Challenges with terrain stability mapping in northern British Columbia – the special case of large complex landslides

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ABSTRACT
In British Columbia the terrain stability mapping system has largely been developed for the forest industry. Generally emphasis is placed on landslide potential relating to tree removal and road construction. Terrain stability mappers develop criteria for their map areas based on airphoto interpretation, the presence of landslide features, slope and soil characteristics, and experience. The system is best suited for simple landslides, but is less effective where complex landslides occur. Special consideration needs to be given to: (1) slopes where rock slides can trigger much larger movements in soil; (2) glaciomarine sediments; (3) areas of potential degrading permafrost; and (4) preglacial buried valleys.

RÉSUMÉ
En Colombie britannique, le système cartographique de stabilité des terrains a été principalement développé pour l'industrie forestière. D'une façon générale, les secteurs susceptibles d'être affectés par des glissements de terrains associés au débardage et à la construction de routes sont considérés en priorité. Les spécialistes en cartographie de la stabilité des terrains définissent des critères pour les zones à cartographier en se basant sur la photo-interprétation, la présence de caractéristiques associées aux glissements de terrains, et l'expérience. Le système est bien adapté pour prévoir les glissements simples, mais est moins efficace pour les glissements complexes. Une attention particulière doit être portée: (1) aux pentes pour lesquelles des glissements rocheux peuvent déclencher des mouvements dans les sols beaucoup plus importants ; (2) aux sédiments glacio-marins ; (3) aux zones pouvant être sujettes à une dégradation du pergélisol ; et (4), aux vallées préglaciaires enfouies.

1. INTRODUCTION

In British Columbia (BC) the basis for most landslide hazard mapping is the terrain map which combines surficial geology with modifying geomorphic processes (Resources Inventory Committee 1996; Howes and Kenk 1997). In the forest sector, terrain stability mapping is used to delineate polygons where timber harvesting or road building may cause landslides (BC Ministry of Forests 1999). In addition to mapping, a terrain stability field assessment (TSFA) is required in potentially unstable areas. The TSFA is used to assess landslide potential for proposed timber harvesting or road construction. The new Forest and Range Practices Act (FRPA – BC Ministry of Forests 2004) states that forest and range practices shall not cause landslides. In neither terrain stability mapping, nor in the TSFA was the potential of upslope hazards normally considered – only the likelihood of activity causing a slope failure. Separate assessments were sometimes done to assess the likelihood of sediment entering a stream. With the exception of road safety considerations, mapping and assessments used in the forest sector were not meant to assess the suitability of sites for infrastructure and are thus to be contrasted with landslide hazard mapping for land use zonation (Hungr et al 1994).

Terrain stability mapping and TSFA's are generally done in remote regions where little previous work has been done and generally where there is no knowledge of subsurface conditions. It follows then that the work is subjective, based on airphoto interpretation, on-site observations, and mapper experience. Experienced terrain scientists in BC have developed considerable skill in this field.

Recently guidelines for terrain stability professionals in the forest sector have been adopted by the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC 2003). Objectives of assessments outlined in section 4.2(a) of the guidelines are *to characterize the existing landslide hazards (terrain and terrain stability conditions) in areas within, adjacent to or connected to the Development area*. This then goes beyond the mandate of simply assessing the landslide hazard of forest development.

The mapping was developed primarily for shallow debris slides and flows – relatively simple mass movements, common on the coast. There are however situations where more complex landslides occur.

It is the purpose of this paper to introduce geological conditions common in northern bc that require special considerations in terrain stability mapping and assessments, where conventional techniques may not be sufficient. the focus will be on important parameters that occur below the ground (not visible) and off site. topics include situations where rock slides can trigger larger movements in soil, glaciomarine sediments, permafrost areas, and preglacial buried valleys. the well-known association of mountain deformation and landslides (bovis 1982, 1990) is not discussed.

General slope hazards, not restricted to forestry, are considered in the remainder of the paper.

