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

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(Article begins on next page)

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

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

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

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

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

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

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

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

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

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56 **ABSTRACT**

57 On 6 August 2010, a large (~50 Mm³) debris avalanche occurred on the flank of Mount
58 Meager in the southern Coast Mountains of British Columbia, Canada. We studied the deposits
59 to infer the morphodynamics of the landslide from initiation to emplacement. Structure from
60 motion (SfM) photogrammetry, based on oblique photos taken with a standard SLR camera
61 during a low helicopter traverse, was used to create high-resolution orthophotos and base maps.
62 Interpretation of the images and maps allowed us to recognize two main rheological phases in
63 the debris avalanche. Just below the source area, in the valley of Capricorn Creek, the landslide
64 separated into two phases, one water rich and more mobile, and the other water poor and less
65 mobile. The water-rich phase spread quickly, achieved high superelevation on the valley sides,
66 and left distal scattered deposits. The main water-poor phase moved more slowly, did not
67 superelevate, and formed a thick continuous deposit (up to ~30 m) on the valley floor. The

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

73 **INTRODUCTION**

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

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

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

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

107 **SETTING**

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

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

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

118 **Landslides on Mount Meager**

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

125 Evidence of active slope processes affecting the massif include sackungen, debris flows,
126 and debris and rock avalanches (Mokievsky-Zubok, 1977; Jordan, 1994; Bovis and Evans, 1996;
127 Jakob, 1996; Friele and Clague, 2004). In particular, Capricorn Creek, a tributary of Meager
128 Creek, was the source of debris flows and debris avalanches larger than 100,000 m³ in A.D.
129 1931, 1933–1934, 1944–1945, 1972, 1998, 2009, and 2010 (Carter, 1932; Jakob, 1996; Bovis
130 and Jakob, 2000; Guthrie et al., 2012). Using dendrochronology, Jakob (1996) extended the
131 historical record of landslides in the Meager Creek watershed to 330 yr ago. He identified 13
132 large debris flows and/or hyperconcentrated flows, an average of one event every 25 yr. These
133 landslides entered Meager Creek and caused significant channel aggradation and instability
134 downstream. Some of them also blocked Meager Creek, forming landslide-dammed lakes
135 (Mokievsky-Zubok, 1977; Bovis and Jakob, 2000; Guthrie et al., 2012). Very large collapses of

136 the flank of the massif have generated at least three Holocene debris flows that have traveled
137 downstream to presently populated areas in Lillooet River valley (Friele and Clague, 2004; Friele
138 et al., 2005; Simpson et al., 2006).

139 **The 2010 Event**

140 On 6 August 2010, the south flank and secondary peak (2554 m asl) of Mount Meager
141 collapsed, producing a long-runout debris avalanche (Guthrie et al., 2012) (Fig. 1). The collapse
142 evolved as several subfailures (Allstadt, 2013; Moretti et al., 2015). The debris accelerated to
143 speeds of 60–90 m/s as it traveled 7 km down Capricorn Creek to Meager Creek (Allstadt, 2013).
144 At the Capricorn Creek–Meager Creek confluence, the front of the debris sheet ran 270 m up the
145 opposing valley wall and split into two lobes, one of which ran ~3.4 km upstream and the other
146 4.7 km downstream to Lillooet River where it spread out over the valley floor before coming to
147 rest 2 km below the Meager Creek–Lillooet River confluence. Field evidence showed that some
148 deposition occurred along the entire travel path, but most of the debris was deposited at the
149 mouth of Capricorn Creek and in Lillooet River valley (Guthrie et al., 2012).

150 Guthrie et al. (2012) concluded that the 2010 landslide involved the failure of 48.5×10^6
151 m^3 of rock. It thus was similar in size to the A.D. 1965 Hope slide **[[Provide geographic**
152 **location]]** (Mathews and McTaggart, 1969; Bruce and Cruden, 1977) and almost twice the size
153 of the famous A.D. 1904 Frank slide **[[Provide geographic location]]** (Cruden and Krahn, 1973;
154 Cruden and Martin, 2007). The vertical elevation drop from the source area to the distal limit of
155 the debris (H) is 2185 m, and the total path length (L) is 12.7 km. These values yield a
156 fahrboschung (travel angle, $\tan H/L$) of 9.8° . The average velocity of the landslide was 45 m/s
157 (Allstadt, 2013). The landslide produced the equivalent of a M 2.6 local earthquake, with long-

158 period seismic waves that were recorded by seismometers as far away as southern California and
159 northern Alaska.

