Rheological evolution of the mount meager 2010 debris avalanche, southwestern british columbia

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[1] Supplemental File 1. **[[Photo of?]]** A block forming a hummock with related streaks of sheared block facies in area 3. Please visit http://dx.doi.org/10.1130/GES01389.S1 or the full-text article on www.gsapubs.org to view Supplemental File 1.

[2] Supplemental File 2. Helicopter view of the debris avalanche surface before the dam breach. Shearing and lithological markers are evident. Please visit http://dx.doi.org/10.1130/GES01389.S2 or the full-text article on www.gsapubs.org to view Supplemental File 2.

[3] Supplemental File 3. **[[Photo of an?]]** Outcrop showing relations among facies in area 1. Please visit http://dx.doi.org/10.1130/GES01389.S3 or the full-text article on www.gsapubs.org to view the Supplemental File 3.

[4] Supplemental File 4. **[[Sketch showing a? Photo of a?]]** Section through a hummock showing facies relations in area 3. Please visit http://dx.doi.org/10.1130/GES01389.S4 or the full-text article on www.gsapubs.org to view Supplemental File 4.

[5] Supplemental File 5. **[[Photo of?]]** Entrained-facies hummocks in the water-rich phase of the deposit, area 4. Please visit http://dx.doi.org/10.1130/GES01389.S5 or the full-text article on www.gsapubs.org to view Supplemental File 5.

[6] Supplemental File 6. Helicopter view of the Meager Creek barrier**[[Meager barrier, as worded throughout text?]]** before the dam breach. Photo courtesy of D.B. Steers. Please visit http://dx.doi.org/10.1130/GES01389.S6 or the full-text article on www.gsapubs.org to view Supplemental File 6.

[7] Supplemental File 7. Helicopter view of the Meager Creek barrier**[[Meager barrier?]]** after the dam breach. Photo courtesy of D.B. Steers. Please visit http://dx.doi.org/10.1130/GES01389.S7 or the full-text article on www.gsapubs.org to view Supplemental File 7.

[8] Supplemental File 8. Sketch showing the inferred structural evolution of the west end of the plug. (A) First compressional ridges formed as the front started to decelerate. (B) The debris divided into different lobes, and strike-slip faults accommodated the differential motion. (C) This area stopped while the front was still moving. Normal faults accommodated the consequent extension. (D) Inset map of the west end of the plug. Extensional structures dominate this area. Please visit http://dx.doi.org/10.1130/GES01389.S8 or the full-text article on www.gsapubs.org to view Supplemental File 8.

Rheological evolution of the Mount Meager A.D. 2010 debris avalanche, southwestern British Columbia

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ABSTRACT

On 6 August 2010, a large (~50 Mm^3) debris avalanche occurred on the flank of Mount Meager in the southern Coast Mountains of British Columbia, Canada. We studied the deposits to infer the morphodynamics of the landslide from initiation to emplacement. Structure from motion (SfM) photogrammetry, based on oblique photos taken with a standard SLR camera during a low helicopter traverse, was used to create high-resolution orthophotos and base maps. Interpretation of the images and maps allowed us to recognize two main rheological phases in the debris avalanche. Just below the source area, in the valley of Capricorn Creek, the landslide separated into two phases, one water rich and more mobile, and the other water poor and less mobile. The water-rich phase spread quickly, achieved high superelevation on the valley sides, and left distal scattered deposits. The main water-poor phase moved more slowly, did not superelevate, and formed a thick continuous deposit (up to ~30 m) on the valley floor. The

water-poor flow deposit has structural features such as hummocks, brittle-ductile faults, and shear zones. Our study, based on a freshly emplaced deposit, advances understanding of large mass movements by showing that a single landslide can develop multiple rheology**[[rheological?]]** phases with different behaviors. Rheological evolution and separation of phases should always be taken into account to provide better risk assessment scenarios.

INTRODUCTION

Landslides are one of the major hazards in mountainous regions. When volcanoes are present in the mountains, the hazard is compounded, as volcanic rocks are weak and hydrothermal alteration further weakens both the volcano and the country rock. Thus, potentially unstable volcanic edifices pose a significant hazard to people living in their vicinity. They are prone to large collapses, which can generate fast-moving debris avalanches that may travel far from their source (Siebert, 2002; van Wyk de Vries and Davies, 2015). Some collapses occur during eruptions, but many happen during quiescent periods and are not directly related to eruptive activity (Friele et al., 2008; Shea and van Wyk de Vries, 2010). Causative factors include rapid uplift and erosion as well as weak materials that form their**[[volcano? (Clarify antecedent)]]** flanks that commonly slowly deform under the influence of gravity (van Wyk de Vries and Francis, 1997; Reid and Brien, 2006; van Wyk de Vries and Davies, 2015).

Volcanic and non-volcanic debris avalanches are complex mass movements in which multiple rheologies can coexist (Iverson et al., 2015; Coe et al., 2016), affecting overall behavior and runout. An understanding of these processes is vital for appropriate modeling, hazard and risk evaluation, and possible mitigation strategies (Kelfoun, 2011; Jakob et al., 2013; Iverson et al., 2015).

The deposits and surface morphology of many prehistoric volcanic debris avalanches have been studied to infer transport and emplacement processes (Vallance and Scott, 1997; Takarada et al., 1999; Capra and Macias, 2000; Bernard et al., 2008; Roverato et al., 2014). Studies of these events, however, are limited, as surface features commonly have been degraded or totally lost. Very few studies document in detail fresh deposits emplaced soon after the events (Plafker and Ericksen, 1978; Glicken, 1996). And even in most of these cases, there is a lack of eyewitness accounts and video documentation.

A landslide in August 2010 at Mount Meager in the southern Coast Mountains of British Columbia (Canada) provided us with a unique opportunity to examine the deposit of a volcanic debris avalanche before it was significantly eroded, and thus to improve understanding of debris avalanche rheology and emplacement mechanisms. The objective of this study is to refine understanding of the emplacement kinematics and dynamics and the rheology of the Mount Meager debris avalanche in order to advance knowledge of such events. We achieved this objective by constructing a high-resolution orthophoto and digital elevation model (DEM) using structure from motion (SfM) and through detailed geomorphologic mapping (at 1:1000 scale) and grain-size analysis. This new technology can be applied to other debris avalanches around the world to offer valuable new insights into the morphodynamics of large landslides.

SETTING

Mount Meager (2680 m above sea level [asl]) is a Pliocene to Holocene volcanic complex 200 km north-northwest of Vancouver, British Columbia (Fig. 1). It lies within the Lillooet River watershed, 65 km upstream of the town of Pemberton.

The Mount Meager massif is a group of coalescent stratovolcanoes that formed during four episodes of volcanism: one minor Pliocene episode and three major Quaternary episodes.

Read (1977, 1978, 1990) subdivided the eruptive products into nine volcanic assemblages. The most recent eruption was an explosive event that occurred 2350 yr ago (Clague et al., 1995; Hickson et al., 1999). Rocks involved in the 2010 landslide were mainly intrusive porphyritic rhyodacite, flows, and breccia units of the Plinth and Capricorn assemblages—the youngest assemblages in the massif (Read, 1990).