2. BACKGROUND

2.1 Terrain mapping

A terrrain classification system was adopted in BC (E.L.U.C.S. 1976), based on a system introduced by R. Fulton (Fulton et al. 1979). The classification has evolved into an elaborate and comprehensive system (Resource Inventory Committee 1996; Howes and Kenk 1997). When terrain maps are created by experienced mappers, they form a sound basis for many derivative maps – among these terrain stability maps.

Besides, identifying surficial material, texture, and surface expression, terrain maps also identify geomorphic processes that have modified the terrain. Mass movement processes are also included. The letters R and F distinguish between rapid and slow mass movement, and each of these can be subdivided into further subclasses (Table 1). Although the subcategories are not comprehensive they work reasonably well for most mass movements. The nomeclature is different from that of Cruden and Varnes (1996) and Hungr et al. (2001). In this paper the nomenclature of Cruden and Varnes (1996) is used primarily.

Table 1. Subclasses for mass movement processes[1]

Subclass name	Map symbol
Initiation zone	“
Soil creep	c
Rock creep	g
Tension cracks	k
Rock spread	p
Soil spread	j
Debris fall	f
Rock fall	b
Debris flow	d
Debris torrent	t
Earthflow	e
Rock slump	m
Soil slump	u
Slump-earthflow	x
Debris slide	s
Rockslide	r

1. Table modified from Howes and Kenk (1997).

2.2 Terrain stability mapping

In BC terrain stability mapping was largely developed for the forest sector. A system was first developed and used on the coast in 1974 by W.W. Bourguois of the forest company, MacMillan Bloedel Ltd (Bourguois 1975, 1978; Bourguois and Townsend 1977), and D.E. Maynard (1982; 1987). The system was modified by Schwab (1982, 1983, 1993), Howes and Swanton (1994) and the BC Ministry of Forests (1995, 1999). The latest iterations included reconnaissance stability mapping (RSTM) and detailed terrain stability mapping (DSTM) with three and five hazard classes, respectively.

The RSTM classes are stable (U), potentially unstable (P), and unstable (U). On the maps, classes P and U include a terrain symbol, geomorphic process (as in Table 1) and a slope range.

The DSTM classes range from I to V, from stable to the most unstable (Table 2). As mentioned above, these classes were created for forestry purposes. DSTM polygons are generally derived from terrain polygons mapped by the same geoscientist. Even though a terrain stability polygon may be in a runout zone of a landslide, if the associated terrain symbol does not have a ”, indicating an initiation zone (Table 1), the stability polygon will likely not be a class IV or V (Table 2).

Table 2. Detailed terrain stability classification[1]

Terrain stability class	Interpretation
I	• No significant problems exist
II	• Very low likelihood of landslides from timber harvesting or road construction • Minor slumping expected in road cuts
III	• Minor instability • Low likelihood of landslides from timber harvesting or road construction
IV	• Moderate likelihood of landslides from timber harvesting or road construction
V	• High likelihood of landslides from timber harvesting or road construction

1. Table modified from BC Ministry of Forests (1999).

3. TERRAIN REQUIRING SPECIAL CONSIDERATION

There seems to be an increase in the frequency of large natural landslides in northern BC (unpublished data on file with the BC Ministry of Forests). For rapid landslides greater than 1 Mm^3 or longer than 1 km 1.3 occurred annually over the last three decades with the last decade, yielding an average of 2.3 landslides per year. This translates to about 0.4 catastrophic landslides per 100 000 km^2 annually over the last decade in the area. It is possible that the northern part of the province is responding to climate change. Figure 1 and Table 3 show a subset of these large landslides that are applicable to this paper. Of course when smaller landslides are considered, the numbers increase.

What follows are examples of terrain susceptible to large landslides where conventional slope stability mapping criteria may need special consideration or re-evaluation.

