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Engineering Geology 83 (2006) 120–143

ENGINEERING GEOLOGY

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An overview of recent large catastrophic landslides in northern British Columbia, Canada

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Accepted 24 June 2005
Available online 4 November 2005

Abstract

At least thirty-eight, large, catastrophic landslides, each either larger than 0.5 M m^3 or longer than 1 km, have occurred in northern British Columbia in the last three decades. The landslides include low-gradient flowslides in cohesive sediments, long-runout rock slides (rock avalanches), and complex rock slide-flows. The flowslides have occurred in a variety of sediments, including glaciolacustrine silt, clay-rich till, and clay-rich colluvium. The rock failures have happened in weak shale overlain by sandstone and volcanic rocks. The frequency of large landslides in northern British Columbia appears to be increasing, suggesting a link to climate change.

Keywords: Large landslide; Climate change; Permafrost degradation; Northern British Columbia

1. Introduction

At least 38 rapid landslides larger than 0.5 M m^3 or with runouts longer than 1 km have occurred in northern British Columbia since 1973 (Fig. 1). They include long-runout landslides in rock, unconsolidated sediment, and in both rock and sediment (Fig. 2, Table 1). With one exception, the large rock slides have happened on slopes above glaciers ($n = 10$), on sedimentary dip slopes ($n = 2$), and on slopes below deforming mountain tops ($n = 2$). The exception is a rock slide from a cliff face at low elevation on the outer BC coast. Soil landslides include flowslides (rapid earth flows) in glacial marine sediments ($n = 2$), glacial lake sediments ($n = 6$), and diamicton (till or colluvium) ($n = 10$). Landslides involving both rock and sediment include rotational rock slide–earth flows ($n = 2$), rock slide–debris flows ($n = 2$), and a rock slide–debris avalanche. Our data set excludes debris flows, debris avalanches, and all landslides either less than 0.5 M m^3 or less than one kilometre in length. The number of large landslides that we have catalogued is a minimum for the number that have occurred in the last three decades due to the remoteness of the study region.

Infrastructure and resources at risk from these large landslides include settlements, forest roads and highways, pipelines, fish habitat, forests, and farmland. One rock avalanche came to rest within 2 km of the Alaska Highway, and another terminated within a few kilometres of a ranch house. Landslides have ruptured

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doi:10.1016/j.enggeo.2005.06.028

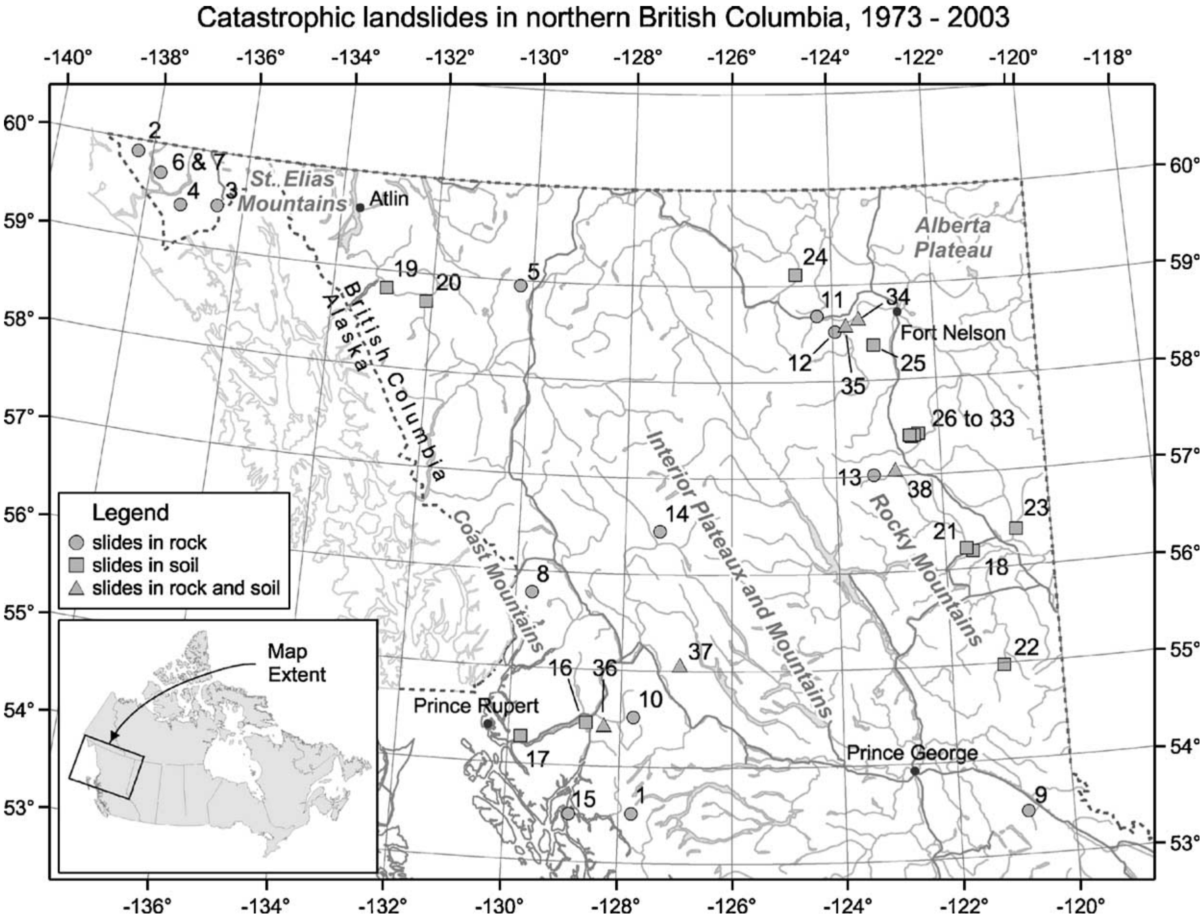


Fig. 1. Map of northern British Columbia showing locations of large, long-runout landslides between 1973 and 2003. See Table 1 for information on individual landslides.

natural gas pipelines in northern British Columbia in 1978, 1999, 2002 (Schwab et al., 2003), and 2003 (Schwab et al., 2004; Boultbee et al., 2006-this issue). Many of the landslides have impounded streams or rivers, thus the hazard associated with upstream inundation and catastrophic dam failure must also be considered (Clague and Evans, 1994).

Large landslides are apparently becoming more frequent in northern British Columbia. The increase may be due to climate change (Evans and Clague, 1999; Huscroft et al., 2004) and perhaps to glacial debuttressing (Holm et al., 2004) and permafrost degradation, as demonstrated in the European Alps (Davies et al., 2001; Bottino et al., 2002).

The objectives of this paper are to provide a brief overview of these large, long-runout landslides, examine the trend of increasing landslide frequency, and discuss the potential impacts of climate change on landslide occurrence in the region.

2. Setting

Northern British Columbia is a vast area, nearly 600 000 km^2 between 53° and 60° latitude, with a great diversity of landscapes (Holland, 1976), ecosystems (Meidinger and Pojar, 1991), climates, and surficial materials (Clague, 1989). On the west are the Coast and Saint Elias Mountains, which have a maritime climate and an extensive cover of snow and ice. East of the Coast Mountains are a series of plateaux and mountains with a more continental climate and less ice cover. Rivers in the interior flow in valleys that are incised into the plateaux and mountains. Most valleys contain thick fills of Quaternary sediments, which themselves have been dissected, leaving behind steep slopes bordering rivers. The plateau and mountain areas of the interior are bordered on the east by the northern Rocky Mountains, which mark the easternmost part of the western Cordillera. Still