Landslides on Mount Meager

Volcanism, associated hydrothermal alteration, and erosion have weakened the rocks that form the Mount Meager massif, as they have at most stratovolcanoes around the world (Finn et al., 2001; Siebert, 2002; Pola et al., 2014). The considerable topographic relief of the massif (up to 2000 m) and its steep slopes, combined with recent thinning and retreat of alpine glaciers (Holm et al., 2004), have left much of the massif in a state of instability (Read, 1990; Friele et al., 2005; Friele and Clague, 2009).

Evidence of active slope processes affecting the massif include sackungen, debris flows, and debris and rock avalanches (Mokievsky-Zubok, 1977; Jordan, 1994; Bovis and Evans, 1996; Jakob, 1996; Friele and Clague, 2004). In particular, Capricorn Creek, a tributary of Meager Creek, was the source of debris flows and debris avalanches larger than 100,000 m^3 in A.D. 1931, 1933–1934, 1944–1945, 1972, 1998, 2009, and 2010 (Carter, 1932; Jakob, 1996; Bovis and Jakob, 2000; Guthrie et al., 2012). Using dendrochronology, Jakob (1996) extended the historical record of landslides in the Meager Creek watershed to 330 yr ago. He identified 13 large debris flows and/or hyperconcentrated flows, an average of one event every 25 yr. These landslides entered Meager Creek and caused significant channel aggradation and instability downstream. Some of them also blocked Meager Creek, forming landslide-dammed lakes (Mokievsky-Zubok, 1977; Bovis and Jakob, 2000; Guthrie et al., 2012). Very large collapses of the flank of the massif have generated at least three Holocene debris flows that have traveled downstream to presently populated areas in Lillooet River valley (Friele and Clague, 2004; Friele et al., 2005; Simpson et al., 2006).

The 2010 Event

On 6 August 2010, the south flank and secondary peak (2554 m asl) of Mount Meager collapsed, producing a long-runout debris avalanche (Guthrie et al., 2012) (Fig. 1). The collapse evolved as several subfailures (Allstadt, 2013; Moretti et al., 2015). The debris accelerated to speeds of 60–90 m/s as it traveled 7 km down Capricorn Creek to Meager Creek (Allstadt, 2013). At the Capricorn Creek–Meager Creek confluence, the front of the debris sheet ran 270 m up the opposing valley wall and split into two lobes, one of which ran ~3.4 km upstream and the other 4.7 km downstream to Lillooet River where it spread out over the valley floor before coming to rest 2 km below the Meager Creek–Lillooet River confluence. Field evidence showed that some deposition occurred along the entire travel path, but most of the debris was deposited at the mouth of Capricorn Creek and in Lillooet River valley (Guthrie et al., 2012).

Guthrie et al. (2012) concluded that the 2010 landslide involved the failure of 48.5×10^6 m^3 of rock. It thus was similar in size to the A.D. 1965 Hope slide**[[Provide geographic location]]** (Mathews and McTaggart, 1969; Bruce and Cruden, 1977) and almost twice the size of the famous A.D. 1904 Frank slide**[[Provide geographic location]]** (Cruden and Krahn, 1973; Cruden and Martin, 2007). The vertical elevation drop from the source area to the distal limit of the debris (*H*) is 2185 m, and the total path length (*L*) is 12.7 km. These values yield a fahrboschung (travel angle, tan *H*/*L*) of 9.8°. The average velocity of the landslide was 45 m/s (Allstadt, 2013). The landslide produced the equivalent of a M 2.6 local earthquake, with longperiod seismic waves that were recorded by seismometers as far away as southern California and northern Alaska.

A mass of debris up to 30 m thick blocked Meager Creek at the mouth of Capricorn Creek, and a 10–15-m-thick debris barrier formed across Lillooet River. A stream gauge on Lillooet River 65 km downstream of Meager Creek recorded an initial rapid drop in discharge, followed ~2 hr later by a rise in discharge after Lillooet River breached its dam. About 19 hr later, discharge spiked following overtopping and breaching of the Meager Creek barrier**[[Meager barrier?]]** (Roche et al., 2011; Guthrie et al., 2012). Because this flood wave was built on a low base flow, it did not exceed the bankfull discharge of Lillooet River in Pemberton and caused no property damage.

The outburst floods resulting from the two dam breaches modified much of the original surface of the landslide deposit. However, an extensive area retained its original structure and morphology a year after the event, allowing us to conduct this study.

We use the term “debris avalanche” to describe the 2010 landslide because most of the deposit shows features typical of a volcanic debris avalanche (Glicken, 1991; Ui et al., 2000; Shea and van Wyk de Vries, 2008; Paguican et al., 2014; van Wyk de Vries and Delcamp, 2015). However, the landslide started as a rockslide before rapidly transforming into a channelized debris avalanche. It left a broad range of deposits, which we describe in detail below, that go from hummocky, faulted debris avalanche deposit through smoother,**[[Comma appears to be misplaced – remove?]]** ridges and striated debris flow–like deposits to turbid water**[[Can this be categorized as a “deposit”? (reword)]]** that scoured bark from trees and embedded stones in trunks.

METHODS

Photography and Structure from Motion

To produce a base map for geomorphic mapping, we took oblique digital photos one year after the landslide with a single lens reflex (SLR) camera during low-level helicopter flights over the accumulation zone. The photos were processed using the SfM and multiview stereo (MVS) algorithms (Snavely et al., 2008; James and Robson, 2012; Westoby et al., 2012; Fonstad et al., 2013; Micheletti et al., 2015) to produce three-dimensional topographic models from which we extracted a high-resolution orthophoto (0.08 m/pixel ground resolution) and a DEM (0.34 m/pixel ground resolution). Centimeter-size clasts are resolvable on the imagery.

Uncertainties and limitations of SfM mostly stem from the automated workflow, in which sources of errors are difficult to individualize and control (James and Robson, 2012; Fonstad et al., 2013; Remondino et al., 2014; Micheletti et al., 2015). Nevertheless, the SfM-derived DEMs are comparable in quality to most lidar DEMs (James and Robson, 2012; Westoby et al., 2012; Fonstad et al., 2013; Remondino et al., 2014; Micheletti et al., 2015; Smith et al., 2015)

We also used oblique digital photos taken from a helicopter the morning after the landslide, before the flood from the Meager Creek dam breach. Although these photos could not be used for SfM analysis, they were useful for evaluating geometries and facies relations that were subsequently destroyed by the flood.

Field Mapping

We produced a geomorphic map of the landslide deposits at a scale of 1:1000 from field observations made between August and October 2012 and from the orthophoto and the DEM. We identified and classified geomorphic features, facies, and related facies associations within those parts of the deposit that had not been modified by erosion. For the purpose of discussion, we subdivide the debris avalanche deposit below the mouth of Capricorn Creek into five areas that we refer to as Meager barrier, terrace, plug, distal up, and distal down (Figs. 1 and 2).

