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Numerical modelling of slope damage in large, slowly moving rockslides: Insights from the Downie Slide, British Columbia, Canada

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Numerical modelling of slope damage in large, slowly moving rockslides: Insights from the Downie Slide, British Columbia, Canada.

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Abstract

The deformation of rock slopes is associated with the formation and accumulation of internal and external features (such as tension cracks, rock mass bulging and dilation, rockfall, etc.) that can be comprehensively referred to as “slope damage”. In this paper, we use a 3D distinct element numerical modelling approach to investigate the role of shear zone morphology and groundwater pressure on the displacement and slope damage accumulation at the

26 Downie Slide, a large, extremely slowly moving rockslide in British Columbia (Canada). First, we briefly review the
27 external slope damage features that can be observed in an airborne laser scanner (ALS) dataset, allowing four slope
28 damage domains (upper, central, northern, and southern domain) to be interpreted within the slide area, based on the
29 orientation and type of features. Using the same ALS dataset we construct a 3D model of the present-day slope,
30 explicitly including the two shear zones along which displacements occur, in order to investigate their role in the
31 later stage of the landslide evolution. We assign a strain-softening constitutive model to the slide body, in order to
32 account for the decrease in material properties due to damage accumulation. Virtual inclinometers are also
33 implemented in the model, allowing for the comparison of simulated and observed displacement direction along the
34 shear zones. The progressive deformation and failure of the slope is then simulated both assuming dry and wet
35 conditions, in order to examine the role of pore water pressure, and the morphology of the upper and lower shear
36 zones on the magnitude, orientation, and distribution of displacements. For each numerical model, the simulated
37 slope damage features are recorded, by analyzing the zone volumetric strain and failure state, and compared with the
38 type and orientation of features observed in each of the interpreted slope damage domains, thus allowing the
39 numerical results to be better constrained and validated. It is clearly demonstrated that the orientation and
40 distribution of slope damage and displacements observed in both the surface ALS and the subsurface borehole
41 inclinometer data can be well reproduced in the 3D numerical models. Numerical modelling results show that the
42 principal factor controlling the spatial distribution of slope damage at the Downie Slide is the morphology of the
43 lower shear zone, whereas a negligible role is played by the upper shear zone morphology. We also observe that
44 models incorporating a groundwater table display larger displacements, without significant effects on the orientation
45 and distribution of simulated slope damage. This paper demonstrates that an analysis of slope damage is very
46 important for understanding the mechanisms underlying the behavior of large landslides and should be a fundamental
47 step in the comprehensive characterization of any major slope failure.

48 **Keywords:** slope damage, Downie Slide, numerical modelling, distinct element method, airborne laser scanning

49

50 1 Introduction

51 The stability and evolution of high rock slopes is controlled by several important factors, including geologic
52 and lithological features that combine to define the global strength of a rock slope. Structural and lithological
53 features, such as faults, folds, rock mass jointing, foliation, and bedding may form release surfaces, along which
54 volumes of the rock mass may slide or detach (Saintot et al. 2011; Stead and Wolter 2015). Many major rockslides
55 have been at least partially controlled by inherited geological structures or lithology. The 1963 Vajont Slide
56 displaced on thin clay-rich layers along a structural, chair-shaped basal surface, and the failed volume was bounded
57 by persistent faults (Semenza and Ghirotti 2000). The failure of the 1965 Hope Slide was promoted by rock mass
58 jointing and structural damage associated with faults and shear zones (Brideau et al. 2005). Badger (2002) illustrated
59 the effects of fracturing in anticlinal folds on the stability of rock slopes, using conceptual drawings and field
60 observations, showing that tensile cracking, perpendicular to the rock mass bedding, may act either as basal or rear
61 rupture surfaces and provide kinematic freedom to potentially unstable blocks. An excellent example is represented
62 by the 1903 Frank Slide, in which basal and rear kinematic freedom was provided by geological structures associated
63 with the Turtle Mountain syncline (Humair et al. 2013). Structural material heterogeneities may also contribute to
64 define the style of deformation of large slope instabilities. Many active, slowly moving rockslides, such as the Aknes
65 Rockslide (Norway, Ganerød et al. 2008) and the Campo Vallemaggia rockslide (Switzerland, Bonzanigo et al.,
66 2007) are actively displacing along sliding surfaces parallel to foliation or schistosity. Structural and geological
67 features at various scales (ranging from significant tectonic lineaments to local variations in rock mass quality) may
68 also promote slope instability indirectly, by decreasing the strength of the rock mass and increasing the permeability
69 within the slope (Ambrosi and Crosta 2006; Agliardi et al. 2013b). It is clear there is a need to characterize rock
70 slopes not only from a geotechnical but also from a structural geology perspective (Stead and Wolter 2015).

71 In addition to the aforementioned geological factors that control the location and volume of the potential
72 instability, the action of exogenic (e.g., alteration, weathering, rainfall, snowmelt) and endogenic processes (e.g.,
73 isostasy, volcanism, earthquakes) gradually weaken the slope, causing a progressive decrease in stability (Whalley
74 1974; Leith 2012). This process, known as “progressive failure”, is often accompanied by the formation of internal
75 and surface features induced by the slope deformation that are referred to as “slope damage” (Stead and Eberhardt
76 2013). Extensional features, such as uphill and downhill facing scarps, double crest ridges, normal faults, tension
77 cracks, closed depressions, and grabens are all slope damage features commonly observed in deep-seated slope
78 deformations (Agliardi et al. 2013a; Jaboyedoff et al. 2013), together with buckling, folds, and reverse faulting
79 (Chigira 1992; Stead and Eberhardt 1997). The progressive rock mass weakening associated with the accumulation
80 of slope damage may facilitate the formation of release surfaces, enhancing the kinematic freedom and mobility of
81 rock slopes (Adhikary et al. 1997; Agliardi et al. 2013b).

82 The investigation of slope damage can provide insights on the mechanisms and processes that control (or
83 controlled) the slope deformation and failure. Wolter et al. (2014) employed an engineering-geomorphological

84 approach to investigate the pre- and post-failure topography of the Vajont slide, and highlighted the role of
85 endogenic and exogenic factors on the evolution of the failure. Paronuzzi and Bolla (2015) also investigated Vajont
86 slide deposit in order to characterize the ductile and brittle features (referred to as gravity-induced rock mass
87 damage) that developed during the failure. The characterization of slope damage can also provide information on the
88 temporal evolution of the instability. Agliardi et al. (2009) employed radiocarbon analyses to characterize the age of
89 trench infilling, in order to reconstruct the chronological evolution of the Mt. Watles deep-seated slope gravitational
90 displacement (DSGSD) in Northern Italy. Carbonel et al. (2013) performed stratigraphic and radiometric analyses to
91 distinguish between tectonic and geomorphic features along a high slope in Northern Spain. Hermanns et al. (2015)
92 employed cosmogenic dating to investigate the age of a slope deformation in the south face of the Aconcagua
93 Mountain (Argentina). Oppikofer et al. (2017) also used cosmogenic dating to investigate and reconstruct the
94 progressive displacement of the Vollan DSGSD (Norway). Using historic aerial photographs to map slope damage
95 features, Clayton et al. (2017) interpreted the failure mechanism of the Mitchell Creek Landslide, highlighting the
96 role of the glacial retreat in the evolution of the slope instability. Donati et al. (2020) investigated the slope damage
97 at the Ten Mile slide site, in British Columbia (Canada) using a series of airborne laser scanner datasets (ALS), and
98 highlighted the geomorphic control of the slope damage accumulating at the slope surface.

99 Although slope damage is recognized as a critical factor controlling and promoting the occurrence of slope
100 instability, the mechanisms and processes through which it accumulates, and the effects on the slope stability are
101 seldom addressed in numerical modelling analyses. Moore et al. (2011) investigated the role of ground-shaking in
102 the stability of the Randa rockslides. Preisig et al. (2016) used numerical modelling to reproduce the displacement
103 and progressive damage accumulation due to hydromechanical fatigue and seasonal water table variations in a deep-
104 seated landslide. Riva et al. (2018) analysed the progressive accumulation of damage in a DSGSD initiated by glacial
105 retreat in the Italian Alps.

106 In this paper, we use a numerical modelling approach to investigate the Downie Slide, a massive, active,
107 composite, extremely slowly moving rockslide in British Columbia, Canada. The objective of the simulation is to
108 identify the factors controlling the orientation, type, and spatial distribution of slope damage features that can be
109 observed at the slope surface. Additionally, this analysis will demonstrate the effectiveness of using slope damage
110 features as constraint for numerical simulation results, potentially enhancing the reliability of numerical modelling of
111 slopes where monitoring data is not readily available.

112 **2 Overview of the Downie Slide**

113 **2.1. Geological, structural, and hydrogeological setting**

114 The Downie Slide has been classified as a massive, active, composite, extremely slowly moving rockslide
115 (Kalenchuk et al. 2009). It is located in south-eastern British Columbia (Canada), along the western shore of the

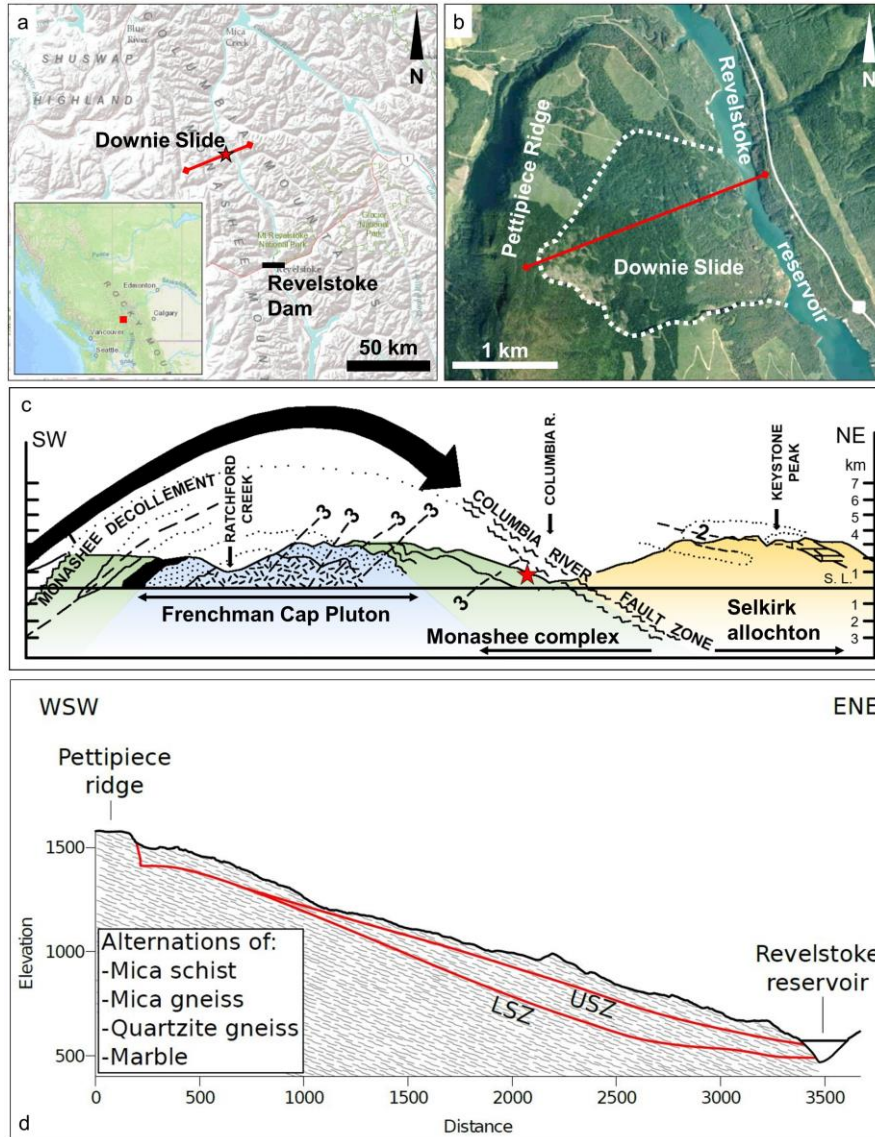
116 Revelstoke reservoir (Figure 1a,b). The reservoir was impounded in 1984 after the construction of the Revelstoke
117 dam by BC Hydro, 70 km south of the slide area along the Columbia River Valley (Imrie and Moore 1993). The
118 elevation of the Columbia River before the reservoir impoundment was 507 m a.s.l., which roughly coincided with
119 the daylighting elevation of the basal sliding surface. After the construction of the dam, water level increased to 573
120 m a.s.l., submerging the toe of the slide.

121 The Downie Slide has a surface area of about 9 km², and extends 2.4 km in the north-south direction and 3.2
122 km in the east-west direction, between ground surface elevations of 500 m and 1520 m a.s.l. The slide is bounded, to
123 the south and west, by sub-vertical scarps up to 125 m high, whereas no prominent scarps can be observed along
124 most of the northern boundary. The slide volume has been estimated between 1.0 billion m³ (Donati 2019) and 1.5
125 billion m³ (Piteau et al. 1978).