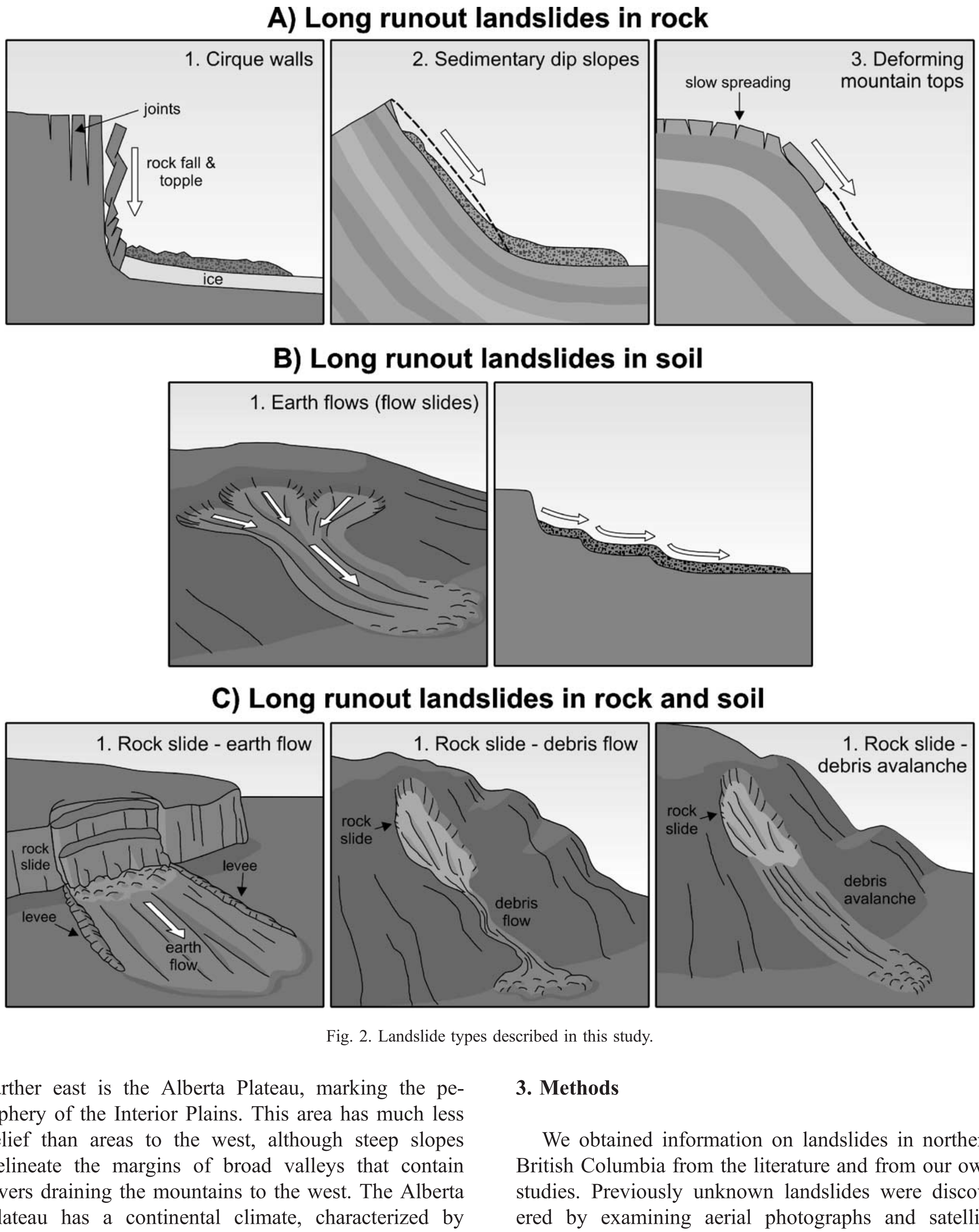


Fig. 2. Landslide types described in this study.

farther east is the Alberta Plateau, marking the periphery of the Interior Plains. This area has much less relief than areas to the west, although steep slopes delineate the margins of broad valleys that contain rivers draining the mountains to the west. The Alberta Plateau has a continental climate, characterized by very cold winters and warm summers. The high mountains of northern British Columbia support alpine permafrost, and some areas at lower elevation in the northernmost part of the province have patchy permafrost.

3. Methods

We obtained information on landslides in northern British Columbia from the literature and from our own studies. Previously unknown landslides were discovered by examining aerial photographs and satellite images. Due to the size and remoteness of the region, the area was not exhaustively examined, thus the number of landslides reported must be regarded as a minimum. Landslide ages were constrained by satellite and airphoto imagery, and in a few cases, by eyewitness accounts. Landslide dimensions were determined from ortho-rectified images. We had detailed aerial photography flown for some landslides. Detailed digital elevation models were prepared for some landslides using pre- and post-failure photographs to determine landslide volume. Previously unreported landslides were visited in the field. Soil samples were collected, and stratigraphy and other physical features were noted.

Many of the landslides in our data set dammed rivers or streams. We examined many of the dams in the field and on airphotos. The dams were classified using the scheme of Costa and Schuster (1988) and include three types: (I) dams that do not cross the valley floor; (II) dams that span the entire valley floor, commonly extending onto the opposite slope; and (III) dams that fill the valley and extend both up and down valley.

4. Landslides in rock

Fifteen of the 38 catalogued landslides occur entirely in rock and can be termed rock avalanches. Three other landslides are rock slides that triggered even longer debris flows, and are discussed in *Landslides involving rock and soil*.

4.1. Landslides on rock slopes above glaciers

The majority of recent large rock avalanches in northern British Columbia have initiated on rock slopes above glaciers, principally in the Coast and St. Elias Mountains (Fig. 1). Since the Little Ice Age, most glaciers in British Columbia have thinned and retreated. The loss of ice has debuttressed slopes adjacent to glaciers, leading to local expansion of rock joints (Fig. 3) and bulging, cracking, and slow movements of rock masses (Bovis, 1982, 1990). Debuttressing has been implicated in many catastrophic landslides in high mountains in British Columbia by Evans and Clague (1999) and, more recently, by Holm et al. (2004).

Triggers may include intense rainfall or earthquakes. Schwab et al. (2003) attributed the 1999 rock avalanche at Howson Range (Fubar Glacier) (Fig. 4) to intense rainfall, and the 1999 rock avalanche at Kendall Glacier (Fig. 5; Couture and Evans, 2002) probably occurred during a summer cloudburst. In the latter case, an intense local storm cell accompanied the landslide (Bob Mitchell, Robson Valley Forest District, personal communication 1999), but was not recorded at the nearest climate station at McBride. The 1979 Saint Elias earthquake (M_s 7.2) triggered many large rock avalanches in southeastern Alaska (Lahr et al., 1979) and in adjacent regions of Canada, including Towagh Glacier (Evans and Clague, 1999), and possibly Tweedsmuir and Jarvis glaciers (Fig. 1; Table 1). Jibson et al. (2006-this issue) describe rock avalanches triggered by the 2003 Denali earthquake in southeastern Alaska. Other large rock avalanches, however, are not seismically triggered, including the rock avalanches at Frobisher Glacier (Fig. 6).

Most of these landslides probably initiate as topples and falls, but rapidly transform into rock avalanches as they travel over glaciers (Couture and Evans, 2002; Schwab et al., 2003) and undergo remarkable thinning (Fig. 7). Evans and Clague (1988) suggest that rock avalanches that travel over glaciers may have anomalously long runouts due to low friction at the debris-glacier interface. Height-over-length (H/L) ratios (Fig. 8) and the fahrböschungen (angles of reach) of these large rock avalanches are presented in Table 1. Fahrböschungen range from 11.3° to 22.3°, within the expected range of values for rock avalanches on glaciers (Scheidegger, 1973; Evans and Clague, 1999).

Most, but not all, of the rock avalanches terminated on glaciers. The landslides at Howson Range in 1978 and 1999 (Schwab et al., 2003) reached the valley floor at Telkwa Pass and ruptured a natural gas pipeline, disrupting service to the communities of Kitimat, Prince Rupert, and Terrace. The Howson landslides generated type II dams, and the lakes persist to this day.

4.2. Landslides on sedimentary dip slopes

The 1988 Tetsa rock avalanche (Fig. 9) and 1996 Chisca rock avalanche (Fig. 10) occurred on sedimentary dip slopes of 27° to 36° in the Rocky Mountain Foothills in northeastern British Columbia (Fig. 1; Table 1). They involved Permian to Carboniferous sedimentary rocks (Kindle Formation) and appear to be associated with fault zones (MacIntyre et al., 1998). The deposits of the two rock avalanches consist primarily of highly fragmented, angular sandstone rubble, with minor amounts of shale (Fig. 11). Rafts of soil and forest floor materials were noted on top of the rubbly debris.

The triggers for these landslides are not known. The Tetsa rock avalanche occurred on a sunny day in May. Its dust cloud was witnessed by a forestry crew working in the area (Myles Thorpe, Fort Nelson Forest District, personal communication, 2000). The Chisca landslide was dated using tree-ring techniques, which are not precise enough to evaluate a hydroclimatic trigger.

