liters/second and 1.31 liters/second every two hours.

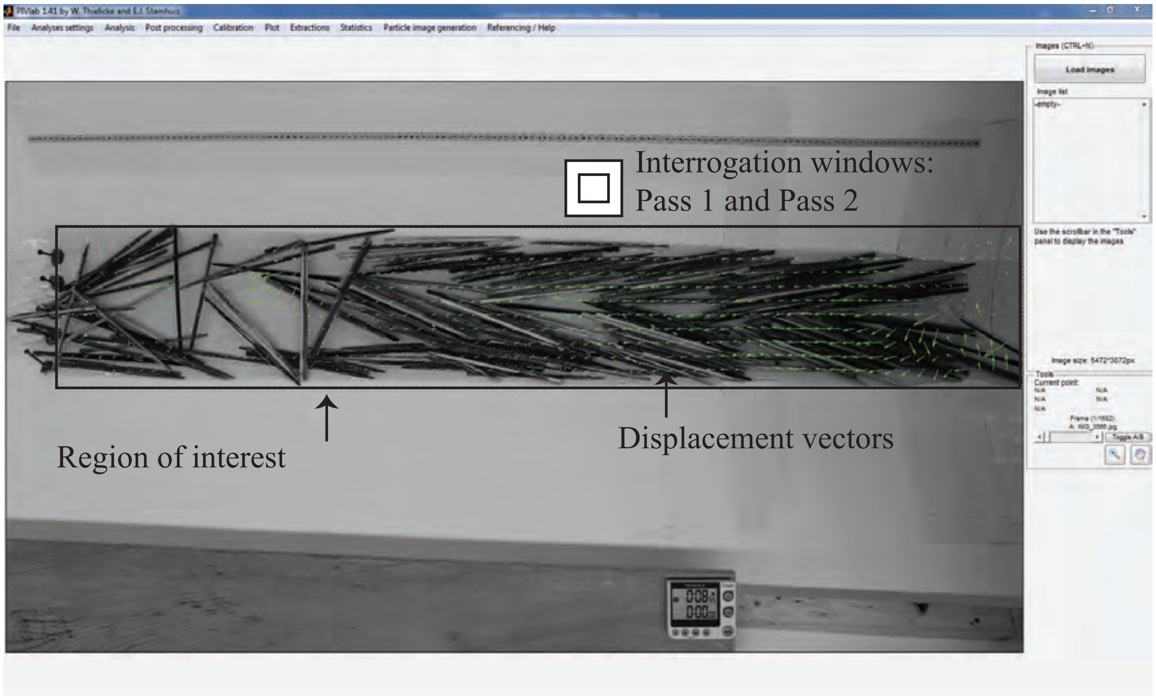

Figure 3.2: PIV GUI, built for MATLAB. Shown is the region of interest, which segmented the image such that pixels outside this boundary would not be included in change detection calculations. The interrogation window set the length scale of precision within PIV: larger interrogation windows provide coarser velocities and smaller windows provide finer-detailed velocity maps. b) An example of an output vector velocity field. The mean of each field at 1 minute intervals was summed over 15 minutes for use in subsequent analysis.

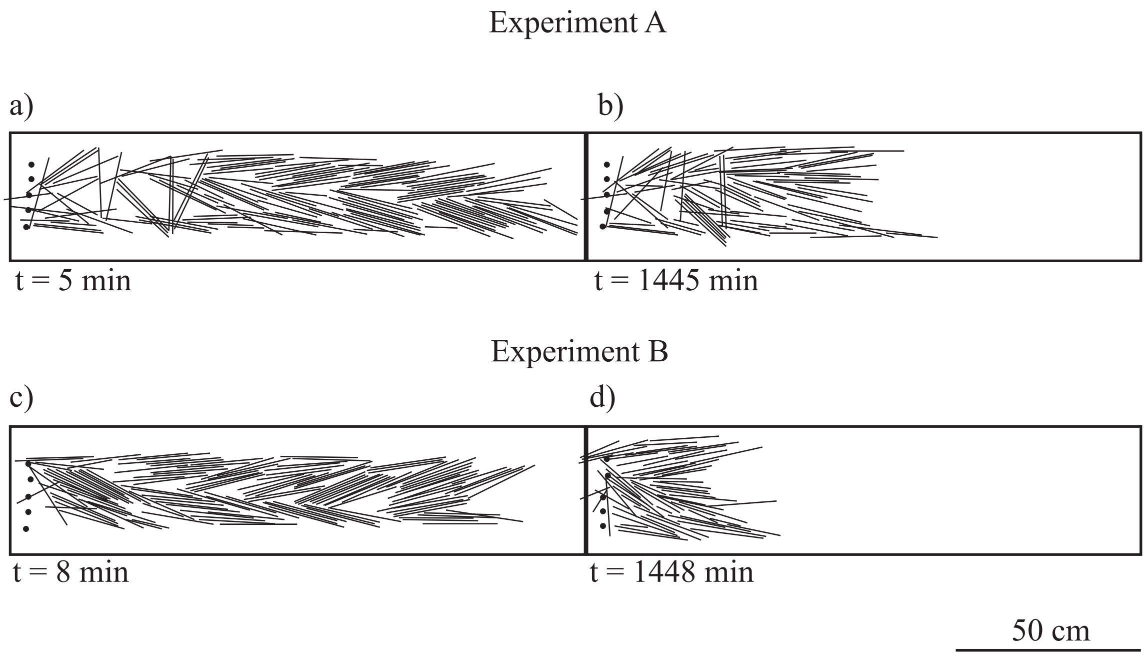

Figure 3.3: Experiment A a) initial and b) final frames. Experiment B c) initial and d) final frames. Over 24 hours of experimental run time, the logjam in Experiment A compresses by ~50%, a length of 64 cm. Experiment B experiences ~75% of compression.