126 The most prominent structural feature in the Downie Slide area is the Columbia River Fault, CRF, which
127 dips 20 to 30° towards the east. The CRF was generated, in the Middle-Late Jurassic, by overthrusting of the Selkirk
128 Allochthon over the Monashee Complex, to the west and east respectively of the CRF (Brown and Read 1983). The
129 CRF is bounded by a cataclastic zone, about 1000 m wide, that predominantly affects the eastern slope of the valley
130 (Figure 1c; Brown and Psutka, 1980). Although the CRF played a key-role in defining the structural setting of the
131 area, no conclusive evidence was found that this geological structure was directly related to the initiation and
132 development of the Downie Slide (Brown and Psutka, 1980).

133 The Downie Slide comprises a succession of mica schists, mica gneisses, and quartzite gneiss that are part
134 of Proterozoic to Lower Paleozoic Monashee Complex (Brown and Psutka 1980; Brown and Read 1983). The
135 material is characterized by a prominent foliation that dips towards the east at an angle of about 20°, sub-parallel to
136 the slope surface, and provides weakness planes along which displacements occur (Brown and Psutka 1980).

137 Geological investigations, including geophysical surveys and borehole drilling, evidenced that the slide is
138 displacing along two sub-parallel shear zones (Imrie et al. 1992), referred to as lower and upper shear zones (USZ
139 and LSZ, respectively, Figure 1d). Monitoring data show that displacement rates are not homogeneously distributed
140 across the slide volume. At depth, borehole inclinometer surveys recorded movements up to 1.7 and 3.2 mm/year
141 along the USZ and LSZ, respectively. Rates of up to 16 mm/year have also been observed near the toe, but these are
142 limited to a shallow layer in colluvial material. Ground surface displacements, monitored using periodical GPS
143 monument surveys, vary between 1 and 58 mm/year, with a peak of 174 mm/year in the northern part of the toe (BC
144 Hydro 2010).



145
 146 **Figure 1** **Geographic and geological overview of the Downie Slide. a:** location of the study area in
 147 **western Canada. The location of the Revelstoke Dam is also indicated. Solid line identifies the**
 148 **geological section in panel c; b:** 2003 satellite image (from Google Earth) of the Downie Slide.
 149 **Note the Revelstoke reservoir submerging the toe of the slide. Solid line represents the trace of the**
 150 **section shown in panel d; c:** geological section through the study area and the Downie
 151 **Slide. Note the interpreted overthrust of the Selkirk Allochthon along the Monashee**
 152 **Decollement and the inferred thickness of the Columbia River Fault zone. Numbers 2 and 3**
 153 **mark fold axes of the relative secondary and tertiary tectonic deformation phases that**
 154 **affected the region (modified from Read and Brown, 1981) d:** conceptual geological section of
 155 **the Downie Slide, showing the foliation orientation, the lower shear zone (LSZ) and the**
 156 **upper shear zone (USZ).**

157 The hydrogeological setting comprises several independent aquifers, located at varying depth within the
 158 slide, which are a primary factor controlling the displacement rates across the slide area. Between 1973 and 1982,
 159 prior to the impoundment of the Revelstoke reservoir, two drainage adits were excavated within the Downie Slide, in
 160 order to increase the stability through the reduction of the piezometric head along the shear zones. In the lower slope

161 the water table was lowered of up to 152 m, resulting in a decrease in displacement rates from 10 mm/year (pre-
162 reservoir rates along the LSZ) to the present-day rates (BC Hydro 2010).

163 The Downie Slide initiated between 7,900 and 10,000 years ago, during or shortly after the glacial retreat in
164 the Columbia River Valley (Piteau et al., 1978; Stantec Inc 2009), and a total displacement of about 300 m was
165 estimated (Stantec Inc. 2009). It has been suggested that the Columbia River was progressively pushed against its
166 eastern bank by the slide, which never blocked the valley, nor evolved into a rapid instability (Stantec Inc. 2009).
167 Such a deformation process resulted in the narrowing of the Columbia River, particularly at two prominent knobs
168 located at the southern and northern boundaries of the slide area (referred to as south knob and north knob,
169 respectively), where rapids formed due to the increase in flow velocity.

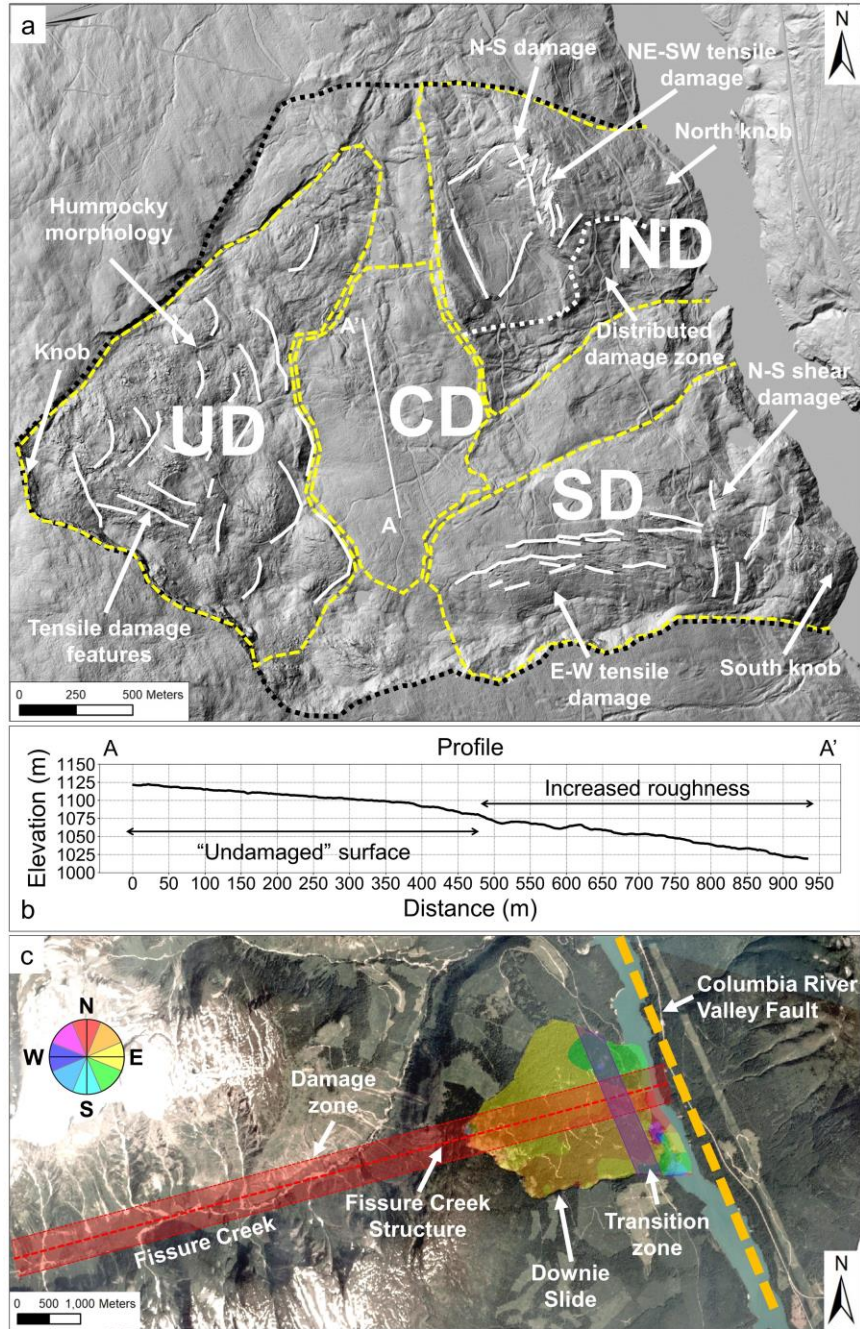
170 Based on geomorphic and structural considerations, various sub-divisions have been proposed for the
171 Downie Slide. Piteau et al. (1978) proposed a sub-division of the slide area into five domains. Based on field
172 reconnaissance and ALS interpretation, Stantec Inc. (2009) and Kalenchuk et al. (2013a) proposed sub-division of
173 the slide area into 8 and 13 domains, respectively. In this paper, we refer to the sub-division by Westin (2017), which
174 proposed 12 domains, interpreted using a mixed structural-geomorphic ALS approach in a GIS environment.

175 **2.2. Slope damage at the Downie Slide**

176 The external slope damage at the Downie Slide was investigated using an ALS dataset. Internal damage was
177 also preliminarily investigated using sub-surface data, including borehole inclinometer, piezometer logs, and
178 underground terrestrial laser scanning (TLS; Donati, 2019; Westin, 2017). Based on the orientation, spatial
179 distribution, and size of the slope damage features mapped on the ALS dataset, the slide area was divided into four
180 slope damage domains: upper distributed slope damage domain, central undamaged domain, northern slope damage
181 domain, and southern slope damage domain (Figure 2a). The upper distributed slope damage domain is characterized
182 by a hummocky morphology generated by the progressive retrogression of the upper headscarp (Kalenchuk et al.
183 2013a; Westin 2017). The central undamaged domain is characterized by a smooth, relatively undisturbed surface
184 with no prominent slope damage features. In the northern slope damage domain, extensive surface cracking can be
185 observed, with fractures, up to 20 m wide, oriented in north-south and northeast-southwest directions. The southern
186 slope damage domain is affected by east-west tensile cracks and grabens, as well as north-south oriented
187 counterscarps in the lower slope (Figure 2a). For a detailed description of each single slope damage domain, the
188 reader is referred to Donati (2019).

189 External and internal slope damage are strongly correlated to the morphology and changes in aspect of the
190 LSZ, which was constructed by interpolating, using a Kriging approach, the shear zone depth observed at the
191 location of 35 borehole and inclinometer logs (Donati, 2019). The LSZ displays a bi-planar configuration, as the
192 gradient at the toe of the slope is lower (less than 15°) than the medium and upper slope (up to > 30°, Figure 3a). As
193 a result, the progressive displacement caused the accumulation of internal slope damage within the transition zone at

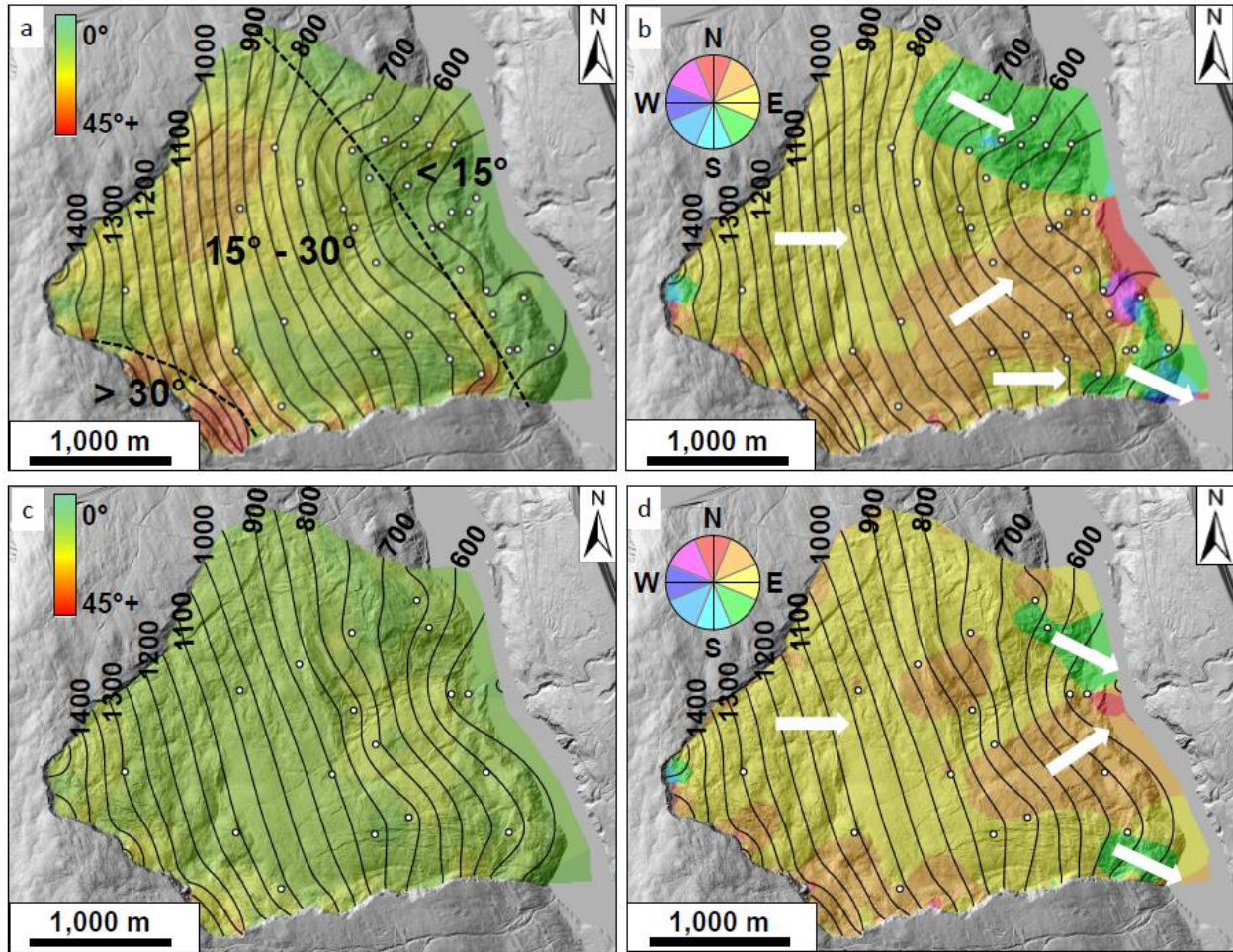
194 the interface between the active (i.e., upper) and passive (i.e., lower) blocks. The LSZ is also characterized by a bi-
195 planar morphology in the north-south direction, as the northern part of the shear zone dips towards the east, while the
196 southern part dips towards the north-east (Figure 3b, Donati 2019). Compared to the LSZ, the USZ appears to be
197 characterized by a more homogeneous surface, with more limited changes in dip direction and slope angle (Figure
198 3c,d). The complex geometric configuration of the LSZ is likely related to a possible geological structure that crosses
199 the slide area, intersecting the headscarp (generating a prominent knob clearly visible in the ALS dataset), and
200 forming the Fissure Creek Valley to the west of the slide area (Fissure Creek Structure in Figure 2c). The damage
201 zone surrounding this geological structure is thought to be the cause of a localized decrease in rock mass quality,
202 which is reflected in an increase in surface roughness observed in the central undamaged domain (Figure 2b), and the
203 presence of a distributed slope damage zone in the northern slope damage domain (Figure 2a). The long-term
204 displacement along the LSZ and USZ also caused the accumulation of internal slope damage. Borehole logs and
205 photographs evidenced that the rock mass forming the shear zones is intensely altered, fractured, and sheared. The
206 thickness of such highly damaged zone in the LSZ and the USZ is up to 62 m and 21 m, respectively, with peak
207 values observed in the lower slope. However, borehole inclinometer logs show that displacements at depth are
208 concentrated within a 1-m thick layer in both the LSZ and USZ. Such thickening may have resulted from a
209 combination of various factors, including the damage accumulation in the transition zone, the displacement along a
210 potentially undulated surface, and the possible activity, in the past of different or multiple sliding surfaces.