Table 1
Landslide data

No. on map	Name	Date	Volume (M m^3)	Length (km)	H/L	Fahrböschung (°)	Location (lat/long)	Reference
A. Landslides involving rock (long runout rock slides) s								
1. Cirque wall								
1	Howson I	1978					53° 31′ N, 127° 46′ W	
2	Tweedsmuir Glacier	1979		1.3	0.37	20.3	59° 53′ N, 138° 19′ W	Evans and Claque (1999)
3	Jarvis Glacier	1979		2.4	0.30	16.7	59° 27′ N, 136° 32′ W	Evans and Claque (1999)
4	Towagh Glacier	1979		4.4	0.20	11.3	59° 24′ N, 137° 17′ W	Evans and Claque (1999)
5	North Creek	1986	1–2	2.8	0.26	14.6	58° 57′ N, 130° 15′ W	Evans and Claque (1999)
6	Frobisher Glacier I	1990		3.1	0.34	18.8	59° 42′ N, 137° 47′ W	Evans and Claque (1999)
7	Frobisher Glacier II	1991		2.4	0.41	22.3	59° 42′ N, 137° 47′ W	Evans and Claque (1999)
8	Kshwan Glacier	Sept 92–May 93	3.2	2.3	0.31	17.2	55° 47′ N, 129° 42′ W	Mauthner (1995, 1996)
9	Kendall Glacier	1999	0.2	1.2	0.17	9.5	53° 27′ N, 120° 48′ W	Couture and Evans (2002)
10	Howson II	1999	1.5	2.7	0.48	25.6	54° 31′ N, 127° 46′ W	Schwab et al. (2003)
2. Sedimentary dip slopes								
11	Tetsa	1988		2	0.25	14.0	58° 41′ N, 124° 18′ W	
12	Chisca	mid 1990's	1	1.5	0.24	13.5	58° 31′ N, 123° 57′ W	
3. Mountain slopes associated with deformation								
13	Turnoff Creek	1992	4	2	0.28	15.6	57° 01′ N, 123° 17′ W	
14	Mosque Mountain	mid 1990's	5	1.2	0.42	22.9	56° 27′ N, 127° 21′ W	Lu et al. (2003)
15	Verney	Before 25 July 03		0.6	0.59	30.5	53° 30′ N, 128° 52′ W	
B. Landslides involving soil (flowslides)								
1. Glaciomarine sediments								
16	Mink Creek	Dec 93–Jan 94	2.5	1.2			54° 27′ N, 128° 37′ W	Geertsema et al., 2006-this issue-b
17	Khyex River	28 Nov. 2003	4.7	1.6			54° 17′ N, 129° 46.5′ W	Schwab et al. (2003)

2. Glaciolacustrine sediments								
18	Attachie	26 May 1973	12.4	1.5			56° 11′ N, 121° 29′ W	Evans et al. (1996)
19	Inklin	1979	2–3	0.7			58° 49′ N, 132° 56′ W	Geertsema (1998)
20	Sharktooth	1980	3–4	1.2			58° 43′ N, 132° 07′ W	Geertsema (1998)
21	Halfway	20 Aug 1989	1.9	0.7			56° 13′ N, 121° 36′ W	Bobrowsky and Smith (1992)
22	Quintette	5 May 1990	10	0.73			54° 59′ N, 121° 03′ W	Golder Associates (1990)
23	Flatrock	October 1997		0.65			56° 23′ N, 120° 39′ W	
3. Diamictons (mostly clayey tills)								
24	Scaffold Creek	mid 1990's		0.5			59° 07′N, 124° 43′ W	
25	Halden Creek	mid 1990's	5	0.6			58° 22′ N, 123° 12′ W	
26	Buckinghorse I	mid 1990's		1.75			57° 26′ N, 122° 24′ W	
27	Buckinghorse II	mid 1990's		1.0			57° 26′ N, 122° 24′ W	
28	Buckinghorse III	mid 1990's		1.77			57° 26′ N, 122° 24′ W	
29	Buckinghorse IV	mid 1990's		0.7			57° 24′ N, 122° 32′ W	
30	Buckinghorse V	mid 1990's		1.3			57° 24′ N, 122° 32′ W	
31	Buckinghorse VI	mid 1990's		0.8			57° 24′ N, 122° 32′ W	
32	Buckinghorse VII	mid 1990's		1.4			57° 25′ N, 122° 29′ W	
33	Buckinghorse VIII	mid 1990's		0.65			57° 25′ N, 122° 34′ W	
C. Landslides involving rock and soil								
1. Rock slump–earth flows								
34	Muskwa	1979	15	2.2			58° 39′ N, 123° 29′ W	
35	Muskwa–Chisca	July 2001		1.5			58° 35′ N, 123° 44′ W	
2. Rock slide–debris flows								
36	Zymoetz	8 June 2002	1.6	4.3	0.29	16.3	54° 26′ N, 128° 18′ W	Boultbee et al. (2006-this issue)
37	Harold Price	22–23 June 2002	1.6	4	0.18	9.9	55° 04′ N, 126° 57′ W	Schwab et al. (2003)
3. Rock slide–debris avalanche								
38	Pink Mountain	June 2002	1	2	0.21	11.6	57° 04′ N, 122° 52′ W	Geertsema et al., 2006-this issue-b

Fahrböschungen (Table 1) are relatively low: 14.0° and 13.5° for the Tetsa and Chisca landslides, respectively. The Tetsa landslide initiated at 1500 m asl, descended to 940 m asl, and ran 100 m up the opposite slope. The total travel distance is 2240 m. The Chisca landslide ran out onto saturated permanently frozen organic soil (muskeg) with a 60 cm thick active layer. Its low H/L ratio (Fig. 8) likely relates to these conditions.

The Tetsa and Chisca landslides did not damage streams, but considerable areas of forest were lost. The Tetsa landslide stopped within 2 km of the Alaska Highway.

4.3. Landslides on slopes below deforming mountain tops

Mountain-top spreading is common in sedimentary rocks in northeastern British Columbia. Several recent catastrophic rock avalanches are associated with such deformation, including the Mosque Mountain (Lu et al., 2003) and Turnoff Creek (Fig. 12; Bednarski, 1999) rock slides. The 2002 Pink Mountain landslide (Geertsema et al., 2006-this issue-b) also occurred in an area of mountain-top deformation, but it is included in the section *Landslides involving rock and soil* because it transformed into a debris avalanche. The Mosque Mountain and Turnoff Creek landslides are not precisely dated, thus their triggers are unknown. Their H/L ratios are 0.28 and 0.42, and their fahrböschungen are 15.6° and 22.9°, respectively.

Fig. 4. Howson rock avalanche. Note cliffs (1), pipeline (2), powerline (3), and new lake (4).

Damage from these landslides includes forest site loss and impoundment of Turnoff Creek. The Turnoff Creek landslide dam is composed of angular rubble and

Fig. 3. Vertical joints that have opened in response to debuttressing adjacent to Howson Glacier west of Smithers.

Fig. 5. Rock avalanche at Kendall Glacier, 45 km northwest of McBride. The runout length is 1200 m. Photo courtesy of Carl Erickson, BC Forest Service.

cohesive soil, and is a type II dam. The small lake dammed by the debris persists to this day.

4.4. Other landslides

The Verney landslide, on the northern British Columbia coast (Fig. 1; Table 1), does not fit into the above categories. It is visible on a 23 July 2002 Landsat 7 image, but not a 20 July 2001 image. The landslide is a rock avalanche, probably initiated as a rock fall at 660 m elevation, low compared to the other rock avalanches. The landslide travelled 630 m, over a vertical range of 370 m, giving an H/L ratio of 0.59 and a fahrböschung of 30.5°.

5. Landslides in soils

Eighteen of the 38 large landslides in northern British Columbia involve only soil and are classified as flows or spreads (Cruden and Varnes, 1996) or flowslides (Hungr et al., 2001). Some of these landslides initiate at eroding riverbanks and retrogress

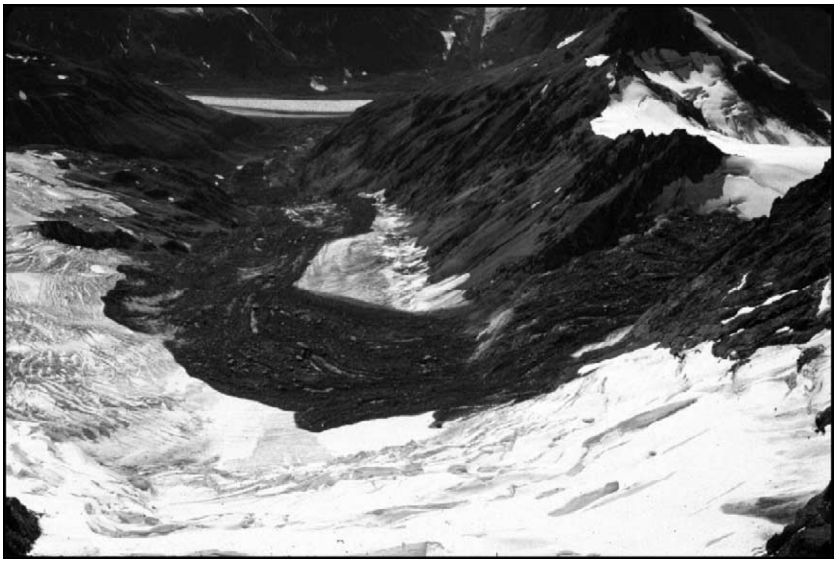


Fig. 6. Large rock avalanche at Frobisher Glacier, Saint Elias Mountains, northwestern British Columbia.