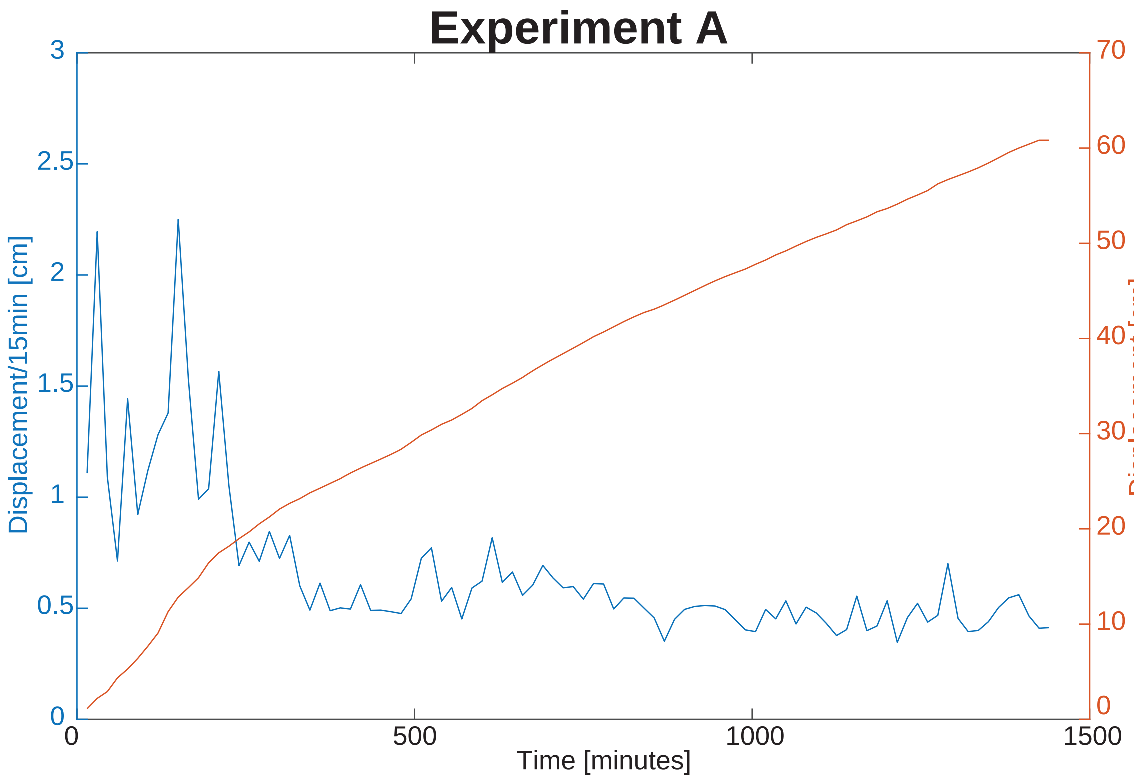

Figure 3.4: Displacement time series for Experiment A. In the initial hours of the experiment, displacements are of relatively large magnitude but somewhat intermittent. 50% of displacement is achieved by hour 9. Although the magnitude of displacement decreases, it never ceases, suggesting that the simulated logjam constantly moving, albeit at a rate that is below perception. Cumulative displacements are steady and ~64 cm of compression occurs.

