16 Large-Scale Rock Slope Deformation from the Tablelands and Lookout Hills of Western Newfoundland, Canada

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Abstract

Five large gravitational slope deformation features (GSDFs) in the Lookout Mountain-Tablelands region of western Newfoundland exemplify bedrock slope instabilities in eastern Canada. The Lookout Hills GSDF (8.3 km^3) on Bonne Bay (glacial trough) may be the largest GSDF in eastern Canada. It appears to be a post-glacial feature, has vertical total displacement up to 100 m, and exhibits a complex arrangement of scarps and fissures. Four other large GSDFs occur along the walls of glacial troughs in the Tablelands of Western Newfoundland with estimated volumes between 1 and 2 km^3. All five features are above steep slopes and have the potential to become catastrophic massive rock slope failures. While it is tempting to link the failure in all 5 GSDFs to the removal of laterally supporting bedrock or glacier ice during the late Pleistocene, the location of these deformations may simply relate to slope steepness. Non-glacial, first order controls on the deformation include changes in the effective shear strength and opening of fractures owing to Holocene permafrost thaw may have induced failure. No discernible movement has occurred in the Tablelands GSDFs in the last 50 years. Nevertheless, the Lookout Hills GSDF requires more detailed study to determine the potential for future movement as rapid collapse into the adjacent fjord may present significant risk to coastal residents, infrastructure and marine ecosystems.

Keywords

Newfoundland • Gravitational slope deformation feature • Sackung • Rock-slope failure • Glaciation • Humber arm allochthon • Long Range Mountains

16.1 Introduction

On June 17, 2017, part of a mountainside, with a volume estimated at between 35 M and 51 M m^3, slid into the sea at Nuugaatsiaq, west Greenland and produced displacement waves that resulted in loss of life (four fatalities) and considerable damage to property (Chao et al. 2018). It was not seismically triggered, and instead was a result of acceleration of mass movement that began months prior to the catastrophic event. Similar conditions to those at Nuugaatsiaq occur in Western Newfoundland where highly jointed and fractured rocks abutting deep fiords are prone to mass movement. Some are in coastal positions where there is potential to generate a displacement wave. A number of factors can promote GSDFs (gravitational slope deformation features), accelerate their motion, and ultimately trigger catastrophic failure. Unloading during deglaciation and post-glacial active isostatic movement may have increased stress and lessened the effective cohesion of these slopes (Vacchi et al. 2018). Seismicity is not uncommon along the passive margin of eastern Canada as well as along the St. Lawrence Trough with recorded earthquakes in the M6.0–7.2 magnitude range (Stein et al. 1979). Stein et al. (1979) contend that large passive-margin earthquakes may occur as

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far south along the eastern Atlantic coast as ice sheets extended. Besides seismic triggering, climate change induced reduction in effective shear strength, fracture propagation, and freeze–thaw processes may also cause mass wasting.

Collectively these conditions indicate that an examination of the potential for acceleration of mass wasting or catastrophic large rock slope failures in eastern Canada is warranted, particularly along western Newfoundland where subaerial relief exceeds 500 m, including slopes above coastal waters or fjord lakes. We describe and illustrate five rock-slope deformation features in the Lookout Mountains-Tablelands region of western Newfoundland, apparently formed in response to gravitational pull on very large rock masses on plateau margins (Fig. 16.1). These margins were steepened by glaciers and then debuttressed as glaciers receded and disappeared. Our objective is to summarize the geological and geomorphological setting of these sites and indicate where further study is warranted, including hazard genesis and risk analysis. We demonstrate that these gravitational deformation features are common in the region and that three of the five sites have the potential to develop into catastrophic rock slope failures of considerable volume. A failure at the Lookout Hills site will have the potential to be a significant displacement wave hazard owing to its coastal position. While submarine mass transport complexes have been identified from the Scotian Shelf to Pond Inlet and can generate similar tsunami (Jenner et al. 2007; Broom et al. 2017), we are limiting this contribution to subaerial processes.

16.1.1 Terminology

Current terminology relevant to subaerial mass wasting in high-relief glaciated regions is rather unwieldy. The term “rock-slope failure” (RSF) is considered by Evans et al. (2007) and Hermanns and Longva (2012) to encompass rockslides, rock avalanches, catastrophic spreads and rockfalls. They consider very large failures “massive rock slope failure” or MRSF. RSFs, whether or not they are massive, occur when (i) stresses within the rock mass are increased by steepening of the constituent slope, most often by glacial erosion, but in some cases tectonics (Harrison and Falcon 1938; Roberts and Evans 2008), (ii) when stresses applied earlier to the rock-mass are relieved, for example by glacial debuttressing (Holm et al. 2004) or (iii) the effective shear strength of the slope is reduced, for example by permafrost thaw or increased effective porewater pressure. These processes can operate in concert. Although Evans et al. (2007) consider only varieties of rapid, or what we could term catastrophic, mass movement, some failures may begin as very slow, small-scale displacements or sags of mountain slopes which produce gravitational deformation features such as cracks, scarps, and perhaps grabens at the top of the failure (Hermanns and Longva 2012).