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

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

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

180 METHODS

181 **Photography and Structure from Motion**

182 To produce a base map for geomorphic mapping, we took oblique digital photos one year
183 after the landslide with a single lens reflex (SLR) camera during low-level helicopter flights over
184 the accumulation zone. The photos were processed using the SfM and multiview stereo (MVS)
185 algorithms (Snavely et al., 2008; James and Robson, 2012; Westoby et al., 2012; Fonstad et al.,
186 2013; Micheletti et al., 2015) to produce three-dimensional topographic models from which we
187 extracted a high-resolution orthophoto (0.08 m/pixel ground resolution) and a DEM (0.34
188 m/pixel ground resolution). Centimeter-size clasts are resolvable on the imagery.

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

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

198 **Field Mapping**

199 We produced a geomorphic map of the landslide deposits at a scale of 1:1000 from field
200 observations made between August and October 2012 and from the orthophoto and the DEM.
201 We identified and classified geomorphic features, facies, and related facies associations within
202 those parts of the deposit that had not been modified by erosion. For the purpose of discussion,

203 we subdivide the debris avalanche deposit below the mouth of Capricorn Creek into five areas
204 that we refer to as Meager barrier, terrace, plug, distal up, and distal down (Figs. 1 and 2).

205 **Grain-Size and Lithologic Analysis**

206 We chose four sample sites distributed along the length of the deposit from the Meager
207 barrier to the distal margin for grain-size and lithological analyses (Fig. 1). At each site, we
208 placed a 100 m tape parallel to the flow direction. Clast lithologies were recorded at 1 m
209 intervals along the tape and visually classified as basement rock (B), gray porphyritic felsic
210 rhyodacite (GPF), red porphyritic felsic rhyodacite (RPF), and other volcanic rocks (OV). “Other
211 volcanic rocks” include gray, red, and white aphanitic rocks, gray and cream colored porphyritic
212 rocks, and pumice. One-kilogram bulk samples were collected for grain-size analysis at stations
213 20, 40, 60, 80, and 100 m along the tape. For each of these samples, 100 of the largest clasts >4
214 mm retained from sieving were also lithologically classified. Ten other bulk samples were
215 collected from selected stations on the deposit, two from mixed debris and four each from
216 pulverized blocks and altered blocks.

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

222 **RESULTS AND DISCUSSION**

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

225 **Facies**

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

234 The **sheared block facies** is localized in shear zones within the block facies and occurs
235 as discrete zones or streaks of coherent lithology in the deposit. It is a product of fragmentation
236 and disaggregation of blocks by shear during the final stage of debris emplacement
237 (Supplemental Files 1¹ and 2²). The form of the block facies has been destroyed, but the
238 lithology of the source block has been retained. Streaks of sheared block facies define the
239 direction of movement of the debris avalanche (Figs. 3C–3E[[Do you mean 3C and 3E? Fig.
240 **3D appears to be a different facies (woody debris)]]).**

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

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

251 The **entrained facies** consists of fluvial channel or overbank sediments and colluvium
252 incorporated into the landslide by scour and thrusting. This facies is distinguished from others by
253 its well-sorted texture and rounded and subrounded clasts. The entrained facies is a minor
254 constituent of the landslide deposit (Supplemental File 3³).

255 **Structures**

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

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

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

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

268 **Hummocks**

269 Hummocks are 1–8 m in height, 1–40 m in length, and 1–30 m in width; volumes range
270 from 1 m³ to ~900 m³. Shapes are round or ellipsoidal. Hummocks are composed of block facies

271 (either gray or red porphyritic rhyodacite), entrained facies, or ~~are~~ a mix of block, mixed, and
272 sheared block facies.

273 Mixed hummocks typically have a core of block facies and sheared block facies and a
274 carapace of mixed facies (Supplemental File 4⁴). The boundary between the core and carapace is
275 sharp to gradational; in some cases **flame** structures intrude the core.