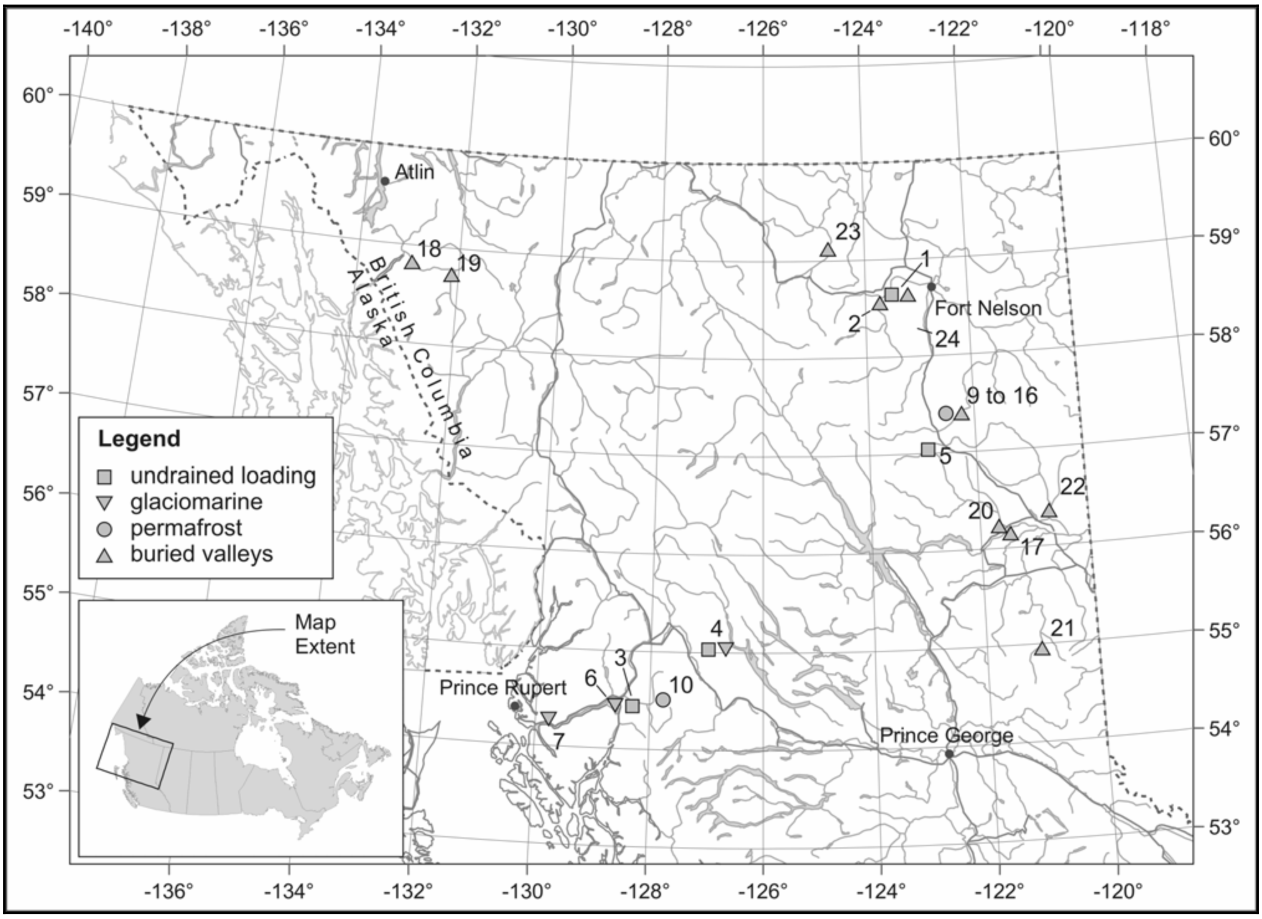

Figure 1. Map of northern British Columbia showing locations of large, long-runout landslides between 1973 and 2003. See Table 3 for information on individual landslides.