Fig. 7. Thin rock avalanche debris covering Jarvis Glacier. The landslide was triggered by a magnitude 7.2 earthquake in southeastern Alaska in 1979.

upslope (Geertsema, 1998). As material slides or flows into the river, toe support is lost, causing more material to move and creating another scarp. Transverse ridges and prisms indicate retrogressive translational movements along nearly horizontal rupture surfaces. These landslides may also fail progressively, for example where a load is placed some distance from the break in slope. In layered, normally consolidated soils, high pore pressures can develop along silty or sandy layers. Spreading and flowing can occur when these pore pressure approach overburden pressures. Subsurface liquefaction may be accompanied by surface

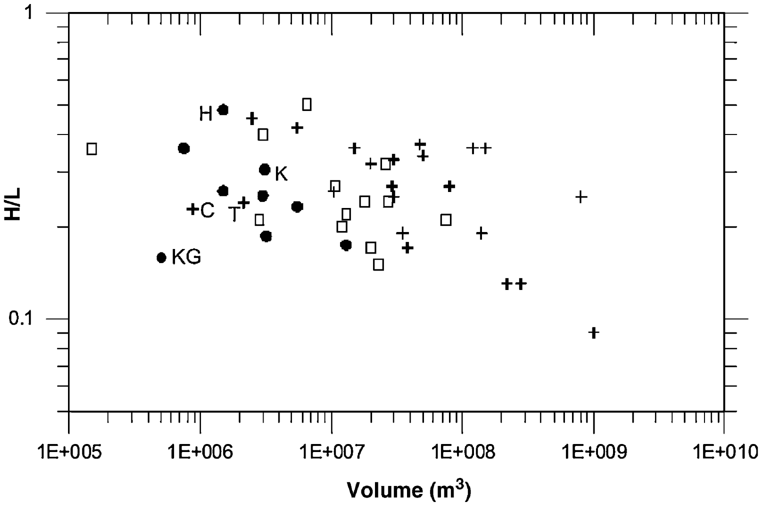


Fig. 8. Plot of rock avalanche volume vs. H/L for non-glacial rock avalanches (+), rock avalanches in glacial environments from other parts of the world (□), and rock avalanches in glacial environments in British Columbia (●). K = Kshwan Glacier rock avalanche; KG = Kendall Glacier rock avalanche; H = Howson II rock avalanche; T = Tetsa rock avalanche; C = Chisca rock avalanche which ran out over permanently frozen muskeg. (Modified after Evans and Clague, 1999.)

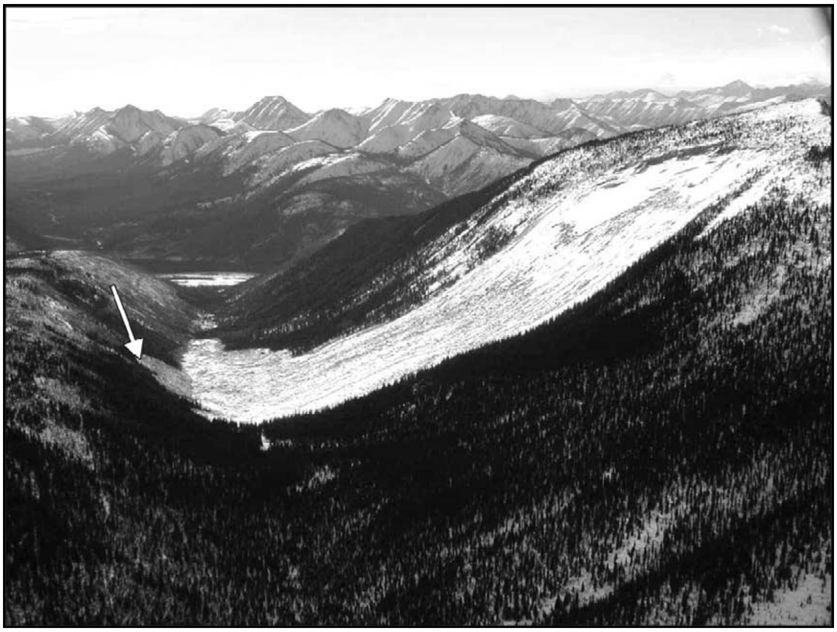


Fig. 9. The 1988 Tetsa rock avalanche in the foothills of the northern Rocky Mountains. The runup (arrow) on the slope opposite the detachment zone is 100 m.

lowering and simultaneous movement over a large area.

A long period of bank erosion may precede failure and rapid movement. In cases where a brittle mass overlies a weak layer, slow deformation and fracturing commonly precede catastrophic failure and rapid movement. Large flowslides are preceded by prolonged, wetter-than-normal weather that allows porewater pressures to build up in the soil.

5.1. Landslides in glacial marine sediments

Large rapid landslides are common in sensitive glacial marine sediments in eastern Canada and Scan-

Fig. 10. The 1996 Chisca rock avalanche on a dip slope in the Rocky Mountain Foothills. The landslide ran out on to permanently frozen muskeg (1).

Fig. 11. Angular sandstone rubble of the Tetsa rock avalanche.

dinavia, and to a lesser extent in Alaska. They are also common in fjords in northern British Columbia (Geertsema and Schwab, 1997; Geertsema, 1998). Retrogressive earth flows occurred in northern British Columbia in December 1993 or January 1994 (2.5 M m^3) at Mink Creek (Figs. 1 and 13; Table 1; Geertsema et al., 2006-this issue-a), and on 28 November 2003 (4 M m^3) at Khyex River (Figs. 1 and 14; Table 1; Schwab et al., 2004). Two flowslides at Lakelse Lake in 1962 were triggered by site loading (Clague, 1978, 1984; Evans, 1982).

Glacial marine sediments become sensitive, in part, through leaching or diffusion of salt from the porewater (Torrance, 1983). The sediments at Mink Creek and Khyex River have salt contents below 1 g per litre. Those at Mink Creek meet the definition of quick clay by having sensitivities greater than 30 and remoulded shear strengths less

Fig. 12. The 1992 Turnoff Creek rock avalanche was associated with deep-seated mountain slope deformation (arrows).

Fig. 13. Oblique aerial photograph of the 1994 Mink Creek flowslide near Terrace. Note the lake formed by the type II landslide dam and the nearly flat slope of the landslide.

than 0.5 KPa (Tables 2–4; Geertsema and Torrance (2005)).

A decade of warmer and wetter conditions and a warm wet fall preceded the Mink Creek flowslide (Geertsema et al., 2006-this issue-a). However, most flowslides, including the Mink Creek and Khyex River events, are triggered by bank erosion (Bjerrum et al., 1969; Lebuis et al., 1983; Tavenas, 1984). Other triggers include earthquakes (the 1964 Turnagain Heights landslide in Anchorage; Updike et al., 1988) and site loading (Rissa, Norway; Gregersen, 1981; Lakelse Lake, Clague, 1978; and Kitsault, Septer and Schwab, 1995).

The gradients of the Mink Creek and Khyex flowslides are 3° or less, with an R/H value of 30 at Mink

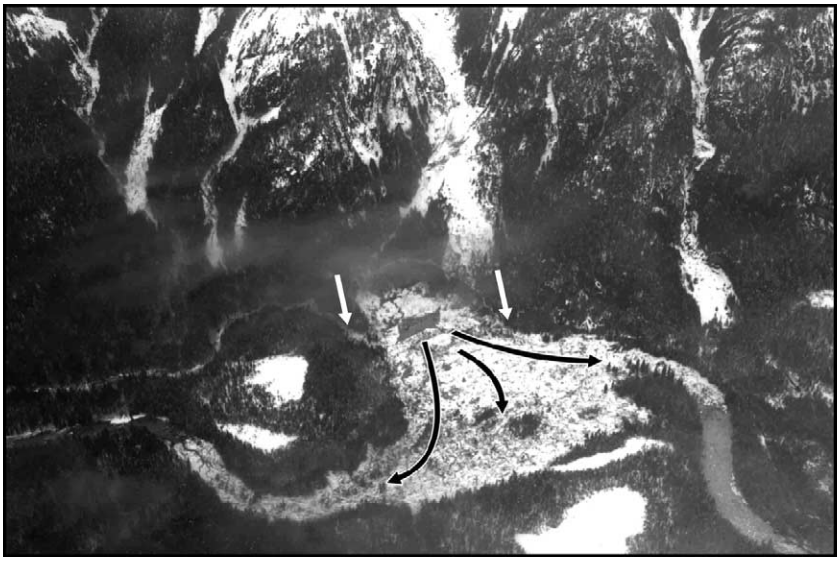


Fig. 14. The 2003 Khyex River earthflow in glacial marine sediments. The landslide ruptured a natural gas pipeline (white arrows), disrupting service to the city of Prince Rupert for about 10 days. Note the type III landslide dam, created where material flowed up and down river. Photo courtesy Prince Rupert Royal Canadian Mounted Police.