276 The entrained facies hummocks are composed of either fluvial sand and gravel or sand
277 (Supplemental File 5⁵). This hummock type is rare and found only at the distal margin of the
278 debris avalanche. The entrained facies hummocks are smaller than the block and mixed
279 hummocks, with a volume of ~1–3 m³.

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

281 ***Area 1: Meager Barrier***

282 The southeastern valley wall of Meager Creek, opposite the mouth of Capricorn Creek
283 (**area 1** in Figs. 1 and 2), was stripped of all trees up to 270 m above the valley floor by the
284 landslide. Only a patchy veneer of landslide debris remains on this slope. At the foot of the slope,
285 and extending across Meager Creek valley to the mouth of Capricorn **Creek valley**, is ~~a~~ thick
286 debris forming the barrier that dammed Meager Creek for 19 h. The Meager barrier deposit is
287 700 m long, 50–500 m wide (increasing in width from the apex to the southeastern side of the
288 valley), and ~30 m thick, thinning toward Capricorn Creek.

289 The barrier supports irregular ridges that are perpendicular to the flow direction (Fig.
290 6A). Seven major compressional ridges are present on the northwestern side of the barrier. In
291 contrast, the southernmost 200 m of the barrier surface, nearest the southeastern valley wall, is an
292 irregular hummocky deposit.

293 The compressional ridges are southeast verging and identified by a basal thrust. The
294 difference in height between each depression and the tops of adjacent ridges is as much as 12 m.
295 The ridges increase in length from 50 to 300 m in a northwest-southeast direction; the longest
296 ridges span the full width of the deposit. Streaks of sheared block facies trend parallel to the
297 ridges (Supplemental File 6⁶). Only a few blocks, in the form of low broad hummocks, rise
298 above the surface of the Meager barrier. Larger blocks (up to 900 m³) locally underlie the ridges
299 (Supplemental File 7⁷). We observed only a few altered blocks in this area.

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

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

310 *Interpretation.* **[[Should this be formatted differently (like a heading), or perhaps**
311 **punctuated or worded differently so it doesn't appear to be a heading? (all**
312 **“Interpretation” sections)]]** The front of the debris avalanche swept across Meager Creek and
313 ran up the southeastern wall of the valley, completely removing the forest and scouring the forest
314 floor. The maximum limit reached by the debris is marked by the conspicuous trimline high on
315 the valley wall. In the barrier deposit, the major compressional ridges formed at the foot of the

316 slope as the forward movement of the debris avalanche in this area was impeded and the debris
317 was compressed. The debris stopped first at its front while the back was still moving. We
318 interpret the Meager barrier deposit to be related to seismometer “signal H” of Guthrie et al.
319 (2012) and the “aftershock” of Allstadt (2013), **representing** a final summit collapse of the
320 secondary Mount Meager peak occurring ~2 min after the main event. The hummocks of gray
321 rhyodacite at the foot of the opposing slope are likely a product of runup and collapse of this
322 late-stage emplacement.

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

328 ***Area 2: Terrace***

329 The terrace (area 2 in Figs. 1 and 2) is located on the northwestern side of Meager Creek.
330 It lies ~60–100 m above the valley floor and is underlain by glacial sediments. Remnants of two
331 Holocene fans overlie the terrace at the mouth of Capricorn Creek. Both of the fans, and the
332 terrace itself, were incised by Capricorn Creek sometime during the Holocene. The modern pre-
333 2010 Capricorn Creek fan is inset into the terrace. Part of the frontal wave of the debris
334 avalanche ran up onto the terrace northeast of Capricorn Creek after being deflected off of the
335 valley wall in area 1. It removed second-growth forest on the terrace and left a veneer of debris.
336 We recognize three subareas of area 2: (1) the Capricorn Creek fan, (2) the terrace tread, and (3)
337 **the** terrace scarp.