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Figure 2

Overview of the external and internal slope damage at the Downie Slide. a: external slope damage domains identified in the ALS dataset. UD: upper distributed slope damage domain; CD: central undamaged domain; ND: northern slope damage domain; SD: southern slope damage domain. Note the varied orientation and type of slope damage features across the slope damage domains, the knob along the upper headscarp, and the south and north knobs at the toe of the slide. The solid line in CD marks the profile trace shown in b; b: N-S profile along the CD domain. Note the increase in roughness in the northern part, interpreted as the result of a lower rock mass quality and higher erodibility; c: factors controlling internal damage at the Downie Slide. Note the alignment between Fissure Creek, the knob in the upper headscarp, and the change in aspect of the LSZ, suggesting the presence of a structural damage zone. In the lower slope, transition zone and vicinity to the Columbia River Valley Fault likely enhance internal damage.



224
 225 **Figure 3** Morphology of the upper and lower shear zones constructed by interpolation of borehole
 226 data (white circles). a: slope map of the LSZ. Note the decrease in steepness of the LSZ in the
 227 lower part of the slope. b: aspect map of the LSZ. White arrows show the average orientation
 228 of the planes composing the shear zone. c: slope map of the USZ. d: aspect map of the USZ.

229 3 Numerical modelling of the Downie Slide

230 In this work, three-dimensional numerical modelling was performed to investigate the factors that are
 231 controlling the evolution of slope damage at the Downie Slide. In particular, the influence of shear zone morphology,
 232 structural and geomorphic domain sub-division, and ground water conditions on the development of internal and
 233 external slope damage was investigated. The spatial distribution, orientation, and type of external slope damage
 234 observed in the ALS dataset were compared with the results from the numerical analysis. It was noted that using a
 235 distinct element method, coupled with a strain-softening constitutive model, slope damage features can be
 236 reproduced in a three-dimensional numerical model, providing an additional tool for constraining numerical analysis.
 237 The numerical model analyzes a slope that is representative of the final evolution stages and present-day conditions
 238 for the Downie Slide (in terms of slope topography, slide boundaries, shear zone morphology, ground water table,

239 rock mass properties), and therefore represents a prototype for forward modelling. Such approach was elaborated in
240 collaboration with the Dam Safety branch of BC Hydro, in order to identify areas where additional borehole data
241 collection, planned for the next few years, should concentrate to enhance understanding of mechanisms controlling
242 the slide behavior.

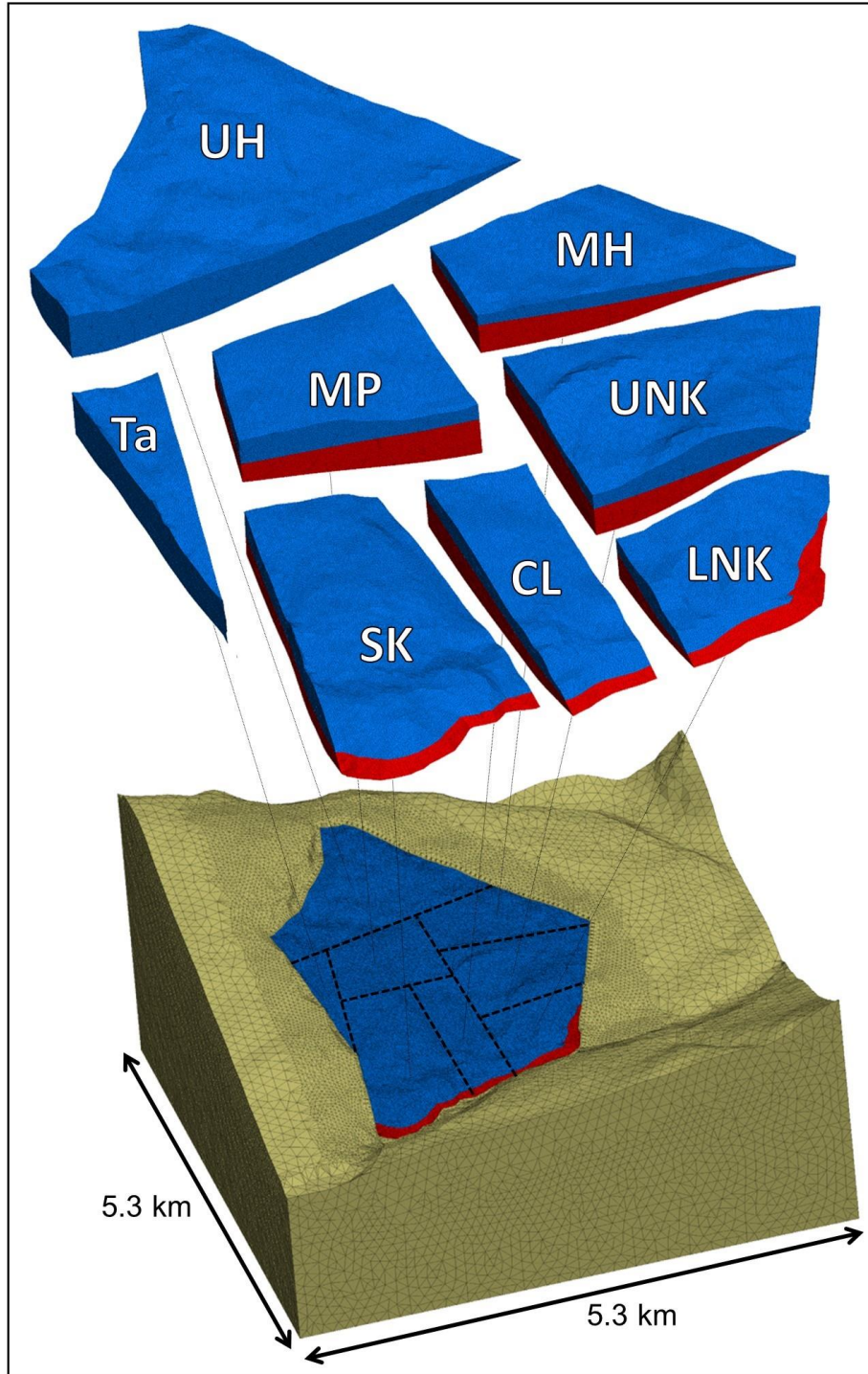
243 **3.1. Construction of the three-dimensional model of the Downie Slide**

244 Since the slide volume can be divided into discrete domains, a three-dimensional distinct element method
245 approach was used for the numerical analysis, and the code 3DEC 5.2 (Itasca Consulting Group 2016a) was
246 employed. In the distinct element method, the rock mass is modelled as an assembly of discrete blocks that may
247 slide, rotate, and completely detach from each other.

248 The numerical analysis was undertaken considering the present-day slope morphology as the initial model
249 condition. The model geometry was created in Rhinoceros 5 (Robert McNeel & Associates 2015) using the ALS
250 dataset. To avoid boundary effects in proximity of the slide area, the model area was extended, using a NASA SRTM
251 dataset (NASA-NGA 2014). The final model geometry covers a surface area of 5.3 km by 5.3 km (Figure 4). The
252 LSZ and USZ, reconstructed from borehole and inclinometer log data as described in Donati (2019), were
253 implemented in the 3DEC model. Finally, using Griddle (Itasca Consulting Group 2016b) a tetrahedral volumetric
254 mesh was exported in a format readable in 3DEC.

255 The Downie Slide area was sub-divided into eight deformable blocks divided by vertical boundaries,
256 roughly based on Westin (2017), in order to provide kinematic freedom to the different parts of the slide. The choice
257 of vertical boundaries in this analysis is for 3D model simplicity and is justifiable as there are currently no existing
258 data on the sub-surface dip of domain boundaries. It is currently unclear whether the block boundaries are structural
259 in origin or formed as a result of the slope deformation, or possibly a combination of both. From the upper to the
260 lower slope, the slide blocks are: upper hummocks, talus, mid plain, mid hummocks, south knob, channelized lower,
261 upper north knob, and lower north knob (Figure 4). Kalenchuk et al. (2013) and Westin (2017) suggested that the
262 upper blocks (namely upper hummocks and talus) formed through the progressive retrogression and erosion of the
263 head scarp of the Downie Slide. The irregular ground surface of the upper slope suggests that large rock blocks
264 progressively detached and failed, “filling the gap” created by the displacing slide and generating a prominent
265 hummocky morphology. It is unlikely that such an accumulation mechanism allowed a foliation-parallel USZ to
266 form, and it was therefore decided not to implement the USZ in these blocks. A strain-softening constitutive criterion
267 was assumed for the slide material, in order to simulate the decrease in rock mass properties caused by the
268 accumulation of internal and external slope damage. Observed in-place stable areas within the large-scale model (i.e.,
269 outside of the slide area) were assumed to be elastic. Rock mass properties were obtained from Kjelland (2004) and
270 Kalenchuk et al. (2012), and were derived from numerous investigations and material testing programs by BC
271 Hydro. In this investigation, residual strength properties for the strain-softening model are assigned after a plastic

272 strain of 2%. This value is within the range used in previous numerical analyses (0.2% to 6%) to simulate rock mass
273 strength softening (Hajiabdolmajid and Kaiser 2002; Badr et al. 2003; Andrieux et al. 2004; Zipf 2007).



274
 275 **Figure 4** Slope domains, based on Westin (2017), implemented in the three-dimensional 3DEC model
 276 of the Downie Slide. UH: Upper Hummocky Block; Ta: Talus Block; MP: Mid Plain Block;
 277 MH: Mid Hummocky Block; SK: South Knob Block; CL: Channelized Lower Block; UNK:
 278 Upper North Knob Block; LNK: Lower North Knob Block; b). The slide volume above and
 279 below the USZ is colored in blue and red, respectively. Note that only the LSZ is
 280 implemented in blocks UH and Ta, as they are considered as secondary failures in this model.