“Sackung” (plural “sackungen”) is a German term used to describe deep-seated, generally slow-moving slope failures which often exhibit a series of linear scarps facing up-slope (anti-scarps). The term has been assimilated into English, although it may sometimes refer to the geomorphic features at the head of the failure rather than the entire failure. “Deep-seated gravitational slope deformation” (DSGSD) is a more specific term defined by Soldati (2013) as a gravity-induced process affecting large portions of slopes evolving over long periods of time, and gravitational slope-deformation features (GSDF) as the geomorphic manifestations of gravitational slope deformation. These would include the cracks, scarps, and anti-scarps commonly included in the definition of “sackungen”.

A simple distillation of current usage is that (a) DSGSD, its shortened version GSD (gravitational slope deformation), and sackungen refer to large rock failures that have begun but have not achieved a state of (rapid) collapse yet; they could be regarded as metastable, (b) GSDF refers to manifestations on the ground of GSD, and (c) RSF, although it technically could include creeping failures that have not collapsed yet, is used for rapid or catastrophic failures. In this paper we will use “GSD” and “GSDF” in the sense that Soldati (2013) defined them, and RSF to mean rapid collapse.

The hazard of GSDFs is that they have the potential to develop into RSFs. According to Soldati (2013), volumes of rock displaced in GSDFs can be up to hundreds of millions of cubic meters, with thicknesses of up to a few hundred meters.

GSD is becoming recognized increasingly as an important contributor to landscape evolution in high-relief terrains (e.g., Hewitt 2009; McColl 2012). As surficial mapping and remote sensing of slope failures have improved, GSDFs have been recognized world-wide as signaling potential hazard to humans in steep mountainous terrains (Crosta and Clague 2006; Evans et al. 2007; Jaboyedoff et al. 2011; Hermanns and Longva 2012).

In eastern Canada, Grant (1974, 1987) and Brookes (1993) identified twenty-four examples of GSD, mostly developed in the ultramafic rocks of western Newfoundland. In western Newfoundland stress on rock masses was likely increased by glacial steepening of valley-walls, and deglacial stress release likely contributed to RSF of plateau-edges and valley-walls (Osborn et al. 2007). GSDFs in this region are characterized by scarps of considerable vertical displacement and the absence of anti-scarps. The lack of anti-scarps may be due in some cases to glacial erosion of the failed mass,

Fig. 16.1 Study area in the Tablelands and Lookout Hills of Western Newfoundland. All GSDF sites mentioned in this paper are situated on glacially steepened valley walls. The region is characterized by highly jointed and fractured ophiolitic rocks; peridotite and gabbro are prominent. Numbers 1–5 refer to GSD sites discussed in text

implying that some failures predated the last glaciation (Grant 1987). At some sites fractures several hundreds of meters long have opened by a few meters, within 100–200 m of, and parallel to, a plateau-edge (Grant 1987). No evidence of the age of these has been gathered and they might have been widening/lengthening at very slow rates since they first formed.

16.2 Geological Setting

The Tablelands and Lookout Hills form the southern part of Gros Morne National Park. The physiography of the study region is dominated by massifs (Fig. 16.1), with steep boundary slopes descending from smoothly undulating or

