More comprehensive characterization of landslides in permafrost

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ABSTRACT
The Working Classification nomenclature established by the Working Party for World Landslide Inventory during the International Decade for Natural Disaster Reduction (IDNRD) has become the basis for an emerging consensus on landslide classification. It lacks, hower, specific identifiers of permafrost that encompass all landslide types in both frozen and unfrozen terrain. We thus propose the addition of “frozen” to the descriptors of water content of materials.

RÉSUMÉ
La terminologie établie par le Working Party for World Landslide Inventory durant la Décennie internationale pour la réduction des désastres naturels (DIRDN) est devenue le fondement d’un concensus émergeant sur la classification des glissements de terrain, la ‘Working Classification’. Toutefois, cette dernière manque d’identificateurs spécifiques au pergélisol qui tiendraient compte de tous les types de glissements de terrain en conditions gelées et non-gelées. Nous proposons l’ajout du terme ‘gelé (frozen in English) aux descripteurs de la teneur en eau des materiaux.

1 INTRODUCTION

Landslide classifications have evolved in the last 50 years and are still subject to modifications. A recent international consensus developed on landslide classification has been summarized in the Multilingual Landslide Glossary (WP/WLI 1993) and translated there into the UNESCO languages. The English and French versions of this document have recently been published on the Society’s website.

The name of a landslide can become more elaborate as more information about movement and material properties becomes available. Therefore, we believe that the Working Classification would benefit from an additional descriptive term. Knowledge of frozen ground and permafrost has also evolved and increased in the last decades. As the Working Classification of Landslides is open, we believe that the addition of a landslide descriptor related to the frozen state of the water content of the materials would allow a more comprehensive characterization of landslides in permafrost. This initiative is part of a broader suggestion aiming at a more comprehensive characterization of landslides involving additions of descriptive terms (Table 1), including those related to States of Activity (Cruden and Couture 2010).

This paper briefly reviews landslide classifications and current descriptors of the Working Classification, and characteristics of permafrost and frozen ground. It discusses the current nomenclature used to describe and name landslides in permafrost terrain and proposes the inclusion of a new material descriptor, “frozen.” The addition of frozen to the four water content descriptors in the Working Classification allows the classification to be applied to the quarter of the Earth’s surface covered by frozen ground.

Table 1. Descriptive terms for forming names of landslides (modified after Cruden and Varnes 1996).

Activity State	**Distribution**	**Style**
Active	Advancing	Complex
Reactivated	Retrogressive	Composite
Suspended	Widening	Multiple
Inactive	Enlarging	Successive
Dormant	Confined	Single
Abandoned	Diminishing	
Stabilized	Moving	
Relict		

Rate	**Water Content**	**Material**	**Type**
Extrem. rapid	Dry	Rock	Fall
Very rapid	Moist	Soil	Topple
Rapid	Wet	Earth	Slide
Moderate	Very wet	Debris	Spread
Slow	FROZEN		Flow
Very slow			
Extrem. slow			

2 LANDSLIDE CLASSIFICATION

2.1 Brief overview of landslide classifications

The Working Classification nomenclature (Cruden and Varnes 1996), established by the Working Party for World Landslide Inventory during the International Decade for Natural Disaster Reduction, has become the basis for an emerging consensus on landslide classification. This classification has been used in the latest edition of the Transportation Research Board's Special Report on landslides (Turner and Schuster 1996) and is an update of Varnes' (1978) widely-used classification of landslides. Hutchinson's classifications of landslides (Hutchinson 1968; 1988) also enriched the nomenclature and contributed to the Working Classification.

2.2 Description of materials

A preferred sequence of terms in naming landslides was proposed by WP/WLI (1990): Activity, Rate of Movement, Water Content, Material, and Type of Movement. This follows a recommended narrowing focus sequence in landslide reconnaissance; first in time, then in space. In this paper, we assume that all the movements we illustrate in permafrost are active, leaving us to describe only the distribution and style of their activity. Rate of movement has not historically been an important factor in classifying permafrost landslides and we do not consider it here.