281 Rock mass dilation has also been considered in the numerical model. It is known that the dilation angle
 282 decreases with the progressive deformation of the rock mass, and becomes null when the maximum volumetric strain
 283 is achieved. However, the definition of an appropriate dilation value for a large scale jointed/foliated rock mass for
 284 use in numerical models remains a challenging task. Based on empirical considerations, Hoek and Brown (1997)
 285 suggest that a preliminary value of $\phi/4$, $\phi/8$, and 0 may be used for good, average, and very poor quality rock masses,
 286 respectively. A more robust approach to evaluate rock mass dilation has been proposed by Alejano and Alonso
 287 (2005) that requires knowledge of the compressive strength, friction angle, and confinement conditions of the rock
 288 mass. In view of the large deformation that occurred at the Downie Slide, limited rock mass dilation may be
 289 expected, and a 2° dilation angle was assumed as a preliminary estimate for the rock mass. The shear strength
 290 parameters of the LSZ were based on previous direct shear testing (BC Hydro, 1974), which provided a friction
 291 angle ranging between 16° and 24°. Preliminary dry models in 3DEC, however, showed that no appreciable
 292 displacement would occur using these values. A back-analysis was therefore performed, allowing displacement to
 293 occur with a friction angle of 15°. Such behavior was expected in a dry model, as the absence of a water table would
 294 increase stability of the slope through increased effective stress along the sliding surface. Parameters assigned to the
 295 USZ were obtained by upscaling the LSZ strength parameters, in order to reproduce the lower displacement rates
 296 observed in the field slope monitoring data. Additionally, the LSZ beneath the blocks forming the upper portion of
 297 the Downie Slide (i.e., the upper hummocky region) was assigned higher strength properties due to the secondary
 298 nature of the failure mechanism. Table 1 and Table 2 summarize the mechanical parameters assigned to the
 299 geological materials and the discontinuities within the model, respectively.

300 **Table 1 Summary of the deformable block properties used for the numerical investigation of the**
 301 **Downie Slide. Residual values are in brackets.**

Property	Slide rock mass	Slope rock mass
Constitutive model	Strain-softening*	Elastic
Dry density (kg/m ³)	2,700	2,700
Saturated density (kg/m ³)	2,730	2,730
Bulk modulus (GPa)	1.8	1.8
Shear modulus (GPa)	0.9	0.9
Friction angle (°)	34 (30)	-
Cohesion (MPa)	2 (0.2)	-
Tensile strength (MPa)	0.4 (0.04)	-
Dilation (°)	2	-

302 *: Residual properties for strain-softening blocks are assigned after a strain of 0.02.

303

304

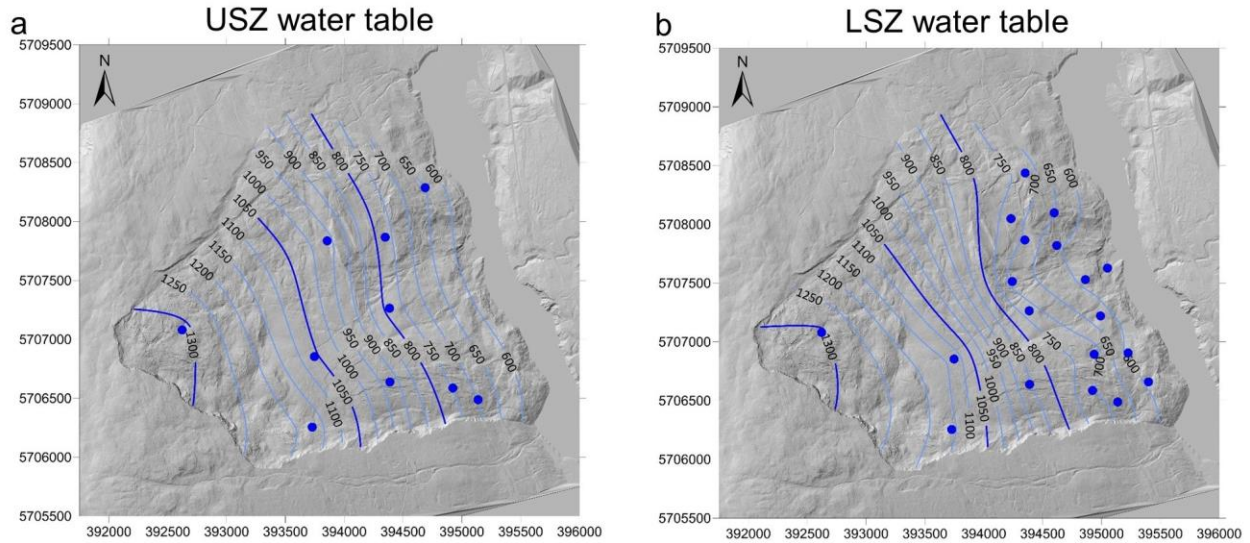
305 **Table 2** **Summary of the shear surface and slide boundary properties used for the numerical**
 306 **investigation of the Downie Slide. Residual values are in brackets.**

Property	LSZ	USZ	LSZ - Secondary failure	Lateral and block boundaries
Constitutive model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Friction angle (°)	15 (12)	18 (15)	20 (18)	20 (18)
Cohesion (kPa)	100 (0)	200 (0)	200 (0)	0
Tensile strength (kPa)	20 (0)	40 (0)	40 (0)	0
Normal stiffness (MPa/m)	50	500	1,000	1,000
Shear stiffness (MPa/m)	25	250	100	100

307

308 In this numerical analysis it was decided, as assumed in Kalenchuk et al. (2012), not to explicitly include
 309 the joint sets within the block domains. This modelling approach provides several advantages, including: a) slope
 310 damage may form as a result of rock mass yielding (conversely, the implementation of joint sets would force slope
 311 damage to develop exclusively through dilation of fully-persistent joints, preventing yielding of intact material); b) a
 312 significant decrease in the model runtime is achieved (to as low as 10 days), potentially allowing limited parametric
 313 analysis to be conducted; c) allowing comparison of the numerical modelling results with previous three-dimensional
 314 analyses of the Downie Slide.

315 Three models were run, using different water table assumptions. Firstly, the model was run simulating a dry
 316 slope (Model 1). Then, two different models were run to investigate the effect of the piezometric head acting along
 317 the LSZ (Model 2a), and the USZ (Model 2b). Two water tables were constructed, using piezometric head data
 318 provided by BC Hydro. For the Model 2a, the hydraulic heads observed in the piezometers positioned at the depth of
 319 the LSZ were interpolated using a Kriging method and the software Surfer (Golden Software 2016). For the model
 320 2b, the piezometers positioned at the depth of the USZ were used, instead (Figure 5). In order to separately
 321 investigate the effect of the pore pressures along the USZ and LSZ, plastic displacements were allowed to occur only
 322 along the shear zone for which the water table is implemented. In other words, in model 2a the USZ was assigned
 323 elastic properties, and sliding was only allowed along the LSZ. Conversely, in model 2b only sliding along the USZ
 324 was permitted, and the LSZ was assigned elastic properties.



325
 326 **Figure 5** Groundwater tables implemented in the numerical models, interpolated in Surfer. **a:** water
 327 table constructed using hydraulic heads observed along the LSZ (implemented in model 2a);
 328 **b:** water table constructed using hydraulic heads observed along the USZ (implemented in
 329 model 2b). Blue dots indicate the location of the piezometers considered for the Kriging
 330 interpolation of the water table.

331 Throughout the numerical analysis, displacement data were recorded at virtual inclinometers implemented
 332 within the model. The location of the virtual borehole inclinometers coincided with installed borehole inclinometers
 333 at the Downie Slide. The virtual borehole inclinometers sampled displacement magnitude at every meter depth in
 334 both N-S and E-W directions, allowing displacement magnitudes to be computed during the post-processing.

335 In all simulations, a multi-stage model approach was used involving the following steps:

- 336 1. Geometry construction, domain subdivision, block zoning, and history point setup;
- 337 2. In wet models, implementation of water table, and initiation of pore pressure;
- 338 3. Elastic properties assigned to blocks and shear zones and the model then run to equilibrium;
- 339 4. Strain-softening constitutive criterion assigned to the rock mass blocks and the model then run to
 340 equilibrium;
- 341 5. High material properties assigned to the shear zones and the model then run to equilibrium;
- 342 6. Assumed material properties assigned to the shear zones, the model then run for 100,000 numerical time
 343 steps (200,000 for Model 2b), and the slope failure simulated.

344 Numerical models were run on a high-end workstation, with 6th generation Intel i7 3.2 GHz 8-core CPU and
 345 128 GB RAM requiring on average, ten to twelve days to complete 100,000 numerical time steps. Results have been
 346 analyzed in 3DEC examining in particular displacement magnitude, failure state, and volumetric strain plots, which
 347 were found to provide useful information about simulated slope damage type and distribution. Volumetric strain
 348 ($\Delta V/V_0$) was employed to highlight areas of extension and compression, which were associated with compressive

349 and/or tensile damage accumulation. Monitoring data obtained from the virtual borehole inclinometers were exported
350 and processed to derive cumulative displacement plots and displacement azimuths to allow comparison with
351 observed slope monitoring data.

352 **3.2. Description of the results**

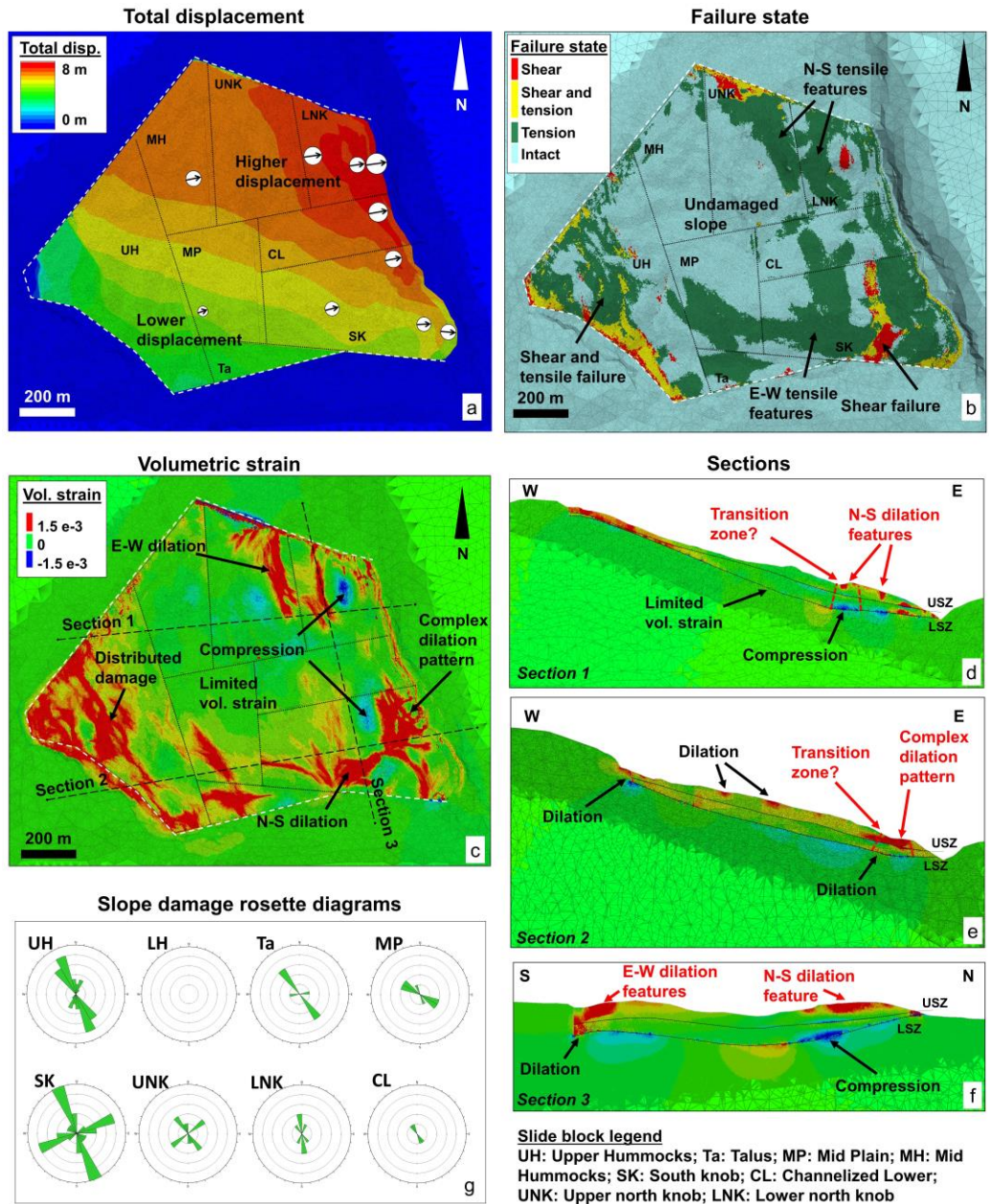
353 **3.2.1. Model 1 – Dry slope**

354 After 100,000 numerical time steps (cycles), maximum simulated displacement values of 7.5 m were
355 observed in the northern section of the toe, with a gradual reduction in simulated displacement towards the western
356 and southern scarps (Figure 6a). The upper portion of the Downie Slide shows the lowest simulated displacement,
357 probably due to the low angle of the LSZ near the western cliff. The displacement of the slide is simulated with an
358 azimuth of 70°N in the mid- and upper slope, which changes in the southern part of the lower slope to 90°N to
359 100°N. The direction of movement is controlled, in the numerical model, by the southern boundary of the slide area,
360 which appears to kinematically constrain the movement of the central and upper slope blocks.