Grain-Size and Lithologic Analysis

We chose four sample sites distributed along the length of the deposit from the Meager barrier to the distal margin for grain-size and lithological analyses (Fig. 1). At each site, we placed a 100 m tape parallel to the flow direction. Clast lithologies were recorded at 1 m intervals along the tape and visually classified as basement rock (B), gray porphyritic felsic rhyodacite (GPF), red porphyritic felsic rhyodacite (RPF), and other volcanic rocks (OV). “Other volcanic rocks” include gray, red, and white aphanitic rocks, gray and cream colored porphyritic rocks, and pumice. One-kilogram bulk samples were collected for grain-size analysis at stations 20, 40, 60, 80, and 100 m along the tape. For each of these samples, 100 of the largest clasts >4 mm retained from sieving were also lithologically classified. Ten other bulk samples were collected from selected stations on the deposit, two from mixed debris and four each from pulverized blocks and altered blocks.

The samples were split into >1 mm and <1 mm fractions. The 1–4 mm fraction was dry sieved while the <1 mm fraction was submitted to ALS Global Laboratory**[[Give location of the lab]]** for hydrometer analysis following ASTM protocol D422. We then integrated the sieve and hydrometer data to produce grain-size distributions truncated at 4 mm. In Figure 4**[[The citation to Figure 4 appears to be out of order.]]** the samples are truncated at 2 mm.

RESULTS AND DISCUSSION

We first describe facies, structures, and hummocks, and then describe and interpret each of the five areas that constitute the debris avalanche deposit.

Facies

The **block facies[[Change bold text to italics (to avoid appearance of a heading in some paragraphs)? (all instances of facies/structure types)]]** comprises highly brecciated but intact masses of red or gray rhyodacite, altered cream colored rhyodacite, and altered and unaltered basement rock derived from the source area. Blocks are tens to hundreds of cubic meters in volume and form hummocks one to several meters high. They commonly have a "jigsaw puzzle" fabric (Fig. 3A) and a silt-to-clay loam matrix. The fine fraction (<2 mm) of zones of hydrothermally altered blocks contains 19%–29% clay, whereas the fine faction of unaltered blocks contains 2%–5% clay (Fig. 4).

The **sheared block facies** is localized in shear zones within the block facies and occurs as discrete zones or streaks of coherent lithology in the deposit. It is a product of fragmentation and disaggregation of blocks by shear during the final stage of debris emplacement (Supplemental Files 1[1] and 2[2]). The form of the block facies has been destroyed, but the lithology of the source block has been retained. Streaks of sheared block facies define the direction of movement of the debris avalanche (Figs. 3C–3E**[[Do you mean 3C and 3E? Fig. 3D appears to be a different facies (woody debris)]]**).

The **mixed facies** is a fully mixed debris consisting of brown matrix-supported diamicton (Figs. 3B, 3C, and 3E). It comprises particles ranging from clay to medium-size boulders. The matrix (<2 mm) is a sandy loam, with a clay content of 3%–8% (Fig. 4). The gravel fraction consists of 19%–29% basement rock, 49%–64% gray porphyritic rhyodacite, 4%–10% red porphyritic rhyodacite, and 9%–12% other volcanic rocks. This facies also contains abraded wood fragments, and its surface supports rare kettle holes left from the melt of blocks of glacier ice derived from Capricorn Glacier in the source area.

The **woody debris facies** comprises partially abraded tree stumps, stems, and branches derived from the forest destroyed by the debris avalanche and pushed to the margins of the deposit (Fig. 3D).

The **entrained facies** consists of fluvial channel or overbank sediments and colluvium incorporated into the landslide by scour and thrusting. This facies is distinguished from others by its well-sorted texture and rounded and subrounded clasts. The entrained facies is a minor constituent of the landslide deposit (Supplemental File 3[3]).

Structures

The principal structures are linear forms associated with thrust, normal, and strike-slip faults. They include scarps, ridges, and linear depressions and, in some cases, mark lithological and facies boundaries (Fig. 5).

Compressional ridges are perpendicular to flow. They are rounded and commonly sinuous along their length (Fig. 5A). At eroded edges of the deposit, compressional ridges are underlain by diffuse shear zones or thrust faults marked by displaced lithologies.

Strike-slip faults are meter- to multi-meter-wide linear depressions with low relief, oriented parallel to the flow direction (Fig. 5B). They are commonly associated with splay faults, grabens, and compressional ridges.

Normal faults are marked by scarps with straight slopes (Fig. 5C). In some cases, they occur in pairs and form grabens (Fig. 5D). Normal faults strike perpendicular to the flow. Where seen in cross-section, normal faults are either single sharp faults or broad shear zones (Fig. 5D).

Hummocks

Hummocks are 1–8 m in height, 1–40 m in length, and 1–30 m in width; volumes range from 1 m^3 to ~900 m^3. Shapes are round or ellipsoidal. Hummocks are composed of block facies (either gray or red porphyritic rhyodacite), entrained facies, or ~~are~~ a mix of block, mixed, and sheared block facies.

Mixed hummocks typically have a core of block facies and sheared block facies and a carapace of mixed facies (Supplemental File 4[4]). The boundary between the core and carapace is sharp to gradational; in some cases flame structures intrude the core.

The entrained facies hummocks are composed of either fluvial sand and gravel or sand (Supplemental File 5[5]). This hummock type is rare and found only at the distal margin of the debris avalanche. The entrained facies hummocks are smaller than the block and mixed hummocks, with a volume of ~1–3 m^3.

Subarea[[Area? (especially because area 2 itself has subareas?)]] Descriptions

Area 1: Meager Barrier

The southeastern valley wall of Meager Creek, opposite the mouth of Capricorn Creek (area 1 in Figs. 1 and 2), was stripped of all trees up to 270 m above the valley floor by the landslide. Only a patchy veneer of landslide debris remains on this slope. At the foot of the slope, and extending across Meager Creek valley to the mouth of Capricorn Creek valley, is ~~a~~ thick debris forming the barrier that dammed Meager Creek for 19 h. The Meager barrier deposit is 700 m long, 50–500 m wide (increasing in width from the apex to the southeastern side of the valley), and ~30 m thick, thinning toward Capricorn Creek.

The barrier supports irregular ridges that are perpendicular to the flow direction (Fig. 6A). Seven major compressional ridges are present on the northwestern side of the barrier. In contrast, the southernmost 200 m of the barrier surface, nearest the southeastern valley wall, is an irregular hummocky deposit.

The compressional ridges are southeast verging and identified by a basal thrust. The difference in height between each depression and the tops of adjacent ridges is as much as 12 m. The ridges increase in length from 50 to 300 m in a northwest-southeast direction; the longest ridges span the full width of the deposit. Streaks of sheared block facies trend parallel to the ridges (Supplemental File 6[6]). Only a few blocks, in the form of low broad hummocks, rise above the surface of the Meager barrier. Larger blocks (up to 900 m^3) locally underlie the ridges (Supplemental File 7[7]). We observed only a few altered blocks in this area.