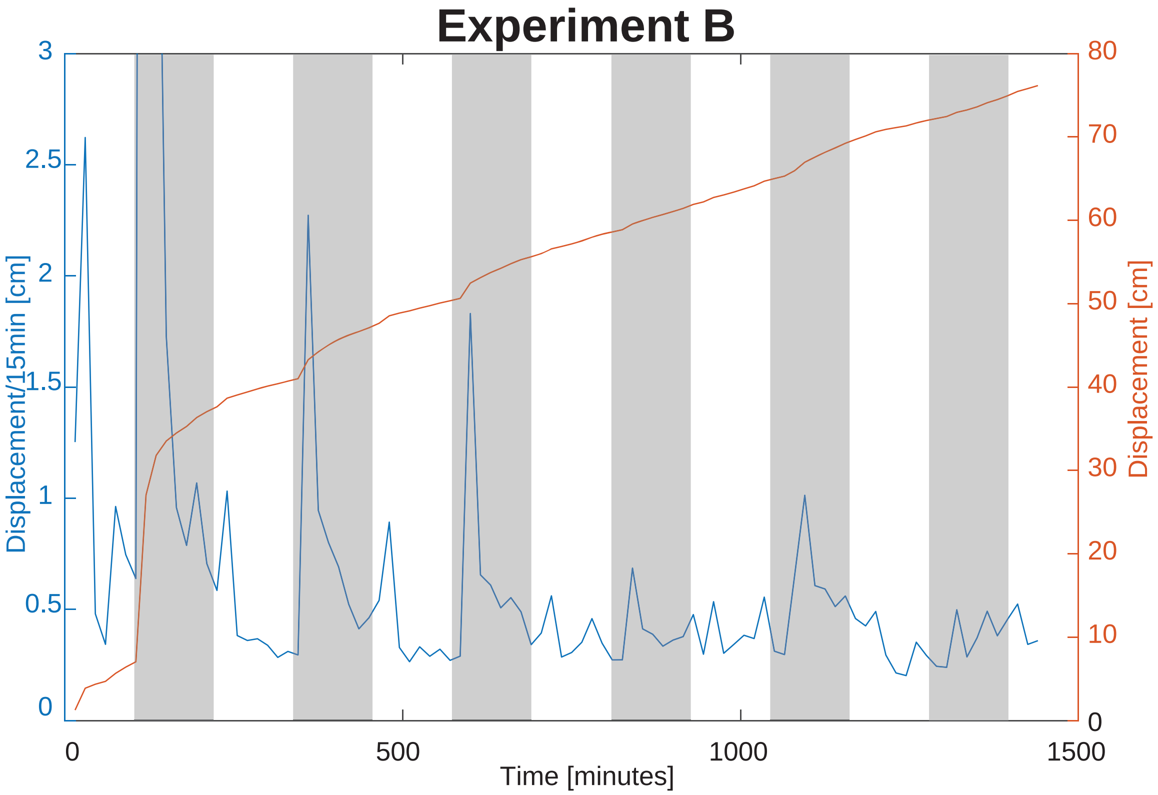

Figure 3.5: Displacement time series for Experiment B. Grey boxes indicate periods of high flow. Similarly to Experiment A, displacement concentrates in the early hours of the experiment. In response to the step-increase in discharge, the logjam compresses ~30 cm. For subsequent increases in flow, the compressional response is present, but dampened. Also like Experiment A, displacement is continuous and gradual.

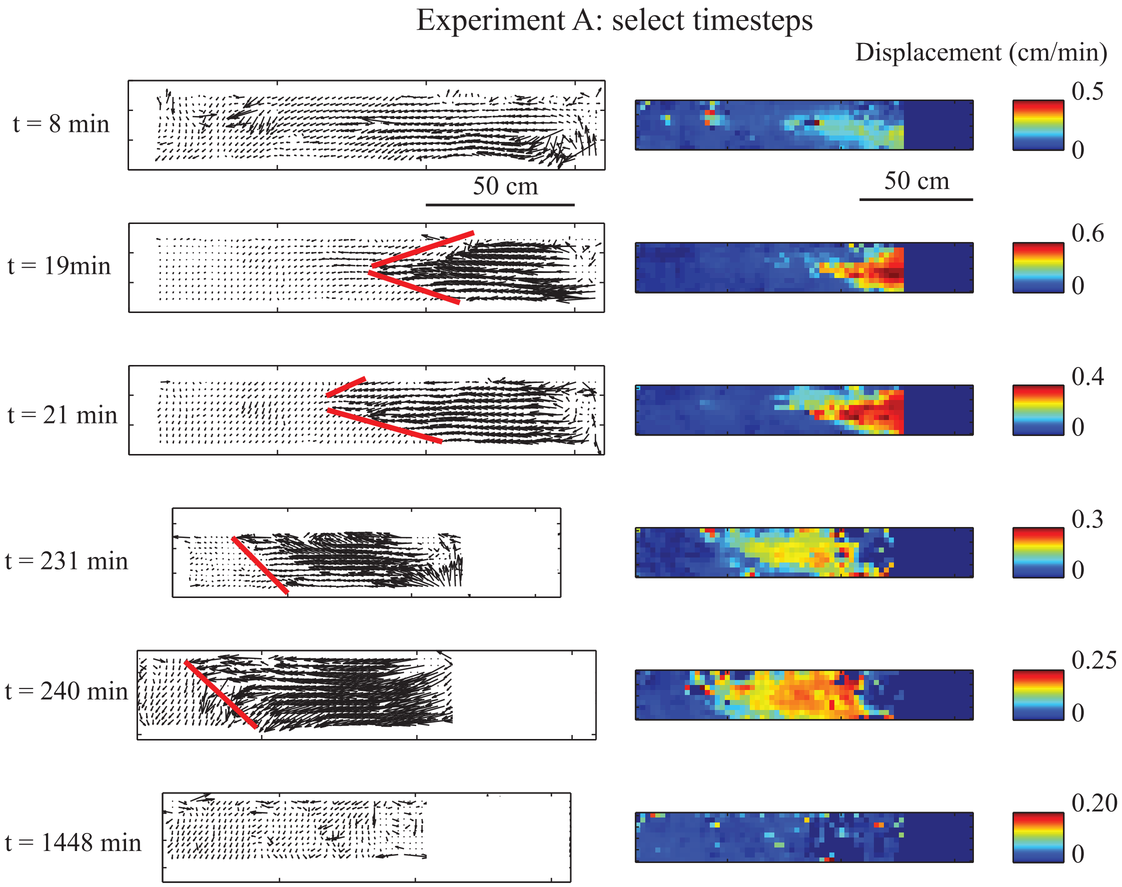

Figure 3.6: Experiment A: select time steps of deformation fields. Deformation begins as a well-organized, triangular shear front that propagates downstream during the experiment. By the end of the experiment, displacement occurs over the entire logjam and is on the scale of millimeters.