361 The analysis of the block plasticity failure state provided information on the failure mechanism in the
362 discrete blocks forming the slide. Failed blocks are distributed between the lower and upper slope, whereas the mid
363 slope remained largely intact, except along the southern boundary (Figure 6b). Tensile failure is predominant, and
364 shear failure is concentrated in limited areas within the south knob and the upper hummocky blocks. Blocks that
365 failed in tension appear to be grouped in north-south trending clusters in the north knob area. Tensile failure is also
366 prominent in the south knob, where blocks failed in tension form clusters that strike in an east-west direction. The
367 slope in this location is traversed by an area of predominantly north-south trending shear failure.

368 The volumetric strain plot shows positive strain (i.e., dilation) in the upper portion of the slope (upper
369 hummocky block), as well as within the northern and southern slide blocks (south knob, upper and lower north knob
370 blocks) (Figure 6c). Groups of zones with relatively high volumetric strain ($\epsilon_v > 2.5e-3$) are organized in linear
371 features, which extend in a north-south direction in the northern portion of the slide. More limited, southwest-
372 northeast features are simulated along the northern boundary of the slide area. Along the southern boundary of the
373 slide, east-west extensional features developed during the simulation. A complex network of extensional features
374 also developed at the toe of the slide, in the northern part of the southern damage domain. Here, north-south features
375 overprint east-west striking features. North-south striking dilational features also developed within the upper damage
376 domain. Negative volumetric strain (i.e., compression) was locally observed in the central part of the northern
377 damage domain, and at the toe of the south knob block. Positive volumetric strain was found to continue with depth,
378 indicating that both external and internal damage exist in the areas where surface dilation was observed (Figure 6d-
379 f). Negative volumetric strain (e.g., compression) was observed along the LSZ, where the gradient of the shear zone
380 decreases, and may be associated with the development of a transition zone at the interface between the active and
381 passive blocks of the slide (Figure 6d).

382 The volumetric strain plot was imported as a raster file in ArcGIS (ESRI, 2017). Here, lineaments simulated
 383 in the analysis were mapped, their average trend computed and plotted on rosette diagrams using DIPS (Rocscience,
 384 2019). A preferential NNW-SSE lineament orientation was noted throughout the slide blocks, while intense NE-SW
 385 features were simulated in the south knob and north knob slide blocks (Figure 5g).



386
 387 **Figure 6** Results of the numerical analysis of Model 1 (dry slope) at 100,000 numerical time steps. a:
 388 total displacement plot. Arrows indicate the modelled displacement azimuth; b: block failure
 389 state plot; c: volumetric strain plot. Red and blue indicate increase and decrease in volume,
 390 respectively (extension and compression); d,e: sections east-west through Downie Slide
 391 showing the simulated volumetric strain; f: section north-south through Downie Slide
 392 showing the simulated volumetric strain; g: rosette diagrams showing the preferential slope
 393 damage feature orientation within the slide blocks.

394 **3.2.2. Model 2a – Water table above the Lower Shear Zone**

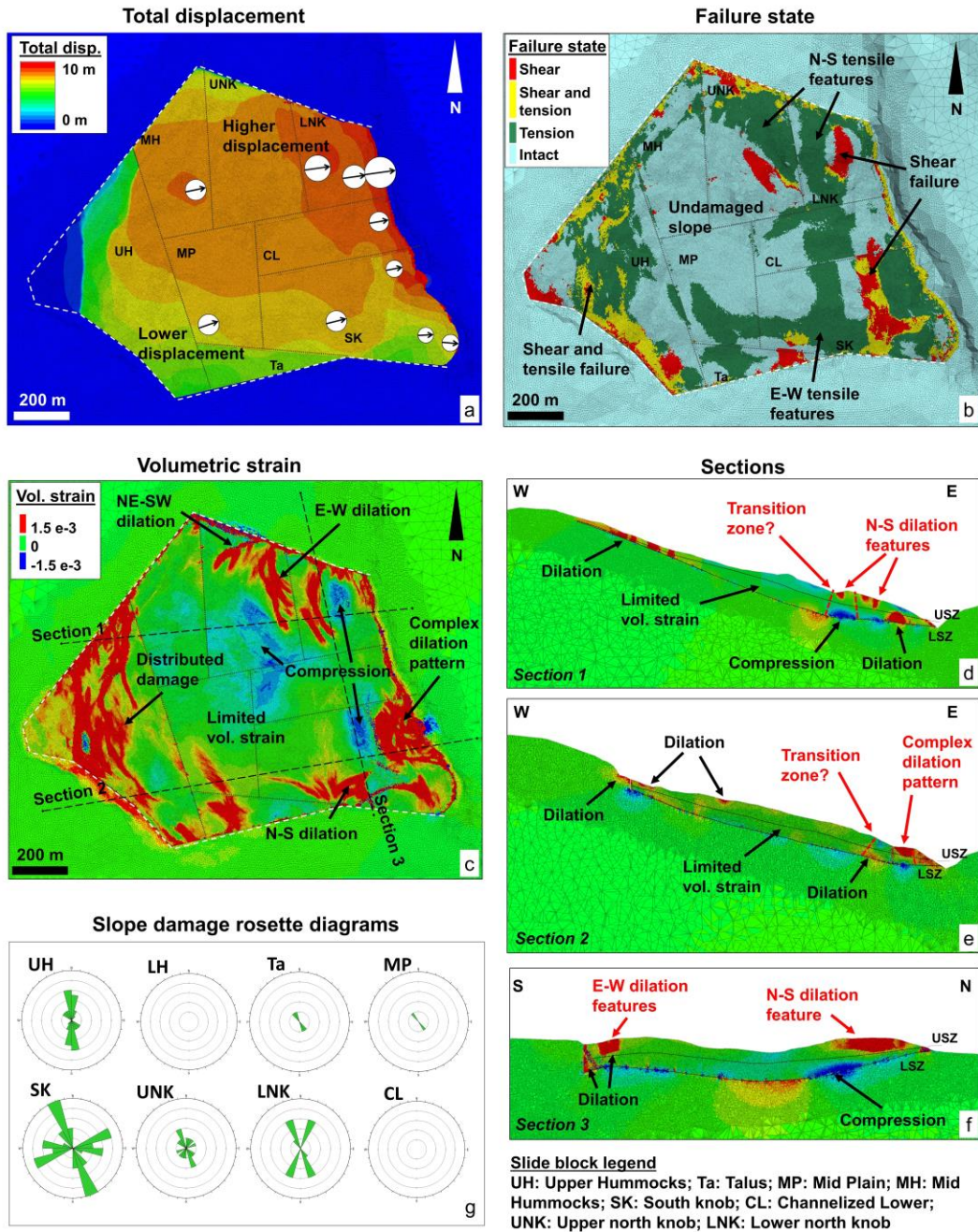
395 Model 2a simulates the slide displacement along the LSZ, and includes the pore pressures acting along the
396 lower sliding surface. A saturated density of $2,730 \text{ kg/m}^3$ was assigned to the material below the water table. An
397 additional, hydrostatic load was also applied to the slope below 573 m, to account for presence of the reservoir.
398 Throughout the Model 2a simulation, an elastic constitutive criterion was assigned to the USZ in order to prevent
399 sliding.

400 The simulation required 12 days, and was terminated after 100,000 numerical time steps (cycles), when a
401 maximum displacement of around 12 m was observed. The greatest displacement magnitude was observed in the
402 northern part of the lower slope. Simulated displacements decrease towards the western and southern scarps (Figure
403 7a). Sliding predominantly occurs in a northeast direction (azimuth 70° N), whereas toward the southern boundary
404 displacements follow an eastward trend ($90\text{-}95^\circ \text{ N}$).

405 The plasticity zone failure state plot indicates that tensile failure occurred throughout the lower slope,
406 whereas shear failure is limited to the south knob and the upper and lower north knob blocks. Mixed tension and
407 shear failure affected the upper portion of the slope (Figure 7b). In the central portion of the slope blocks were
408 subjected to low volumetric strain and showed limited failure throughout the numerical simulation.

409 The volumetric strain plot for Model 2a shows strong similarities to Model 1. North-south and northeast-
410 southwest trending extensional features developed in the northern portion of the slope (Figure 7c-d). A complex
411 network of damage features was simulated at the base of the south knob (Figure 7e). Positive volumetric strain is
412 distributed throughout the upper slope, where no clear damage accumulation pattern can be observed. In the southern
413 portion, east-west features were simulated, which continue with depth reaching the LSZ (Figure 7f).

414 The lineaments modelled in the analysis were approximately mapped and plotted on rosette diagrams.
415 Modelled lineaments predominantly strike in a NNW-SSE direction. Slope damage features striking in a southwest-
416 southeast direction were also modelled within the south and north knob slide blocks (Figure 7g).



417

418 **Figure 7**

419 **Results of the numerical analysis of Model 2a (water table above the LSZ) at 100,000**
 420 **numerical time steps. Note the similarity with Model 1. a: total displacement plot. Arrows**
 421 **indicate the modelled displacement azimuth; b: block failure state plot; c: volumetric strain**
 422 **plot. Red and blue indicate increase and decrease in volume, respectively (extension and**
 423 **compression); d,e: sections east-west through Downie Slide showing the simulated volumetric**
 424 **strain; f: section north-south through Downie Slide showing the simulated volumetric strain;**
 425 **g: rosette diagrams showing the preferential slope damage feature orientation within the**
slide blocks.

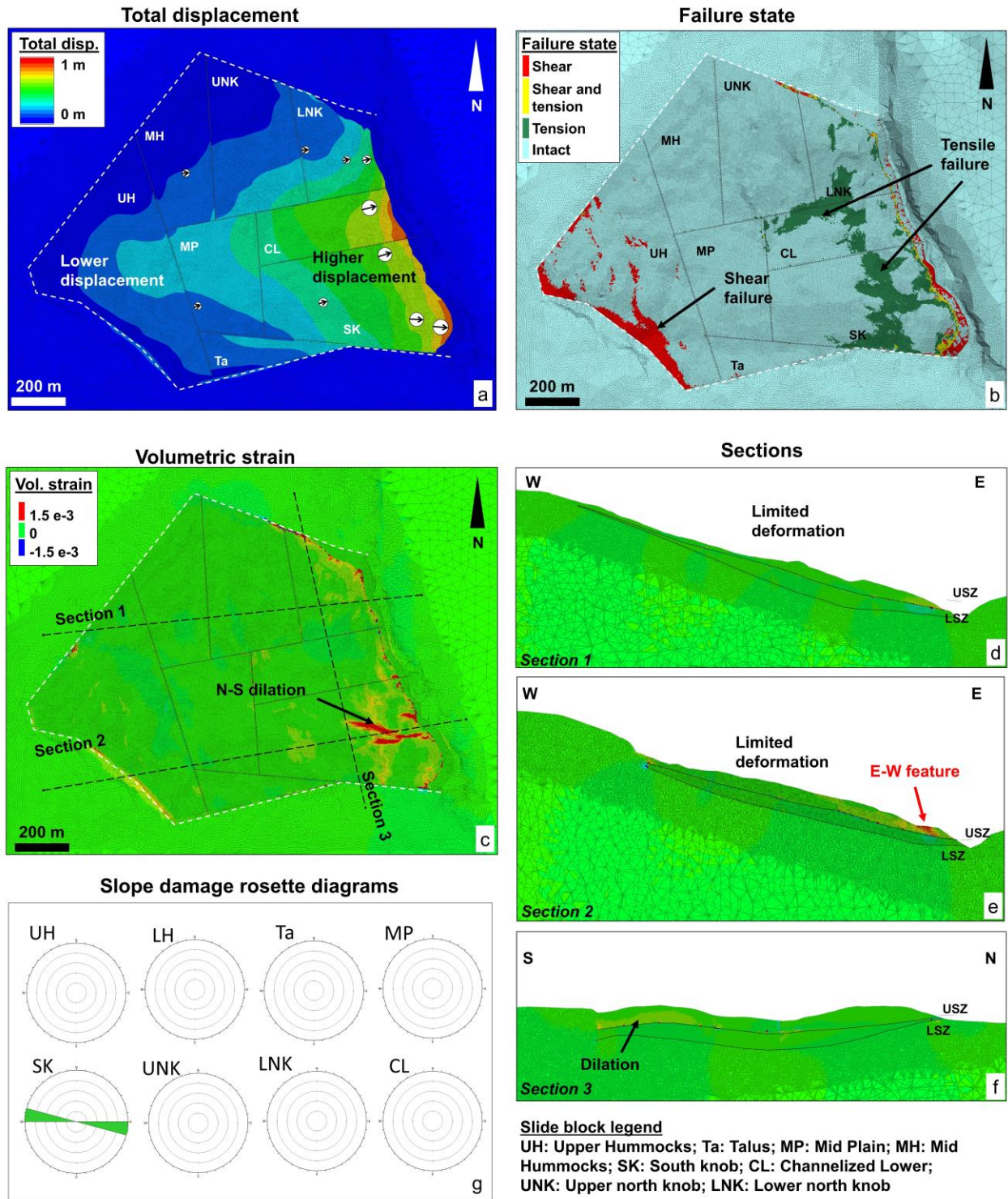
426 **3.2.3. Model 2b – Water table above the Upper Shear Zone**

427 Model 2b analyzes the effects of the displacement along the USZ, considering the pore pressure that exists
428 above the upper sliding surface. A saturated density of $2,730 \text{ kg/m}^3$ was assigned to the material below the water
429 table. The water mass forming the reservoir was also accounted for by applying an additional load below 573 m a.s.l.