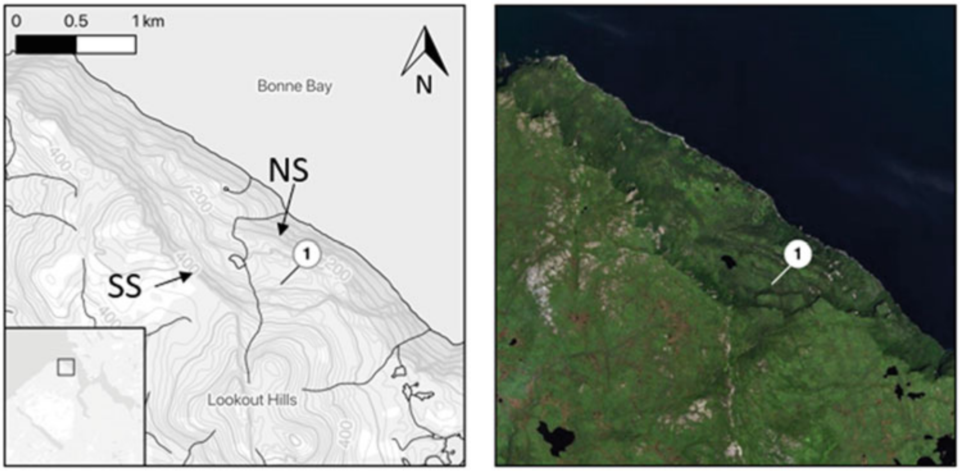


Fig. 16.2 The Lookout Hills GSDF. The Southern Slump which may contain 10 km^3 of material, appears to have been lowered as a coherent block. The southern scarp (SS) is characterized by many narrow scarps which are sub-parallel to the coastline. NS is the northern scarp

rolling plateaus at 600–800 m asl. Between or bordering these massifs are lowland corridors which were occupied by pre-Quaternary rivers and Pleistocene glaciers that drained from inland divides into the proto-Gulf of St. Lawrence. Valleys incised into the margins of these massifs, which were initiated fluvially in the mid-Cenozoic (Eyles 1996), show a range of glacial erosional overprints, particularly U-shaped low-gradient troughs which have resulted from glacial erosion.

The majority of the Long Range Mountains in Gros Morne National Park are underlain by Proterozoic granite and gneiss (Berger et al. 1992). Adjacent to the coast, a 5–10-km-wide piedmont is underlain mainly by tilted Paleozoic continental-margin clastic and carbonate sediments. In the southern part of the park, the subject of this paper, peridotite and gabbro of the Gros Morne ophiolite suite are distinctive for their orange color, barrenness owing to plant toxicities, and flat-topped landscapes controlled by regional structures, glaciation, and post-glacial surface processes.

16.3 Methods

Field work was conducted in 2002, 2003, 2010, and 2016. In 2002 and 2003 geochronology study on the timing of fjord deglaciation was conducted by Osborn et al. (2007). Mapping of glacial and periglacial deposits was completed at a scale of 1:25,000 with the aid of air photos. We reviewed aerial photography and a 50+ year photographic record of landscape change (Berger 2017). In 2016, the sites were again investigated in the field, although the Lookout Hills feature was examined primarily using remote sensing imagery.

16.4 Results

16.4.1 Lookout Hills GSDF

The Lookout Hills GSDF (Site 1, Fig. 16.1 and 16.2) consists of a primary scarp, and several lower secondary scarps that may represent two or more generations of failure. The composite feature is almost 6 km long, contains 8.3 km^3 of material and is sub-parallel to the Bonne Bay coastline. This feature is the largest aerially of the five GSDFs described in this paper and the largest known in eastern North America (Spooner et al. 2013).

The Lookout Hills GSDF has been described by Cumming and Grant (1974) and Grant (1974). Brookes (1993) remarked that the "confused terrain of ridges, cracks, and depressions which, near the edge of the cliff overlooking the entrance to Bonne Bay, is very treacherous for hikers". The Lookout Hills GSDF occurs in an area which, because of its rugged relief, has not yet been mapped in detail. The feature formed in heavily jointed, coarse-grained crystalline rocks composed of gabbro and anorthositic gneiss (Williams and Cawood 1989). Joint patterns on the undisturbed surface to the south of the feature are roughly orthogonal and are clear in both photographs and satellite images. An area of intense crevice development (Fig. 16.3) appears fresh, with some suggestion of alteration since early airphotos have been taken on the site.

The largest headscarp is associated with a feature that Grant (1974) called the Southern Slump. It is 75–130 m in height, and the scarp (Southern Scarp, Fig. 16.2) extends for almost 3 km. The main escarpment is likely of composite origin as it appears to be scalloped and may have formed from two or more discrete movements (Figs. 16.2, 16.3, 16.4 and 16.5). The eastern side of the escarpment is smaller in height and lateral extent and the headscarp is less clearly defined (Fig. 16.2). The surface of the Southern Slump appears to have been lowered as a coherent block. Three small ponds are located on the surface. However, domal features with prominent crevices (tension cracks) are also present and have formed parallel to the main scarp. The more northerly and smaller headscarp (Northern Scarp, Fig. 16.2) delineates an elongated lens-shaped block characterized by many narrow scarps which are sub-parallel to the coastline.

