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Using pre-failure and post-failure remote sensing data to constrain the three-dimensional numerical model of a large rock slope failure

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Using pre-failure and post-failure remote sensing data to constrain the three-dimensional numerical model of a large rock slope failure Davide Donati ¹*(ORCiD: 0000-0003-4083-5910); Doug Stead ¹; Marc-André Brideau ²; Monica Ghirotti ³

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12 Abstract

13 Factors governing rock slope stability include lithology, geological structures, hydrogeological conditions, 14 and landform evolution. When certain conditions are met, rock slopes may become unstable, inducing deformation 15 and failure. In this study, an integrated remote sensing-numerical modelling approach investigates the deformation 16 mechanisms leading to the 1965 Hope Slide, BC, Canada and the effect of slope kinematics on the long-term 17 evolution of the slope. Pre- and post-failure datasets were used to perform a large-scale geomorphic and structural 18 characterization, including kinematic and block-theory analyses. Extensive data collection was also undertaken using 19 state-of-the-art remote sensing techniques, including digital photogrammetry (Structure-from-Motion), laser 20 scanning (aerial and terrestrial), and infrared thermography. New evidence is provided that one or more prehistoric 21 failures caused the removal of a key-block, and the initiation of long-term slope deformation and cumulative slope 22 damage ultimately resulting in the catastrophic 1965 event. Detailed characterization of the rock slope has allowed 23 the first three-dimensional, distinct element numerical model of the Hope Slide to be conducted. The results of the 24 numerical simulations involving gradual reduction of the rupture surface shear strength indicate that 1965 slope 25 failure may represent the outcome of a long-term, progressive failure mechanism that initiated after a prehistoric 26 landslide. This combined field mapping-remote sensing- numerical modelling study clearly highlights the role of 3D 27 slope kinematics on the geomorphic evolution of the slope, along with the associated failure mechanisms.

28

Keywords: Hope Slide; remote sensing; 3D-numerical modelling; slope kinematics; GIS analysis

29 **1 Introduction**

Investigating the stability of high rock slopes is becoming increasingly important, as higher and steeper slopes are accommodating exponential population growth and increased demand for resources (Petley, 2010). As part of a detailed rock slope hazard assessment, a careful geological investigation of the slope is therefore critical to identify the mechanisms that may cause the occurrence of major landslide events.

34 The deformation and failure of rock slopes is controlled by many interacting geological factors and 35 processes. Geological structures, such as faults, folds, and rock mass jointing, as well as lithological features, such as 36 bedding planes, can provide basal, rear, or lateral release to unstable volumes of rock mass (Stead and Wolter, 2015). 37 The vast majority of large landslide events were at least partially controlled by geological structures, including the 38 Frank Slide (Humair et al., 2013), the Vajont Slide (Semenza and Ghirotti, 2000; Wolter et al., 2014), and the 39 Palliser rockslide (Sturzenegger and Stead, 2012). Slope morphology can also control the development of slope 40 instability, by providing lateral kinematic release to potentially unstable rock slopes (Ganerød et al., 2008; Brideau, 41 2010). The condition for which discrete blocks may be removable from the slope is generally referred to as 42 "kinematic freedom". While geological structures with high persistence and step-path geometries formed by 43 intersection of discontinuities are essential in providing kinematic freedom to large rock slope failures, time-44 dependent and dynamic processes can modify the kinematic conditions of rock slopes and enhance the mobility of 45 landslides. For instance, the steepening of slopes due to river erosion and glacial advance and retreat can promote 46 instability by causing stress concentration at the toe and daylighting of the basal rupture surface (Clayton et al., 47 2017). The progressive accumulation of damage is also critical in the evolution of slope stability (Stead and 48 Eberhardt, 2013). The action of endogenic factors, such as earthquakes (Gischig et al., 2015; Wolter et al., 2016), 49 and exogenic factor, such as extreme weather events (Azzoni et al., 1992), and cyclic fluctuation in groundwater 50 table (Preisig et al., 2016), causes the formation of internal and external features, referred to as slope damage, that 51 progressively weaken the rock slope (Stead and Eberhardt, 2013). Brittle fracturing of intact rock bridges may reduce 52 kinematic constraints, causing failures to occur in otherwise stable rock slopes (e.g. Donati et al., 2019).

53 Due to the complex interaction of the factors described above, the identification of the mechanisms and 54 processes underlying large-scale slope instability requires a comprehensive analysis. The introduction and 55 improvement of remote sensing techniques has enhanced the amount and quality of geological data that can be 56 collected. Structural and geomorphic data at various scales may be extracted from point clouds obtained from 57 airborne and terrestrial laser scanning (ALS/TLS; Jaboyedoff and Derron, 2020) or photogrammetric techniques, 58 such as terrestrial digital photogrammetry (TDP; Birch, 2006; Francioni et al., 2019) and Structure-from-Motion 59 (SfM; Westoby et al., 2012; Vanneschi et al., 2019). Small-scale rock mass and slope damage features may also be 60 mapped using high-resolution photography (HRP; Donati et al., 2018; Spreafico et al., 2017a). Water seepage in rock slope may be investigated using Infrared Thermography, (IRT; Vivas, 2014). Recently, IRT has been employed to 61 62 identify near-surface intact rock bridges (Guerin et al., 2019). Numerical modelling is also beneficial for detailed

63 characterization of the processes driving the deformation and failure of rock slopes. Kinematic analyses and limit 64 equilibrium methods may be used in preliminarily investigation of the failure mechanisms and the factor of safety of 65 a slope (Hungr and Amann, 2011; Lu et al., 2016). Continuum methods, such as finite element and finite difference 66 methods (FEM/FDM), model the material forming the slope as a continuum and are best suited to investigate 67 problems where rock mass strength controls slope failure (Grøneng et al., 2010; Riva et al., 2018). In recent years, 68 continuum-based numerical modelling codes have been introduced that are capable of implementing discontinuities 69 within a Finite Element or a Finite Difference mesh, making them capable of simulating fractured rock masses 70 (Hammah et al., 2007; Spreafico et al., 2017b). Discontinuum methods, such as the distinct element method (DEM), 71 consider the material as an assembly of blocks that can rotate, slide, and detach from each other, and have been 72 largely employed for the analysis of slopes where the stability is governed by structures and block interaction 73 (Havaej et al., 2016). Hybrid finite-discrete element methods (FDEM; Munjiza et al., 1995) and lattice-spring 74 methods (Cundall, 2011) have been introduced to investigate the role of the brittle fracturing of rock on the stability 75 of a slope. Increasingly sophisticated numerical modelling methods allow more complex failure mechanisms to be 76 modelled; in turn, their use requires input data that is both more sophisticated and challenging to collect (Stead and

77 Coggan, 2012).

78 In this paper, an integrated remote sensing-numerical modelling approach was used for the investigation of 79 a major rock slope failure, the 1965 Hope Slide, in British Columbia, Canada. First, several remote sensing 80 techniques and approaches were employed to investigate the structural and geomorphic setting of the slope and 81 analyse its kinematic configuration. A re-interpretation of the slope failure is provided highlighting the role of a 82 large, pre-historic event that occurred at the same site on the long-term stability evolution of the slope and the 83 progressive accumulation of slope damage. A three-dimensional, distinct element numerical analysis is performed to 84 investigate the role of the geological structures and progressive cohesion degradation on the long-term stability and 85 deformation of the rock slope. Using such an integrated approach, we highlight the role of slope kinematics on the 86 stability of high rock slopes, and the importance of using three-dimensional numerical methods in the investigation 87 of structurally controlled slope failures.