3.1 Where rock slides trigger larger movements

There is ample evidence in northern BC of rock slides triggering larger movements. These include rotational rock slides (slumps) that trigger much larger earth flows on low gradients, rock slides that trigger channelized debris flows, and rock slides that trigger debris avalanches. In the first example the rock slide moves only a small distance. In the latter examples the rock disintegrates and becomes entrained over most of the landslide distance. In every case, the energy from the rock slide results in movements much larger than would be expected from landslides initiating on the lower slopes. Thus assessments of the lower or mid slopes without considering upslope hazards would result in a severe underestimation of the stability of that site.

3.1.1 Rotational rock slide – earth flow

In recent decades, large rock slide – earth flows have occurred in the Muskwa River area on slope gradients that would be considered stable in terrain stability field assessments where upslope hazards are not accounted for (BC Ministry of Forests 1999) and using limit equilibrium analysis. It is only through undrained loading (Hutchinson and Bandhari 1971) by a moving rock slide that these slopes fail catastrophically.

The Muskwa landslide (Figure 2) is a remarkable geomorphic feature. Clayey, relatively stone free diamicton occupying a preglacial valley liquefied and flowed on a 3º slope after being impacted by a rock slide. The distance from crown to tip was 3.25 km. The landslide involved 15 M m^3 and covered an area of 180 ha, There was no evidence of previous slope deformation on aerial photographs.

The Muskwa-Chisca landslide (Figure 3) occurred in July 2001 (Geertsema et al. 2003). Heavy rains may have triggered an initial rotational slide in sedimentary bedrock. This triggered a large earth flow that entered Muskwa River. The landslide is 1.5 km long and covers an area of 43 ha. In this case there was evidence of previous landsliding. Nonetheless, based on an on-site investigation such a large movement would not have been expected without taking into acount the undrained loading mechanism from an upslope rock slide.

Table 3. Landslide data[1]

# on map	Name	Date	Volume (M m^3)	Length (km)
A. rock slides triggering larger movements in soil				
	1. Rock slide – earth flows			
1	Muskwa	1979	15	3.25
2	Muskwa-Chisca	July 2001		1.5
	2. Rock slide - debris flows			
3	Zymoetz	June 2002	1.6	4.3
4	Harold Price	June 2002	1.6	4
	3. Rock slide - debris avalanche			
5	Pink Mountain	June 2002	1	2
B. Glaciomarine sediments				
6	Mink Creek	Dec 93 - Jan 94	2.5	1.2
7	Khyex River	Nov. 2003	4.7	1.6
C Slopes associated with potential degrading permafrost				
4	Harold Price	June 2002	1.6	4
9	Buckinghorse I	mid 1990's		1.75
10	Buckinghorse II	mid 1990's		1.0
11	Buckinghorse III	mid 1990's		1.77
12	Buckinghorse IV	mid 1990's		0.7
13	Buckinghorse V	mid 1990's		1.3
14	Buckinghorse VI	mid 1990's		0.8
15	Buckinghorse VII	mid 1990's		1.4
16	Buckinghorse VIII	mid 1990's		0.65
D. Preglacial buried valleys				
	1. Glaciolacustrine sediments			
17	Attachie	May 1973	12.4	1.5
18	Inklin [9]	1979	2-3	0.7
19	Sharktooth	1980	3-4	1.2
20	Halfway	Aug 1989	1.9	0.7
21	Quintette[1]	May 1990	10	1
22	Flatrock	Oct 1997		0.65
	2. Diamictons (mostly clayey tills)			
1	Muskwa	1979	15	3.25
9	Buckinghorse I	mid 1990's		1.75
10	Buckinghorse II	mid 1990's		1.0
11	Buckinghorse III	mid 1990's		1.77
12	Buckinghorse IV	mid 1990's		0.7
13	Buckinghorse V	mid 1990's		1.3
14	Buckinghorse VI	mid 1990's		0.8
15	Buckinghorse VII	mid 1990's		1.4
16	Buckinghorse VIII	mid 1990's		0.65
23	Scaffold Creek	mid 1990's		0.5
24	Halden Creek	mid 1990's	5	0.6

1. Table modified from Geertsema et al (2003). The list only includes very large landslides from 1973-2003.

Both landslides had conspicuous lateral ridges at the earthflow margins. Such ridges are also evident in other areas, and start below rotational rock blocks such as near site 24 on Figure 1. These then are excellent indicators of earth flows generated by undrained loading.