Grant (1973) noted that the southern scarp (Fig. 16.2) appears to truncate a post-glacial marine terrace fringing Bonne Bay at about 60 m asl. He also contended that following retreat of glacial ice from Bonne Bay failure of the over-steepened walls occurred sometime after the deposition of a raised marine terrace. Grant (1973) also suggested that collapse of the underlying soluble strata in the over-deepened floor of Bonne Bay may have contributed to collapse of the Southern Slump (Fig. 16.3).

16.4.2 GSDF in the Tablelands

The "Tablelands" (generally expressed in the plural) refer to a steep-flanked, rolling plateau rising to 711 m asl, south of the Bonne Bay fjord system (Fig. 16.1). The edges of the plateau are steepest and best-defined on the north, where the margin is demarcated by a once glaciated valley and on the southwest, where Trout River Pond fills the bottom of a fjord valley (Fig. 16.1). The plateau is underlain by ophiolitic rocks of the Humber Arm Allochthon (Williams and Cawood 1989). Gabbro is exposed in the northwestern third of the upland, but elsewhere highly fractured peridotite is at the surface. The Tablelands are characterized by barren, frost-shattered rock, brown-weathering where peridotite is exposed and somewhat more vegetated on gabbro surfaces. Soils are thin to non-existent, and evidence of active cryoturbation is common. The summit plains of the Tablelands are generally regarded as remnants of a planation surface(s) uplifted in Eocene time (Berger et al. 1992; Brookes 1993) but unpublished thermochronologic evidence suggests the summit plateaus and some of the relief existed as early as the Jurassic.

16.4.2.1 GSDF Site 2: Shoal Brook

The Shoal Brook GSDF (Site 2, Fig. 16.1) is located on the northeastern escarpment of the Tablelands Plateau where the edge of the plateau is steepest and best-defined (Fig. 16.6). The head scarp of the Shoal Brook GSDF is about 750 m long, slightly concave to the west and exhibits vertical displacement of about 20 m (Fig. 16.7). The failure surface is characterized by many small, stepped failures as well as overlying younger debris cones.

16.4.2.2 GSDF Sites 3, 4, 5: Sandy Top, G4 and Miners Point

On the south side of the Tablelands GSDFs of two possible generations have been recognized—one likely pre-LGM (Last Glacial Maximum) and two post-last glaciation (<12.0 ka; Osborn et al. 2007). Relative ages of these features were first proposed by Brookes (1993). The rock-mass of Miners Point (Site 5, Fig. 16.8) is composed of peridotite on its eastern side, and of foliated peridotite and gabbro at its western end. The same transition occurs at the southern edge and across the width of the Tablelands plateau, some 600–700 m above Miners Point. Previous publications have explained the elevation difference by Early Paleozoic faulting (e.g., Smith 1958). However, while a fault zone must indeed separate the Tablelands massif to the north of Trout River Ponds from mafic volcanic Gregory Plateau to the south, the much more recent origin of the movement of the Miners Point block is indicated by its relationship to glacial features. At best the Paleozoic fault is a fault line scarp.

As shown in Brookes (1993), the Miners Point rock-mass overrode glacially streamlined till. The mass itself is also glacially streamlined across its rocky summit, which indicates that failure occurred pre-LGM (between ~40 and 12 ka). Also noteworthy is the plan shape of the Miners Point mass, which easily fits into an indentation in the cliff edge of Tablelands plateau.

The rock mass NW of Miners Point, known as Sandy Top (Site 3, Figs. 16.8, 16.9 and 16.10), is located vertically half-way between pond level and the edge of Tablelands plateau, at 600 m asl. Its gabbroic rock can be matched to the plateau-edge above. A post-LGM age is suggested by the lack of glacial streamlining of the failed block.

Between Miners Point and Sandy Top, immediately below the plateau-edge, a valley wall failure called G4 (Smith 1958; Brookes 1993) has dropped a third integral mass, this of gabbroic rock at 530 m asl, only ~70 m from the plateau-edge (Site 4, Figs. 16.8 and 16.9). The outward-sloping surface of the block has been roughened by jostling of joint-bound blocks during failure, but there are no glacial features on it. If this surface had been glaciated it would not be as intact as it is. At this elevation glacial over-steepening was likely not a factor in destabilization; dilation of the rock-mass in response to earlier (possibly much earlier) steepening is a possible mechanism.