338 The Capricorn Creek fan subarea is characterized by two fan levels, both of which are
339 inset into the terrace. The lower fan surface is 20 m above the floor of Capricorn Creek and
340 extends ~250 m up Capricorn Creek and 160 m down Meager Creek. The higher fan surface is
341 60 m above the floor of Capricorn Creek and extends 200 m down Meager Creek. Two units, *a*
342 and *b*, of landslide debris are present within the Capricorn Creek fan (Fig. 7A). Unit *a* occurs in
343 what Guthrie et al. (2012) termed “the spray zone”, a discontinuous veneer of silt, sand, and
344 gravel within an area of stripped and damaged trees at the limit of the debris avalanche. Unit *b*,
345 which borders unit *a*, is a blanket of mixed-facies material with a surface characterized by up to
346 1-m-high compressional ridges and longitudinal and transverse ridges. Unit *b* has three lobes; the
347 first (*b1*) is a major northwest-southeast-trending debris ridge parallel to the terrace scarp on the
348 northeastern side of Capricorn Creek. It is 220 m long, 25 m wide, and 2 m high. The second
349 lobe (*b2*) is associated with an east-west-oriented fold that is 70 m wide and 100 m long. This
350 lobe contains an east-west ridge that is 10 m wide, 80 m long, and 0.5 m high. A third debris lobe
351 (*b3*) overlaps lobes *b1* and *b2* and is parallel to and near the edge of the terrace.

352 The second subarea of area 2—the terrace tread—extends ~600 m along Meager Creek
353 valley. It is up to 200 m wide and 60–80 m above the valley floor. The tread is dissected by five
354 gullies that are older than the landslide (Fig. 2). Two units of landslide debris (*a* and *b*), similar
355 to those present in the Capricorn Creek fan, are present here (Fig. 7B). Unit *a*, located between
356 the undamaged forest and unit *b*, comprises a thin **[[layer of?]]** discontinuous debris within a
357 zone of stripped and damaged vegetation up to 30 m wide. Downed tree stems at the margin of
358 the deposit indicate the direction of flow, which is slightly transverse to the trend of the limit of
359 the landslide. Lobes of debris entered the forest obliquely to the main flow direction. Unit *b*
360 sharply borders unit *a* along a front 0.5–1 m high and comprises scattered block facies

361 hummocks within a blanket of mixed facies up to 1.5 m thick. Compressional ridges 10–20 m
362 long, 1–8 m wide, and up to 0.5 m high are parallel to the valley side. The hummocks are up to
363 12 m in diameter and 2.5 m high. Some of the hummocks have extensional grabens and **partially**
364 **collapsed** sides. The boundary between units *a* and *b* at the downstream end of the terrace
365 coincides with a concentration of altered blocks and sheared block facies streaks.

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

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

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

387 ***Area 3: Plug***

388 The plug is in the center of the Meager Creek fan in Lillooet **River** valley (area 3 in Figs.
389 1 and 2). It has a triangular shape and is ~1200 m long and 100–500 m wide. Debris of the 2010
390 landslide in this area is up to 15 m thick. Lateral lobe wings and late-stage slurries were present
391 along the external margins of the lobes but were removed by the dam-breach flood.

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

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

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

407 Two distal debris lobes extend from the main mass of debris and terminate on the
408 Lillooet River floodplain with sharp fronts 7–10 m high, forming the east edge (front) of the
409 plug. The point where the two lobes separate is 620 m from the west end of the plug. The more
410 northerly lobe is 500 m long and up to 330 m wide. The southerly lobe is 450 m long and up to
411 150 m wide. The northern lobe is characterized by an echelon sigmoidal ridges, bounded by
412 shear zones that accommodated the deformation at the point of bifurcation. The distal front of the
413 lobe is marked by compressional ridges oriented northwest-southeast and northeast-southwest
414 that terminate against and partially overtop hummocks. The north margin of the lobe is
415 characterized by a system of dextral strike-slip faults spaced 30–50 m apart and oriented
416 southwest-northeast. They displace hummocks and form pull-apart basins and push-up
417 landforms. The strike-slip faults separate steps and drop down to the north-northwest.

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

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

427 *Interpretation.* The hummocks are rigid portions of the landslide mass that commonly
428 slowed and came to rest sooner than the surrounding material. This is evidenced by flow
429 structures and spreading and extension of some hummocks in the flow direction. As the

430 hummocks were carried, rotated, and tilted by the flowing mass, they were also deformed,
431 fractured, and disaggregated. Mixed material wraps around individual hummocks.