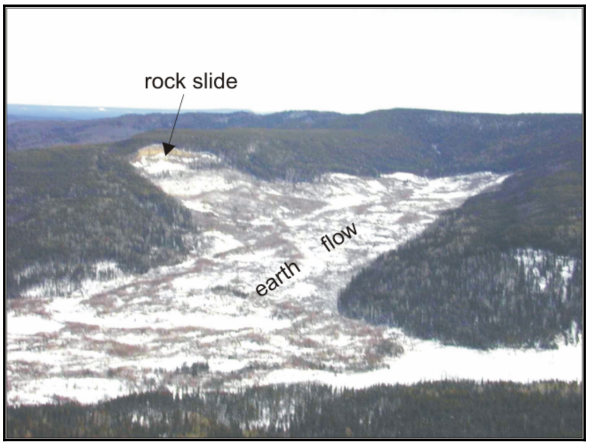

Figure 2. The 1979 Muskwa rock slide - earth flow in clayey diamicton on a 3º slope in a preglacial buried valley. The distance from crown to tip is 3.25 km.

Figure 3. The 2001 Muskwa-Chisca landslide – a rotational rock slide –earth flow involving undrained loading.

3.1.2 Rock slide – debris flow

In June 2002 two large rock slides triggered long runout channelized debris flows. These are the Zymoetz and Harold Price landslides. The Harold Price landslide involved permafrost and is discussed in section 3.3.

The Zymoetz landslide originated on a steep cirque headwall. Rubble entered a channel and induced a debris flow that dammed Zymoetz River causing flooding 1.5 km upstream. The landslide travelled a distance of 4.3 km with a fahrböschung of 16.3°. Hungr and Evans (In press) discuss the important undrained loading mechanism of entrained rock rubble from rock slides impacting soil. This results in a much larger landslide than if a movement involving only rock or only soil occurred.

3.1.3 Rock slide – debris avalanche

A large landslide at Pink Mountain (Figure 4) with a 2 km travel distance occurred in June 2002 (Geertsema et al. (2003). Pre-slide deformation of the slopes above the landslide has been significant. The scarps of at least two earlier landslides, and evidence of slow deformation are visible above the 2002 landslide and the zone of detachment underwent previous movement.

The rock slide entrained underlying fine textured till and colluvium resulting in a rock slide - debris avalanche (Geertsema et al. 2003). Hungr and Evans (In press) argue that an initial rock slide on to soil can cause rapid undrained loading of the soil, elevating pore water pressures, and causing liquefaction, drastically reducing soil friction. The travel distance of the Pink mountain landslide, the degree of spreading and thinning, and the low fahrböschung (11.6°) were likely enhanced by partial liquefaction of this lower material as a result of rapid undrained loading.

Figure 4. The Pink mountain landslide – a 2 km long rock slide – debris avalanche that achieved remarkable spreading and thinning through the undrained loading of entrained rock slide debris.

3.2 Glaciomarine sediments

Sensitive glaciomarine sediments are common in uplifted fjordal valleys of northern British Columbia, particularly in the Nass River and Terrace-Kitimat areas (Geertsema 1998). Recent landslides include retrogressive earth flows at Lakelse Lake in 1962, Mink Creek (Figure 5) in 1994 (Geertsema and Schwab 1995), and Khyex River in 2003 (Schwab et al. this volume). Although the Lakelse landslides were triggered by site loading, typically a small landslide in an exposed bank exposes quick clay and triggers a large retrogressive flow or spread.