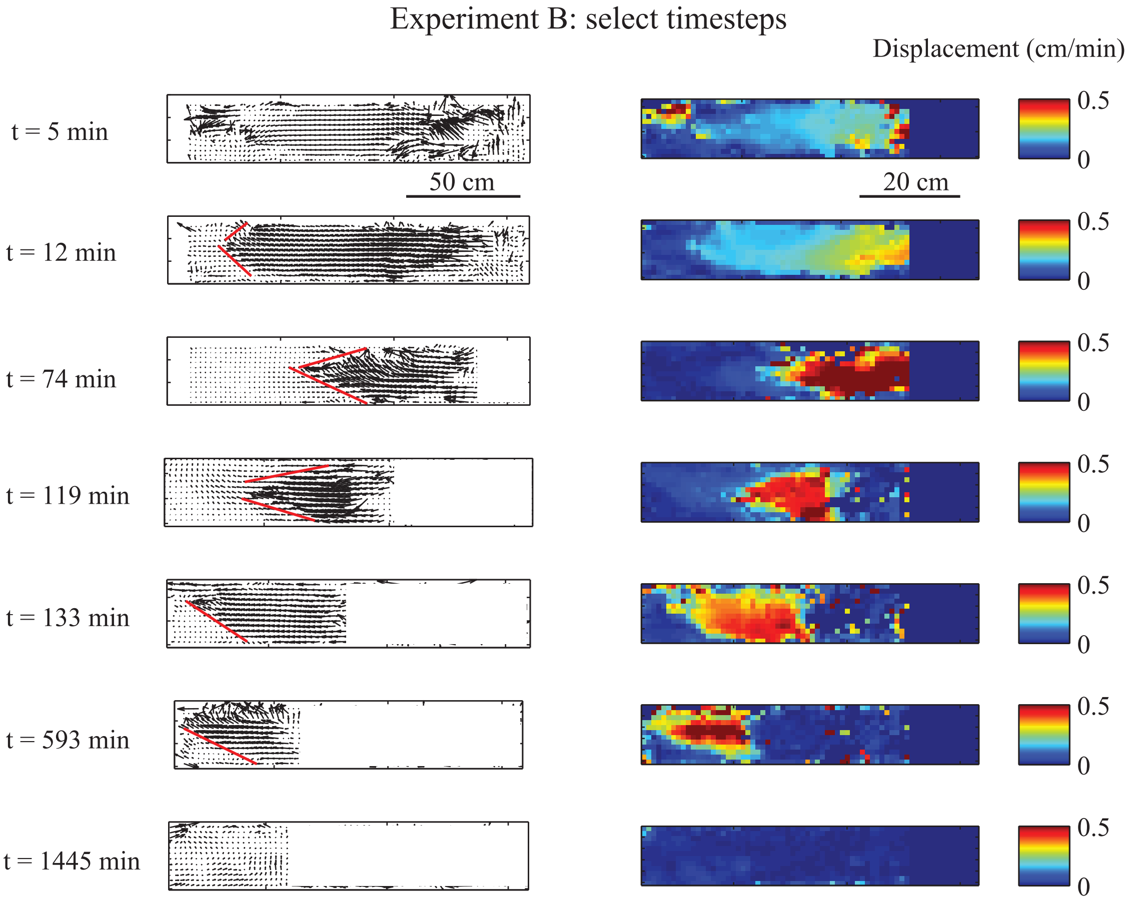

Figure 3.7: select time steps of deformation fields. Similarly to Experiment A, the downstream propagation of a triangular shear plane is the main mechanism of compression and deformation. Because large steps in discharge provide additional fluid shear and buoyant lift to chopsticks, the total magnitude of displacements are greater than Experiment A. Additionally, the shear plane propagates further downstream.