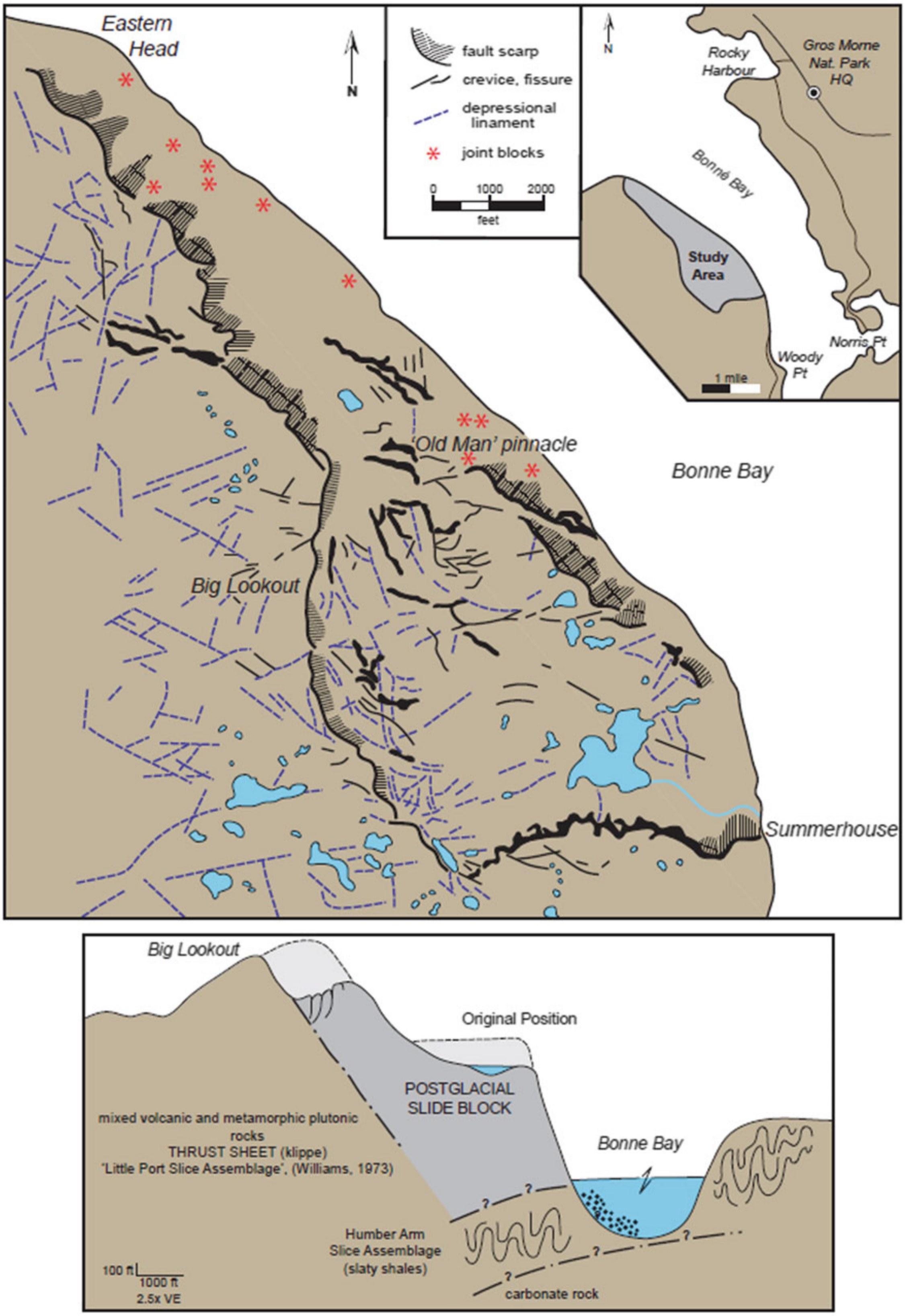


Fig. 16.3 The Lookout Hills GSDF. Grant (1974) hypothesized that the age of the feature was post-LGM and failure was associated with either the removal of the formerly supportive glacier, collapse of soluble underlying strata or by gravity slip of the fractured rock mass. (Figure after Grant 1974)