The 200-m-long distal portion of the Meager barrier, below the opposing wall of Meager Creek, was eroded during the dam breach, but pre-breach helicopter photos (Fig. 6A) show a northwest-verging thrust associated with a ridge, indicative of compression and contraction. Many hummocks of gray rhyodacite are present near the valley side in this area.

Three lineaments are evident on the southeastern valley wall above the barrier (Fig. 6B). The highest lineament is a debris line that extends up to 270 m above the valley floor and marks the limit of the debris avalanche on the slope. The debris boundary separates the area stripped of trees from undisturbed forest. An intermediate lineament marks the limit of the debris barrier on the slope. The lowermost lineament is ~20 m above the valley floor and is consistently parallel to it.

*Interpretation.***[[Should this be formatted differently (like a heading), or perhaps punctuated or worded differently so it doesn’t appear to be a heading? (all “Interpretation” sections)]]** The front of the debris avalanche swept across Meager Creek and ran up the southeastern wall of the valley, completely removing the forest and scouring the forest floor. The maximum limit reached by the debris is marked by the conspicuous trimline high on the valley wall. In the barrier deposit, the major compressional ridges formed at the foot of the slope as the forward movement of the debris avalanche in this area was impeded and the debris was compressed. The debris stopped first at its front while the back was still moving. We interpret the Meager barrier deposit to be related to seismometer “signal H” of Guthrie et al. (2012) and the “aftershock” of Allstadt (2013), representing a final summit collapse of the secondary Mount Meager peak occurring ~2 min after the main event. The hummocks of gray rhyodacite at the foot of the opposing slope are likely a product of runup and collapse of this late-stage emplacement.

We interpret the three lineaments on the southeastern valley wall to have formed during different phases of the debris avalanche. The high lineament was produced by the energetic and mobile front of the water-rich phase of the debris avalanche. The intermediate line is slightly younger and associated with barrier emplacement (Fig. 6B). The lowest line marks the trace of the valley-confined flowing mass—the water-poor phase—that reached Lillooet River valley.

Area 2: Terrace

The terrace (area 2 in Figs. 1 and 2) is located on the northwestern side of Meager Creek. It lies ~60–100 m above the valley floor and is underlain by glacial sediments. Remnants of two Holocene fans overlie the terrace at the mouth of Capricorn Creek. Both of the fans, and the terrace itself, were incised by Capricorn Creek sometime during the Holocene. The modern pre-2010 Capricorn Creek fan is inset into the terrace. Part of the frontal wave of the debris avalanche ran up onto the terrace northeast of Capricorn Creek after being deflected off of the valley wall in area 1. It removed second-growth forest on the terrace and left a veneer of debris. We recognize three subareas of area 2: (1) the Capricorn Creek fan, (2) the terrace tread, and (3) the terrace scarp.

The Capricorn Creek fan subarea is characterized by two fan levels, both of which are inset into the terrace. The lower fan surface is 20 m above the floor of Capricorn Creek and extends ~250 m up Capricorn Creek and 160 m down Meager Creek. The higher fan surface is 60 m above the floor of Capricorn Creek and extends 200 m down Meager Creek. Two units, *a* and *b*, of landslide debris are present within the Capricorn Creek fan (Fig. 7A). Unit *a* occurs in what Guthrie et al. (2012) termed "the spray zone", a discontinuous veneer of silt, sand, and gravel within an area of stripped and damaged trees at the limit of the debris avalanche. Unit *b*, which borders unit *a*, is a blanket of mixed-facies material with a surface characterized by up to 1-m-high compressional ridges and longitudinal and transverse ridges. Unit *b* has three lobes; the first (*b1*) is a major northwest-southeast–trending debris ridge parallel to the terrace scarp on the northeastern side of Capricorn Creek. It is 220 m long, 25 m wide, and 2 m high. The second lobe (*b2*) is associated with an east-west–oriented fold that is 70 m wide and 100 m long. This lobe contains an east-west ridge that is 10 m wide, 80 m long, and 0.5 m high. A third debris lobe (*b3*) overlaps lobes *b1* and *b2* and is parallel to and near the edge of the terrace.

The second subarea of area 2—the terrace tread—extends ~600 m along Meager Creek valley. It is up to 200 m wide and 60–80 m above the valley floor. The tread is dissected by five gullies that are older than the landslide (Fig. 2). Two units of landslide debris (*a* and *b*), similar to those present in the Capricorn Creek fan, are present here (Fig. 7B). Unit *a*, located between the undamaged forest and unit *b*, comprises a thin **[[layer of?]]** discontinuous debris within a zone of stripped and damaged vegetation up to 30 m wide. Downed tree stems at the margin of the deposit indicate the direction of flow, which is slightly transverse to the trend of the limit of the landslide. Lobes of debris entered the forest obliquely to the main flow direction. Unit *b* sharply borders unit *a* along a front 0.5–1 m high and comprises scattered block facies hummocks within a blanket of mixed facies up to 1.5 m thick. Compressional ridges 10–20 m long, 1–8 m wide, and up to 0.5 m high are parallel to the valley side. The hummocks are up to 12 m in diameter and 2.5 m high. Some of the hummocks have extensional grabens and partially collapsed sides. The boundary between units *a* and *b* at the downstream end of the terrace coincides with a concentration of altered blocks and sheared block facies streaks.

A thin veneer of mixed-facies debris covers the third subarea of area 2—the terrace scarp. Two lineaments are present on the scarp and are parallel to its margin (Fig. 7C). The higher lineament, which is about one-third of the vertical distance below the top of the terrace, slopes down-valley and merges with the valley floor at the end of the terrace. It is continuous with lobe *b3* in the Capricorn fan area and extends up the largest upstream gully dissecting the terrace. The lower lineament is ~5 m above the valley floor. The two lineaments merge at the down-valley end of the scarp.

Interpretation. The many units and debris lines present in this area indicate that the terrace records different landslide pulses. In the terrace fan, unit *a* and lobe *b1* are traces of the flow coming down Capricorn Creek before reaching the Meager Creek valley side. Unit *a* is the deposit of the frontal highly mobile flow (water-rich phase) while *b1* is of the less-mobile debris-rich flow (water-poor phase). Lobes *b2* and *b3* are the deposits of different pulses of the flow after the impact on the southeastern wall of Meager Creek valley. Then**[[Following deposition of the lobes?]]** the debris avalanche overrode the terrace tread and scarp. On the terrace tread, unit *a* is the expression of the frontal water-rich phase, and unit *b* is the deposit of an intermediate-water-content phase. Unit *b* on the terrace tread was water-rich enough to run over the terrace but could still support structures and hummocks. It is continuous with *b2* on the terrace fan. The debris lines on the terrace scarp correlate with pulses of the water-poor phase.

The upper debris line is continuous with lobe *b3* and marks the maximum thickness of the water-poor material responsible for the plug deposit (see below); the lower line records the tail of the flow, or a surge related to the final "aftershock" collapse at the headwall of the landslide.