430 A maximum displacement of about 1 m was obtained after 200,000 numerical time steps (cycles). The
431 largest displacements occurred in the southern portion of the slide, between the channelized lower and the south
432 knob blocks (Figure 8a). Displacement magnitude decreased towards the north and west. The predominant
433 displacement azimuth is approximately 75° N , except for in the southern portion of the south knob block where the
434 direction of movement sharply changes to 100° N , causing a single, linear, extensional feature to form parallel to the
435 southern scarp (Figure 8c). Small areas of positive volumetric strain are limited to the toe of the slide, with no
436 significant deformation simulated elsewhere in the slide area.

437 The block failure state plot shows limited tensile failure in the lower slope, mostly concentrated in the
438 southern and central portions of the slide (Figure 8b). Shear failure can be observed in the upper slope, particularly
439 along the western headscarp.

440 The low level of slope damage is also highlighted by the slope damage rosette plots, which show that
441 damage features, striking in an east-west direction, were only modelled in the south knob slide block (Figure 8g).



442
 443 **Figure 8** Results of the numerical analysis of Model 2b (water table above the USZ) at 200,000
 444 numerical time steps. a: total displacement plot. Arrows indicate the modelled displacement
 445 azimuth; b: block failure state plot; c: volumetric strain plot. Red and blue indicate increase
 446 and decrease in volume, respectively (extension and compression); d,e: sections east-west
 447 through Downie Slide showing the simulated volumetric strain; f: section north-south
 448 through Downie Slide showing the simulated volumetric strain; g: rosette diagrams showing
 449 the preferential slope damage feature orientation within the slide blocks.

450 **4 Discussion**

451 **4.1. Comparison with slope damage domains**

452 Numerical modelling of the Downie Slide assuming a plastic, strain-softening constitutive criterion has
453 allowed slope damage to be progressively simulated throughout the analysis. A validation of the numerical results
454 has been undertaken by visually comparing the volumetric strain and failure state plots with the slope damage
455 domains identified in the ALS hillshade map (Figure 9, Figure 10, Figure 11). The 3DEC damage modelling results
456 compare well with the observed external slope damage in the ALS dataset. The virtual inclinometer plots (i.e., the
457 displacement directions) were also compared with real monitoring datasets (Figure 12).

458 A good agreement was observed between the ALS maps and the results of Model 1 and Model 2a. The
459 north-south and northeast-southwest focused tensile features observed in the volumetric strain plot are similar to the
460 external slope damage features mapped in the ALS along the northern damage domain (Figure 9). Compared to the
461 observed slope damage, simulated damage within the slope appears to be more curved and less linear. The inclusion
462 of rock mass jointing would provide additional constraint on the orientation of the extensional features but would
463 require an impractical increase in computational requirements and time. In the southern part of the slide area, east-
464 west trending extensional features simulated in the models are consistent with the slope damage orientation observed
465 in the southern damage domain on the ALS map (Figure 10). The accumulation of shear damage along the southern
466 boundary, as observed in the failure state plots, appears to agree well with the presence of the counterscarps
467 recognized in the ALS dataset. The central part of the lower slope, the most active area of the Downie Slide, shows a
468 slight compression (i.e., negative volumetric strain values) in Model 1 and Model 2a. This result is expected, as the
469 area is located at the intersection between the southeast- and northeast-dipping portions of the lower shear zone. All
470 the model simulations indicate that the central part of the Downie Slide remained substantially undamaged and
471 undeformed throughout the simulation, in good agreement with the external slope damage observed in the ALS
472 (Figure 2a). This lack of slope damage is likely due to the uniform dip of the LSZ, which allows the unstable mass to
473 slide without significant internal deformation. Distributed, tensile and shear damage is simulated in the upper slope
474 in Model 1 and Model 2a, which appears to agree well with the damage and hummocky surface observed both in the
475 ALS and in the field (Figure 11). It is interesting to note that both Model 1 and 2a display relatively high absolute
476 values of volumetric strain along both the LSZ and the USZ, suggesting that a significant accumulation of internal
477 slope damage can be simulated for displacements as low as 8-10 m. This area of increased internal slope damage
478 appears to agree with the observed increase in thickness of the USZ and LSZ, suggesting that the progressive slide
479 displacement (estimated at about 300 m) was an important factor in the shear zone thickening process.

480 Results of Model 2b indicated the simulation of east-west extensional features at the base of the south knob
481 block (Figure 10). Although these features cannot be readily compared with any lineament visible in the ALS, its

482 orientation and location are consistent with a north-south extension that is apparent throughout the southern portion
483 of the slide in Models 1 and 2a.

484 Model 1 (which includes both LSZ and USZ) and Model 2a (LSZ only) were capable of reproducing the
485 spatial distribution of slope damage observed in the ALS, as well as the mode of failure of the material (e.g., shear
486 vs. tensile). Conversely, Model 2b (which included the USZ only) does not reproduce the damage features
487 recognized in the ALS.

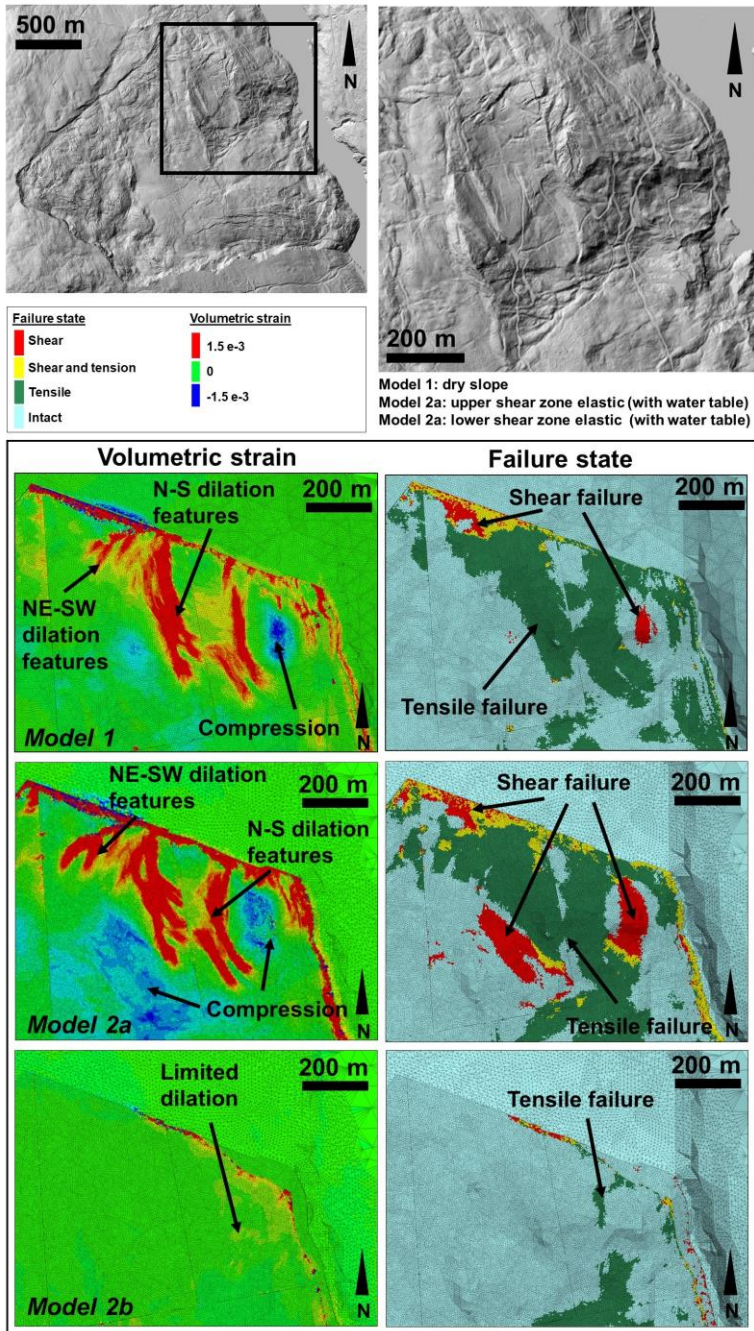
488 Numerical modelling appears to indicate that the lower shear zone played a critical role in formation of the
489 damage that is observed in the field. The role of the upper shear zone appears more limited, however further analyses
490 should be undertaken to investigate in detail its effects on the evolution of surficial or localized external slope
491 deformations.

492 From a comparison with the observed slope damage features, modelled slide activity on the USZ is not
493 considered to have created the larger scale slope damage, which is attributed to significant slide displacement activity
494 on the LSZ, but contributed to complementary slope damage effects. These model observations collectively suggest
495 that the initial and significant slide displacement activity occurred on the LSZ, while the USZ developed during the
496 evolution of the slide, and has now become a significant contributor to the present day slide mechanism.

497 A comparison of the virtual borehole inclinometer records with the slope monitoring data was also
498 undertaken (Figure 12). As an example, Figure 12b shows the comparison between the monitoring log from the
499 inclinometer S51, and its virtual counterpart, obtained from Model 1. Deformation occurring along the lower shear
500 zone in the east and north directions were plotted to investigate the direction of displacements. The resulting virtual
501 displacement vectors were then compared with the directions of displacement calculated for the real inclinometers
502 (see table inset in Figure 12a). The virtual inclinometer results for both Model 1 and Model 2a are characterized by a
503 more a uniform distribution in azimuth compared to the real monitoring data, with the largest differences observed in
504 inclinometers at the base and in the northern part of the slope (Figure 12a). No appreciable difference was observed
505 between the displacement direction in Model 1 and Model 2a. Factors that may affect the comparison of simulation
506 with borehole inclinometer records include the quality of the field monitoring data and the material properties
507 assigned to the blocks in the model. Data quality may be limited for the older borehole inclinometers, installed in the
508 1980s, which are mainly located in the lower slope. Experience gained through the analysis of similar instruments at
509 other BC Hydro sites suggests that uncertainties in the displacement direction may be in the order of $\pm 20^\circ$, due to
510 outdated installation techniques and potential deformations of the casing. The material properties assigned to the
511 blocks within the 3DEC model may also affect the direction of movement. Numerical modelling has been conducted
512 using a single set of mechanical rock mass properties, ignoring the type and varying amount of damage already
513 present within the various blocks. Correcting the mechanical parameters to include the slope damage mapped in the
514 ALS may affect the ongoing deformation behavior of the blocks, allowing for displacement azimuths to be obtained
515 with increased confidence. It should also be stressed that the variations in the shear surface dip and dip direction are
516 dependent upon the distribution of the borehole and their spacing; it is to be expected that localized errors in the

517 interpolation of the shear surface topography will inevitably be present that would influence any comparison between
518 simulated and observed displacement. Notwithstanding such uncertainties, the comparison between simulated
519 displacements and observed borehole inclinometers logs shows remarkable agreement given the necessary data
520 assumptions used in this study.