Varnes (1978) described materials in landslides as either rock or soil; the former being a hard or firm mass that was intact and in its natural place before the initiation of movement, and the latter an aggregate of solid particles generally of minerals and rocks which has either been transported or formed by the weathering of rock in place. Soil is divided into debris and earth. Debris contains a significant proportion of coarse material; 20 to 80 percent of the particles are larger than 2 mm, the remainder are less than 2 mm. Earth describes material in which 80 percent or more of the particles are smaller than 2 mm; it includes a range of materials from non-plastic sand to highly plastic clay.

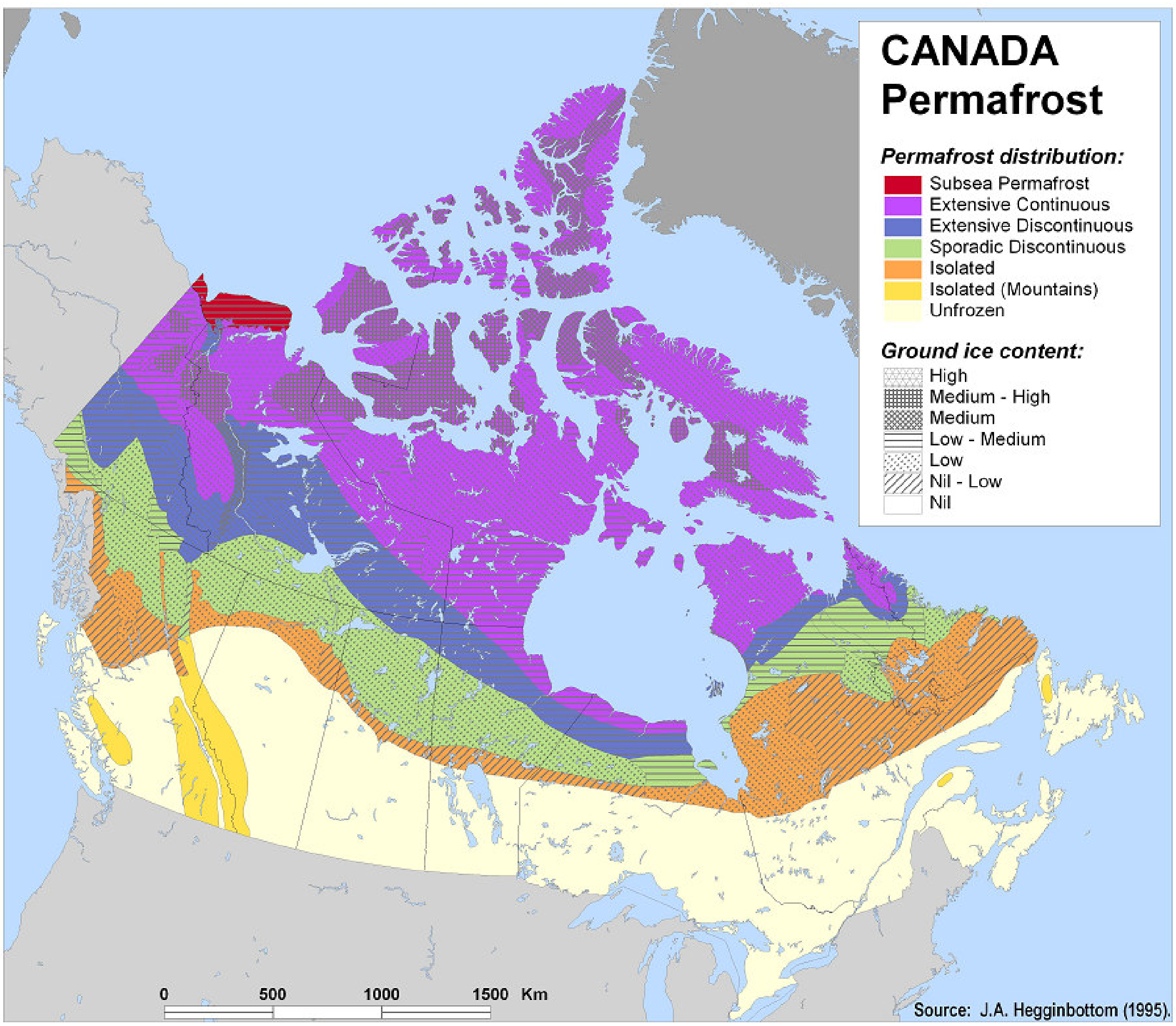

Figure 1. Permafrost distribution in Canada (After Hegginbottom et al. 1995).