Area 3: Plug

The plug is in the center of the Meager Creek fan in Lillooet River valley (area 3 in Figs. 1 and 2). It has a triangular shape and is ~1200 m long and 100–500 m wide. Debris of the 2010 landslide in this area is up to 15 m thick. Lateral lobe wings and late-stage slurries were present along the external margins of the lobes but were removed by the dam-breach flood.

The plug is composed of block, sheared block, and mixed facies, with lithologic zoning resulting from the disaggregation of blocks into long tails, streaks, and discrete zones of sheared block facies. Hummocks are common and are 1–8 m high, 1–20 m wide, and 1–40 m long; they have volumes of 1–1.9 × 10^3 m^3. Low areas between hummocks exhibit deformation structures including shear zones, ridges, grabens, and lobes.

The west end of the plug, where Meager Creek enters Lillooet River valley, is characterized by collapsed hummocks, thrust and strike-slip faults, and well-developed grabens. Compressional features are cut by shear structures that are, in turn, cut by extensional structures (Fig. 8).

Farther east, toward the center of the plug area, the deposit is characterized by flow-parallel strike-slip faults. The faults are dextral and oriented southwest-northeast on the north side of the plug, and sinistral and oriented west-east on the south side. Grabens transverse to the flow direction have northwest-southeast orientations (Fig. 8). Strike-slip faults occur in areas of ridges, depressions, and sheared hummocks and mark the boundaries between the central part and the lateral parts of the debris avalanche that continued to flow to the east.

Two distal debris lobes extend from the main mass of debris and terminate on the Lillooet River floodplain with sharp fronts 7–10 m high, forming the east edge (front) of the plug. The point where the two lobes separate is 620 m from the west end of the plug. The more northerly lobe is 500 m long and up to 330 m wide. The southerly lobe is 450 m long and up to 150 m wide. The northern lobe is characterized by en echelon sigmoidal ridges, bounded by shear zones that accommodated the deformation at the point of bifurcation. The distal front of the lobe is marked by compressional ridges oriented northwest-southeast and northeast-southwest that terminate against and partially overtop hummocks. The north margin of the lobe is characterized by a system of dextral strike-slip faults spaced 30–50 m apart and oriented southwest-northeast. They displace hummocks and form pull-apart basins and push-up landforms. The strike-slip faults separate steps and drop down to the north-northwest.

In the southern lobe, the flow direction changes from southeast to east, then to the northeast. Strike-slip faults on the north side of this lobe are sinistral; those on the south side are dextral (Fig. 8). The area between the two lobes has an irregular surface morphology, which we attribute to compression and thrusting by the debris flowing around it; some dead trees are still standing in this area.

In photos taken the morning after the landslide (Fig. 3E) and before the breach of the Meager barrier, fluid slurries are visible at the margins of the plug. Muddy after flow**[[afterflow?]]** continued from the Capricorn Creek valley for days after the event as loose debris was eroded and flushed downstream by the creek.

Interpretation. The hummocks are rigid portions of the landslide mass that commonly slowed and came to rest sooner than the surrounding material. This is evidenced by flow structures and spreading and extension of some hummocks in the flow direction. As the hummocks were carried, rotated, and tilted by the flowing mass, they were also deformed, fractured, and disaggregated. Mixed material wraps around individual hummocks.

Discrete faults, shear zones, pull-apart basins, and push-up structures are evidence of the dynamic interactions between different parts of the flowing mass. Cross-cutting relations between faults indicate multiple generations of deformation structures. Differential movement of the debris led to localized compressional, extensional, and transtensional stresses. Extensional structures are dominant at the west end of the plug, where they cut thrust and strike-slip faults. Strike-slip structures are dominant in the central part of the plug, cutting and displacing thrusts. Later normal faults are also present in this area, providing evidence for a change from a compressional to an extensional regime. The plug front to the east is dominated by thrust faults, reflecting the compressional regime in the area. There is no evidence of a highly mobile water-rich phase extending beyond the steep leading east edge. This may be related to different trajectories of the frontal wet-phase and the subsequent dry-phase flows, with the former caroming more as it traveled down Meager Creek and the latter being more valley confined.

Geometrical patterns and kinematic indicators allow a possible reconstruction of the deformation history of the debris in the plug area (Supplemental File 8[8]). Primarily, compression dominated as debris, flowing in a single direction, rapidly decelerated at the flow front. Then, the debris started to flow in several different directions while decelerating at different rates. Lateral margins of the plug continued to move and deposit debris downstream in areas 4 and 5. Strike-slip faults formed to accommodate the deformation. Finally, the debris mass stopped and there was a general spreading and relaxation, with normal faults forming over the entire surface. The later slurries indicate that after the emplacement of the plug material, water remobilized part of the debris.

Area 4: Distal Zone Up-Valley of the Campsite ("Distal Up")

Area 4 encompasses the marginal zone of the landslide between Lillooet River and the unaffected forest to the east, and is northwest of the **[[unaffected?]]** British Columbia Forest Service campsite.**[[Give more detail on where the campsite is located]]** The distal-up area is 470 m wide and 450 m long (area 4 in Figs. 1 and 2). The maximum thickness of the debris is 4 m. Piles of trees up to 3 m high form the eastern edge of the landslide. Lillooet River sediments were entrained by the landslide in this area. The most distinctive feature in area 4 is a 2.5–4-m-high scarp, which marks the underlying, pre-landslide east bank of Lillooet River.

Two units of landslide debris are present in the distal-up area (Figs. 9A and 9B). Unit *a* is <1 m thick and consists mainly of mixed and woody debris facies, but includes hummocks of both block and entrained facies that were bulldozed to the margin of the deposit (Fig. 9A). Tree stems are oriented orthogonal to the flow direction and are in contact with standing, abraded, and tilted trees. At the river edge, entrained fluvial sediment was bulldozed into compressional ridges and hummocks.

Unit *b* is thicker and comprises debris similar to the deposits that form the plug, with meter-high hummocks and compressional ridges (Fig. 9A). In the northwestern part of area 4, unit *b* can be further subdivided into two different subunits. One has compressional ridges up to 3 m high and 20 m long and is in contact with the buried bank of Lillooet River. The other, which laps onto the first, has subdued ridges and lobes and some faults. Unit *a* flowed onto the terrace on which the Forest Service campsite is located, whereas unit *b* was stopped by it (Fig. 9B).

Moving downstream (southeast) in area 4, a fan-shaped lobe of thick debris covers the terrace and terminates in a 3–4-m-high front that is in contact with standing trees. Some trees were pushed forward and tilted back into the debris field by this lobe.

Further downstream, at the southeastern end of area 4, Lillooet River has eroded the terrace to form a new bank. The contact between the river sediments and the landslide debris is exposed in the riverbank, and here the debris is 0.5–2 m thick.

Interpretation. The deposit in area 4 reflects interactions with preexisting topography and different flow rheologies. The riverbank divided the flow in two: the water-rich phase (unit *a*) ran up over the bank, whereas the water-poor debris (unit *b*) was largely redirected and channeled by the bank. At the downstream end of area 4, unit *b* is in contact with, and laps onto, unit *a*.