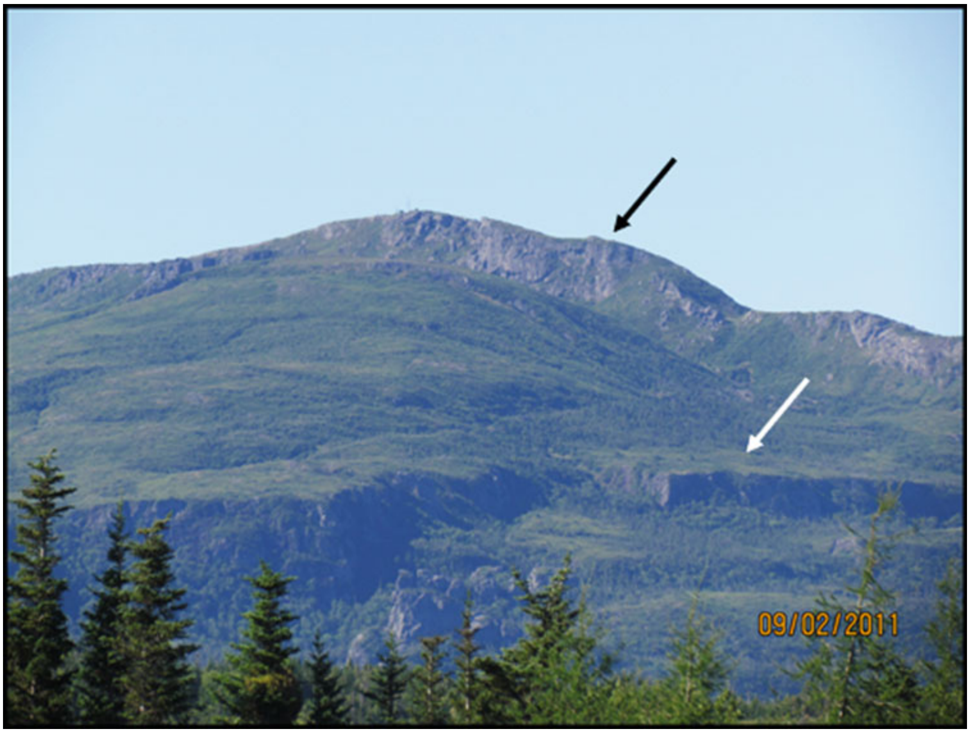


Fig. 16.4 View across Bonne Bay from Lobster Cove Head, to Lookout Hills showing the main southern failure scarp (black arrow) and the smaller northern failure scarp (white arrow). There is about 80 m of displacement on the southern failure scarp

Fig. 16.5 Significant vertical displacement and crevices in a domal region below the Southern Scarp. These crevices are tension cracks, and most are parallel to the main scarp. This domal area was originally a part of a low hill which rose above the general level of the surrounding surface of the plateau

16.5 Discussion

The causal mechanism for the GSDFs described in this paper is uncertain. As all are located adjacent to glacially over-steepened valleys, the failures may have developed in response to the removal of laterally supporting bedrock during glaciation, triggering lateral expansion when the ice ablated. Similar slope failures, albeit on smaller scales, are associated with valley down-cutting and “valley rebound” in other areas (e.g., Babcock 1977).

Grant (1974) assigned timing of initial failure of the Lookout Hills GSDF to the post-LGM period though apparent glacially-truncated spurs on the lower slopes of the northern headscarp may indicate that some movement either pre-dates the LGM or occurred within this glaciation

Fig. 16.6 Shoal Brook GSDF (1). The Shoal Brook GSDF is on the easternmost edge of the Tablelands and comprises about 0.7 km^3 of material in highly fractured peridotite. This failure does not present a significant risk or hazard to humans

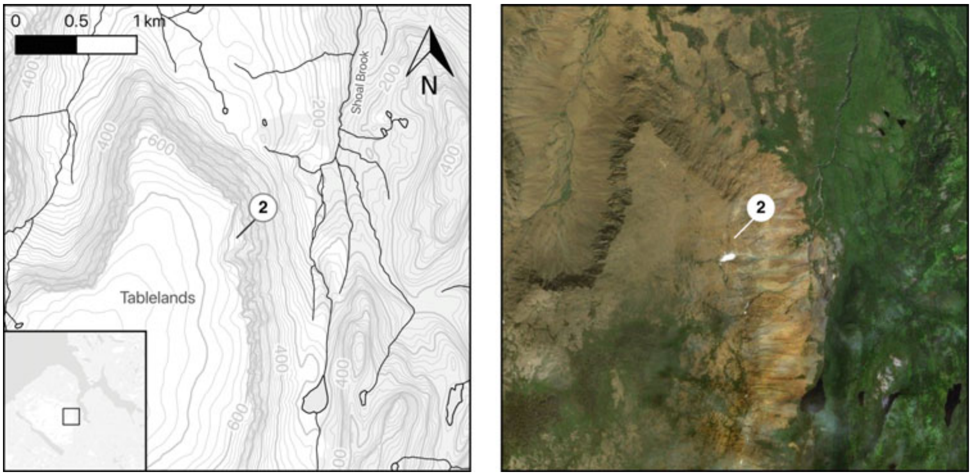
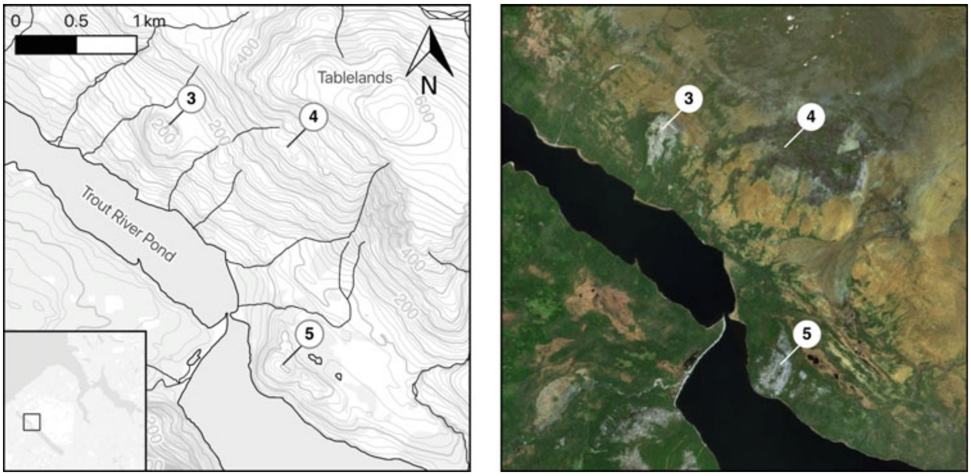