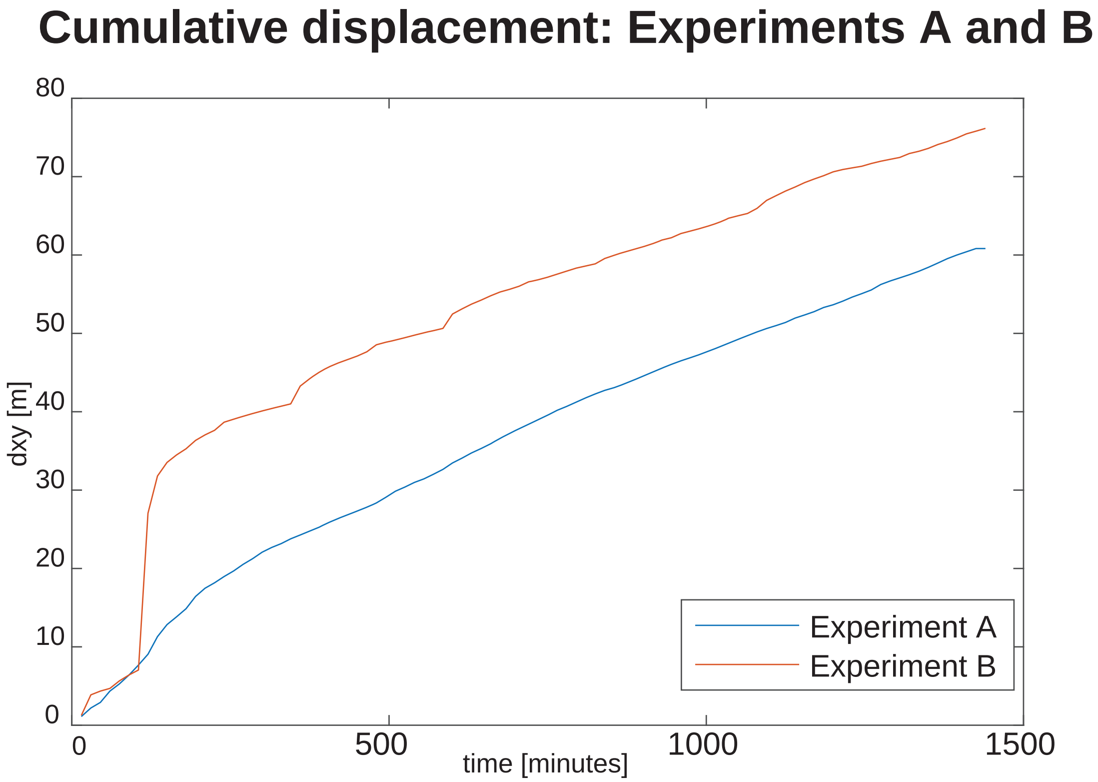

Figure 3.8: Comparison of cumulative rates. Despite very different hydrodynamic forcing, rates of cumulative deformation are strikingly similar for Experiment A and B. The total amount of compression in Experiment B exceeds that in Experiment A, due to the large magnitude compression following step increases in discharge.

Chapter 4: Conclusions and Recommendations

4.1 Summary of Thesis Work

4.1.1 Why study logjams?

Logjams are accumulations of wood in rivers whose persistence in the landscape affects both biotic and abiotic components of stream function. Therefore, understanding the physics and transport mechanics of logjams and namely, large, channel-spanning logjams in mountainous environments, is critical for informing river management and restoration best practices, stream rehabilitation efforts and collective understanding of geomorphology and natural phenomena. We are historically blinded by the consequences of Westward expansion, logging practices and the systematic removal of large wood from rivers, which has fundamentally altered river-wood feedbacks in North America, rendering us poor in empirical examples to guide studies of logjam dynamics. Current understanding of wood transport mechanics is rooted in a theoretical model derived from first principles. While this framework has been the dominant lens through which quantitative wood transport has been examined, the physics are not rigorous or adequate to capture the full dynamism of field observations. Nor is it designed to account for the kinematics of channel-spanning logjams, which are composed of an ensemble of individual logs and therefore a complex network of physical interactions that govern movement.

Granular physics is a discipline within soft-matter physics that deals with precisely these problems: the ensemble kinematic behavior of ‘grains’. ‘Grains’ encompass a variety of shapes and configurations; sand particles, glass beads, rice, wooden dowels, corn kernels, pharmaceutical pills, staples, and nails are all granular materials. Workers within this community have casually suggested that logjams are granular phenomena, although accompanying field data to support this claim are lacking. This is intriguing, as the namesake ‘logjam’ also contains a current buzzword in physics: ‘jam’, which has a precise definition and is an active area of current research. Jamming in granular media occurs when the system transitions from a flowing to rigid state (also referred to as ‘the glass transition’). While appearing straightforward, the approach to the jammed state intrigues researchers because particles remain disordered and highly heterogeneous, despite the bulk characteristics of the system becoming more ‘ordered’ by becoming solid. Therefore, logjams are uniquely poised as an area of research with the potential to bridge very different scientific disciplines by adopting the analytical perspective of one (granular physics), with the intention of advancing collective knowledge and practical application of the other (geomorphology). In recent years, geomorphologists well-versed in statistical mechanics and granular physics have made many inspiring observations along these lines [*Houssais et al.* 2015], which suggests that this is a fruitful and worthwhile direction of scientific inquiry.

In this thesis, we have conducted field investigations and physical experiments to explore the kinematic behavior and spatio-temporal patterns of deformation in channel-spanning mountain logjams, inspired by the allure of a thread of universality between granular materials and logjams. We do not seek to provide a fully developed, physically-based model to predict, describe and quantify logjam deformation. Rather, we present a suite of high-precision measurements and vetted observations that guide the development of a conceptual model for modes of deformation and how these evolve over time. The results of this work carry theoretical implications for physicists, practical considerations for river management and philosophical challenges for dialectic materialists.

4.1.2 Big Creek: a natural experiment

To understand the deformation of channel-spanning logjams, we take advantage of a natural experiment in Big Creek, Idaho, a tributary of the Middle Fork Salmon River. In March 2014, a rain-on-snow event initiated a series of avalanches in the upper reaches of Big Creek, delivering thousands of burned, standing-dead Douglas Fir and Lodgepole pine into the channel. By the late spring, logs stored in multiple debris jams had blown out, floated downstream and coalesced into a thousand-member, channel-spanning logjam, 80 meters long and 20 meters wide. Using time-lapse photography, repeat total station surveys and measurements of river stage, we track the tips of 134 logs to characterize logjam deformation as it experiences spring snowmelt.