Table 2
Range of grain size distributions from selected landslides

Grain size	Glacial marine (Mink Ck. slide)	Glacial lake (Attachie slide)	Clayey till (Halden slide)	Clayey till (Muskwa slide)
Sand (%)	0–13	8–32	21–22	1–28
Silt (%)	44–62	34–74	47	21–55
Clay (%)	45–58	26–65	30.5–32	31–78

Creek. The Mink Creek landslide shows evidence of both spreading (Fig. 15; Eden et al., 1971; Evans and Brooks, 1994) and flowing (Geertsema et al., 2006-this issue-a). The Khyex River landslide is a flow, with few transverse ridges (Schwab et al., 2004). Examples of similar flows include the 1971 St. Vianney landslide in Québec (Tavenas et al., 1971) and the Rissa landslide in Norway (Gregersen, 1981).

The Mink Creek and Khyex landslides caused considerable damage. A type II dam filled Mink Creek, an important salmonid stream, over a distance of 1200 m. It inundated another 1200 m of the valley upstream to beyond a Canadian National Railway trestle. The lake remains, although the water level has lowered. The landslide also destroyed 43 ha of forest. The Khyex River landslide filled Khyex River, also an important salmonid river, over a distance of 1700 m. The displaced material travelled up and down stream, creating a type III dam. The dam persisted until mid or late September 2004. The landslide destroyed 32 ha of forest and flooded riparian forests up to 10 km upstream. It ruptured a natural gas pipeline, cutting service to the city of Prince Rupert for about 10 days.

5.2. Landslides in glacial lake sediments

Glacial lake sediments are common in many valleys in northern British Columbia (Clague, 1989). Most of the sediments were deposited at the beginning and end of the last Pleistocene glaciation. Those deposited at the beginning of the last glaciation were overridden by thick glacier ice and, consequently, are overconsolidated and dense. Late-glacial lake deposits were not overridden by glaciers and are normally consolidated. Large rapid landslides are largely restricted to advance-phase glacial lake sediments in preglacial buried valleys (Fig. 16) in Alberta (Cruden et al., 1997; Lu et al., 1999) and British Columbia (Geertsema, 1998; Geertsema and Schwab, 2004). An exception is the 1990 landslide at Quintette Mine on Murray River (Fig. 1; Table 1), which apparently occurred in sensitive clayey silts with thin sand strata that are not overlain by till (Golder Associates Ltd., 1990). The 1989 Halfway River landslide (Bobrowsky and Smith, 1992) had two distinct surfaces of rupture, an upper one in till and a lower one in lake sediment.

Table 3
Atterberg limits

Atterberg test	Glacial marine (Mink Ck. slide)	Glacial lake (Attachie slide)	Clayey till (Halden slide)	Clayey till (Muskwa slide)
Liquid limit (%)	30–35	42.5	36.6–40.5	32–40
Plastic limit (%)	17–22	22.9	17.5–19.8	19–25
Plasticity index	10–18	19.6	19.1–20.7	9–17
Activity	0.26–0.42	0.31	0.63–0.65	0.26–0.41

Table 4
Strength characteristics

Strength test	Glacial marine (Mink Ck. slide)	Glacial lake (Attachie slide)	Clayey till (Halden slide)	Clayey till (Muskwa slide)
Undisturbed shear strength (kPa)	46	–	–	215
Remoulded shear strength (kPa)	0.65	–	–	119
Sensitivity	72	–	–	1.8
Direct shear (kPa)	n/a	230	–	–

In some cases, there is ambiguity as to whether a landslide involves till or advance-phase lake sediments. The surface of rupture commonly is not exposed, and the covering material is not representative of the in situ sediment associated with the failure surface. Without drilling or exposures, the nature of the material at the rupture surface remains unknown.

The Attachie flowslide, which dammed Peace River (type II dam) for approximately six hours in 1973 (Evans et al., 1996; Fletcher et al., 2002), occurred in glacial lake sediments filling the ancestral Peace River valley. The failed slope likely had been moving for thousands of years. The landslide thus involved colluvium as well as glacial lake sediments. Fletcher et al. (2002) suggest that pre-shearing of lake sediments may have played an important role in this landslide and other flowslides in similar materials. Geotechnical data for the Attachie landslide are summarized in Tables 2–4.

The Inklin and Sharktooth landslides in northwestern British Columbia also occurred on slopes developed in buried valley fills (Geertsema, 1998). In these cases,

Fig. 15. Prism of glacial marine sediments in the Mink Creek landslide. The prism is part of a transverse ridge that formed by translational movement along a nearly horizontal rupture surface (dashed line). Arrow indicates direction of movement.

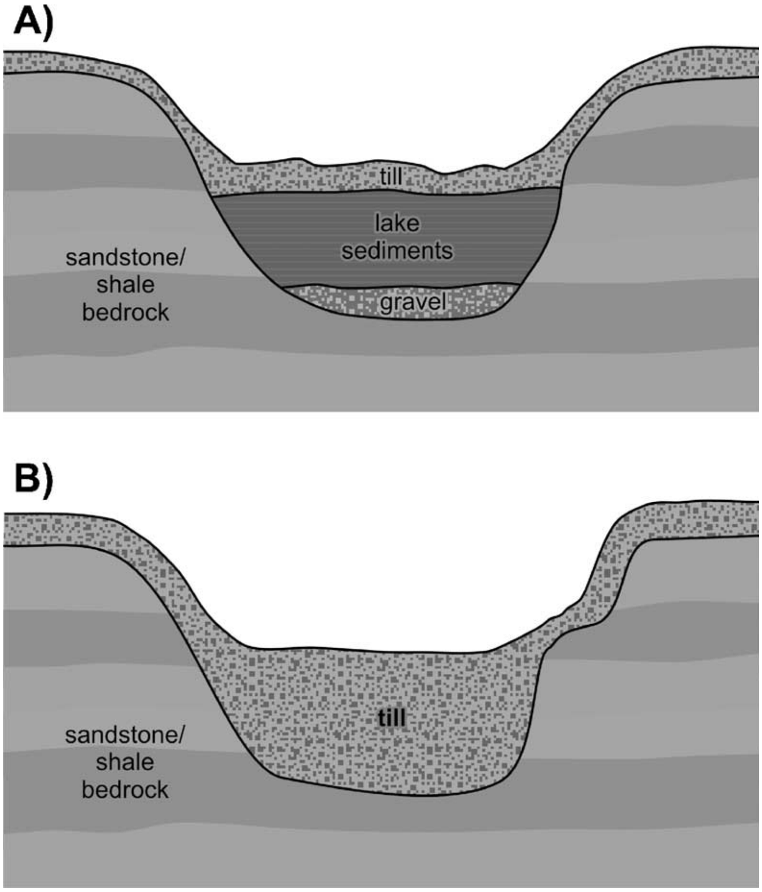


Fig. 16. Schematic drawing of preglacial valley fills: A) advance-phase glacial lake sediment is covered by till; B) till fills the entire valley.

the lake sediments fill narrow tributary valleys, thus the landslides are more confined and narrower than the Attachie landslide. The Sharktooth landslide had a length of 1200 m and extended approximately 800 m into the hillslope (Fig. 17). It covered an area of about 40 ha and had a volume of 3–4 M m^3. It was likely retrogressive and was triggered by bank erosion at the outside of a bend in the Sheslay River. The surface of the landslide is marked by ridges that translated along a nearly horizontal rupture surface and that resemble prisms in other translational flowslides. These features, and the extent of retrogression (R/H of about 50), suggest that the material associated with the slide, while perhaps not sensitive, was very weak (Geertsema, 1998).

The 1997 Flatrock landslide also occurred in a buried valley, but it has a much longer width than length. This landslide, like the Sharktooth landslide, has spectacular transverse ridges (Fig. 18), indicating translational retrogressive movement.

All of the flowslides in glacial lake sediments impounded streams (type I and II dams) and damaged forests. The 1979 Inklin landslide (type II dam) dammed Inklin River for about one month, creating a lake 20 m deep and 12 km long (Geertsema, 1998).