Northern damage domain



521

522 **Figure 9**

523

524

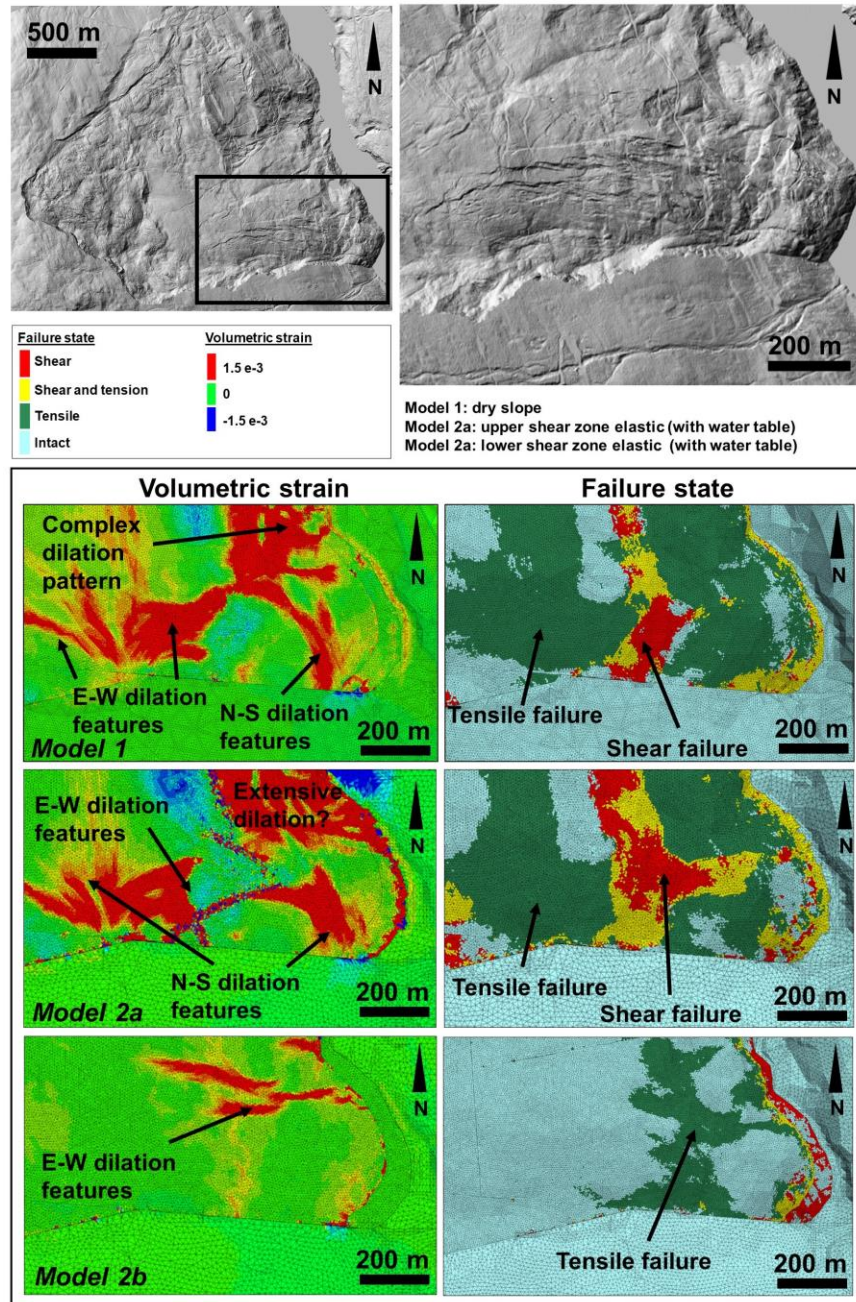
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527

Northern damage domain: damage comparison between the volumetric strain and zone failure state 3DEC plots at 100,000 numerical time steps (200,000 for Model 2b) and the ALS hillshade map. Focused tensile damage developed in Models 1 and 2a. North-south oriented features in the volumetric strain plot correlate closely with slope damage and deformations observed in the ALS. Failure state plots show predominantly tensile damage throughout the domain. Model 2b shows limited deformation and failed zones.

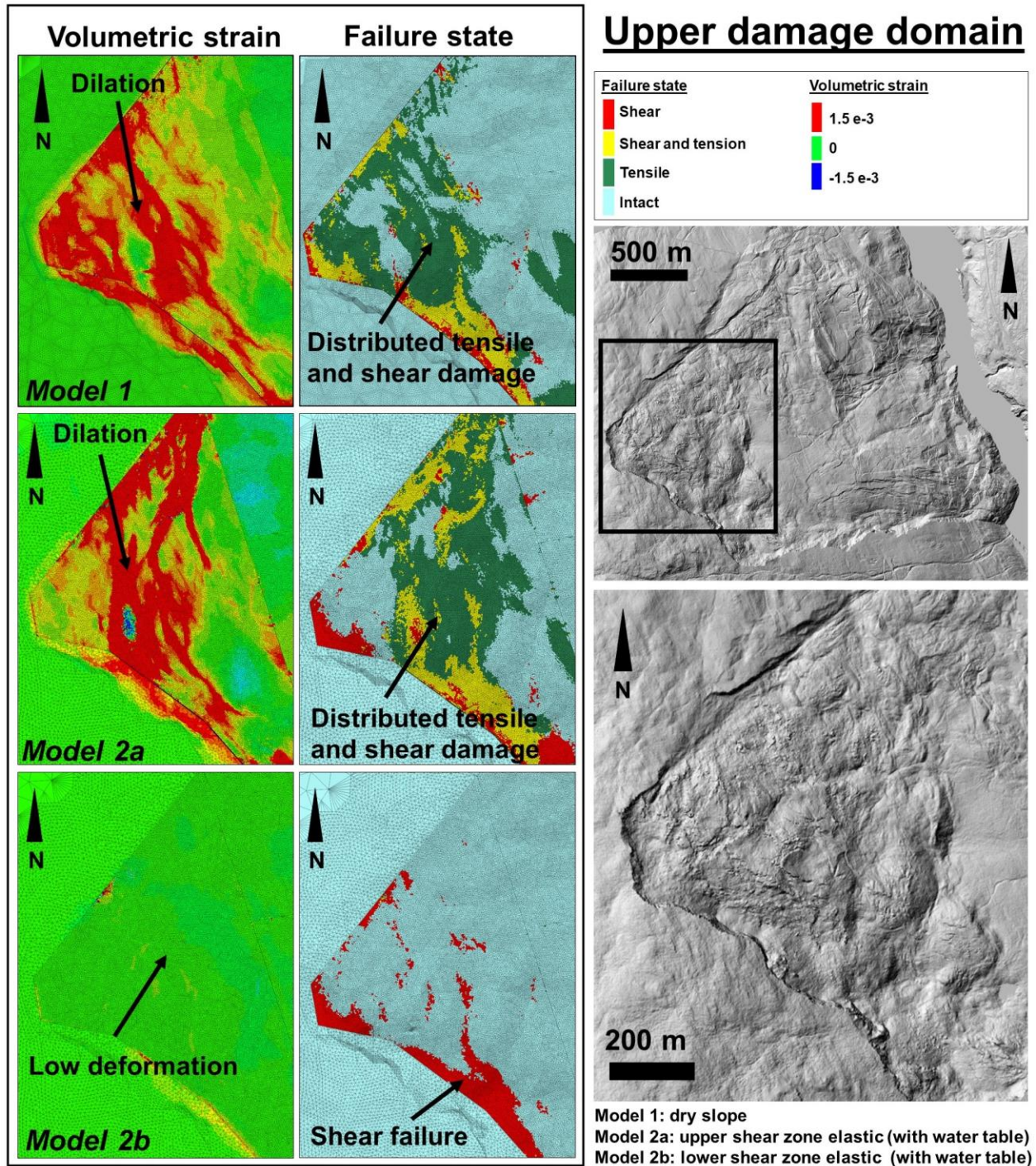
Southern damage domain



528

529 **Figure 10**

530 Southern damage domain: damage comparison between the volumetric strain and zone
 531 failure state 3DEC plots at 100,000 numerical time steps (200,000 for Model 2b) and the ALS
 532 hillshade map. Focused tensile damage developed in Models 1 and 2a. East-west oriented
 533 features, resulting from a north-south extensional behavior of the slope, agree with slope
 534 damage mapped in the ALS. Failure state plots show predominantly tensile damage
 535 throughout the domain, with shear failure in proximity of the base of the slope. The location
 536 of zones failed in shear is similar to the countercarp recognized in the ALS. Model 2b shows
 537 the simulation of a dominantly east-west trending feature that results from north-south
 extension.



538

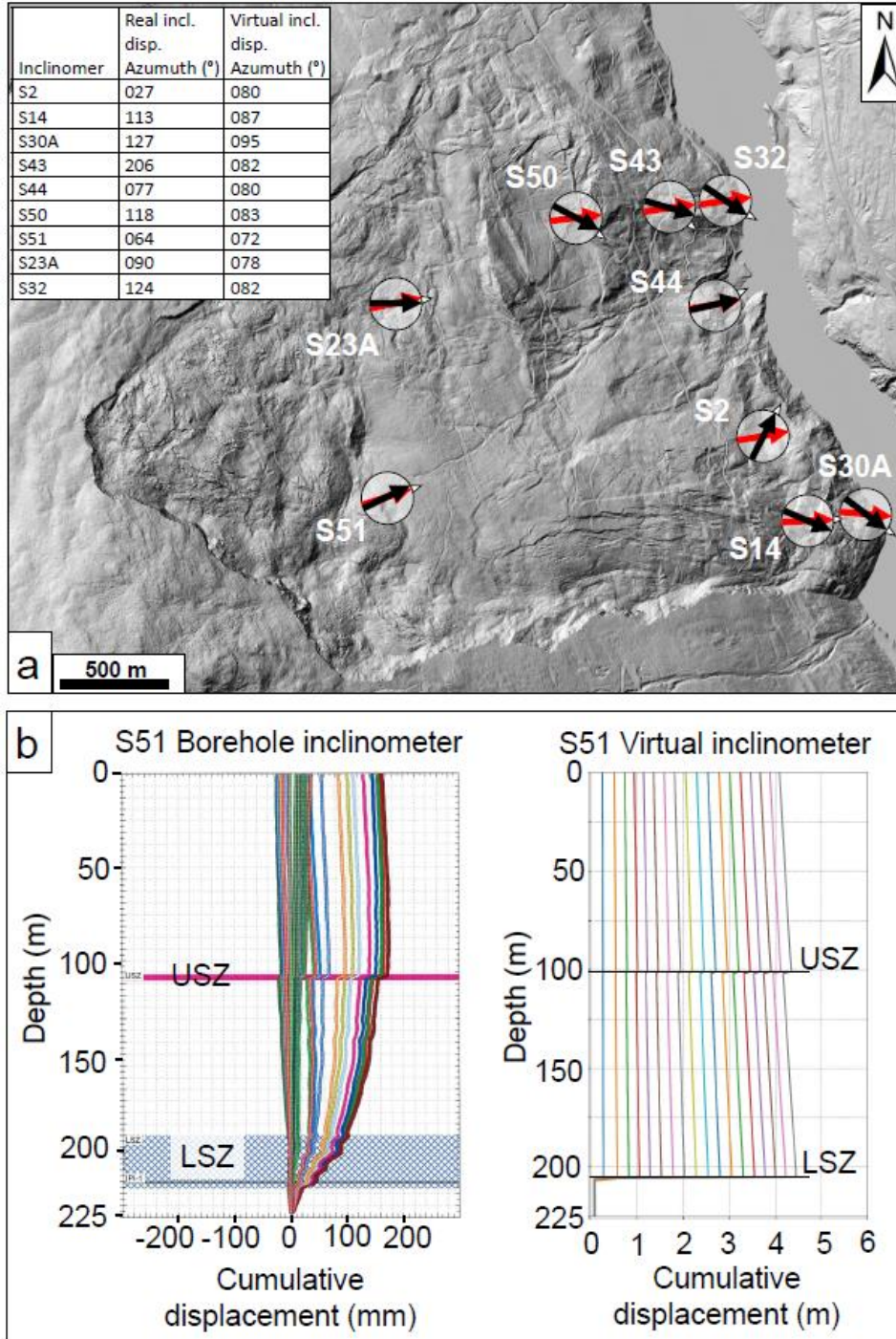
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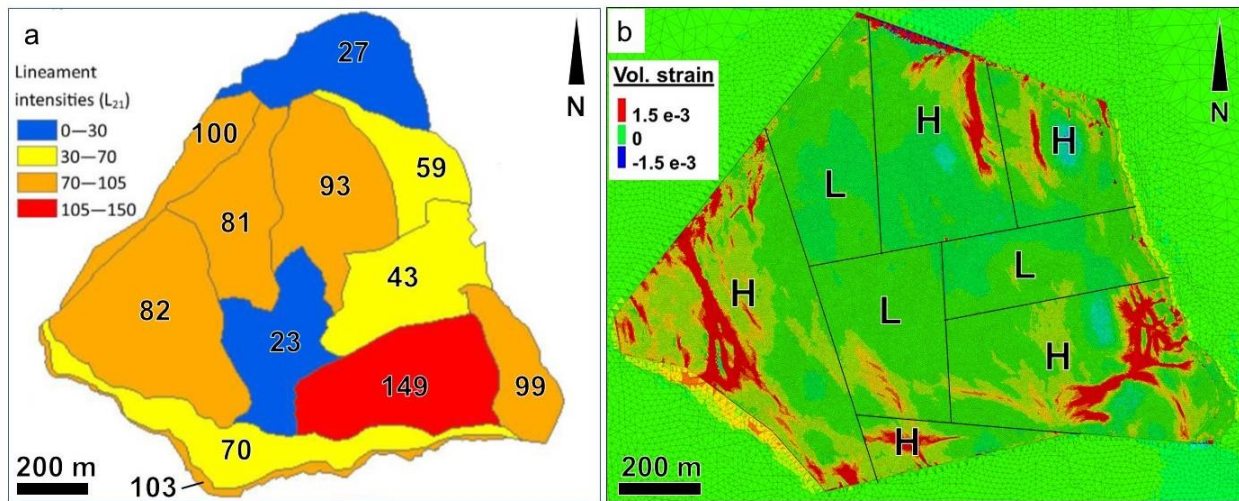
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Figure 11 Upper damage domain: damage comparison between the volumetric strain and zone failure state 3DEC plots at 100,000 numerical time steps (200,000 for Model 2b) and the ALS hillshade map. Distributed slope damage in the form of volumetric strain and failed zones can be observed in Models 1 and 2a. Model 2b showed only limited deformation and failure.