Varnes (1978) also suggested four terms derived from simple observations of the water content of the material: 1) Dry, no moisture, 2) Moist, contains some water but no free water, the material may behave as a plastic solid but does not flow, 3) Wet, contains enough water to behave in part as a liquid, has water flowing from it, or supports significant bodies of standing water, and 4) Very wet, contains enough water to flow as a liquid under low gradient.

3 PERMAFROST AND FROZEN GROUND

Permafrost is a thermal condition, not a type of soil or rock, and both rock and soil can be in a permafrost state. Permafrost is defined as soil, sediment, or rock that remains at or below 0℃ for at least two years (Muller 1947).

About one quarter of the Earth's surface is covered by frozen ground. In the Northern Hemisphere, approximately 55% of the land surface is covered by seasonally frozen ground, while 24% of the land surface is underlain by permafrost. In some countries like Russia and Canada, permafrost covers 50-55% of their land surface (Figure 1). In the Southern Hemisphere, permafrost is found in Antarctica, the Antarctic islands, and the Andes Mountains (Boelhouwers and Hall 2002). At lower latitudes, permafrost can occur at high elevations and is often called alpine permafrost, such as in the European Alps and cordilleras in the Americas.

Permafrost regions (Figure 1) can be described by the percentage of frozen ground underlying their land surface. In the extensive continuous permafrost zone, permafrost occurs everywhere beneath the ground surface except under large bodies of water. Discontinuous permafrost is broken into two divisions: the extensive permafrost zone, where permafrost underlies 50-90% of the land area, and the sporadic permafrost zone, where it underlies 10-50% of the land area. Permafrost can also be found as isolated patches, where it affects less than 10% of the land area.

Frozen ground can also be classified based on ground ice content and whether ice is visible or not (Pihlainen & Johnston 1963, Linnell & Kaplar 1963; ASTM 2009).

Ground temperature distribution and profiles (Figure 2) are used to define the main components of permafrost, such as the active layer (the uppermost layer of soil that thaws and freezes seasonally) and the permafrost zone (Brown et al. 1981). Changes in the ground thermal regime of permafrost can result from either changes in natural factors (e.g., precipitation, vegetation, wildfires, and climate change), or from anthropogenic factors (e.g., snow plowing, removal of vegetation cover). Such changes often lead to significant effects on hydrological regimes and ecosystems, as well as infrastructure that relies on permanently frozen ground. Erosion, ground subsidence and landslides (Figures 3, 4) are the most obvious consequences of permafrost degradation. Changes in strength properties of material and ground pore pressure due to ground thawing or freezing can results into slope movements and landslides (Figures 3 to 6).

4 NOMENCLATURE OF LANDSLIDES IN PERMAFROST

Slope movements and landslides in permafrost areas can be found in both frozen and unfrozen ground (Figures 3 and 4). Tart (1996) illustrated numerous examples of permafrost landslides and stability problems found in natural and engineered frozen slopes.

McRoberts and Morgenstern (1973; 1974a; b) first proposed a classification of permafrost landslides based merely on descriptive features and containing three main types of movements: flow, slide, and fall.

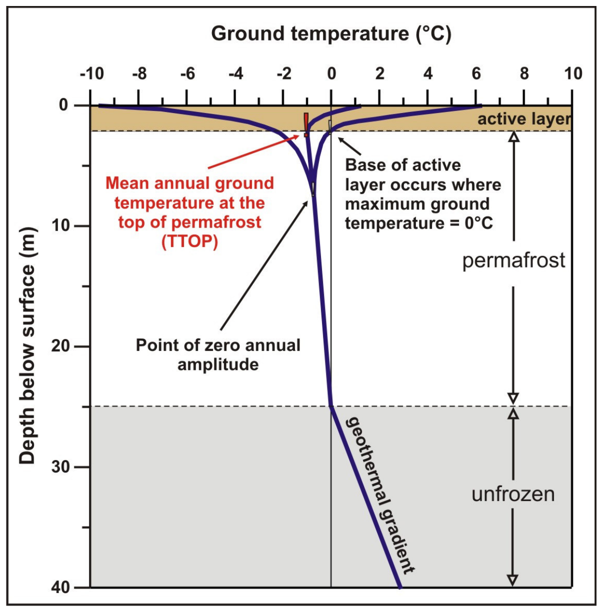

Figure 2. Thermal profile showing annual maximum, minimum and mean temperature as a function of depth. (Source: Wright et al. 2003).