The problem with doing conventional terrain stability analysis on this type of terrain, from field evidence, is that the dimensions of these landslides depend in large part on conditions below the ground (Carson and Geertsema 2002). It is relatively easy (from slope morphology) to predict the likelihood of an initial triggering landslide that exposes quick clay. However, without any knowledge of the sensitivity of zones behind the predicted landslide it is not possible to assign a proper terrain stability hazard for these conditions some distance from the break in slope.

Mitchell (1978), Lebuis et al. (1983), and Viberg (1983) have developed methods for mapping landslide hazard in sensitive marine clays in Ontario, Quebec, and Norway, respectively –areas with long experience with quick clays. While their methods consider terrain morphology, they also all rely heavily on subsurface strength measurements.

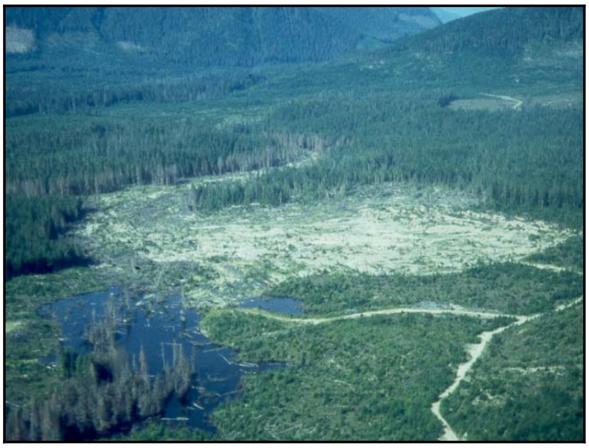

Figure 5. The Mink Creek earth flow-spread involved quick clays and occurred in glaciomarine sediments near Terrace, BC.

3.3 Slopes with degrading permafrost

Sporadic permafrost occurs in mountains and northeastern lowlands of northern BC. Typically mountain permafrost is evidenced by periglacial features such as solifluction lobes, rock glaciers, and patterned ground. Sometimes permafrost is encountered in muskeg in the Fort Nelson Lowland of northeastern BC (Holland 1976), but it is not easy to recognize from aerial photographs.

Mountain permafrost may be particularly sensitive to climate change in mid latitudes, as demonstrated in the European Alps (Etzemüller et al. 2001; Harris et al. 2001). Melting of alpine permafrost decreases the stability of mountain slopes (Davies et al. 2001; Harris et al. 2001). Although there is only one recent documented case in northern BC – the 2002 Harold Price landslide (Schwab et al. 2003), recent large rock avalanches in the European Alps have been attributed to the degradation of mountain permafrost (Dramis et al. 1995; Bottino et al. 2002).

As permafrost degrades, materials will no longer be able to stay in their present slope positions and loading of unstable slope positions can occur – this can lead to catastrophic failure.

The Harold Price landslide (Figure 6; Schwab et al. 2003) originated at the lip of a southwest-facing cirque occupied by a rock glacier. Interstitial ice was observed in the main scarp after the landslide. After travelling 1.3 km, the rock slide transformed into a debris flow, which became channelized at 2.2 km. The total travel length of the landslide was 4 km, but a hyperconcentrated flow carried sediments and logs an additional 3.5 km down Harold Price Creek. The volume of the landslide is about 1.6 M m^3 and its fahrböschung is 9.9°. This slide was related to melting permafrost, but also became much larger by undrained loading of till resulting from entrainment of the displaced rock rubble – a mechanism explained by (Hungr and Evans, In press).

Figure 6. The Harold Price rock slide - debris flow (June 28, 2002) involved permafrost at its head. The smaller landslide to the right is a catastrophic earth spread that occurred in 1999.