The debris avalanche displaced Lillooet River water in area 4. Thus the fluid front is well developed here, extending as much as 180 m beyond the dense deposit. Eyewitnesses described a rush of muddy water along the logging road behind the campsite associated with this phase of the landslide (Guthrie et al., 2012).

Area 5: Distal Zone Down-Valley of the Campsite (“Distal Down”)

Area 5 is the most distal part of the landslide, located southeast (downstream) of the Forest Service campsite and extending from Lillooet River to the undisturbed forest on the east. The distal-down area is ~1000 m wide and 350 m long (area 5 in Figs. 1 and 2). The deposit thickness decreases from ~5–7 m to zero toward the direction of flow.

We recognize two main depositional units (*a* and *b*) in area 5 (Figs. 10A and 10B). Unit *a* is the transition from a zone of dead drowned trees into woody debris and then sparse debris, and small hummocks.**[[Clarify whether this refers to transition into sparse debris and also into**

small hummocks, or means that the deposit also contains small hummocks (apart from the "transition" description)]] In unit *a*, the number of standing trees decreases inward toward unit *b*. Some trees are tilted and their stems abraded to heights of 6 m, with pebbles and cobbles embedded in the wood. The zone of dead drowned trees with no debris (Fig. 10A) is 500 m wide and up to 200 m long with respect to the northeastern flow direction. An accumulation of woody debris, which lies west of the zone of dead trees, is up to 6 m thick and has a width of 8–100 m. Still further west is an area of discontinuous debris with small (1–9 m^3) hummocks of block and entrained facies and sparse tree stems (Fig. 10B). The debris in this area occurs in several lobes, the largest of which is 20–180 m wide

Unit *b* is a deposit of hummocky debris up to 7 m thick. It extends as much as 150 m outward (northeast) from Lillooet River (Fig. 10A). The hummocks are mainly block facies and have volumes of 100–120 m^3 (Fig. 10B). Areas between hummocks have a slightly ridged morphology, but the structure is not well expressed. This unit laps onto unit *a*; locally the two are separated by a scarp ~2 m high.

Interpretation. The deposits in area 5 record a succession of events. A flood of water-rich material arrived first. It inundated the forest at the distal margin of the debris avalanche and left a frontal log jam and, just behind it, a zone of small hummocks (unit *a*). Water-poor debris arrived next, depositing unit *b* against the water-rich deposits. As was the case in area 4 upstream of the campsite, the front of the debris avalanche incorporated or displaced water from Lillooet River, sending unit *a* as much as 350 m beyond the limit of the denser material.

DISCUSSION

Detailed study of the facies and surface morphology of the 2010 Mount Meager debris avalanche allows us to infer emplacement mechanisms, the relative timing of phases, and flow rheology. The structure and form of the deposit differ along the landslide path, providing information on transport and depositional processes and the evolution of the debris avalanche. Our interpretation of the flow dynamics and flow separation are presented below, along with their hazard implications.

Lithology and Grain Size

The lithology of the landslide debris provides insight into its depositional processes. The distribution of altered material is particularly instructive. Altered materials are associated with block facies and sheared block facies streaks. Altered block and sheared block facies are more common at the downstream end of the plug than at the upstream end. Mud balls and altered sheared block facies streaks were also noted along the downstream margin of the terrace area. Conversely, the Meager barrier has less debris of the altered block and sheared block facies; it is primarily composed of very large gray porphyritic rhyodacite blocks within mixed material. We infer that this lithological zoning reflects the structure of the original rock mass in the source area: hydrothermally altered rock at the base of the source scarp and fresh rock typical of the volcanic plug higher up on the scarp.

The mixed material is dominantly silty clayey sand with clay percentages ranging from 5% to 8%. Altered sheared block facies samples may have up to 30% clay, whereas the fresh unaltered sheared block facies is 2%–5% clay (Fig. 4). The average clay content by facies is 6.1% mixed, 24.6% altered block, and 3.6% pulverized block. A mixing ratio of 12% altered to 88% pulverized is required to get 6.1% clay in the mixed facies. This simple analysis suggests that ~12% of the failed rock mass was hydrothermally altered. Furthermore, within the mixed material there is no apparent trend in the mean**[[mean clay content?]]** from upstream to downstream, suggesting that the material became well mixed as it traversed Capricorn Creek.

Rheology Phases

There is evidence of multiple pulses of flow of diminishing magnitude **[[over time?]]**, but the deposits can be generally classified into two main rheology types: water poor and water rich (Fig. 11). These two rheology types are, in reality, end members in what was a continuum. The water-poor end member produced thick debris avalanche–like deposits, with abundant large hummocks. Kinematic structures reveal sequential movement related to pulses in the emplacement process (Fig. 12A). The water-rich end member is responsible for a flood-like deposit with sparse tree stems amid standing trees with meter-high splash lines and trunk erosion, and has no significant lithic debris (Fig. 12B). This end member, however, transitions into woody debris, which in turn transitions into an area with hummocks morphologically similar to **[[those of the?]]** debris flow and hyperconcentrated flow deposit**[[deposits?]]**. Structural discontinuities, including faults, shear zones, and compressional ridges, delineate zones with distinct internal morphological characteristics that are related to one of the two end members. However, the boundaries between these deposits are not everywhere sharp, suggesting gradual phase transitions (areas 4 and 5). Distinct debris lines indicate multiple pulses (areas 1 and 2) with different rheologies.

The water-rich phase is evident along the margins of the debris avalanche deposit, except at the front of the plug area. Water-rich flow deposits are overlain by, but extend beyond, the deposits of the water-poor phase. In the plug area (area 3), the debris terminates with a sharp front and there is no evidence of a leading water-rich phase, suggesting that the two phases followed different trajectories as they entered the Meager Creek–Lillooet River confluence area

The two phases had different velocities and different paths that were controlled by the complex topography over which the debris avalanche traveled. The sinuous longitudinal form of

Capricorn Creek valley (Fig. 1) resulted in centripetal and centrifugal forces that generated a marked separation of debris. The water-rich phase accelerated, achieving higher velocities and thus reaching farther up the valley sides, while the less-mobile water-poor core moved along the valley bottom. These differences in trajectory led to different deposits along Meager Creek and in Lillooet River valley.

Our evidence suggests that the water-rich phase preceded the water-poor phase, in contrast with the conclusion of Guthrie et al. (2012) that a first, drier front came to rest in the plug area ~10 km from the source area and "…was later passed by wetter deposits that flowed further"**[[Provide page number for quotation]]**. A water-rich phase followed by a water-poor phase is not unusual in debris flows and debris avalanches (cf. Oso landslide, Washington, USA; Iverson et al., 2015).

However, the water-rich slurries at the west end and margins of the plug suggest that some water-rich flows followed the emplacement of the plug. Copious water may have flowed from the source scar and remobilized part of the newly deposited material after the plug came to rest. It is thus difficult to distinguish a fluid tail contemporaneous with the debris avalanche from secondary debris mobilization by water flowing down Capricorn Creek.