We demonstrate that the logjam is not jammed, but rather in continuous movement at a slow rate analogous to creep in materials science. Time-lapse videos reveal that diel fluctuations in stage during the rising limb of the hydrograph facilitate horizontal movement. As stage recedes, the logjam collapses gravitationally. Because water surface profiles are similar in geometry throughout the survey, we infer that the energetics of the flow exerted on the logjam are constant, and that creep is made possible by buoyant lift, releasing intertwined or grounded logs to be sheared by flowing water. Total station surveys and interpolation techniques provide spatially-explicit distributions of displacement, indicating that horizontal logjam displacements are greatest in the rear of the logjam and decrease linearly on approach to the front while vertical displacements concentrate within the center of the logjam. To account for a heterogeneous displacement field, compression must be invoked as an explanatory mechanism, which in turn implies that the logjam strengthens its internal structure by reducing interstitial spaces between logs and increasing frictional resistance. Our results demonstrate that logjams are not static features.

4.1.3 Flume experiments

Results from the field inspired a suite of physical experiments to explore logjam kinematics in a simplified but controlled setting. Using chopsticks as surrogates for logs, we conduct experiments in a 1.22 m wide x 6 m long flume with a semi-circular bed, with nails driven into the bed to impede the downstream progression of chopsticks and to initialize logjam formation. We conducted experiments for 24 hours and under two discharge conditions: A) a constant discharge and B) a square wave of alternating flow. After letting an initial configuration of chopsticks stabilize, we take high-resolution photographs at one-minute intervals to construct time-lapse videos and for Particle Image Velocimetry (PIV), which allows us to quantify the magnitude and direction of changes within a series of images.

Despite identical experimental protocols, the configurations of chopsticks were markedly different for both runs: Experiment A was visibly less ordered in the orientations and packing of chopsticks in comparison with Experiment B. However, deformation was accomplished by three mechanisms, common to both experiments: 1) plate-like movements that propagate downstream as ‘v’-shaped shear planes, 2) logjam-wide adjustments in response to the change in position of a key member, and 3) independent logs whose trajectories either travel underneath the logjam or in the backwater. Total compression was 46% and 80% for experiment A and B, respectively.

Time-series of displacements for both experiments were noisy, but zero displacement was never reached. We therefore suggest that our experiments show the approach to jamming. Despite very different hydrologic forcings, rates of deformation for both experiments were similar, suggesting that the mechanisms of logjam displacement are constant over a spectrum of forcing.

4.2 Comparing Flume and Field

Observations from Big Creek and physical simulations of logjam initiation and evolution indicate several similarities between the two systems. The first of which is that logjams are not jammed, but accrue small displacements over long time scales, i.e. they creep, analogous to the same process observed in materials science. Water surface profiles collected in Big Creek suggests that the logjam is experiencing a constant and persistent drag force that is able to push logs only when there is sufficient buoyant lift. Similarly, Experiment B in Chapter 2 introduces flow conditions such that chopsticks are able to travel underneath the logjam during periods of deeper flow, which buoyantly raises the body of the logjam, thickening and increasing packing amongst chopsticks. Orientational consistency amongst logs and chopsticks are also important: less order is observed for logs and chopsticks closer to the front of the logjam than in the backwater. We suggest that the backwater is critical in facilitating a more ordered state, as logs carry less momentum in a deeper, slower flow and are able to more favorably arrange and pack in amongst neighbors. Azimuthal orientations of shear planes are also similar in Big Creek and in flume experiments: they ‘v’ in shape and are similar to the herringbone structure of both the logjam and the chopstick-jam.

4.3 Opportunities for Future Work

Future field studies in Big Creek should more carefully consider the response of the logjam to variable hydrograph shapes and timing. Furthermore, the use of accelerometers to resolve the vibrations of logs will refine the spatial distribution of energetics within the logjam. A missed opportunity in this work was fully exploiting the quantitative data latent within the time-interval photos as they contain finer temporal resolution than our total station surveys. However, shadow, color correction, stabilization and the orthorectification within each oblique image frame is non-trivial and may not yield changes of position on an appropriately constrained length-scales. Un-evenly timed total station surveys obfuscate the operative temporal scales of logjam movement. It is difficult to suggest a satisfactory remedy for this, as surveys were ~5-7 hours in length and rain and snow made surveying unsafe or unfeasible on many days.

Flume experiments do not incorporate the effect of sediment or realistic hydrograph shapes although we neglected these purposefully to simplify the experiment. We did not carefully calculate scaling relations between the field and experiment and thus extrapolating metrics other than the qualitative behaviors of the deformation field or the modalities of logjam movement are wholly inappropriate. Measurements of water velocity, surface topography and turbulence would greatly help in constraining the physical parameters of the experiments. Realistic aspect ratios or grain-size distributions of chopsticks may reveal dynamics that did not emerge from the experiments we conducted. Flume experiments also have the potential to measure the drag force of the logjam by constructing an experimental design that incorporates a load cell, perhaps by means of a pulley that spans the channel or obstruction. Towards the end of our experiments, rates of movement approached the detection limit in PIV. Although we are confident that displacements late in the experiment are real and not noise (time-lapse videos confirm continuous movement), image tracking algorithms designed specifically for tracking rod shaped particles would improve our capacity to resolve behavior as the chopsticks approach the jammed state.