The following discussion presents a brief description of these types of landslides as they were first defined.

4.1 Flows

Flows were first subdivided into skin, bimodal, and multiple retrogressive. Non-standardized terms were then introduced to describe subdivisions of these slope movements. Skin flows were defined as *'the detachment of thin veneer of vegetation and mineral soil and subsequent movement over a planar inclined* *surface'* (McRoberts and Morgenstern 1974, p. 450). Commonly found as elongate forms (Hardy & Morrison 1972; Isaacs & Code 1972) they can evolve into large, more symmetrical landslides. They are also called active layer detachment glides (Mackay and Mathews 1972), or slides. Forest fires are often the main factor leading to the development of skin flows (Hardy & Morrison 1972; Mackay and Mathews 1973; Savigny et al. 1995; Dyke 2000; Figure 4). Lewkowicz and Harris (2005) looked at the geomorphology and processes of active layer detachments in different types of permafrost conditions.

McRoberts and Morgenstern (1974) described extensively bimodal flows which can be briefly summarised as a form of mass movement that has a biangular profile most of time associated to two distinct modes of failure. Steep headscarp and low-angle tongue characterize bimodal flows (Figure 6). Kerfoot (1969) described two types of bimodal flows, mudslumps and mudflows. In the former type, there is no well developed terminal area, whereas mudflows involve an extensive terminus of displaced material.

Brown et al. (1981, p. 64) provided a description of multiple retrogression flows, *'multiple retrogressive flows have an overall flow form, but retain some portion of their pre-failure surface.'*

A fourth class of flow, solifluction (also called gelifluction), was then added to the classification (Brown et al. 1981). Solifluction is defined as *'the slow downslope flow of saturated, unfrozen earth materials'* (NRC 1988). Gelifluction is defined as *'the slow downslope flow of unfrozen earth materials on a frozen substrate'* (Cormier 1992, p. 31). It can be identified by lobate flow features and in periglacial environments are associated with patterned ground. Solifluction or gelifluction are common in high altitudes and in the far north (Brown et al. 1981).

4.2 Slides

Slide movements were divided into three classes: block, multiple retrogressive and rotational. Block slides are usually a large single block that has moved down with little of no back tilting (Brown et al. 1981).

Multiple retrogressive slides usually display a series of arcuate, concave-toward-the-toe blocks which step upwards toward the headscarp. They are often very large slide failure into frozen ground as shown in Figure 3.

Brown et al. (1981) restricted the use of rotational slides to unfrozen ground.

4.3 Falls

Falls can occur in rock, but also in frozen soils. They are the results of a downward movement of detached blocks falling under the influence of gravity. They commonly occur along river banks where erosion and thawing are most active, leading to bank undercutting and break-off of frozen blocks, sometimes along ice wedges (Hoque and Pollard 2009).

Figure 3. Example of slope failure that occurred in 1997 in frozen glaciolacustrine sediments in the bank of the Mackenzie River, south of Old Fort Point, Northwest Territories. (GSC-ESS Photo 2000-93).

Figure 4. Example of unfrozen ground-related landslides in permafrost areas. These active layer detachments along the Mackenzie River (Northwest Territories) began in 1995 as a result of permafrost degradation due to forest fires over previous years. (GSC-ESS Photo No. 2007-41).

5 INCLUSION OF A NEW DESCRIPTOR

Recent permafrost and landslide studies in the Canadian sub-Arctic and Arctic have brought new insights on landslide occurrence and characteristics in permafrost areas (Dyke and Brooks 2000). Aylsworth et al. (2000) incorporated some elements of Varnes' (1978) landslide classification, wherein landslides in permafrost regions were categorized by "class" of movement (flow, slide, complex) and subdivided into "type" which included terminology unique to permafrost regions, such as shallow, active layer detachments (or skin flows), deeper retrogressive thaw flows, (or bimodal flows/ground ice slumps), and rapid debris flows. Lewkowicz and Harris (2005) detailed the geomorphological characteristics of active layer detachments in Canadian permafrost regions. Couture and Riopel (2008a; b) also inventoried and studied various types of landslides in the Mackenzie Valley. Kokelj et al. (2009) looked at the initiation and growth of slumps in ice-rich sediments in the Canadian tundra.