5.3. Landslides in till

Some of the most spectacular and rapid flowslides in British Columbia have occurred in diamicton interpreted to be till (Fig. 1; Table 1). Till has not commonly been linked to rapid, low-gradient flowslides, but ten of the landslides in our inventory are in this material. None has been precisely dated, but all appear to have occurred in the mid-1990s. Eight of the ten landslides occurred in the Buckinghorse River area, along with additional unrecorded smaller flowslides and numerous older large landslides. All of the landslides appear to be associated with preglacial buried valley fills (Fig. 16). Two landslides at Muskwa River are included in the category *Landslides involving soil and rock*, because they are complex, involving both till and bedrock.

Till in northeastern British Columbia is derived largely from Cretaceous shale and sandstone (Mathews, 1980). The shale breaks down more readily than sandstone and imparts a fine texture to the till matrix. The

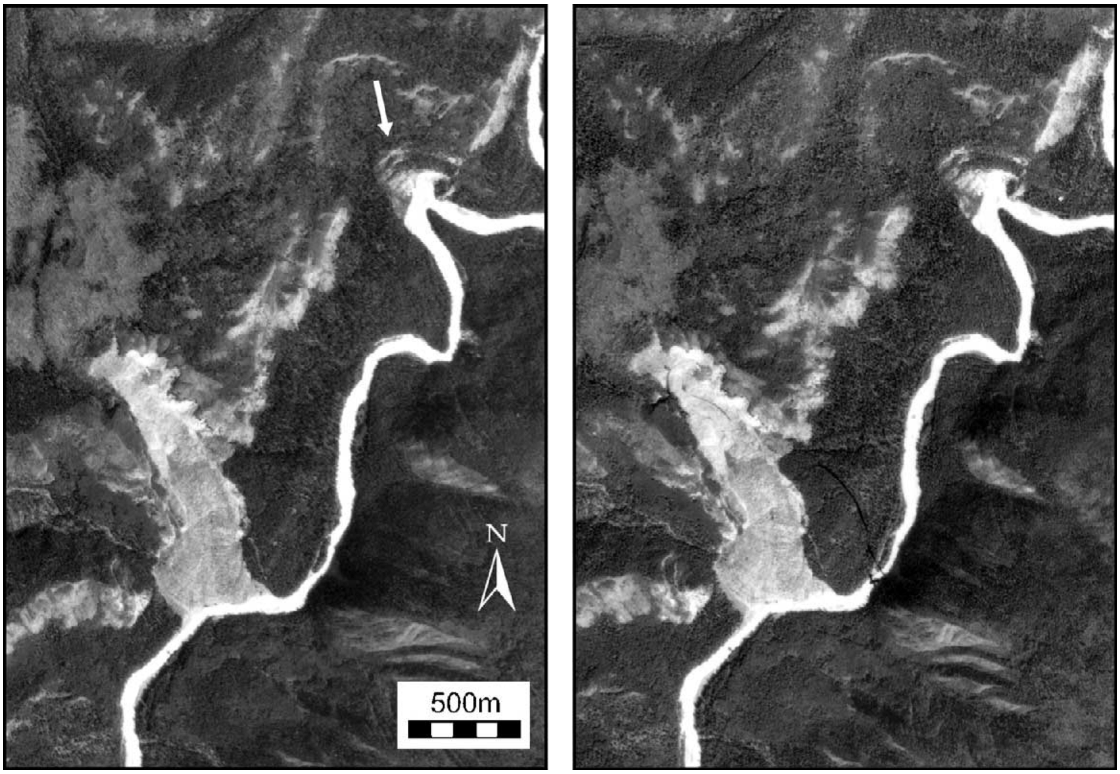


Fig. 17. Photo stereopair of the Sharktooth landslide, a flowslide in glacial lake sediments overlain by till along Sheslay River. Note the incipient landslide to the north (arrowed). Province of British Columbia airphotos BC5614: 209, 210.

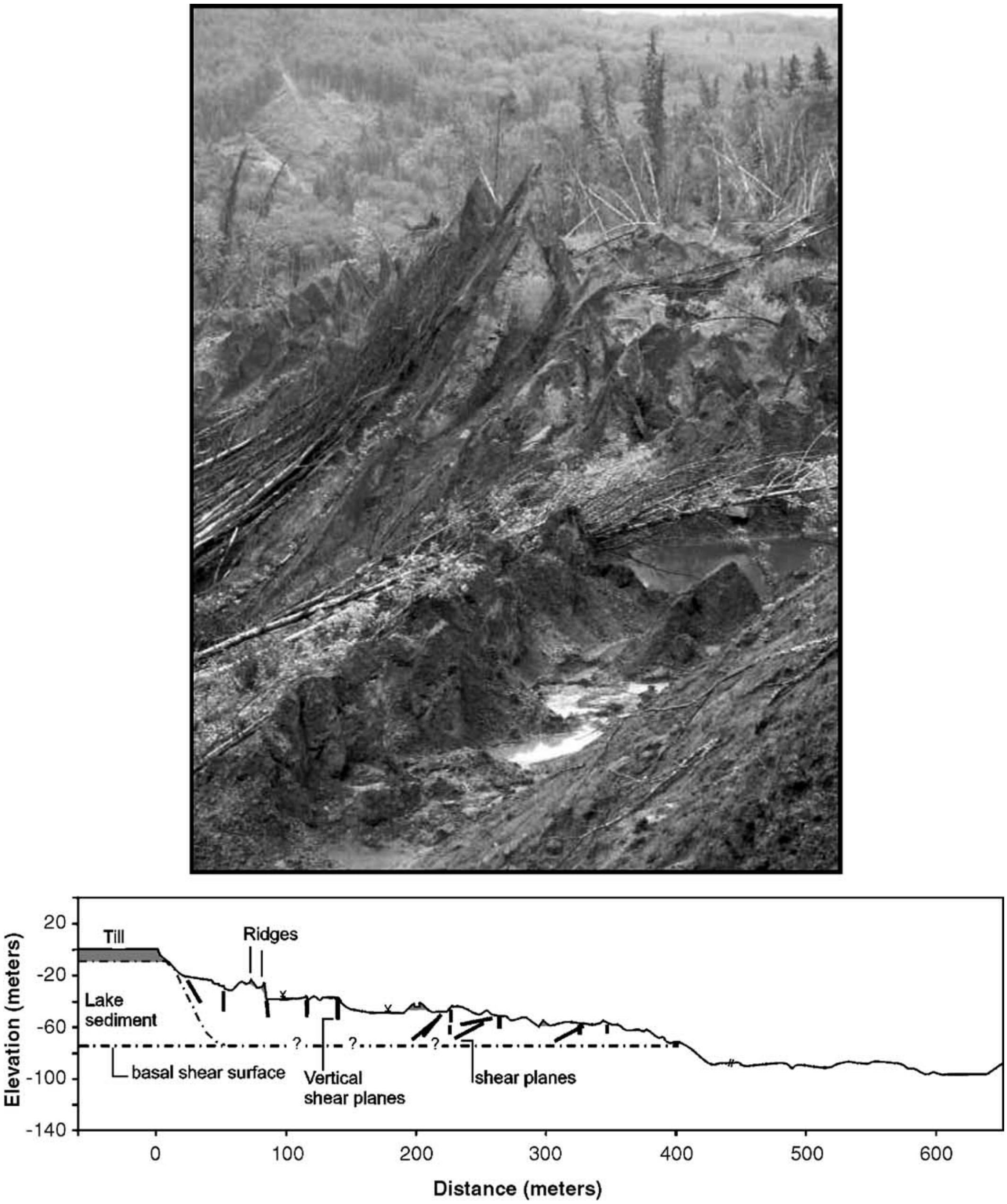


Fig. 18. Top: Transverse ridge, indicative of retrogressive translational movement, at the 1997 Flatrock landslide. The ridge is about 6 m high. Bottom: long profile of the Flatrock landslide showing ridges, shear planes, and a horizontal rupture surface.

till typically has a low stone content and a low to medium plastic clay matrix (Tables 2–4).

The landslides at Halden Creek and Scaffold Creek may have been caused by bank erosion. In contrast, the landslides at Buckinghorse River are perched high above incised streams and thus require other causes and triggers. Earthquakes in the area have been too small to trigger landslides (Keefer, 1984).

The Buckinghorse River landslides (Figs. 19, 20) are retrogressive and extremely mobile, with travel distances up to 1765 m along gradients as low as 3°. The abundance of flowslides in this area in the 1990s suggests a climatic link. The warming trend at that time (Fig. 21) may have contributed to degradation of permafrost or to seasonal changes in precipitation that could have triggered landslides in the Buckinghorse River basin.

Fig. 19. Two coalescent flows in diamicton at Buckinghorse River (foreground). The travel distance is greater than 1.7 km.

All of the documented till flowslides produced type I or II dams. Dams on rivers, such as Buckinghorse River, appear to have been short lived (hours to days), but dams on tributary streams remain to this day.

6. Landslides involving rock and soil

The landslides documented in this section are complex, involving both rock and soil and more than one mode of movement.