Fig. 16.7 View southward along the eastern edge of the Tablelands showing the westward-convex scarp of the Shoal Brook GSDF with 20 m vertical displacement. Small, stepped failures are evident as well as younger debris cones (Photograph was taken in July 1988)

Fig. 16.8 Miners Point failures. The Sandy Top feature (3) is likely pre-LGM whereas the Miners Point Feature (5) is likely post-LGM. Feature 4 is post-LGM and comprises about 1 km^3 of material



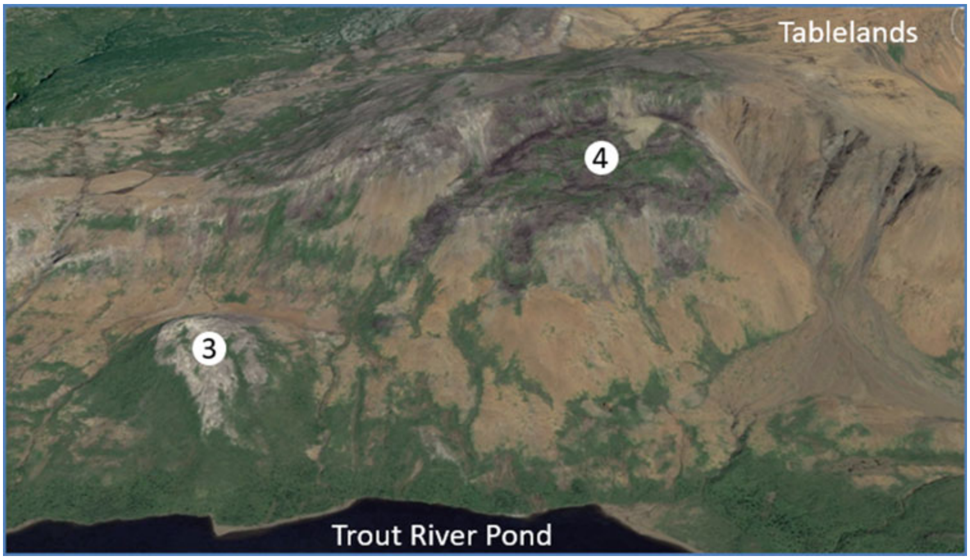


Fig. 16.9 Sandy Top GSDF (3) and GSDF G4 (©Google Earth 2019). The Sandy Top feature comprises almost 1 km^3 of material

Fig. 16.10 Sandy Top GSDF

(25–12 ka). Cumming and Grant (1974) also noted that initial glacial rebound followed by more recent regional subsidence may have resulted in “crustal warping” which would be expected to stress the rocks and lessen their effective cohesion.

The role of jointing in the Lookout Hills GSDF is likely very significant. The rocks of the slumped area of the Lookout Hills are highly jointed. Terzaghi (1962) noted that a mechanism in all rock slides is the development of joints after removal of lateral support and that the critical height of slopes on unweathered rock is influenced more so by joints and faults than by the intact strength of the rock. In the Lookout Hills GSDF lateral support was provided by glacial ice during glaciation.