88 **2** The Hope Slide

89 **2.1.** History of the slide

The Hope Slide involved a volume of 48 million m³ of rock and it is the second largest historical rock
avalanche in Canada. The slope failure occurred, in two stages, early in the morning of January 9th, 1965, between
4:00 am and 7:15 am (Anderson, 1965). The slide affected the southern slope of the Johnson Ridge, 15 km east of

the municipality of Hope, in British Columbia, between a ground elevation of 870 and 1,800 m above sea level

94 (a.s.l), (Mathews and McTaggart, 1969) (Fig. 1a). The slide debris completely filled the Outram Lake, located at the

95 base of the slope, climbed up the opposite side of the Nicolum Valley, and travelled down valley for about 2 km. The

- rock slope failure intersected and buried the Hope-Princeton Highway, raising the valley floor up to 60 m above its
- 97 original elevation, and killing four people (Anderson, 1965). Two low intensity earthquakes (M=3.2 and M=3.1)
- 98 were registered at the Penticton seismic station (120 km east of the Hope Slide) at the same time as the failures and
- 99 were initially proposed as the trigger mechanism for the failure (Mathews and McTaggart, 1969). The hypothesis
- 100 was initially confuted by Wetmiller and Evans (1989), who observed that larger earthquakes registered in the area
- 101 failed to trigger major slope failures. A seismic trigger was later shown to be incorrect by Weichert et al. (1994), who
- also suggested that the two earthquakes were the result, rather than the cause, of the slope collapse. The 1965 event
- 103 occurred on the same slope as a pre-historical failure (Cairnes, 1924), of similar volume (Mathews and McTaggart,
- 104 1969). Evans and Couture (2002) excavated trenches to investigate the stratigraphy of the material above the 1965
- 105 headscarp and concluded that the event was not an episodic failure, but rather the catastrophic outcome of a
- 106 progressive, long-term deformation of the slope.

107 Presently, the activity of the slope is predominantly characterized by small rockfalls occurring at the 108 intersection of fault-damage zones and the headscarps. Several events were observed while the photogrammetric 109 surveys described in this study were being undertaken, particularly along the lateral scarp. InSAR investigations 110 have also shown that marked displacement is occurring at the upper headscarp, although within limited, localized 111 areas (Hosseini et al., 2018). Similar deformation was also recognized by von Sacken (1991), who observed the 112 opening of a tension crack behind the headscarp. Slow deformation was also observed within the debris field and has been interpreted possibly as a result of the consolidation of sediments at depth due to surcharge by the 1965 deposit, 113 114 or a slow-moving creep that developed within the Hope Slide debris (Hosseini et al., 2018).

115 2.2. Geological and structural overview

The Hope Slide is located within the Northern Cascades Mountain Range, in southern British Columbia. The slide area is presently bounded on the northern and north-western sides by sub-vertical slopes, up to 150 m high, which define the lateral scarp and upper headscarp, respectively. The rupture surface dips in a westward direction at an angle of 30°. The basal sliding surface is largely covered by debris, except for a steeper, 200 m by 150 m area in the central part of the slope, where the bedrock outcrops (Fig. 1b).

The slope is formed by Paleozoic greenstone of the Hozameen Complex, a weakly metamorphosed mafic volcanic rock (Fig. 1c,d). The rock is massive in nature, and the volcanic texture and structure have been obliterated by metamorphic recrystallization (McTaggart and Thompson, 1967). Locally, the greenstone is intruded by sills and dikes of felsite, an aphanitic, volcanic rock that occurs as pinkish and buff colour varieties. Buff felsite is organized in sills dipping out of the slope. Two such sills clearly stand out within the daylighting portion of the rupture surface (Fig. 1d). Felsite-greenstone lithological contacts appear to be sharp and devoid of gouge, except within or close to tectonic structures (faults and shear zones), where clay-rich infill can be observed (Brideau et al., 2005).

- 128 The slide area is traversed by several NNW-SSE striking faults that form gullies and crevices on both sides
- 129 of the Johnson Ridge (Fig. 1a). Von Sacken (1991) suggested that the structures controlled the behavior of the slide,
- 130 and that one of the faults divided the volumes that failed in the two stages of the 1965 event. Brideau et al. (2005)
- 131 further investigated the structurally controlled nature of the slope failure, suggesting that tectonic shear zones may
- have acted as lateral release surfaces along the northern and southern boundaries of the slide. They also observed
- 133 changes in orientation of the basal rupture surface, which were associated with a regional scale synform.

134 **3 Methods**

The investigation of the rock slope involved in the 1965 event was undertaken at progressively larger scales,
in order to characterize the slope in an increasingly higher level of detail. The workflow proposed in Donati et al.
(2017) was followed for the data collection and processing, and is summarized in Fig. 2.

138 **3.1.** Slope-scale structural and geomorphic characterization

We reviewed and processed both existing and new data to assess the long-term evolution of the slope, and the potential underlying mechanisms. A set of historical aerial photographs taken in 1961 (four years prior to the event) was obtained from the Province of British Columbia database (roll BC4014, frames 21-25), and a pre-failure DTM with 10 m resolution was reconstructed using a SfM approach in Photoscan (Agisoft LLC, 2018; Fig. 3). Easily identifiable natural points outside of the area affected by the slide were selected in the pre-failure imagery, and their location obtained from the 2015 ALS dataset that was made available for this study by the Ministry of Transportation and Infrastructure (MoTI) of British Columbia.

The pre- and post-failure failure topographic surfaces were employed to characterize structural and geomorphic features within the area of interest, and to investigate the relationship between first-order geological structures and slope stability. The analysis was undertaken in ArcGIS 10.5 (ESRI, 2017), where hillshade, aspect, and slope maps of the pre- and post-failure DTMs were created and used to perform lineament mapping (e.g., Donati et al., 2020; Francioni et al., 2018). The long-term evolution of the slope considering the prehistoric event that affected the slope (Mathews and McTaggart, 1969) was investigated, from a kinematic perspective, by performing a block-theory analysis (Goodman and Shi, 1985).

A volume estimation was also undertaken, by comparing the elevation change between the pre- and postfailure models. For this analysis, both the TLS and the ALS dataset were employed, and the resulting volume computations compared. The TLS dataset was collected using a Riegl VZ-4000, full-wave form TLS characterized by a maximum operating range of 4,000 m (Fig. 4a). The raw dataset was first pre-processed in RiSCAN Pro 2.6 (Riegl LMS GmbH, 2018), then, CloudCompare (CloudCompare 2.10, 2019) was used to build a high resolution DTM of the slide area and the headscarp.

159 **3.2.** Outcrop-scale remote sensing characterization

A detailed characterization of the slide area was performed using both remote sensing and traditional field methods. The use of remote sensing techniques allowed for large amounts of high-resolution data to be collected from a distance. Traditional field work procedures were employed to collect discontinuity surface data, such as roughness, infilling, and alteration conditions. In this study, the outcrop-scale characterization of the slope was conducted using primarily TLS, photogrammetric techniques and IRT.

The detailed geomechanical characterization of the rock mass was performed using the TDP technique. Photographs of the lateral scarp and headscarp were collected using a Canon EOS 5D Mark II, 21 Mega Pixel digital single-lens reflex (DSLR) camera with an f = 400 mm focal length lens (Fig. 4b). 3D models were constructed and discontinuities mapped using 3DM Analyst mapping suite 2.5 (AdamTechnology, 2017). Discontinuity spacing, persistence, and orientation were obtained from the models, and the results were compared to the trend of lineaments

170 mapped during the large-scale investigation.

A preliminary analysis of the groundwater seepage was performed using the IRT technique, which allows for the infrared (IR) radiation emitted by an object to be captured and converted into a temperature value. In this study, a FLIR SC7750 was employed (Fig. 4c), and thermal imagery was processed using Research IR (FLIR Systems Inc., 2015).