6.1. Rock slump–earth flows

The 1979 Muskwa (Fig. 22) and 2001 Muskwa–Chisca (Fig. 23) landslides, located west of Fort Nelson (Fig. 1; Table 1), initiated as slumps in flat-lying shale and sandstone (MacIntyre et al., 1998). Slumping triggered earth flows in cohesive till through the process of undrained loading (Hutchinson and Bandhari, 1971). The earth flows have conspicuous levees (Corominas, 1995) along their lateral margins (Fig. 24), indicating that they were viscous.

The 1979 Muskwa landslide had a volume of 15 M m^3, covered an area of 179 ha, and travelled 3.25 km on an average slope of 3.4°. It is the largest of the landslides reported in this paper. Geotechnical properties of the landslide debris are provided in Tables 2–4. The trigger is unknown.

The Muskwa–Chisca landslide occurred in July 2001 (Doug Mckee, Fort Nelson, personal communication, 2001). The landslide is 1.5 km long and covers an area of 43 ha. Heavy rains may have triggered the initial rotational failure (Fig. 25).

Both landslides impounded watercourses and destroyed forests. The Muskwa landslide has a type II dam that has been only partially breached by the stream. The smaller Muskwa–Chisca landslide created a much larger impoundment with a type I dam.

6.2. Rock slide–debris flows

Two large rock slide–debris flows occurred in northwestern British Columbia in June 2002 (Schwab et al., 2003; Fig. 1; Table 1)—the Zymoetz (Copper) River landslide on 8 June (Boultbee et al., 2006-this issue) and the Harold Price landslide (Fig. 26) between 22 and

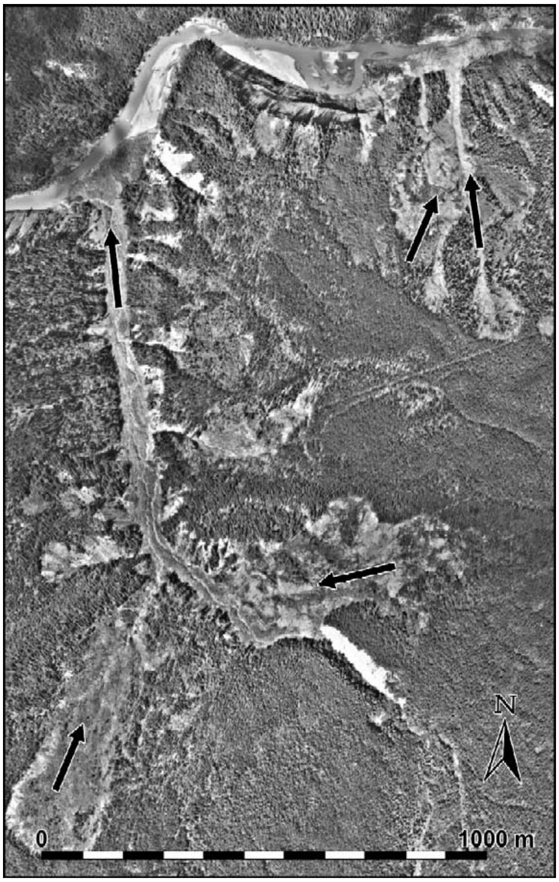
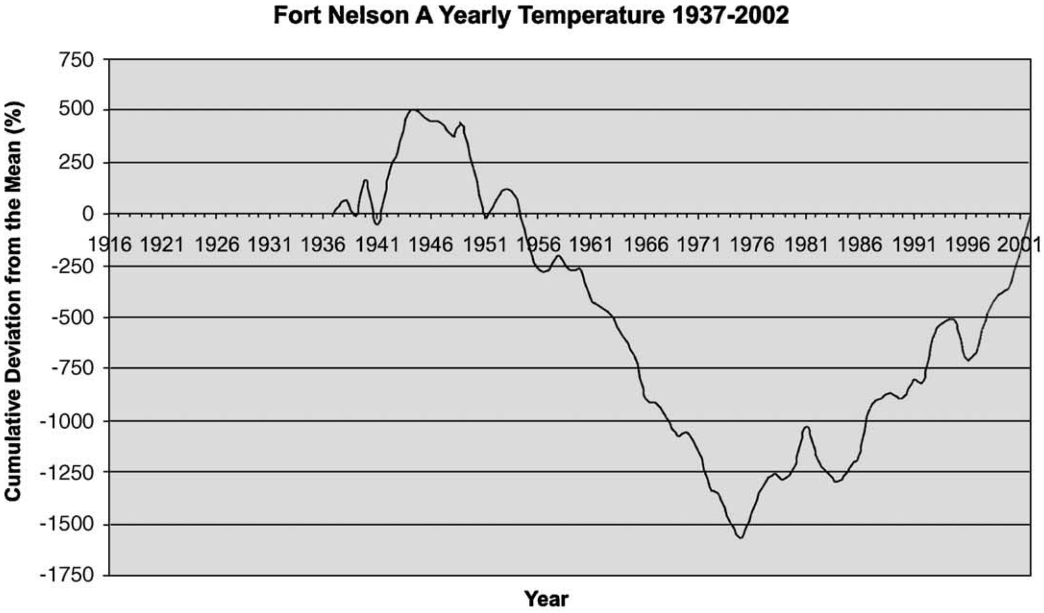


Fig. 20. Three large rapid earth flows and many smaller ones in diamicton at Buckinghorse River. British Columbia Forest Service airphotos IAS(02)54474: 195 (June 21, 2002).



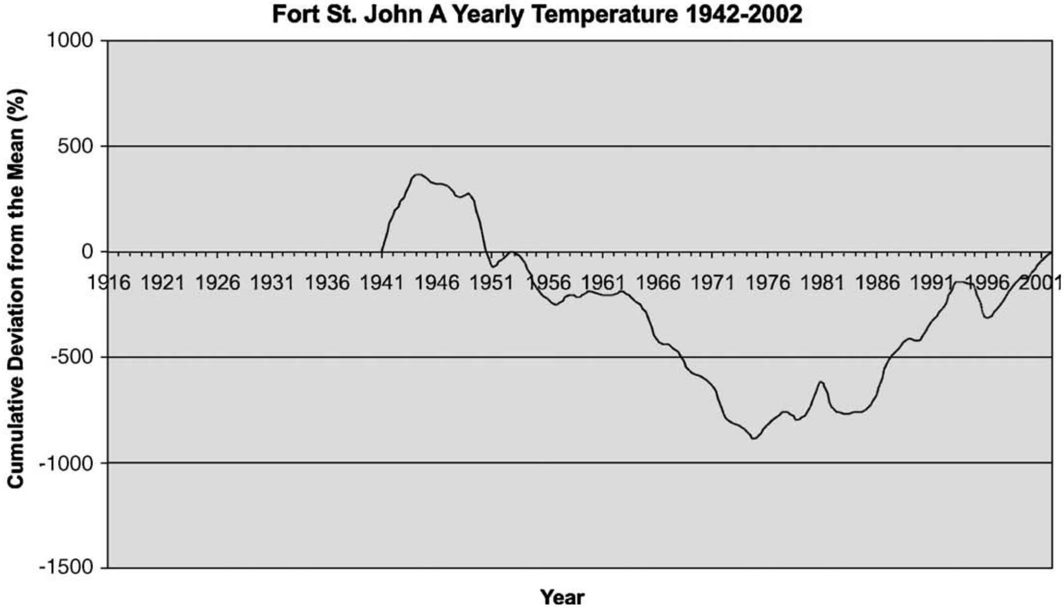


Fig. 21. Graphs of cumulative deviation of yearly mean temperature for Fort Nelson and Fort St. John. The graphs indicate nearly three decades of increasing temperature.

24 June. The Pink Mountain rock slide–debris avalanche (Geertsema et al., 2006-this issue-b), described in *Rock slide–debris avalanches*, and the McCauley Mountain rock slide in southern British Columbia (Evans et al., 2003) also occurred at this time. The Verney rock slide, described in *Landslides in Rock*, may also have happened at this time. The landslides are associated with delayed melting of an above-normal snowpack (Schwab et al., 2003).