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

444 Geometrical patterns and kinematic indicators allow a possible reconstruction of the
445 deformation history of the debris in the plug area (Supplemental File 8⁸). Primarily, compression
446 dominated as debris, flowing in a single direction, rapidly decelerated at the flow front. Then, the
447 debris started to flow in several different directions while decelerating at different rates. Lateral
448 margins of the plug continued to move and deposit debris downstream in areas 4 and 5. Strike-
449 slip faults formed to accommodate the deformation. Finally, the debris mass stopped and there
450 was a general spreading and relaxation, with normal faults forming over the entire surface. The
451 later slurries indicate that after the emplacement of the plug material, water remobilized part of
452 the debris.

453 ***Area 4: Distal Zone Up-Valley of the Campsite (“Distal Up”)***

454 Area 4 encompasses the marginal zone of the landslide between Lillooet River and the
455 unaffected forest to the east, and is northwest of the **[[unaffected?]]** British Columbia Forest
456 Service campsite. **[[Give more detail on where the campsite is located]]** The distal-up area is
457 470 m wide and 450 m long (area 4 in Figs. 1 and 2). The maximum thickness of the debris is 4
458 m. Piles of trees up to 3 m high form the eastern edge of the landslide. Lillooet River sediments
459 were entrained by the landslide in this area. The most distinctive feature in area 4 is a 2.5–4-m-
460 high scarp, which marks the underlying, pre-landslide east bank of Lillooet River.

461 Two units of landslide debris are present in the distal-up area (Figs. 9A and 9B). Unit *a* is
462 <1 m thick and consists mainly of mixed and woody debris facies, but includes hummocks of
463 both block and entrained facies that were bulldozed to the margin of the deposit (Fig. 9A). Tree
464 stems are oriented orthogonal to the flow direction and are in contact with standing, abraded, and
465 tilted trees. At the river edge, entrained fluvial sediment was bulldozed into compressional ridges
466 and hummocks.

467 Unit *b* is thicker and comprises debris similar to the deposits that form the plug, with
468 meter-high hummocks and compressional ridges (Fig. 9A). In the northwestern part of area 4,
469 unit *b* can be further subdivided into two different subunits. One has compressional ridges up to
470 3 m high and 20 m long and is in contact with the buried bank of Lillooet River. The other,
471 which laps onto the first, has subdued ridges and lobes and some faults. Unit *a* flowed onto the
472 terrace on which the Forest Service campsite is located, whereas unit *b* was stopped by it (Fig.
473 9B).

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

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

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

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

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

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

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

497 **small hummocks, or means that the deposit also contains small hummocks (apart from the**
498 **“transition” description)]** In unit *a*, the number of standing trees decreases inward toward unit
499 *b*. Some trees are tilted and their stems abraded to heights of 6 m, with pebbles and cobbles
500 embedded in the wood. The zone of dead drowned trees with no debris (Fig. 10A) is 500 m wide
501 and up to 200 m long with respect to the northeastern flow direction. An accumulation of woody
502 debris, which lies west of the zone of dead trees, is up to 6 m thick and has a width of 8–100 m.
503 Still further west is an area of discontinuous debris with small (1–9 m³) hummocks of block and
504 entrained facies and sparse tree stems (Fig. 10B). The debris in this area occurs in several lobes,
505 the largest of which is 20–180 m wide

506 Unit *b* is a deposit of hummocky debris up to 7 m thick. It extends **as much as** 150 m
507 outward (northeast) from Lillooet River (Fig. 10A). The hummocks are mainly block facies and
508 have volumes of 100–120 m³ (Fig. 10B). Areas between hummocks have a slightly ridged
509 morphology, but the structure is not well expressed. This unit laps onto unit *a*; locally the two are
510 separated by a scarp ~2 m high.

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

517 **DISCUSSION**

518 Detailed study of the facies and surface morphology of the 2010 Mount Meager debris
519 avalanche allows us to infer emplacement mechanisms, the relative timing of phases, and flow

520 rheology. The structure and form of the deposit differ along the landslide path, providing
521 information on transport and depositional processes and the evolution of the debris avalanche.
522 Our interpretation of the flow dynamics and flow separation are presented below, along with
523 their hazard implications.