A block size distribution analysis of the slide deposit was undertaken using a UAV-SfM (Unmanned aerial vehicle-SfM) approach. A DJI Phantom 3 Pro Quadcopter (Fig. 4d) was employed to collect imagery along a predetermined flight path, designed to provide an 80% overlap between adjacent images. A total of 680 photographs were collected, covering an area of 2 km² of debris deposit at the base of the slope. The photographs were then processed using Photoscan software, and the obtained orthorectified image was used to perform the block size analysis.

181 The surface area covered by each remote sensing datasets collected and/or processed during this study, as 182 well as the survey stations, are outlined in Fig. 5. For each dataset, Table 1 summarizes the resolution and the 183 intended application.

184 **3.3. Numerical modelling**

The main objective of the simulations was to investigate the role of slope kinematics on the behavior and long-term evolution of the Hope Slide. The data obtained from field mapping and analysis of both historical imagery and remote sensing surveys were used as input in the numerical modelling of the 1965 Hope Slide. Material and discontinuity properties assigned in the model were obtained from geotechnical laboratory test results, including direct shear tests performed on fault gouge, performed and described in previous studies (Brideau et al., 2005; von

- 190 Sacken, 1991). However, the residual friction angle for the lower order discontinuities (i.e., rock mass jointing) were
- defined through a trial-and-error approach, based on the overall behavior of the model, and its ability to realistically
- 192 reproduce the failure.

193 **4 Results**

194 4.1. Slope-scale characterization

195 **4.1.1. Structural investigation**

196 The analysis of the ALS dataset using hillshade, slope, and aspect maps allowed for the identification and 197 mapping of slope-scale structural lineaments (Fig. 6a). Over 200 lineaments were mapped, and their bearing 198 computed in ArcGIS. The orientations were plotted in a rosette diagram, which show that three orientation trends 199 occur across the slide area, referred to as I (025°), II (070°), and III (125°) (Fig. 6b). The NNE trending faults that 200 intersect the lateral scarp can be ascribed to trend I. The lateral scarp itself appears to be formed by the intersection 201 of trend I and trend II lineaments. Conversely, the orientation of trend III is roughly parallel to the upper headscarp, 202 suggesting that this feature is structurally controlled by ESE- to SE-trending geological structures. In the upper slope, 203 the headscarp intersects three counterscarps roughly oriented parallel to lineament trend III, suggesting that these are 204 at least partially structurally controlled (Fig. 6c).

Presently, the slide area is largely covered in debris, precluding identification of structural lineaments except for the outcropping part of the rupture surface in the central part of the slope. Therefore, the pre-failure DTM created based on the historical aerial photographs was used to investigate the structural configuration of the part of rock slope that failed in 1965. From the analysis of the hillshade, aspect, and slope maps, six large, first-order structural features were identified within the slide area and denoted as L1 to L6. The first-order structures subdivide the slide volume into five slide blocks, progressively numbered from the bottom of the slope to the crest, B1 to B5 (Fig. 7a-c).

212 A large-scale block theory investigation was then performed using the identified first-order structures. 213 Block theory analysis identifies all the blocks that may potentially form within a simplified slope, and classifies them 214 into "stable", "unstable", "infinite", and "key" blocks (Goodman and Shi, 1985). The objective of the analysis was to 215 identify key blocks, the removal of which may have caused the remaining blocks to fail retrogressively. According to 216 von Sacken (1991) and Brideau et al. (2005), the basal release surface of the Hope Slide was formed by a 217 discontinuity set sub-parallel to the slope, which was therefore included in the block theory investigation. The 218 analysis shows that block B1 represents a key block for the slope, and its removal would allow the subsequent failure 219 of blocks B2 to B5 (Fig. 7d).

4.1.2. Geomorphology of the slope before the failure

221 The 1961 aerial photographs show abundant evidence of slope activity prior to the 1965 Hope Slide. At the 222 base of the slope, a large, vegetated debris fan can be observed, that exceeds the elevation of the surrounding valley 223 floor by about 60 m (Profiles B-B' and C-C' in Fig. 8a,c). It is currently unclear whether its formation was caused by 224 a single, relatively large event, or rather a prolonged accumulation of material caused by debris flows and rockfalls 225 under varying climatic conditions. The former Outram Lake, which was subsequently completely filled by the 1965 226 Hope Slide, is located in front of the fan, and lies on the deposit of a prehistoric landslide (Cairnes, 1924; Mathews 227 and McTaggart, 1969). The elevation of the lake was about 710 m a.s.l. in 1961, and at its downstream side the 228 valley floor was located at a ground elevation of 750 m a.s.l. In this elevated area, a hummocky morphology can be 229 observed in the aerial photograph, and boulders appear to be scattered throughout the area (Fig. 8b). About 550 m northwest from the lake, the valley floor elevation drops to about 680 m a.s.l., possibly outlining the edge of the 230 231 ancient landslide deposit (Profile A-A' in Fig. 8a,c). Radiocarbon analyses on organic material collected below the 232 deposit yielded an age of 9,680 years B.P., which marks a minimum age for the event (Mathews and McTaggart, 233 1978).

234 Several rockfall source areas can be identified between elevation 1,130 m a.s.l. (near the northern boundary 235 of the 1965 slide area) and 1,740 m a.s.l. (below the upper 1965 headscarp). Mathews and McTaggart (1969) 236 suggested that the cliffs bounding the pre-1965 active slide area also outline the headscarp of the prehistoric 237 landslide event. From the source areas, active debris channels follow the steepest path toward two main deposition 238 areas. The first deposition area is located above the debris fan at the base of the slope and accommodates rockfall 239 material from the northeastern sector of the active area. The second deposition area is located on a structural ledge in 240 the central part of the slope. This accumulation area is clearly visible in the pre-1965 slope map, in the form of a flat 241 surface 300 m wide and up to 150 m long. Cliffs, debris channels and accumulation areas are largely free of 242 vegetation, in view of their active state as captured in the 1961 aerial photographs, whereas a dense canopy existed 243 elsewhere within the slope (Fig. 8d).

244 The analysis of the pre-1965 aspect map shows a series of counterscarps in the upper portion of the slope, 245 partially or completely free of vegetation (Fig. 8d). These features were truncated during the failure, as noted in the 246 ALS dataset (Fig. 6c). Such external slope damage features have been associated with the evolution of deep-seated 247 gravitational slope deformations of sackung type (Agliardi et al., 2012; Ambrosi and Crosta, 2006). The uppermost 248 counterscarp was only partially involved in the 1965 event, and presently shows evidence of slope movements (von 249 Sacken, 1991). Additionally, geomorphological field analyses showed evidence of a long-term deformation that was 250 ongoing prior to the 1965 slope failure, suggesting that the 1965 event represents the catastrophic outcome of a 251 sagging rock slope (Evans and Couture, 2002).

A visual analysis of the 1961 aerial photographs shows the presence of a prominent cliff, located at the boundary between slide blocks B2 and B5, which is recognizable in the slope both in the pre- and post-failure

- 254 imagery (Fig. 9a). This evidence suggests that only a minor volume of material originated from the section of the
- slope below this cliff feature. We propose that the prehistoric slope failure involved the detachment of slide blocks
- B1 and B2, with only limited contribution of material from the upper blocks, and, conversely, the 1965 event
- 257 predominantly involved the failure of blocks B4 and B5 (Fig. 9b).