Summary of the Event

Figure 13 summarizes our view of the 2010 Mount Meager debris avalanche in terms of rheology and velocity from its beginning to its end. The *x*-axis in the figure is the proportion of water and sediment in the flow, from debris avalanche to clear-water flood; the *y*-axis indicates both the strain rate and velocity. The different fields are based primarily on morphology. We postulate four stages in this history:

[[Format stages as bulleted (or numbered) list]]Stage 1. The south flank of Mount Meager failed following infiltration of water generated by snowmelt and permafrost thaw into hydrothermally altered rock and colluvium on the lower part of the slope. In the first several seconds, the collapsed material behaved as a single mass and the motion was relatively slow, with an average speed of 4 m/s (Allstadt, 2013) (Fig. 14A).

Stage 2. The failed mass accelerated rapidly, disaggregated, and spread as it started to flow down the valley of Capricorn Creek. High water pressure caused liquefaction and forced the water upward and outward, creating a mobile, water-rich frontal flow (Fig. 14B).

Stage 3. The water-rich flow accelerated and superelevated at the bends in Capricorn Creek valley, causing the high runups documented by Guthrie et al. (2012). It entered Meager Creek valley slightly in advance of the slower water-poor flow. Both ran up the opposing valley wall and turned back toward the opposite side of the valley. The water-rich phase split in two lobes (Fig. 14C). One lobe overrode the terrace (area 2) and then flowed back toward Meager Creek to affect area 5 down-valley of the Forest Service campsite. A second lobe was deflected by the terrace and followed a straight trajectory to area 4 up-valley of the campsite. Both lobes decelerated, leaving thin debris, small hummocks, and standing water, indicative of further flow separation. The most distal deposit of the water-rich phase in areas 4 and 5 shows evidence of extreme water content as the flow displaced and incorporated water from Lillooet River.

Stage 4. After impacting the southeast wall of Meager Creek valley, the water-poor phase deposited thick debris in the Meager Creek–Lillooet River confluence area (Fig. 14D). During final emplacement, it separated into three lobes: a central, less mobile one (area 3) and two lateral wings that flowed farther, crossing Lillooet River and leaving the water-poor deposits in areas 4 and 5. As the water-poor phase decelerated and came to rest, it developed ductile-brittle deformation structures. It did not travel as far as the water-rich phase.

Although the water-rich and water-poor phases had different trajectories due to their differences in volume and velocities, they did not behave totally independently. The presence of intermediate deposits suggests that they interacted. Furthermore, their separation in time was minor, perhaps only seconds.

The scenario outlined above is consistent with an analysis of seismic records of the landslide by Allstadt (2013). She concluded that "there is a hint of what could be interpreted as two separate surges visible in the vertical component of the force-time function. The vertical component of the force...has a shorter duration than the eastward component and is followed by a second smaller upward pulse."**[[Provide page number(s) for quotation]]** The multiple debris lines on the valley sides, however, suggest more than two surge waves; some may not have been large enough to generate clear seismic signals.

Hazard Implications

Transformation of a dry debris avalanche into a saturated debris flow has been inferred for many events (Palmer and Neall, 1989; Vallance and Scott, 1997; Capra and Macias, 2002**[[2000 to match reference list entry?]]**; Scott et al., 2002; Tost et al., 2014). In the case of the Mount Meager event, the transformation was partial, and multiple rheologies coexisted, with different mobilities, velocities, and trajectories. Our observations show that debris avalanches can be multiphase events with debris avalanche, debris flow, hyperconcentrated flow, debris flood, and flood-like components or phases (Fig. 13). This complexity may be more common than presently thought and may apply to other debris avalanche events. Here, different rheologies were clearly expressed in the deposit textures because the high sinuosity of the valley caused extreme separation of water-rich and water-poor phases. Also, the photo documentation immediately after the event allowed us to differentiate ephemeral water-rich deposits and flow traces that are not preserved in older events.

Numerical modeling of debris avalanches takes into account only dry granular material (Pudasaini and Hutter, 2003; Zahibo et al., 2010), and the models typically are single phase (Takahashi, 2007; Pudasaini, 2011). Only simplified, two-phase models traditionally are used for debris flows (Iverson, 1997; Pudasaini et al., 2005; Jakob et al., 2013). Recently, Pudasaini (2012) and Pudasaini and Krautblatter (2014) have proposed a more complete two-phase model for debris flows and debris avalanches that simulates the separation of a fluid front, drier core, and fluid tail.

The complexity of the 2010 Mount Meager debris avalanche highlights the difficulties of modeling such events and assessing the risk they pose to down-valley populations and infrastructure. The separation of water-poor and water-rich phases in complex topography has to be simulated to reproduce the different deposit types and the runout of each phase.

SUMMARY AND CONCLUSIONS

Field evidence and detailed geomorphic mapping of the 2010 Mount Meager landslide allowed us to document the development of multiple rheology phases with different mobilities and trajectories. As the collapsed mass disaggregated and started to flow along Capricorn Creek, it separated into a faster water-rich phase and a slower water-poor phase. The water-rich phase caromed down Capricorn Creek, ran high up the southeastern wall of Meager Creek valley, and overtopped a terrace on the opposite side of the valley, while the water-poor phase was more confined to the valley floor. The shapes of Capricorn and Meager Creek valleys contributed to the phase separation and deposit emplacement. The water-rich phase left the most distal deposit, but its deposit is not observed everywhere at the distal margin because the flow separated and was deflected by the topography. The less-mobile, water-poor phase left a continuous deposit.

Lithological zones in the deposit preserve the original distribution of rock in the source area, with hydrothermally altered rock derived from the base of the scar reaching the distal limit of the debris avalanche and gray rhyodacite rock higher on the flank of Mount Meager dominating more proximal deposits. Grain-size analysis and rough mixing estimates suggest that ~12% of the failed rock mass was hydrothermally altered.

Finally, this event raises new challenges for multi-rheology phase modeling of debris avalanches and hazard mapping. There were no fatalities in this particular event, but lack of understanding of the complex behavior of such landslides could result in inaccurate hazard assessment, placing populations at risk from catastrophic rock slope failures.