5.1 Confusion in terminology and description

Although there are some similarities in the current nomenclature used to describe landslides in permafrost and the current Working Classification terms, none of the studies mentioned above have contributed to a standardized classification of landslides in permafrost. To the contrary, there is confusion in terms used to define landslide types in permafrost.

For example, McRoberts and Morgenstern (1973; 1974a) and Tart (1996) indicated that sliding mechanisms are observed in multiple retrogressive flows. Aylsworth et al. (2000) and Lewkowicz and Harris (2005) showed clear evidence of sliding in active layer detachments, which are also known as skin flows. However, no indication of type of movement is provided in the Canadian definition of active layer detachment (NRC 1988).

In Russia, cryogenic landslides are the equivalent of active layer detachments or skin flows in the North American literature. Cryogenic landslides, which include both slides and flows, are defined as "…*quick movements of soil blocks or earth flows coupled with turf and moss cover*…" (Liebman 1995, p. 259).

The use of the term "bimodal flow" appears anomalous as the adjective indicates two modes of failure whereas the noun indicates only one mode of movement. Kerfoot (1969) distinguished two types of bimodal flows, mudflows and mudslumps. In this latter, the dominant mode of failure is sliding. Hughes (1972) called this type of bimodal flow, retrogressive thaw flow slides.

In their description of multiple retrogressive flows, Brown et al (1981) also indicated that the morphology of their scarps suggests a series of retrogressive failures, but also, in some cases, the presence of rotational slides. Thus, the main mode of movement, sliding, is used to describe a type of flow.

The terms thaw flows and thaw slides were both used by Aylsworth et al. (2000) and Couture and Riopel (2008a; b) to characterize slopes in ice-rich soils that thaw in their scarps and the resulting water-saturated sediments flow down slope away from the main scarps. The current use of these terms does not bring sufficient clarity in properly defining landslides occurring in permafrost environments.

5.2 Inclusion of 'Frozen '

The Working Classification of Landslides lacks any specific identifiers of permafrost to encompass all landslide types in both frozen and unfrozen terrain. The addition of "frozen" to the descriptors of materials (water content) may address that need. This newly proposed material descriptor applies to the material that becomes displaced.

For example, the slope failure shown in Figure 3 is a retrogressive, multiple, rapid, frozen earth slide. The active layer detachments in Figure 4 (skin flows, Aylsworth et al. 2000) are enlarging, complex, very rapid, wet debris slides-debris-flows in the Working Classification. Multiple, retrogressive, thaw flows (Couture & Riopel 2008a; b) are retrogressive, complex, slow, moist, earth slide-wet earth flows in the Working Classification. In the example shown in Figure 5, the lead author witnessed the reactivation of landslide in summer 2006. Thus, in this particular case, the proper name is reactivated, retrogressive, complex slow, moist, earth slide-very rapid wet earth flow. A bimodal flow (McRoberts and Morgenstern 1973) or retrogressive thaw flow (Couture and Riopel 2008a; b) can be more fully described as a retrogressive, complex, slow-moderate, earth slide-very wet, earth flow (Figure 6). Brown et al. (1981, Table 2.2) provided a summary of the measured rate of movement of headscarps for this type of landslide, most of them showing slow to moderate rates.

The last two examples show that adding "frozen" to the terms describing water contents of displaced materials results in more comprehensive characterization of landslides occurring in permafrost. Because the terms used in the Working Classification are well-defined, the precision of the characterizations is also improved and landslides in permafrost become more directly comparable to landslides in unfrozen soils.

Figure 5. Retrogressive thaw flows are retrogressive, complex, slow, moist, earth slide-wet earth flows in the Working Classification (GSC-ESS Photo No. 2007-51).

Figure 6. A bimodal flow or retrogressive thaw flow is a retrogressive, complex, slow-moderate, earth slide-very wet, earth flow in the Working Classification (GSC-ESS No. Photo 2007-59).

6 CONCLUSION

The Working Classification of Landslides would benefit from the inclusion of "frozen" as a descriptor of water content, in order to better capture landslides in permafrost terrain. Landslides described by the new term show how their characterizations are more comprehensive.

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