524 **Lithology and Grain Size**

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

535 The mixed material is dominantly silty clayey sand with clay percentages ranging from
536 5% to 8%. Altered sheared block facies samples **may** have up to 30% clay, whereas the fresh
537 unaltered sheared block facies is 2%–5% clay (Fig. 4). The average clay content by facies is
538 6.1% mixed, 24.6% altered block, and 3.6% pulverized block. A mixing ratio of 12% altered to
539 88% pulverized is required to get 6.1% clay in the mixed facies. This simple analysis suggests
540 that ~12% of the failed rock mass was hydrothermally altered. Furthermore, within the mixed
541 material there is no apparent trend in the mean[[**mean clay content?**]] from upstream to
542 downstream, suggesting that the material became well mixed as it traversed Capricorn Creek.

543 **Rheology Phases**

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

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

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

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

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

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

582 **Summary of the Event**

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

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

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

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

606 Stage 4. After impacting the southeast wall of Meager Creek valley, the water-poor phase
607 deposited thick debris in the Meager Creek–Lillooet River confluence area (Fig. 14D). During
608 final emplacement, it separated into three lobes: a central, less mobile one (area 3) and two
609 lateral wings that flowed farther, crossing Lillooet River and leaving the water-poor deposits in

610 areas 4 and 5. As the water-poor phase decelerated and came to rest, it developed ductile-brittle
611 deformation structures. It did not travel as far as the water-rich phase.

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

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

623 **Hazard Implications**

624 Transformation of a dry debris avalanche into a saturated debris flow has been inferred
625 for many events (Palmer and Neall, 1989; Vallance and Scott, 1997; Capra and Macias,
626 2002[\[\[2000 to match reference list entry?\]\]](#); Scott et al., 2002; Tost et al., 2014). In the case of
627 the Mount Meager event, the transformation was partial, and multiple rheologies coexisted, with
628 different mobilities, velocities, and trajectories. Our observations show that debris avalanches
629 can be multiphase events with debris avalanche, debris flow, hyperconcentrated flow, debris
630 flood, and flood-like components or phases (Fig. 13). This complexity may be more common
631 than presently thought and may apply to other debris avalanche events. Here, different rheologies
632 were clearly expressed in the deposit textures because the high sinuosity of the valley caused

633 extreme separation of water-rich and water-poor phases. Also, the photo documentation
634 immediately after the event allowed us to differentiate ephemeral water-rich deposits and flow
635 traces that are not preserved in older events.

636 Numerical modeling of debris avalanches takes into account only dry granular material
637 (Pudasaini and Hutter, 2003; Zahibo et al., 2010), and the models typically are single phase
638 (Takahashi, 2007; Pudasaini, 2011). Only simplified, two-phase models traditionally are used for
639 debris flows (Iverson, 1997; Pudasaini et al., 2005; Jakob et al., 2013). Recently, Pudasaini
640 (2012) and Pudasaini and Krautblatter (2014) have proposed a more complete two-phase model
641 for debris flows and debris avalanches that simulates the separation of a fluid front, drier core,
642 and fluid tail.

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

647 **SUMMARY AND CONCLUSIONS**

648 Field evidence and detailed geomorphic mapping of the 2010 Mount Meager landslide
649 allowed us to document the development of multiple rheology phases with different mobilities
650 and trajectories. As the collapsed mass disaggregated and started to flow along Capricorn Creek,
651 it separated into a faster water-rich phase and a slower water-poor phase. The water-rich phase
652 caromed down Capricorn Creek, ran high up the southeastern wall of Meager Creek valley, and
653 overtopped a terrace on the opposite side of the valley, while the water-poor phase was more
654 confined to the valley floor. The shapes of Capricorn and Meager Creek valleys contributed to
655 the phase separation and deposit emplacement. The water-rich phase left the most distal deposit,

656 but its **deposit** is not observed everywhere at the distal margin because the flow separated and
657 was deflected by the topography. The less-mobile, water-poor phase left a continuous deposit.

658 Lithological zones in the deposit preserve the original distribution of rock in the source
659 area, with hydrothermally altered rock derived from the base of the scar reaching the distal limit
660 of the debris avalanche and gray rhyodacite rock higher on the flank of Mount Meager
661 dominating more proximal deposits. Grain-size analysis and rough mixing estimates suggest that
662 ~12% of the failed rock mass was hydrothermally altered.

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

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874 **FIGURE CAPTIONS**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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