4.1.3. Volume estimation

259 The volume and the thickness of the material involved in the 1965 Hope Slide event was estimated by 260 subtracting the pre-failure DTM (obtained from the SfM model) from the post-failure topography within the slide 261 area (Fig. 10a-d). For the volume calculation, the ALS and TLS datasets were considered independently. First, all datasets were registered considering the ALS as the reference surface. The volume was calculated using a cut-fill 262 analysis in ArcGIS 10.5. A total volume loss of 47.8 x 10⁶ m³ and 46.5 x 10⁶ m³ was computed using the ALS and 263 264 TLS ground surface, respectively. The differences are probably related to the presence of occlusions within the TLS 265 dataset, which resulted in local surface interpolation during the creation of the DTM. In both cases, the maximum thickness of the slide was observed in the upper portion of the slope, within block B5 (141 m) and block B4 (134 m). 266 267 Within blocks B1, B2, and B3 the maximum elevation difference ranges between 24 m and 53 m (Fig. 10c). The volume of the blocks forming the slide were separately investigated, and it was noted that the upper blocks (B4 and 268 269 B5) comprised approximately 80% of the volume lost during the 1965 failure. The contribution to the estimated 270 volume loss from the lower slope in the 1965 event (20% of the total volume) may be constituted by loose material 271 incorporated during the failure.

The volume loss computed in this research agrees well with previous estimations, which ranged between 47.3 x 10⁶ m³ (Mathews and McTaggart, 1969) and 48.3 x 10⁶ m³ (von Sacken, 1991). These calculations were based on the same isopach map described in Mathews and McTaggart (1969), created by computing the difference between topographic maps prior to and after the 1965 event.

4.2. Outcrop-scale rock mass and debris characterization

277 4.2.1. Rock mass characterization

The objective of the detailed remote sensing investigation was to collect rock mass discontinuity data including orientation, persistence, and spacing. The characterization was undertaken using TDP, performed on the lateral scarp and upper headscarp, and the daylighting portion of sliding surface at mid-slope. Over 1,600 discontinuities were mapped in the 3DM Analyst software, and their orientation plotted on stereonets using DIPS (Rocscience, 2016). Three main discontinuity sets were identified, namely J1, J2, and J3. J1 is sub-parallel to the slope surface (30°/245° Dip/Dip Direction on average) and likely provided a basal rupture surface for the 1965 event (Brideau et al., 2005; von Sacken, 1991), and possibly also for the prehistoric failure. Discontinuity sets J2 and J3

285 (76°/297° and 84°/350° on average, respectively) are both sub-perpendicular to J1 (Fig. 11a). Virtual scanlines were

- also traced on photogrammetric models at various locations along the lateral scarp and the upper headscarp, to
- 287 characterize the discontinuity persistence and spacing. The average persistence of the identified discontinuity sets is
- 288 16 m, 10 m, and 11 m, for J1, J2, and J3, respectively. Both discontinuity sets J1 and J2 are closely spaced within the
- 289 slide area, whereas spacing for the set J3 is uncertain due to limited discontinuity visibility and unfavorable
- 290 orientation for estimation. The structural analysis suggested that five structural domains are present within the slide
- area, which are approximately delineated by the first-order geological structures identified in the slope-scale
- structural and geomorphic analysis. Throughout the domains, a progressive counter-clockwise rotation of the main
- discontinuity sets can be recognized between the headscarp and the base of the slope (Donati et al., 2013). Von
- 294 Sacken (1991) also observed a change in the orientation of the discontinuities between the upper and lower slope.
- Brideau et al. (2005) suggested that a large-scale fold may exist, that affects the structural setting of the slide area.
- 296 The results from this study agree well and further expand their findings.

A comparison between the orientation of the first-order geological structures and lineaments, and that of the mapped second-order discontinuity sets was performed. A significant agreement was noted between the orientation main lineament trends I, II, III, and the discontinuity set J2, J3, and J1, respectively, as shown in the rosette diagrams (Fig. 11b,c). It is therefore suggested that the structural features mapped at slope-scale are strongly correlated to rock mass jointing. The orientation of the geological structures that intersect the slide area, and sub-divide the slide body into blocks (i.e., structures L1, L3, and L4 in Fig. 7), also display a general agreement with the orientation of the lineament trends and discontinuity sets, particularly trend I and discontinuity set J2.

304 **4.2.2. Seepage analysis**

305 A seepage investigation was performed using IRT. The FLIR SC7760 thermal camera was employed to 306 capture infrared imagery of the rupture surface from the viewpoint at the southwestern edge of the debris field (Fig. 307 5). Several seepage areas were identified and mapped, mostly located within the daylighting portion of rupture 308 surface in the central part of the slope (Fig. 12). Most of the seepage was found to occur along discontinuities in set 309 J1 and at lithological contacts between greenstone and felsite. The presence of excessive pore water pressure along 310 discontinuities sub-parallel to the slope orientation may have decreased the effective stresses along the rupture 311 surface, thus acting as a predisposing factor for the failure. However, the role of groundwater in 1965 is still unclear. 312 Mathews and McTaggart (1969) argued that pore water pressure did not have a primary role in the slope failure, due 313 to the low, below-freezing temperature observed in the area in the weeks prior to the event. In fact, they suggested 314 that freezing temperatures prevented snowmelt, while a continued seepage, due to the geothermal gradient, led to the 315 gradual depletion of hydrostatic pressure in the rock fractures. Conversely, Brideau et al. (2005) suggested that cold 316 temperature could have caused the groundwater to freeze at the surface, preventing seepage and thus the dissipation 317 of the hydrostatic pressure. Additionally, an increase in minimum temperature from -12°C to 0°C was registered at 318 the "Hope A" weather station (located at the Hope Aerodrome) in the two days prior to the failure. This increase in 319 temperature, together with the typically high rainfall in December and January (around 250-280 mm monthly

320 precipitation) may have induced snowmelt and thus a sudden increase in hydrostatic pressure along the rupture 321 surface, possibly triggering the failure.

322 **4.2.3.** Rock avalanche deposit block size analysis

The slide deposit was characterized using a SfM approach. Photographs collected with the DJI Phantom 3 Pro Quadcopter were used for the construction of a 3D model and an orthorectified image (Fig. 13a-c). Photographs were obtained by flying the UAV at a constant altitude of 30 m, allowing for a constant ground pixel size of 4 cm throughout the entire image dataset.

327 A block size analysis distribution was performed on the orthophoto using ArcGIS 10.5. A modified version 328 of the workflow described in Shugar and Clague (2011) was employed. The outline of over 2,000 blocks larger than 329 16 m² was manually digitized, and their area computed. The smallest enclosing rectangle was then obtained for each 330 of the digitized polygons. The block volume was then estimated as the product of the surface area of the block 331 outlined in the orthophoto and the average side length of the enclosing quadrangle. The maximum estimated block 332 volume within the slide debris is about 4,000 m³, while the average volume is 78 m³ (Fig. 13d). For each block, a 333 two-dimensional block aspect ratio was also calculated, defined as the ratio between the length of the major and 334 minor sides of the enclosing rectangle. Aspect ratio was computed to constrain the relative spacing of each of the 335 discontinuity sets to be considered in the numerical models (see next section) The aspect ratio distribution has a log-336 normal distribution when all the blocks are considered (Fig. 13e). Conversely, when blocks larger than 500 m³ only 337 are considered, an average aspect ratio of 1.5 is obtained (Fig. 13f). This evidence suggests that while the shape of 338 large blocks may reflect the joint spacing within the intact rock mass, brittle fracturing processes and comminution 339 due to impacts with other blocks and the ground during the failure cause the original, structurally controlled block 340 shape to be lost. It should be stressed that the purpose of this analysis was not an accurate characterization of the 341 block size distribution representative of the entire deposit, but rather a more general indication of the potential size of the blocks that detached from the slope, prior to any significant comminution. 342

343 **4.3. Numerical modelling**

4.3.1. Construction of the 3D numerical model

345 The results of this study confirmed the structurally controlled nature of the slide, expanding on the findings

from previous works (Brideau et al., 2005; von Sacken, 1991. In view of the strong structural control and complex

347 kinematics, the use of a three-dimensional distinct element method (DEM) approach was deemed to be instrumental

348 in simulating realistically the deformation and failure of the Hope Slide

351

The three-dimensional simulation of the 1965 Hope Slide was performed using a rigid block approach in 3DEC (Itasca Consulting Group, 2016). This assumption allowed to focus on the kinematic behavior of the slide, rather than the role of the internal failure and deformation of individual blocks.