The use of ‘creep’ can be perceived as problematic, as workers in materials science have precise definitions for such processes. However, we stress that the use of this term is a rheological analogy, not a rigorous description of process. We hope that this work contributes to challenging paradigms and perceptions of material transport processes in geomorphology so that we can begin more formal treatments from the perspective of statistical mechanics, such that geomorphology (specifically, wood transport) may progress by adopting more quantitative, rigorous and integrative perspectives.

Appendix A: Statistical data for Chapter 2

Kriging is a geostatistical interpolation tool that operates on a suite of assumptions [*Curran* 1988]. It is beyond the scope of this work to rigorously engage in the statistical assumptions and model-selection process that underlies kriging. However, we do recognize the importance of providing both the raw histograms of displacement and semivariograms that were used in generating kriged surfaces.

Histograms: horizontal displacement

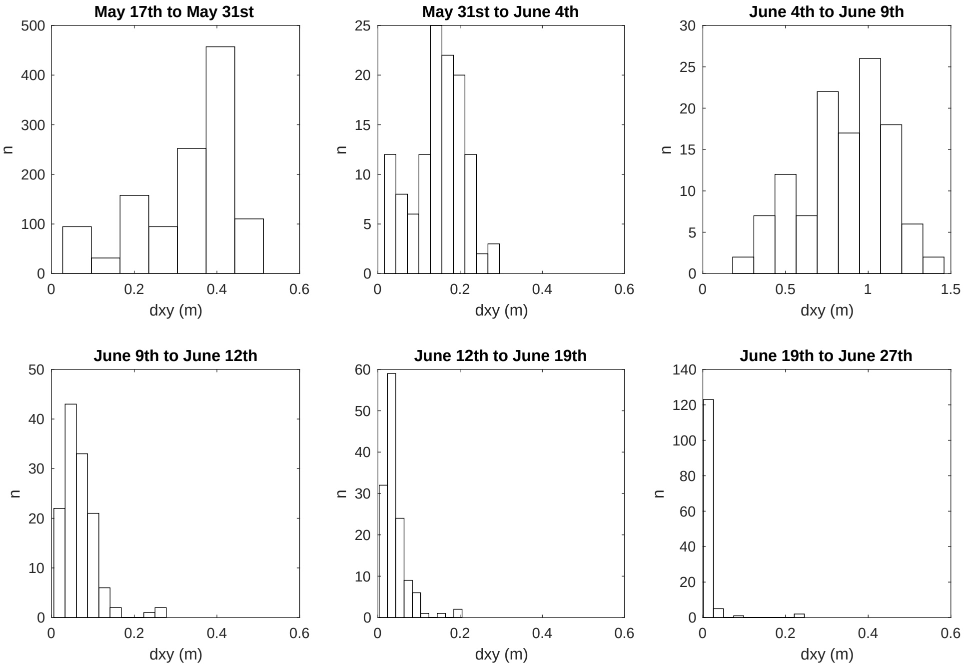

Figure A1: Raw histograms of horizontal displacements.

Histograms: vertical displacement

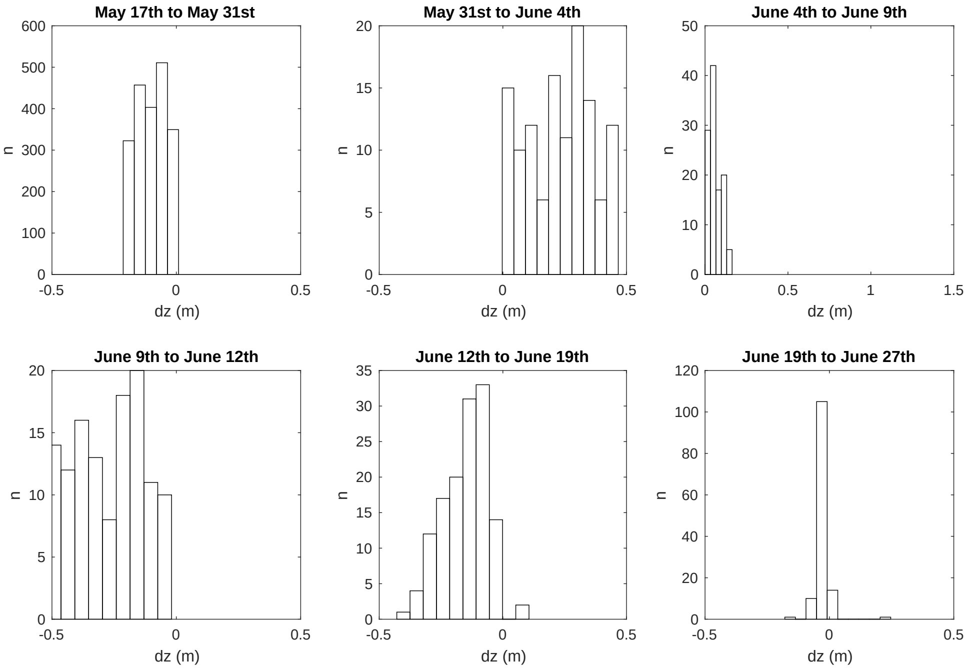

Figure A2: Raw histograms of vertical displacements.