A significant cluster of retrogressive earth flows occurs in the Buckinghorse area of northeastern BC (Figure 1; Table 3). They occur on extremely low gradients (3°) with travel distances up to 1.75 km. Although there is not yet a confirmed link, these landslides occur in an area where sporadic permafrost is encountered. In addition, they also occupy preglacial buried valleys. Thus unknown, hidden elements may include permafrost as well as subsurface bedrock topography.

3.4 Buried preglacial valleys

Most rapid deep-seated landslides in northern BC (Geertsema 1998; Geertsema et al. 1998, 2003) and Alberta (Lu et al. 1999) occur in buried preglacial valleys. The associated sediments are usually advance phase glaciolacustrine (glacial lake) sediments covered with till, or the clayey diamictons of northeastern BC (probably tills). There are numerous recent examples of landslides in these settings.

The problem with doing terrain stability evaluations in these settings is that the subsurface bedrock topography is not always known where thick overlying drift masks preglacial valleys (or even gullies). Thus knowledge of subsurface conditions is required to assess the potential for large rapid landslides in these materials.

Figure 7. The Buckinghorse area of northeastern BC has reported sporadic permafrost and large rapid earth flows, such as this one which is 1.75 km long on a gradient as low as 3°.

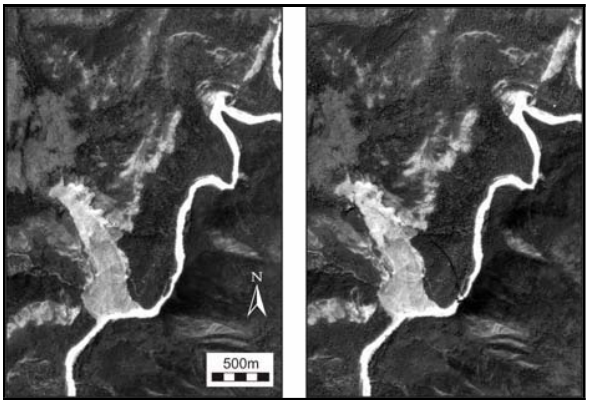

Figure 8. Steropair of the 1.2 km long Sharktooth landslide - a large earth flow involving glaciolacustrine sediments overlain by till in a preglacial valley in northwestern BC.

Excellent examples of large landslides in diamicton-filled preglacial valleys include the Muskwa (Figure 2) and the Buckinghorse (Figure 7) landslides.

The other category of valley fill subject to catastrophic landsliding includes glaciolacustrine sediments. In most instances only the advance phase lake sediments are involved with rapid catastrophic movements (Geertsema et al. 2003). Advance phase lake sediments were deposited at the beginning of the last (Fraser) glaciation as growing glaciers blocked tributary valleys (Clague 1989). During full glacial conditions these lakes were covered by ice and till. Late phase lakes developed as the ice downwasted and retreated at the end of the Fraser glaciation. These lake sediments are not commonly associated with catastrophic movements. A possible reason for large movements in the advance phase lake sediments may relate to pre-shearing of the material (Fletcher et al. 2002).

Examples of catastrophic landslides in advanced phase lake sediments in northern BC, include the famous 1973 Attachie landslide on the Peace River (Fletcher et al. 2002) and the 1.2 km long Sharktooth landslide (Figure 8) on the Sheslay River (Geertsema 1998). In both cases the lake sediments were covered with till.

4. CONCLUSIONS

Accurate assessment of terrain stability hazard can be challenging in certain landscapes of northern BC. This is especially true of landscapes:

- where upslope rock slides trigger larger landslides in soil – phenomena not possible without the undrained loading mechanism; and

- where key elements that effect landslide kinematics are not discernable (or readily discernable) from surface morphology.

Key elements include sensitive or quick zones in glaciomarine sediments, permafrost, and subsurface bedrock topography. In the latter case terrain is particularly prone to large catastrophic landslides where preglacial valleys are infilled with clayey tills or with till-covered glaciolacustrine sediments.

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