352 A simplified, pre-failure topography was constructed, which includes the volume that is assumed to have 353 failed during the prehistoric event. The first-order geological structures mapped in the pre-failure geometry were 354 used to subdivide the slope model into the five blocks, B1-B5. The first-order geologic structures are fully persistent 355 in the 3DEC model and represented as cohesionless discontinuities. This assumption was considered adequate 356 because these geological structures are faults with soft gouge (up to 30 cm thick) that had been observed at their core 357 (Brideau et al., 2005). Additionally, a planar basal rupture surface was created, parallel to the discontinuity set J1. 358 The rupture surface in the model intersects the daylighting portion of sliding surface visible in the central part of the 359 slide area. Brideau et al. (2005) suggested that the slide may have moved along a stepped sliding surface, however, in 360 this numerical analysis a step-path failure surface morphology has not been implemented, as the true morphology of 361 the rupture surface is largely not visible due to the debris cover.

362 The second-order geological structures (i.e., discontinuity sets) were implemented in the model by 363 considering both the results of the rock mass characterization and the debris block size analysis. The average orientation of the discontinuity sets was obtained from TDP mapping of the lateral scarp and upper headscarp. The 364 365 spacing of each discontinuity set was based on the aspect ratio of the largest blocks digitized in the orthorectified 366 photograph of the debris. The ratio between the spacing of each discontinuity set was maintained equal to the 2D 367 aspect ratio of the largest blocks mapped in the orthophoto. In other words, as J3 and J2 have the wider and the 368 closest discontinuity spacing, respectively (as determined from the virtual scanline mapping), a ratio of 1.5, equal to 369 the average aspect ratio for larger blocks, was maintained in the numerical model between the spacing of J3 and J2. 370 Similarly, a ratio of 1.25 was maintained between the spacing of J3 and J1. These simulations were conducted, using 371 a constant discontinuity set spacing ratio, while varying the block volume. This approach allowed the potential, 372 initial block size that may have characterized the slide mass at the onset of failure, and prior to any comminution, to 373 be considered. It should be noted that considering spacing values obtained directly from the virtual scanline mapping 374 ignores the presence of rock bridges along discontinuity planes, causing the block size to be under-estimated, and the 375 slide volume to consist of blocks much smaller than those visible in the deposit. A similar approach was employed in 376 Spreafico et al. (2016). A block size of 80,000 m³ (20 times the maximum block size observed in the debris) was 377 used for model 1, 40,000 m³ for model 2 (10 times the maximum block size), and 20,000 m³ for model 3 (5 times the 378 maximum block size). Material density and discontinuity strength parameters were assigned following geotechnical 379 laboratory test results and estimates described in von Sacken (1991) and Brideau et al. (2005) (Table 2). A water 380 table was not implemented in these 3D model simulations and the slope was assumed to be dry. The sides and the 381 base of the 3D model were fixed, and any lateral displacement prevented.

The model was initially run with high discontinuity strength parameters, to allow stresses to be correctly computed along the joints, preventing the global failure of the slope, and avoiding shock loading of the model. Block

- B1 and block B2 were then deleted from the model, simulating the occurrence of the prehistoric rockslide and the
- resulting debuttressing effect in the upper slope. After equilibrium was achieved in the 3DEC model (i.e., based on
- unbalanced force in the model), discontinuities were assigned the parameters obtained from laboratory tests (or based
- 387 on literature data). Finally, the cohesion of the rupture surface was gradually reduced in 0.02 MPa increments at each
- 388 simulation stage, until the failure of slide blocks B4 and B5 was simulated. Each stage was considered complete
- 389 when a new equilibrium condition was achieved. This incremental strength reduction is to approximate a progressive
- 390 slope failure due to failure of rock bridge and strain-softening due to static (creep and fatigue) and cyclic loading
- 391 (seismic, freeze-thaw, and seasonal groundwater variation).

392 **4.3.2.** Numerical modelling results

393 Three-dimensional numerical modelling of the Hope Slide realistically simulated the 1965 slope failure in 394 two stages as observed on site. The numerical results show that the block size affects the stability of the slope. When 395 larger block sizes are considered (10 and 20 times the largest block observed in the debris), a two-stage failure is 396 simulated (Fig. 14a,b), in which the failure of the slide block B4 occurs for higher cohesion values, compared to the 397 slide block B5. In model 2, the numerical displacement rate of block B5 immediately after the detachment of slide 398 block B4 (400,000 numerical time steps) is relatively low, possibly due to the interlocking of individual joint 399 bounded blocks. As the individual blocks become kinematically free, the numerical displacement rate increases (Fig. 400 14b). The joint bounded block comprising the history point of slide block B4 acquired full kinematic freedom after 401 900,000 numerical time steps, as indicated by the steepening of the numerical displacement vs. numerical time step 402 curve (Fig. 14b). The curve flattens when the joint bounded block comprising the history point reaches the deposit 403 (Fig. 14a,b). No obvious block interlocking has been observed during the failure of slide block B5. When a smaller 404 block size (5 times the largest block) is used in model 3, the failure occurs in a single stage, and the displacement 405 rates within the slide blocks B4 and B5 increase at the same time (Fig. 14c). Table 3 summarizes the cohesion 406 magnitudes at which the failure of slide blocks B4 and B5 was simulated.

407 **5 Discussion**

408 5.1. Interpretation of the Hope Slide based on slope kinematics

409 Characterization of the Hope Slide conducted using the new methods and collected data from this research 410 has provided important insight into the evolution of the slope before and after the 1965 failure. It has been previously 411 suggested that the prehistoric slope failure caused the removal in the lower part of the slope of a volume of rock 412 similar to the 1965 slide (Mathews and McTaggart, 1969). In contrast, the material removed during the 1965 event 413 originated predominantly from the upper slope. 414 The prehistoric event is suggested to have had an important role in the 1965 rockslide. Block theory 415 analysis indicates that the prehistoric event caused removal of a key block, and propagation of the instability due to 416 reduced kinematic restraint on the upper blocks. The event occurred approximately 9,700 years b.p., shortly after the 417 disappearance of the Pleistocene Cordilleran Ice Sheet, about 10,000 years b.p. (Clague et al., 1983). In view of its 418 low elevation, it is likely that the Johnson Ridge was completely overtopped by the ice sheet, as hypothesized by 419 Waddington (1995). The prehistoric slide was probably induced by removal of support following glacial retreat and 420 fluvial erosion at the base of the slope. The relation between the retreat of Holocene glaciers and slope stability has 421 been described for both recent and historic events (Clayton et al., 2017; Roberti et al., 2018). In fact, long-term glacial history also affects present-day slope stability. Cruden and Hu (1993) suggest that an "exhaustion" process 422 423 may condition rock slopes for failures even thousands of years after glacial retreat or rapid fluvial incision. Riva et 424 al. (2018) modelled the long-term deformation of a rock slope previously buttressed by a glacier and observed that 425 the accumulation of internal damage can progress for long periods of time (> 15,000 years) in sagging rock slopes. 426 Eberhardt et al. (2004) and Leith (2012) similarly show, using numerical models, that the removal of glacier resulted 427 in damage at the toe of the 1991 Randa rockslide. It is suggested that a large slope failure may result in progressive 428 internal damage, and that the 1965 Hope Slide may represent the final stage of an extremely slow slope degradation 429 and weakening process that started with the prehistoric failure. We suggest that after such a slope toe failure, a long-430 term deformation initiated in the upper slope, inducing the formation and accumulation of slope damage both within 431 the slide volume, in the form of tension cracks, counterscarps (as those visible in the pre-failure aerial imagery), and 432 rock mass dilation, and more importantly along the rupture surface, through gradual failure of rock bridges and sub-433 critical crack propagation, until failure occurred. This hypothesis agrees with the findings of Evans and Couture 434 (2002). Table 4 summarizes conceptually the proposed mechanism, focusing on the slope damage that may have 435 characterized the slope throughout the different stages of its geomorphic evolution.