The time and rate of movement of the Lookout Hills GSDF remains uncertain. Though significant post-glacial movement has occurred, all that can be said for certain is that about 80 m of movement has occurred in about 10,000 years (Grant 1987). However, the slope failure at Lookout Hills probably took place within a short interval of time. A future paleolimnological approach in which ponds on the Lookout Hills and the Shoal Brook GSDF are cored and basal dates obtained may provide some insight into the timing of surface deformation associated with movement. Coring in Bonne Bay has the potential to provide insight into the timing of post-glacial movement if it indeed took place.

Periglacial processes have been very active in the study region and may have also played an important role in initiating movement. Osborn et al. (2007) noted that relict rock glaciers are common in the Tablelands and likely contained significant volumes of ice in their cores when they formed. Osborn et al. (2007) suggested that abundant snow-and-debris avalanches during the spring and early summer led to accumulation in talus aprons at a time when snow accumulation was more substantial than it is now. This same mechanism, combined with active freeze–thaw and intense jointing may have been an important contributor to slope instability for all of the GSDFs discussed.

Evaluating the effects of these features may have application to the continuing development of models of deglaciation for eastern North America. An understanding of the timing and causal mechanism of GSDFs in the Tablelands region may provide context to recent research that suggests that some parts of western Newfoundland deglaciated much earlier than others (Osborn et al. 2007). New technologies (drones, high resolution topographical models developed from drone imagers (e.g., Rossi et al. 2015)) offer the opportunity to produce high resolution images of the surfaces of these features, providing greater clarity of geomorphic processes.

Landslide-generated displacement waves are more limited than tsunamis produced by ocean earthquakes. However, the displacement of water can create massive waves (>100 m run-up heights) that can be devastating locally. A landslide-generated wave which occurred in Lituya Bay, Alaska in 1958 was a result of an earthquake triggered rock avalanche (Weiss et al. 2009). The rock avalanche, which had an estimated volume of 30 M m^3, impacted on the waters at the head of the bay and generated a wave inundation distance of 524 m, the highest recorded in history. As noted earlier, a massive rock slope failure in western Greenland produced tsunamic waves that resulted in considerable damage to property and loss of life. The Lookout Hills GSDF contains approximately 8.3 km^3 of material. If even a small fraction of this entered Bonne Bay as a rock avalanche a destructive tsunamic wave could be generated. The proximity of the Lookout Hills GSDF to significant coastal population (approx. 3000) within 10 km and the low to moderate potential for a magnitude 4 or greater earthquake warrants a more quantitative examination of the risk that this feature may pose.

Catastrophic failure into Trout River Pond of either the Miners Point or Sandy Top GSDFs could be equally destructive as the village of Trout River (pop. 600) is constructed upon an ice-marginal marine delta that lies at the mouth of Trout River Pond. However, the potential for the generation of a rapidly moving rock avalanche from either GSDF appears to be minimal due to the low-angled glide plane for both features.

Seismic shaking might well trigger future movements of these GSDFs. Distant earthquakes were felt in Bonne Bay in 1925 and 1929 (Berger 2014). Moreover, the Lower St. Lawrence Seismic Zone is a seismically active region of eastern Canada that is located less than 500 km from the western Newfoundland coastline. On June 23, 1944, an earthquake of magnitude 5.1 on the Richter scale occurred east of Baie-Comeau and on March 16, 1999, an earthquake of magnitude 5.1 occurred in this region, at about 60 km south of Sept-Iles (Adams and Basham 1989).

We recommend follow-up studies of these sites. Monitoring the changes in fracture widths in key locations with annual tensiometer measurements could provide immediate insight into the activity of selected fractures. In addition to chronology of the basal ponded sediments mentioned above, exposure dating of the sliding planes and breakout surfaces would provide direct chronology on the displacements to evaluate whether or not they formed shortly after deglaciation, or if there is any evidence of acceleration of the GSDFs. Exposure dating of boulders in catastrophically failed rock slides and rock avalanches in the region, along with chronology of the slip faces, could also help establish links to climate change or paleoseismicity.

16.6 Conclusion

GSDFs occur along steep bedrock slopes of western Newfoundland but their age, activity, and causes have not been adequately determined. Despite documented seismic triggering of submarine landslides around Newfoundland, there is no evidence that GSDFs in the study region were generated by seismic ground acceleration. Other plausible causes include a re-balancing of stress fields along slopes which were erosionally over-steepened. There is potential that the GSDF in the Lookout Hills and Shoal Brook regions could become catastrophic massive rock slope failures. The Lookout Hills GSDF could pose a considerable hazard considering its potential to generate a displacement wave in Bonne Bay which could affect a number of coastal communities. Opportunities for risk analysis of large scale GSDFs along the Atlantic Canada coastline exist especially in light of new technologies and approaches.

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