Semivariograms: horizontal displacement

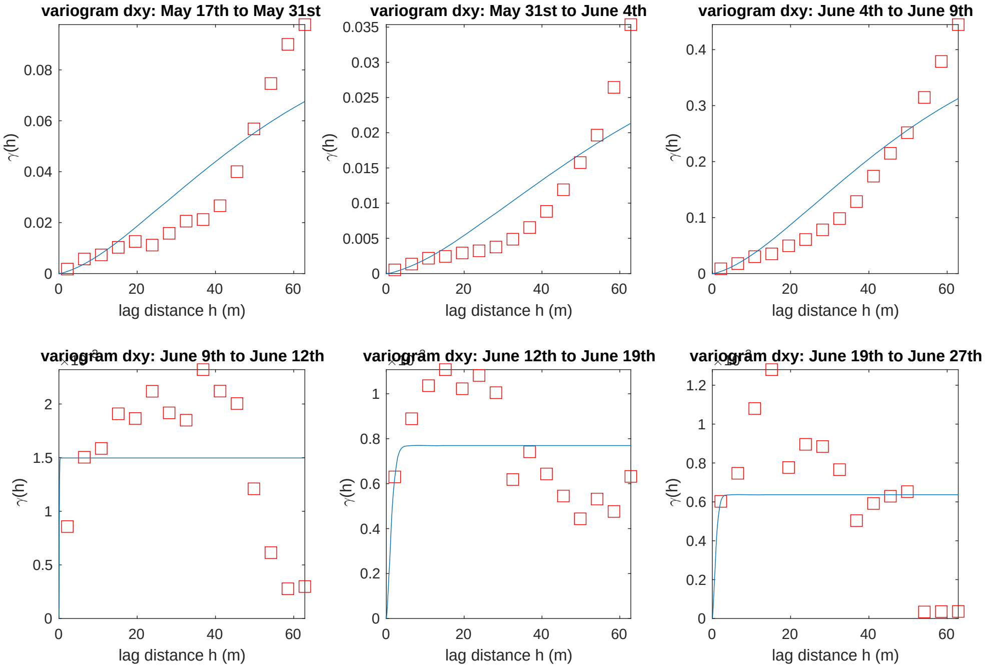

Figure A3: Semivariograms, which illustrate the degree of dissimilarity (γ) as a function of lag distance (distance between measured points). We fit ‘stable’ models to the empirical variograms.

Semivariograms: vertical displacement

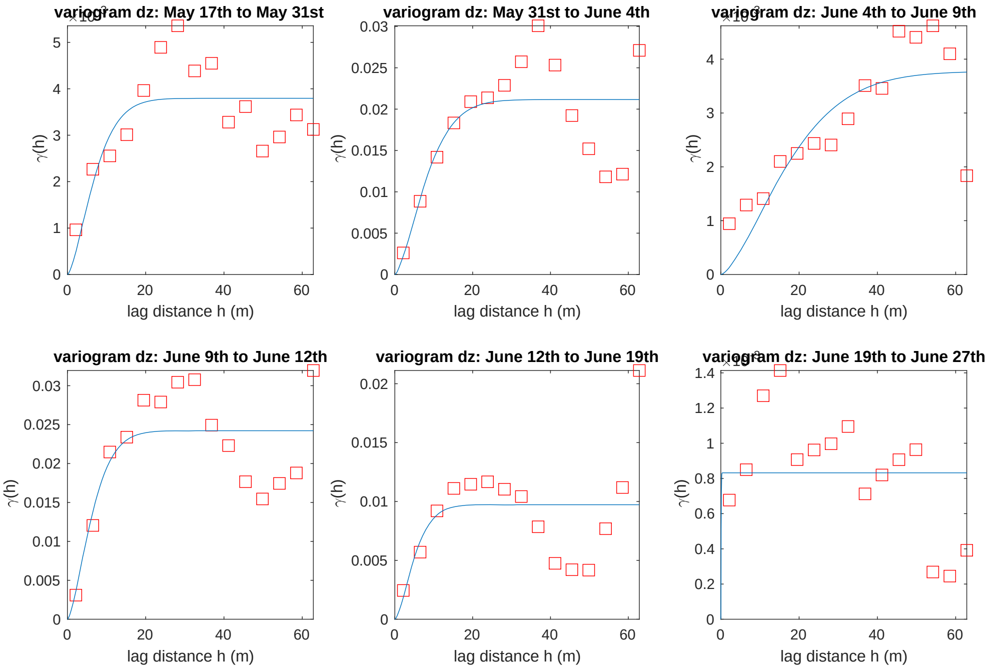

Figure A4: Semivariograms, which illustrate the degree of dissimilarity (γ) as a function of lag distance (distance between measured points). We fit ‘stable’ models to the empirical variograms.

Appendix B: Time-lapse videos from Big Creek, Idaho and experimental analogs

At this time of writing, an online repository containing time-lapse videos from the field campaign in Big Creek, Idaho (Chapter 2) and from the flume experiments (Chapter 3) is still under construction.

Please contact Nakul Deshpande (nakul.s.deshpande@gmail.com) or Dr. Benjamin Crosby (crosby@isu.edu) for access to the completed repository and access to the time-lapse videos.

If you have made it this far, thanks for your attention!