436 The remote sensing and numerical modelling analyses show that, from a kinematic perspective, the two 437 main blocks that failed during the 1965 event were characterized by a substantially different displacement behavior. 438 The slide block B4, bounded by the first-order structures L3 and L6, probably slid along a basal surface parallel to 439 the slope and discontinuity set J1. This configuration indicates a planar sliding mechanism, with displacement 440 occurring in a 248° direction (Fig. 15). Slide block B5 may have been initially buttressed by slide block B4. The 441 failure of slide block B4, then, caused the instability to propagate towards slide block B5. This block, however, does 442 not appear to have failed through a planar sliding mechanism: the presence along the lower boundary of the first-443 order structure L2 may have led instead to a translational wedge failure, with displacement in a 291° direction (along 444 the intersection with the basal surface; Fig. 15). Brideau et al. (2005) observed that most of the failure material 445 accumulated in the northwestern part of the deposit, and that the slide material largely travelled in a westerly 446 direction. This observation appears to agree well with a sliding direction partially controlled by L2, and a wedge 447 failure mechanism for the largest slide block involved in the 1965 event and is also supported by the numerical 448 modelling results. In the 3DEC model simulation, the occurrence of a two-stage failure varies due to the different 449 kinematic conditions between slide blocks B4 and B5 at model scale. It was observed that the failure of slide block 450 B4 occurs as a result of a purely planar sliding along the rupture surface (i.e., discontinuity set J1). The trend/plunge

451 of the sliding direction is $32^{\circ}/248^{\circ}$, and the lateral release surfaces are provided by the first-order structures L6 and

- 452 L3. This kinematic setting is also reproduced in the models at the element scale, where sliding of individual joint
- 453 bounded blocks occurs along discontinuity set J1, with J2 and J3 acting as lateral release surfaces. As a result, at both
- 454 model and element scales the shear strength is only mobilized along the J1 planes. At the element scale, the tensile
- 455 strength (lower in magnitude, compared to the shear strength) is implicitly provided by intact rock bridges and is
- 456 mobilized along J2 and J3. In contrast, failure of slide block B5 kinematically resembles a wedge failure at the model
- 457 scale. The intersection between the basal surface and structure L2 causes sliding along a plunge/trend of $24^{\circ}/291^{\circ}$. At
- 458 element the scale, the individual joint bonded blocks slide along J1 and J3, causing the mobilization of the shear
- 459 strength on both joint sets. The trend and plunge of the line of intersection, i.e., the sliding direction, is $31^{\circ}/263^{\circ}$.
- 460 Discontinuity set J2 within slide block B5 acts as a rear release surface, and the tensile strength is therefore
- 461 mobilized along this discontinuity set only (Fig. 15).

The numerical model results suggest that the slide block B4 acted as key block in the 1965 Hope Slide failure, its removal providing kinematic freedom for slide block B5 to displace. According to this interpretation, the first-order geological structure L2 plays a critical role in the evolution and progression of the failure. The slope below this structure was not involved in the 1965 Hope Slide failure, and may have acted as a buttress, resulting in the development of the wedge failure mechanism.

467 **5.2.** Comparison with previous studies

468 Since the occurrence of the Hope Slide, in 1965, several studies have been undertaken, which have 469 progressively enhanced our understanding of the mechanisms underlying the failure. Anderson (1965) compiled a 470 comprehensive timetable of the event, based on witnesses' accounts. His work, although not strictly a geological 471 investigation, provides an overview of the environmental conditions that existed at the site in the days and hours 472 before the slide occurred. The first geological investigation is described by Mathews and McTaggart (1969,1978). 473 Their work represents the first significant appraisal of the landslide, in terms of lithological factors, involved volume, 474 and long-term evolution of the slope. Bruce and Cruden (1977) presented the first limit equilibrium analysis of the 475 Hope Slide, using direct shear tests to constrain input data. Von Sacken (1991) performed and described the first 476 extensive field work focussed on the structural characterization of the slope, highlighting for the first time the 477 important role of geological structures on the slide evolution. She also suggested for the first time that the Hope Slide 478 might have occurred in two stages, instead of a single event, preceded by a snow avalanche, as reported in Anderson 479 (1965), and highlighted the presence of sackung-type features in the upper slope. The hypothesis of a long-term slope 480 deformation prior to the failure was later substantiated by field work and trenching undertaken by Evans and Couture 481 (2002). Brideau et al. (2005) further investigated the structural control on the Hope Slide, highlighting the correlation 482 between rock mass damage and proximity to slope-scale geological structures, and noting the presence of gouge at 483 the core of major faults. They also produced the first three-dimensional conceptual model of the Hope Slide, which 484 included the principal features controlling the slope stability (faults, shear zones, lithological contacts, rock mass 485 jointing). The findings we have presented in this study build upon and agree with the observations and results

486 described above. Furthermore, we provide a new and enhanced insight on the long-term evolution and the control of

- 487 structural geology factors on the Hope Slide. We use, for the first time at this site, multiple remote sensing
- 488 techniques crucial in investigating the inaccessible parts of the scarps. Together, historical, and new data showed that
- 489 slope kinematics, and especially its evolution, was a critical factor in defining the behavior of the slide both during
- 490 the failure, and since the original post-glacial retreat triggered slope failure. The three-dimensional distinct element
- 491 modelling was instrumental in realistically simulating the failure and demonstrated that structurally controlled
- 492 failures such as the Hope Slide cannot be adequately investigated using two-dimensional approaches alone, which
- tend to over-simplify and often ignore the kinematics of the true failure mechanism. Fig. 16 outlines the principal
- 494 studies that contributed to our current understanding of the Hope Slide, highlighting, for each, the major
- 495 contributions, findings, and innovative aspects.

496 5.3. Scale effects in numerical modelling

497 The role of scale and scale effects on numerical models is of major importance in slope stability analyses. 498 The effects of a change in block size (and thus, in discontinuity spacing) on the failure mechanism has been 499 investigated by several authors. Hencher et al. (1996) employed a physical-numerical modelling approach to 500 conceptually investigate the failure of open pit slopes and underground excavations. Using base-friction physical 501 models they noted that, when the same discontinuity orientation, persistence, and relative set spacing is maintained, 502 the slope failure mechanism was strongly controlled by the size of the blocks composing the slope. A simulated slope 503 constituted by very small block was noted to be affected by a shallow translational slide. As the block size increased 504 (together with discontinuity spacing), the failure mechanism progressively switched to a planar sliding and then to a 505 toppling failure. Using a 2D continuum numerical modelling approach, Hammah et al. (2007) also investigated the effect of joint persistence and block size on the failure mechanism and strength of conceptual rock slopes constituted 506 507 by jointed rock masses. The progressive decrease in discontinuity persistence and block size caused the slope failure 508 mechanism to progressively change from planar sliding to a pseudo-rototranslational failure, typical of weak, heavily 509 fractured rock masses. Using a 3D distinct element numerical modelling approach, Corkum and Martin (2004) 510 analyzed the effects of block size on the stability and kinematic freedom of the Block 731, a stabilized rock slope 511 near the abutment of the Revelstoke Dam (British Columbia, Canada). They noted that the block size, and in turn the 512 number of blocks, selected for the simulation strongly affected the stability and evolution of the simulated slope. 513 Using the same modelling approach, Brideau and Stead (2012) studied the effects of block shape, discontinuity 514 orientation on the slope failure mechanism. They noted that the style and volume of the failure are affected by 515 changes in the orientation of the basal, lateral, and rear release surfaces affected, as well as the kinematic 516 confinement of the simulated slope. Sitar et al. (2005) employed a Discontinuous Deformation Analysis (DDA) to 517 study the effects of block size and block number in a numerical model of the Vajont Landslide, and noted that the 518 velocity and kinematic freedom of the slide increased together with the number of blocks considered in the 519 simulation. They concluded that the progressive disintegration and fracturing is an important factor that should be 520 kept into consideration in the analysis of large rockslides.