543
 544 **Figure 12** Comparison of displacement direction of real and virtual borehole inclinometers along the
 545 **LSZ** at 100,000 numerical time steps. **a:** circles show the location of the investigated
 546 boreholes. White arrowheads show the dip direction of the **LSZ** at the borehole location.
 547 **Black and red arrows** show the displacement azimuth of real and virtual inclinometer,
 548 respectively. The table shows the azimuth values computed from the recorded and simulated
 549 inclinometer plots. As no significant differences were observed between displacement
 550 direction in Model 1 and Model 2a, the virtual displacement azimuth are representative of
 551 both models; **b:** example of real and virtual borehole inclinometer logs (S51 inclinometer
 552 monitoring log, provided by BC Hydro, is presented as an example).

553 The volumetric strain plot for Model 1 was qualitatively compared with the lineament intensity analysis
 554 presented in Westin (2017). In that work, each of the twelve domains was assigned a L_{21} value, computed as the total
 555 length of the lineaments mapped in the domain divided by the surface area of the domain, thus providing a
 556 preliminary quantification of the external slope damage intensity. In particular, high lineament intensities were
 557 observed within the south knob area, in the north knob area, and in the upper slope. High lineament intensity was
 558 also observed in the northern part of the central slope. A good agreement exists between the lineament intensity map
 559 of Westin (2017) and the volumetric strain plot with positive volumetric strain increments simulated in the upper part
 560 of the slope, in the northern domain, and in the southern domain (Figure 13).



561
 562 **Figure 13** Comparison between the lineament intensity map (a, modified from Westin, 2017), and the
 563 3DEC volumetric strain plot from Model 1 (b). In the lineament intensity map, the numbers
 564 show the lineament intensity ($\times 10^{-4}$) for each domain. In the volumetric strain plot, L and H
 565 qualitatively indicate low and high relative external slope damage, respectively.

566 4.2. Comparison with previous numerical modelling of the Downie Slide

567 Previous investigations conducted at the Downie Slide, described in published and unpublished reports and
 568 papers largely focussed on four main aspects: the structural and regional setting of the area where the Downie Slide
 569 formed, the mechanisms underlying the initiation of the instability, the geomorphic characterization of the landslide
 570 area and the role of the assumed sliding surface morphology on surface displacement distribution. Kjelland (2004)
 571 investigated the initiation of the failure using the finite difference software FLAC 4 (Itasca Consulting Group 2000).
 572 He modelled the gradual retreat of the glacier from the Columbia River Valley, and the resulting slope failure at the
 573 Downie Slide due to debuttrressing and kinematic release. He observed a good agreement between the numerical
 574 results and the displacement distribution at depth in the slope using a strain-softening, ubiquitous joint constitutive
 575 model. Kalenchuk et al. (2012) employed the three-dimensional distinct element software 3DEC (Itasca Consulting
 576 Group 2016a) to investigate the effect of the shear zone thickness over the displacement rates, comparing the
 577 displacement distribution of the numerical results with the slope monitoring data. The shear zone was modelled as a

578 joint with variable stiffness values throughout the slide area. High shear zone thickness was associated with lower
579 shear and normal stiffness values. A good agreement was observed between simulated and measured displacement
580 rates, and the importance of secondary shear zones within the slide area was highlighted. Subsequently, the influence
581 of changes in the water table level (e.g., rapid reservoir drawdown, loss in drainage capacity) on the deformation
582 rates of the Downie Slide was investigated (Kalenchuk et al. 2013b).

583 Compared to previous studies, we employ a 3D DEM, strain-softening numerical model to investigate in
584 detail the correlation between displacement distribution, basal sliding surface morphology, ground water, and slope
585 damage. The effectiveness of the numerical model to reproduce the slope damage features observed on the ALS
586 dataset is demonstrated, suggesting that, if certain conditions are met (e.g., presence of a complex sliding surface),
587 surface features can be used to constrain and validate numerical modelling results. Additionally, the capability of
588 virtual borehole inclinometers to register not only the displacement magnitude, but also the displacement direction
589 with depth (i.e., when displacement magnitude is monitored in mutually orthogonal directions) has also been
590 highlighted, allowing for improved comparison and correlation between in-situ monitoring systems and numerical
591 models.

592 **4.3. Comparison with other slowly moving rockslides**

593 Slowly and extremely slowly moving rockslides often involve the displacement of material along foliation
594 and schistosity. These slope instabilities in some cases may involve significant volumes of rock mass, and assessing
595 the mechanisms underlying the deformation is of primary importance for the safeguard of nearby communities and
596 infrastructure. It has been observed that slowly moving landslides may display periods of increased velocity, but are
597 generally unlikely to evolve into fast movements without external disturbances (Bonzanigo et al., 2007; Zangler et
598 al., 2010; Glastonbury and Fell, 2008). However, in view of the very large volumes of rock mass involved, the
599 understanding of the mechanisms controlling their behavior and displacement, together with the monitoring of the
600 displacements, is critical to ensure a timely response in case of an evolution in displacement style and rate. In
601 general, these large slope instabilities share some important characteristics:

- 602 • *Geotechnical and lithological characteristics.* They generally develop in crystalline rocks that are
603 characterized by pervasive foliation or schistosity. As a result, a creeping behavior may develop within
604 the slide material, which becomes increasingly evident in the long-term. In the short term, deformations
605 remain predominantly concentrated along sliding surfaces and shear zones;
- 606 • *Multi-block structure.* They are generally constituted by multiple blocks formed as a result of the slope
607 deformation (such as internal shears), or divided by inherited geological structures. The complex, multi-
608 block structure can enhance the kinematic freedom of the entire slide body and the single blocks, and
609 therefore it plays a critical role in controlling displacement distribution;
- 610 • *Sliding surface characteristics.* They often displace along one or more sliding surfaces with complex
611 morphology, as a function of the structural setting where the slide develops. In some cases, movements
612 can be observed between the blocks forming the slide body;

- 613 • *Landslide stage*. From a geotechnical perspective, sliding surface(s) are often in a condition of residual
614 strength, which limits the likelihood of sudden displacement accelerations. This often indicates that the
615 landslide is in a post-failure or reactivation stage;
- 616 • *Hydrogeology*. They are typically characterized by a complex hydrogeological setting, with multiple
617 independent aquifers sometimes with artesian conditions. Distribution of ground-water pressure along
618 the sliding surface(s) often controls the displacement rates.
- 619 • *Geomorphology*. They generally develop in slopes that are over-steepened at the toe, due to river or
620 glacial erosion. The remaining part of the slide area can be characterized by gentler slopes.

621 Many examples of very and extremely slowly moving deep-seated rockslide have been described in
622 literature. Table 3 list some of the most significant: for each site, the geological factors controlling the displacements,
623 and similarities with the Downie Slide are presented.

624 **Table 3 Summary of the geological characteristics of selected very and extremely slowly moving**
625 **rockslides described in literature, and observed similarities with the Downie Slide.**

Landslide	Description	Similarities with the Downie Slide	References
Dutchman Ridge Slide (British Columbia, Canada)	Translational, first time slide (volume = 115×10^6 m ³ , max thickness = 110 m) on the W shore of the Mica Lake. Slide is composed of mica-schist, mica-gneiss, quartz-gneiss, and marble, with foliation dipping into the slope. Displacement (up to 20 mm/y) started with reservoir impoundment along a fault dipping 29° downslope. Drainage adit and drainholes were installed to slow down the moving mass (down to 1-2 mm/y).	Similar lithology, but with different foliation orientation; displacement driven by ground water pressure in compartmentalized aquifers.	Moore, 1993
Campo Vallemaggia landslide (Switzerland)	Massive translational rockslide (volume = 0.8×10^9 m ³ , max thickness = 300 m). Slide body is formed by amphibolites, micaceous schist, gneiss. Slope oversteepening due to river erosion initiated deep-seated displacement, along down-slope dipping foliation. Monitoring system shows variable displacement rates with intermittent increases, 1-2 cm/y, up to 3-4 m/y. A drainage adit was excavated below the sliding surface to increase stability.	Similar size and geomorphic characters; complex hydrogeological setting, including artesian aquifers, driving slope displacement; slide body subdivided in multiple independent blocks	Bonzanigo et al., 2007 Eberhardt et al., 2007
Aknes Slide (Norway)	Translational rockslide (volume = $35-40 \times 10^6$ m ³ , max thickness = 65-70 m) on the shore of the Geirangerfjord. Slide is composed of quartz-dioritic to granitic gneiss, with foliation sub-parallel to the slope, heavily folded at the headscarp. Observed surface displacement rates averaging 3-4 cm/y. Displacement direction is partially controlled by a crevice that provides lateral release.	Displacement along slope-parallel foliation; slide composed of 4 partially overlapping blocks displacing at different rates and directions.	Ganerod et al., 2008

Nine Mile creek landslide (New Zealand)	Massive compound rockslide (volume = $> 1 \times 10^9$ m ³ , max thickness = 260 m) on the E shore of the Clyde Dam reservoir. Slide is constituted by schists, with foliation dipping sub-parallel to the slope. Measured surface displacement rates up to 2 mm/y.	Similar size and geomorphic characters; displacement along slope-parallel foliation; compartmentalized aquifers within the slide body, sometimes in artesian conditions	O'Brein et al., 2016 Macfarlane, 2009
Hochmais–Atemkopf rockslide system (Austria)	Cluster of nested translational rockslides along the shore of the Gepatsch reservoir (total volume = 290×10^6 m ³ , max thickness = 220 m). Slide is composed of paragneiss, mica schist, and orthogneiss, with foliation dipping into the slope. Displacements occur along discontinuities normal to foliation. Ground surface displacement rates are up to 2.5 cm/y.	Complex, multi-block landslide structure; structurally-controlled sliding surface	Zangler et al., 2010

626 5 Conclusions and future work

627 Lithology, geological structures, and the geomorphic evolution of the valleys are all important factors that
628 influenced, and continue to influence, the kinematic configuration of the slope, and in turn the nature, distribution,
629 and orientation of the slope damage developed at the Downie Slide. The investigation of slope damage from ALS,
630 boreholes, and remote sensing can provide important insights on the spatial variations in slope deformation.

631 In this study, 3D numerical modelling of the Downie Slide was undertaken to investigate the role of shear
632 zone morphology and groundwater on the characteristics of external slope damage observed in the ALS dataset.
633 Simulation results showed that the complex geometry of the lower shear zone has a strong control on style and
634 spatial distribution of external slope damage at the Downie Slide. Conversely, the geometry of the upper shear zone
635 has limited influence on the evolution of slope damage. Additional investigations should focus on the role of the
636 USZ on the evolution of local, smaller scale instabilities. Future analyses should also explore the effects of the pre-
637 existing slope damage on the displacements within the slide. Specifically, initial material properties for each block
638 should be down-scaled proportionally to the amount of damage observed in the ALS dataset. The quality in the
639 reconstruction of the lower and upper shear zones is directly related to the borehole density across the slide area.
640 Therefore, the collection of additional subsurface data in areas sparsely instrumented, including the boundaries and
641 the upper part of the slope, may be beneficial in further constraining the shear zone geometry and improve the
642 reliability of the numerical modelling results.

643 Numerical modelling results indicate that the principal effect of pore water pressure along the shear zones is
644 on the magnitude of the simulated displacement. However, a simplified approach was used in this preliminary study,
645 which involved the analysis of the water pressure acting on the lower and upper shear zones in two distinct models.

646 In order to include both shear zones in a single model, the variations in pore pressure within the slope should be
647 known a priori, due to the complexity of the hydrogeological system at the site. Therefore, a detailed three-
648 dimensional hydrogeological model would be required to assess the pore pressure distribution throughout the slope
649 before incorporation into three-dimensional geomechanical models. This approach would allow a more
650 comprehensive validation of critical pressures levels, and the assessment of their variations. Additionally, the effects
651 of slope damage formation and accumulation on the permeability of the rock mass should be addressed. An increased
652 porosity may facilitate the migration and redistribution of pore water pressure within the slope, with potential
653 controls on the displacement rates of the slide.

654 This paper highlights an innovative method of comparing observed and simulated slope damage features
655 using ALS – GIS analysis and 3DEC modelling respectively. The orientation, type, and distribution of ALS slope
656 damage features has been shown to be a valuable method of validating and constraining the 3DEC numerical
657 modelling results, particularly when used in combination with subsurface borehole inclinometers and GIS
658 characterisation of the sliding surface geometry. The authors suggest that detailed characterization of slope damage
659 using remote sensing, if possible combined with change detection and/or InSAR, should be considered a fundamental
660 part of site investigation and monitoring of major landslides and unstable slopes. Such studies would lead to an
661 improved understanding of slope deformation mechanisms with benefits for future slope hazard and risk assessment.

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