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FIGURE CAPTIONS

Figure 1. Mount Meager area (British Columbia) (geology after Read, 1978), margins of the Mount Meager A.D. 2010 landslide, and the five deposit areas discussed in the paper. The locations of the lithology transects are shown by red lines. Inset map shows the location of the study area in western Canada (BC—British Columbia).**[[Explain (or delete?) “P9” and “P8”, and explain what is meant by “2 hr dam” and “19 hr dam”]] [[In the figure, change**

“Capricorn Valley” to “Capricorn Creek valley”, “Meager Valley” to “Meager Creek valley”, and “Lillooet valley” to “Lillooet River valley”; change “2h” and “19h” to “2 hr” and “19 hr”; change “run up” to “runup”; in the symbol explanation, capitalize “Breccias” and change “flows” to “flow”]]

Figure 2. Map of Mount Meager landslide deposits and structures. Also shown are locations of photographs in other figures. Numbers in circles identify the five deposit areas.**[[In the figure, change “Capricorn Valley” to “Capricorn Creek valley”, “Meager Valley” to “Meager Creek valley”, and “Lillooet Valley” to “Lillooet River valley”]]**

Figure 3. Photographs of typical Mount Meager landslide deposit facies. White arrows indicate flow direction. (A) Block facies. (B) Contacts between mixed facies (a), sheared block facies of gray rhyodacite (b), and sheared block facies of red rhyodacite (c).**[[Give length of hammer]]** (C) A coherent but highly brecciated block (a) disaggregated by shear to form sheared block facies (b). The surrounding material is mixed facies (c). (D) Woody debris facies. (E) Aerial photograph of the debris avalanche deposit in Lillooet River valley taken the morning after the event, before the dam on Meager Creek breached (photo courtesy of D.B. Steers).

Figure 4. Sand-silt-clay ratios of samples of the Mount Meager debris avalanche matrix.**[[Provide a reference for the fields in the diagram?]]**

Figure 5. Photographs of typical structures in the Mount Meager landslide debris. White arrows indicate flow direction. (A) Compressional ridges (hammer**[[Give hammer length]]** for scale). The black lines show thrusts separating compressional ridges of gray rhyodacite and cream-colored, altered sheared block facies. (B) Panoramic view of a shear zone (circled person for scale). The red line marks a strike-slip fault; the white dotted lines highlight lithological markers that show the displacement along the fault. A graben is visible in the foreground. (C) View down

Lillooet River valley showing extensional features in the plug; normal fault scarps are indicated by white lines. The graben in front of the circled standing person is perpendicular to the flow direction. Note the runup on the valley side. (D) Normal fault trace exposed in section.**[[Explain the dotted white line, and provide indication of scale]]**

Figure 6. (A) Sketch of the Meager Creek barrier**[[Meager barrier, as worded throughout the text?]]** based on a photograph taken before the dam breach, showing compression. (B) Sketch of the barrier area after the dam breach. The limit of the debris avalanche and lower debris lines on the valley side are marked: 1—high lineament caused by runup of the first pulse; 2—debris line left by the bulk of the mass flowing toward Lillooet River valley; 3—debris line left by runup and collapse of Meager barrier debris. Arrows indicate the direction of movement. Photos courtesy of D.B. Steers.**[[In the figure, change "Capricorn Valley" and "Meager Valley" to "Capricorn Creek valley" and "Meager Creek valley"]]**

Figure 7. (A) Orthophoto of the Capricorn Creek fan (Mount Meager landslide area), showing unit *a* and unit *b* (the latter a product of three lobes: *b1*, *b2*, and *b3*). (B) Orthophoto of the central portion of the terrace tread showing unit *a* (water-rich flow deposit) and unit *b* (intermediate-water-content phase) supporting hummocks,**[[Comma confuses the meaning – are deformation structures associated with "unit *b* supporting…" or with "central portion of the terrace tread showing…"?]]** and deformation structures. Ridges indicate compressional motion against the valley side. (C) Panoramic view of the terrace scarp, debris trimlines, and post-depositional sloughing (person in the circle at lower right for scale). Image courtesy of C.-A. Lau. **[[In the figure, change "Capricorn Valley" and "Lillooet Valley" to "Capricorn Creek valley" and "Lillooet River valley"]]**

Figure 8. Orthophoto of the plug area, Mount Meager landslide. Structures indicate different stress regimes: extension (light blue) at the west corner of the plug; shear (purple) in the central part and at the sides; and compression (red) at the front and between the two lobes. Box indicates location of Supplemental File 8 (see footnote 8), which shows structures and deformation sequence~~ (Supplementary File 8 [see footnote 8])~~.**[[In the figure, change “Centre” to “Center”]]**

Figure 9. (A) Orthophoto of the distal part of the Mount Meager landslide deposit upstream of the unaffected Forest Service campsite (area 4), showing units *a* and *b*. Location of B is shown. (B) Partially buried terrace scarp showing the boundary between units *a* and *b*.

Figure 10. (A) Orthophoto of the distal part of the Mount Meager landslide deposit downstream of the unaffected Forest Service campsite (area 5) showing units, hummocks, shear zones, and the direction of movement. Location of B is shown. (B) Contact between thick hummocky debris (unit *b*) and the discontinuous debris veneer with small hummocks (unit *a*).

Figure 11. Top: Summary sketch map showing the distribution of water-rich and water-poor deposits of the Mount Meager landslide. Bottom: Flow chart summarizing the correlation between rheology phases, areas, and deposits. The water-rich phase produced the high debris line at the Meager barrier and deposited unit *a* in the terrace, distal up, and distal down areas. There are no traces of the water-rich phase in the plug area. The water-poor phase produced the lower debris line at the Meager barrier and left the thick body of debris in that area. It left the debris lines on the terrace scarp and unit *b* (lobes *b1* and *b3*) on the terrace fan and in the distal up and distal down areas. The plug was also deposited by the water-poor phase. Unit *b* on the terrace tread and lobe *b2* on the terrace fan are interpreted as deposited by an intermediate-water-content

phase.**[[In the figure, lower panel, remove parentheses from lobe designations, change “run up” to “runup”, and capitalize “No” (in “No deposit due to variable trajectory”)]]**

Figure 12. Rheology end-member deposits, Mount Meager landslide. (A) Thick debris, hummocks, and faults of the water-poor phase in area 3. The red line marks strike-slip faults; the white dotted lines delineate block and sheared block facies. (B) Woody debris and dead trees of the water-rich phase downstream of the unaffected Forest Service campsite. White arrow indicates the direction of movement.

Figure 13. Conceptual diagram showing stages in the evolution of the Mount Meager debris avalanche. (1) The south flank of Mount Meager fails. (2) The rock mass breaks up, spreads, and liquefies as it begins to accelerate down Capricorn Creek valley. Water escapes from beneath the debris avalanche, forming the advance water-rich phase (blue line); the bulk of the mass, in comparison, is relatively dry (red line). Although the two phases interact, they follow different paths and leave separate deposits. (3) Both phases achieve very rapid velocities before impacting the south valley wall of Meager Creek. They decelerate as they spread up and down Meager Creek and into Lillooet River valley. (4) Final deceleration and cessation of flow.**[[In the figure, capitalize “Strain” and remove hyphen from “Strain rate”; correct the spelling of “hyperconcentrated”]]**

Figure 14. Schematic diagram showing the evolution of the Mount Meager debris avalanche with inferred rheological behavior. (A) At initiation, the collapsed material behaves as a single phase. (B) The water-rich phase forms as the debris avalanche moves down the valley of Capricorn Creek. Upon reaching Meager Creek, it runs 270 m up the south valley wall. (C) It then flows both up and down Meager Creek valley. (D) The water-rich phase travels farther than the water-

poor phase. The latter leaves a thicker deposit, which displays deformation structures that develop during final emplacement. d. aval.—debris avalanche; hyperc.—hyperconcentrated.