521 In this paper, the results of the numerical modelling confirmed the important relation between the size of the 522 simulated blocks and the behavior of the slope. The size of the simulated blocks affected the evolution of the slope, 523 as it controlled the occurrence of a single-event failure (using a smaller block size) or a two-stage failure (when larger blocks were considered). In the simulated models, the change in block size in the investigated model did not 524 525 affect the failure mechanism, however, it did significantly affect the overall strength of the slope. The model 526 constituted by larger blocks remains stable for lower values of cohesion, compared to one constituted by smaller 527 blocks. This observation has potentially significant implications for back-analysis stability studies, as the back-528 calculated shear strength of the rupture surface appears to be strictly correlated to the model geometry and block size, 529 even if the same failure mechanism is simulated.

530 6 Conclusions

The Hope Slide, one of the largest historical rock avalanches in Canada, occurred as two events in the early morning of January 9th, 1965. The slope had been affected by a prehistoric slope failure, which had left a clearly visible scar in the topography and a 60 m-thick deposit at the bottom of the valley.

In this study, we highlighted the important role of tectonic structures on the behavior and evolution of the 1965 Hope Slide. We observed that the tectonic structures that controlled the 1965 slide also appeared to control the location of the prehistoric event. Although the occurrence of the prehistoric instability has been recognized by several authors prior to the 1965 failure, its effects on the kinematics of the remaining slope had not been addressed in detail. It is suggested in this research that the prehistoric slope failure caused the removal of a key-block from the lower slope, thus initiating a long-term slope deformation that eventually led to the 1965 Hope Slide.

540 We suggest that in order to reconstruct the evolution of the stability and geomorphic evolution of a rock 541 slope, a detailed slope characterization is required. The objective of the slope investigation should be to characterize 542 large, first-order structures that govern the global behavior of the slope, and the lower order features (e.g., joints, 543 block size) that are critical in defining the slope kinematics and the mechanical strength of the rock mass. This 544 research highlights that the stability of rock slopes is not only strongly influenced by slope kinematics, but also by 545 the geomorphic end geomechanical evolution of the slope with time. Glacial retreat, oversteepening, and removal of 546 key blocks from the slope may initiate a progressive failure process. Gradual weakening of the slope is accompanied 547 by the formation of internal and external rock slope damage features, which may enhance kinematic freedom within 548 the slope, potentially leading to major rockslides. It is therefore suggested that a three-dimensional slope kinematics 549 and damage investigation should be a required component in any major rock slope characterization, and that the 550 potential evolution of kinematic freedom should be addressed to realistically assess the long-term stability of large 551 rock slopes.

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730	Using pre-failure and post-failure remote sensing data to			
731	constrain the three-dimensional numerical model of a large			
732	rock slope failure			
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738				
739	Figures and tables follow			
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744 Figures



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Fig. 1Geographic and lithological overview of the Hope Slide. a: 2018 satellite image (Planet Team,
2019) of the slide area. Dashed lines indicate linear structural features. Dotted curve outlines
the Johnson Ridge. Solid line shows the boundary of the 1965 slide area. In the inset, the star
indicates the location of the Hope Slide in British Columbia; b: view of the slide area from
the viewpoint at the base of the slope (photograph summer 2015); c,d: detail of the rock mass
and lithology contacts along the lateral scarp and within the daylighting part of the rupture
surface (photographs taken fall 2011).



Fig. 2

Workflow of the investigation conducted at the Hope Slide. The slope characterization has been performed by progressively increasing the level of detail.



Fig. 3

Conceptual workflow for the reconstruction and analysis of the pre-failure slope topography. The 1961 historical aerial imagery was processed using a SfM approach to obtain the pre-1965 slope geometry. The dotted curve outlines the area affected by the slide.



Fig. 4

Remote sensing equipment employed for the investigation of the Hope Slide; a: Riegl VZ-4000 terrestrial laser scanner; b: Canon EOS 5D Mark II DSLR camera with f = 400 mm focal length lens, mounted on a panorama frame; c: FLIR SC7750 thermal camera with f = 100 mm focal length lens; d: DJI Phantom 3 Pro Quadcopter.



Fig. 5

Location of the remote sensing stations (photograph from Google Earth). Dots identify the camera stations used for the TDP survey of the headscarp; the star marks the location of TLS and IRT stations; polygons outline the areal coverage of each survey, including the surface of the slide deposit investigated using UAV-SfM. Historical imagery SfM datasets extend beyond the boundaries of the photograph.



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72 Fig. 6 73 74 75 Summary of the lineament analysis conducted on the ALS post-failure DTM of the Hope Slide. a: map of lineaments, color-coded based on the trend orientation. The dotted outline represents the boundary of the failed slope. The square window outlines the area represented in c. The basemap is the hillshade view of the ALS dataset. b: rosette diagram of the lineaments. The principal lineament trends are highlighted, and coloured based on the trends observed in a. c: aspect map of the western headscarp, showing the intersection with counterscarps with trend similar to III.



Summary of the lineament analysis conducted on the SfM pre-failure DTM of the Hope Slide. a: hillshade map. The inset table displays the orientation (dip/dip direction) of the mapped geological structures; b: aspect map; c: slope map; d: imagery draped onto prefailure 3D model. Note that B1 has been interpreted as a key block. In each map, dashed lines represent the mapped first-order lineaments, and the dotted curve outlines the area involved in the 1965 event. Lineaments are labelled from L1 to L6, blocks from B1 to B5.



Fig. 8

Pre-failure geomorphic and slope damage analysis of the Hope Slide slope (photographs 1961). a: Orthorectified image obtained from the SfM model, showing the location of the investigated profiles and outlining prehistoric landslide deposit (PLD) and debris fan (DF). The former highway 3 (HWY 3) is also labelled. b: detail of the orthorectified image showing the surface of the prehistoric landslide deposit. The hummocky morphology north of the former Outram Lake (OL) and the boulders scattered throughout the deposit are labelled. c: interpreted profiles traced in the orthorectified image, highlighting the inferred northern edge of the prehistoric landslide deposit (A-A') and the morphology of the debris fan at the base of the slope (B-B', C-C'). d: detail of the rockfall deposition areas recognized in the prefailure slope, located above the debris fan in the lower slope, and on a structural ledge located mid-slope. e: aspect map of the upper pre-failure slope from the SfM model, highlighting the counterscarps resulting from slow, long-term slope deformation.





Pre- and post-failure aerial photograph comparison. a: location of the geomorphic feature observed in both pre- and post-failure imagery, identified at the boundary between blocks B2 and B5. b: conceptual reconstruction of the formation of the feature highlighted in a.



804	Fig. 10
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Comparison between pre-failure and present-day 3D models. a: oblique view of the 1961 SfM point cloud. b: oblique view of the present day slope from Google Earth (2016 imagery). c: oblique view of the 1961 hillshade SfM model. Colour scale shows the elevation loss after the 1965 event. d: hillshade model built by overlaying the 2015 TLS dataset onto the pre-failure SfM topography. Red, dotted curve outlines the 1965 slide area. In the present-day models (b,d) the arrow indicates the inferred displacement direction.



811	Fig. 11	Overview of the outcrop-scale second order discontinutiy mapping performed at the Hope
812		Slide. a: summary of the results from the TDP discontinuity mapping described in Donati et
813		al. (2013). All the stereonets are equal angle, lower hemisphere projections. On the aerial
814		photograph, the dashed lines outline the boundaries of the structural domains derived from
815		the discontinuity mapping (photograph 1996, courtesy of Province of British Columbia, roll
816		BCC96082, frame 19). b: rosette diagram that includes the mapped discontinuities. The
817		orientations of the principal discontinuity sets identified are highlighted. c: rosette diagram
818		obtained from the slope-scale lineaments. Note the similarities with the discontinuity set
819		orientations in b.



821	Fig. 12	Example of the thermal imagery collected at the Hope Slide. Darker colours indicate lower
822		temperatures, whereas brighter colours indicate higher temperatures. Low temperatures
823		(10°C to 12°C) identify groundwater seepage from J1 discontinuities and the
824		greenstone/felsite sill contacts. Imagery summer 2016.







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curves display total displacement magnitude of history points in slide blocks 4 and 5, respectively. a: Model 1 (Block size 20x largest block in landslide deposit). Plots 1-4 show block displacements for increasing numerical time steps. b: Model 2 (Block size 10x largest block in landslide deposit. c: Model 3 (Block size 5x largest block in landslide deposit). The failure of both slide block 4 (dotted curve) and slide block 5 (dashed curve) was simulated at the same time.



842	Fig. 15	Kinematics of the Hope Slide blocks at large and small scale. At model scale, the slide block
843	-	B4 acts as key block for the failure of the slide block B5. Black arrows indicate the
844		displacement direction of the slide blocks. Slide block B4 is kinematically free to slide along
845		the basal rupture surface. Slide block B5 slides along the basal rupture surface and L2, with
846		the latter kinematically constraining the block along the lower side. At the element scale, the
847		stability of the individual joint bounded blocks forming slide block B4 is governed by the
848		shear strength (dashed traces) along J1 and the tensile strength (solid traces) along J2 and
849		J3. In slide block B5, only J2 fails in tension, while shear strength controls sliding along J1
850		and J3. White arrows indicate the sliding direction of the individual joint bounded blocks.

852 **Tables**

Remote sensing		Resolution of the	
technique	Coverage	dataset	Purpose of the analysis
			Large-scale structural analysis (post-
			event lineament mapping);
	Entire slide area and		Volume estimation (post-failure slope
ALS	surroundings	Cell size: 1 m	surface)
			Large-scale structural analysis (pre-
SfM (historic			event lineament mapping);
aerial			Pre-event geomorphic analysis;
photograph	Entire slide area and		Volume estimation (pre-failure slope
imagery)	surroundings	Point spacing: 5-10 m	surface)
	Entire sliding surface,		
	including lateral scarp		Volume estimation (post-failure slope
TLS	and upper headscarp	Point spacing: 20-40 cm	surface)
	Lateral scarp and upper		
	headscarp daylighting	Ground pixel size: 3 cm	Discontinuity mapping and detailed
ТПР	part of the sliding surface	Point spacing: 10 20 cm	rock mass characterization
	part of the shulling surface	Fount spacing. 10-20 cm	
UAV-SfM	Landslide deposit	Point spacing: 10 cm	Deposit block size analysis
	Entire sliding surface,		
	including lateral scarp	Ground pixel size: 20-30	
IRT	and upper headscarp	cm	Seepage investigation

853 Table 1 Summary of coverage, detail, and use of the collected datasets

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855Table 2Summary of the properties used for the numerical simulation of the 1965 Hope Slide.856Residual values are shown in parentheses.

Rock mass

	Material 1
Density	2850 kg/m ³
Constitutive model	Rigid blocks

Discontinuities

	Rupture surface	J1, J2, J3	First-order structures
Friction angle (°)	28 (20)	28 (20)	24 (18)
Cohesion (MPa)	1.5 (0) *	2.5 (0)	0
Tensile strength (MPa)	0	0.2 (0)	0
Normal/Shear stiffness (GPa/m)	10 / 1	10 / 1	10 / 1

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* Peak cohesion value was progressively decreased until 3DEC slope failure was simulated.

859 Table 3860

Rupture surface cohesion value at failure in 3DEC models. In brackets, the percentage of decrease from the original value is reported.

	Assumed block size (m ³)	Slide block B4 rupture surface cohesion at failure (MPa)	Slide block B5 rupture surface cohesion at failure (MPa)
Model 1	80,000	0.98 (-34.7%)	0.92 (-38.6%)
Model 2	40,000	1.12 (-25.3%)	1.02 (-32.0%)
Model 3	20,000	1.10 (-26.6%)	1.10 (-26.6%)

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Table 4

Conceptual evolution of the slope damage at the Hope Slide. Sketches describe conceptually the evolution of the Hope Slide since initiation of the instability after glaciation.

	Conceptual sketch	Geomorphic conditions	Slope damage evolution
Stage 1	Ice sheet L2 N L6 L4 L3 Sills	 Ice-covered valley Buttressed slope Slopes over-steepened by glacier advance 	 Tension cracks, counterscarps formed during previous stages of glacial retreat Fractures possibly propagated in sub-critical conditions during previous stages of glacial retreat and advance
Stage 2	Scarps and counterscarps glacier L2 N L6 L4 L3	 Glacial retreat Slope deformation initiates; the boundaries of the deforming slope are structurally controlled 	 Tension cracks, counterscarps, and scarps extend to the boundary of the unstable area Freeze-thaw cycles causes opening and propagation of fractures Brittle fracturing initiates the formation of a continuous rupture surface Bulging causes dilation and rock mass damage at the toe
Stage 3	Prehistoric headscarp	 Prehistoric failure. Keyblock removed (slideblocks B1 and B2) Valley floor filled withdebris and raised by tens of meters Initiation of slowdeformation due to stress redistribution in the upper slope 	 A steep, sharp headscarp forms as a result of the failure Syn-failure cracks due to stress relaxation form behind the headscarp Stress relaxation causes propagation of fractures in the volume not involved in the failure
Stage 4	Tension cracks, counterscarps Debris fan L2 k L6 L4 L3	 Prehistoric headscarp "smoothed" and eroded Eroded material forms a debris fan at the base of the slope Blocks from rockfall source areas deposit in the accumulation surfaces along the slope 	 Counterscarps form in the upper part of the unstable area, due to slow, progressive slope creep Freeze-thaw cycles cause opening and propagation of fractures Brittle fracturing of rock bridges between non-persistent discontinuities leads to the formation of a continuous rupture surface in the upper slope Increasing weathering and alteration at the base of the debuttressed blocks enhance cliff erosion and the rock mass damage
Stage 5	1965 Relict counterscarps Daylighting rupture surface Slide deposit	 Upper slope collapses in two stages (slide blocks B4 and B5) Slide material obliterates the debris fan and the Outram Lake at the base of the slope 	 Localized instability at the edges of the slide area Opening of a tension crack behind the headscarp Freeze-thaw cycles cause opening and propagation of fractures Localized accumulation of rock mass damage within areas undergoing deformation along the headscarp