The Zymoetz landslide (1.6 M m^3) originated at 1390 m asl on a steep cirque headwall. Rubble entered a channel and induced a debris flow. An estimated 0.5 M m^3 of debris, including blocks up to 7 m in diameter, dammed Zymoetz River (type II dam) causing flooding 1.5 km upstream. Although the dam was overtopped almost immediately, it is still an obstruction to river flow. The landslide travelled a distance of 4.3 km, dropping 1255 m in

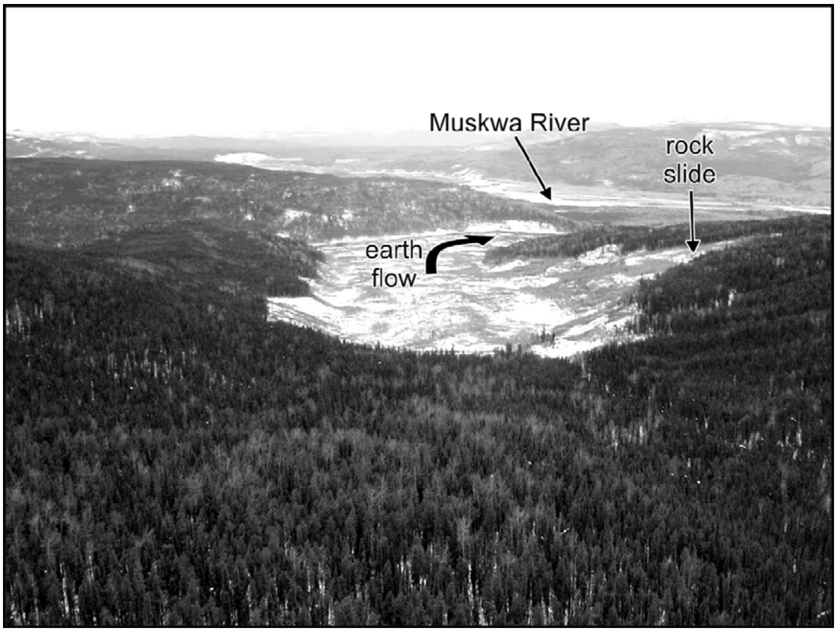


Fig. 22. The 1979 Muskwa landslide in clay-rich diamicton. The earth flow was triggered by a slump in sandstone. The distance from the crown of the landslide to the tip is 3.25 km.

elevation over this distance. The fahrböschung is 16.3°.

The Harold Price landslide originated at 1723 m asl at the lip of a southwest-facing cirque occupied by a rock glacier. Interstitial ice was observed in the scarp face after the landslide. Debris dropped 300 m into the valley, expanding to a width of about 360 m and rapidly accelerating. After travelling 1.3 km, the landslide transformed into a debris flow, which became channelized 2.2 km from the source. The total travel length of the landslide is 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°.

Both landslides damaged forest and fish habitat. The Zymoetz landslide also ruptured a gas pipeline, interrupting service to the cities of Kitimat, Terrace, and Prince Rupert and blocking access to a 3000 km^2 basin for more than one year due to the flooding of the road adjacent to the river. Schwab et al. (2003) estimate the indirect costs of the Zymoetz and Harold Price landslides to be 27.5 and 1.6 M Canadian dollars, respectively.

6.3. Rock slide–debris avalanche

A 2-km-long landslide occurred at Pink Mountain (Geertsema et al., 2006-this issue-b) in late June or early July 2002. The Pink Mountain landslide is a rock slide-debris avalanche according to the classification of Hungr et al. (2001). Geertsema et al. (2006-this issue-b) describe extensive mountain top deformation above the landslide and argue that the landslide may have been triggered by the delayed melt of an above-normal snowpack, followed by a week of intense rainfall.

The landslide has a relatively low fahrböschung of 11.6° (Table 1). Geertsema et al. (this volume) suggest that the excess mobility of the landslide is due to rapid undrained loading of till by the initial rock slide.

The landslide destroyed 43 ha of non-commercial forest, covered an access road, and came to rest within a few kilometres of a ranch house.

7. Discussion and conclusions

In this overview, we have attempted to show the importance of recent large landslides in northern British Columbia. Recent catastrophic and long-runout landslides occur in a variety of environments and materials in this region. Some landslides initiate in bedrock on high, steep mountain slopes, whereas others occur at low elevation in a variety of glacial sediments, notably in buried valleys. Our data suggest that landslides in this part of British Columbia are increasing, which warrants further discussion.

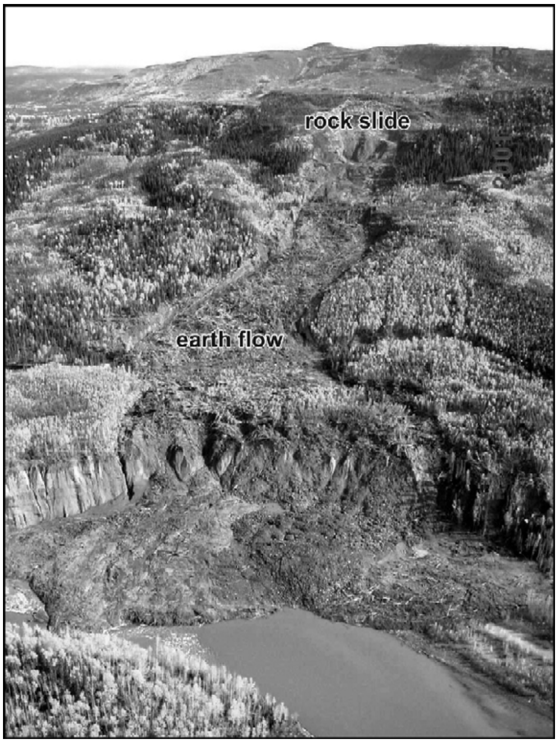


Fig. 23. The 2001 Muskwa–Chisca earth flow, triggered by a slump in sandstone at the confluence of Muskwa and Chisca rivers. The irregular topography of the slope is the product of older landslides.

An average of 1.3 large, rapid landslides has occurred annually over the last three decades. Twenty eight of the 38 catalogued landslides have happened within the last 15 years, an average of 1.4 landslides per year. Possibly up to 23 of the landslides have occurred in 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 study area. The apparent increase in landslides begs the question: Is landsliding in northern British Columbia sensitive to climate forcing?

Landslides in mountainous terrain are strongly influenced by climatic factors, including precipitation and temperature (Evans and Clague, 1994). Catastrophic landslides at high elevations may be particularly responsive to increases in temperature. Researchers have suggested that recent melting of glaciers in British Columbia has debuttressed rock slopes adjacent to glaciers, causing deep-seated slope deformation and catastrophic failure (Clague and Evans, 1994; Holm et al., 2004). Although a significant number of the rock avalanches in our inventory were seismically triggered, we attribute the ten rock avalanches on glaciers to such debuttressing.

Alpine permafrost may be degrading under the present warmer climate, decreasing the stability of slopes (Davies et al., 2001; Harris et al., 2001). Recent large rock avalanches in the European Alps have been attributed to the melting of mountain permafrost (Dramis et al., 1995; Bottino et al., 2002), and this phenomenon may also play a role in initiating landslides in northern British Columbia, as in the case of the Harold Price landslide (Schwab et al.,

Fig. 24. Levee on the Muskwa–Chisca landslide.

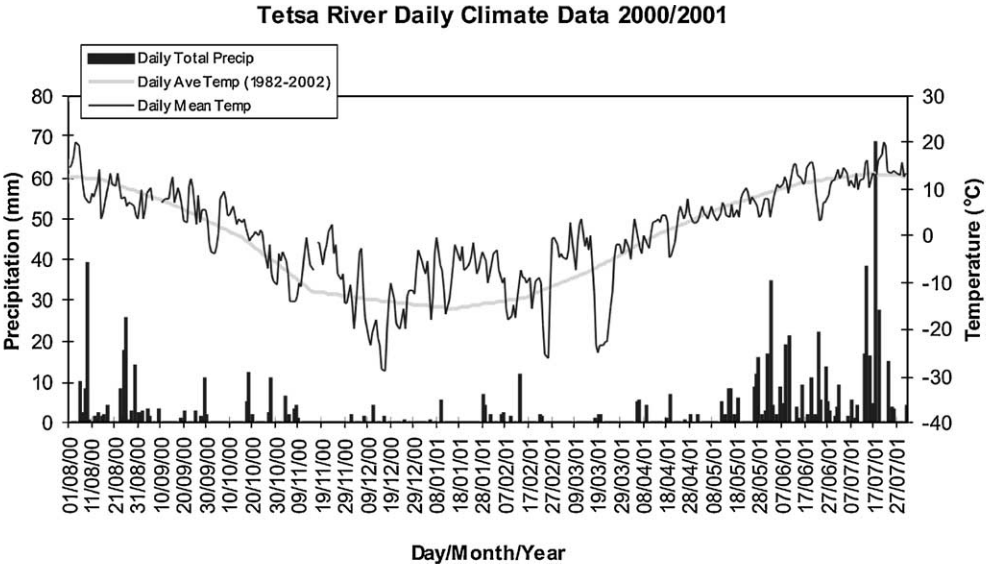


Fig. 25. Climate data associated with the Muskwa–Chisca landslide. The landslide may have been triggered by intense rainfall in July 2001.

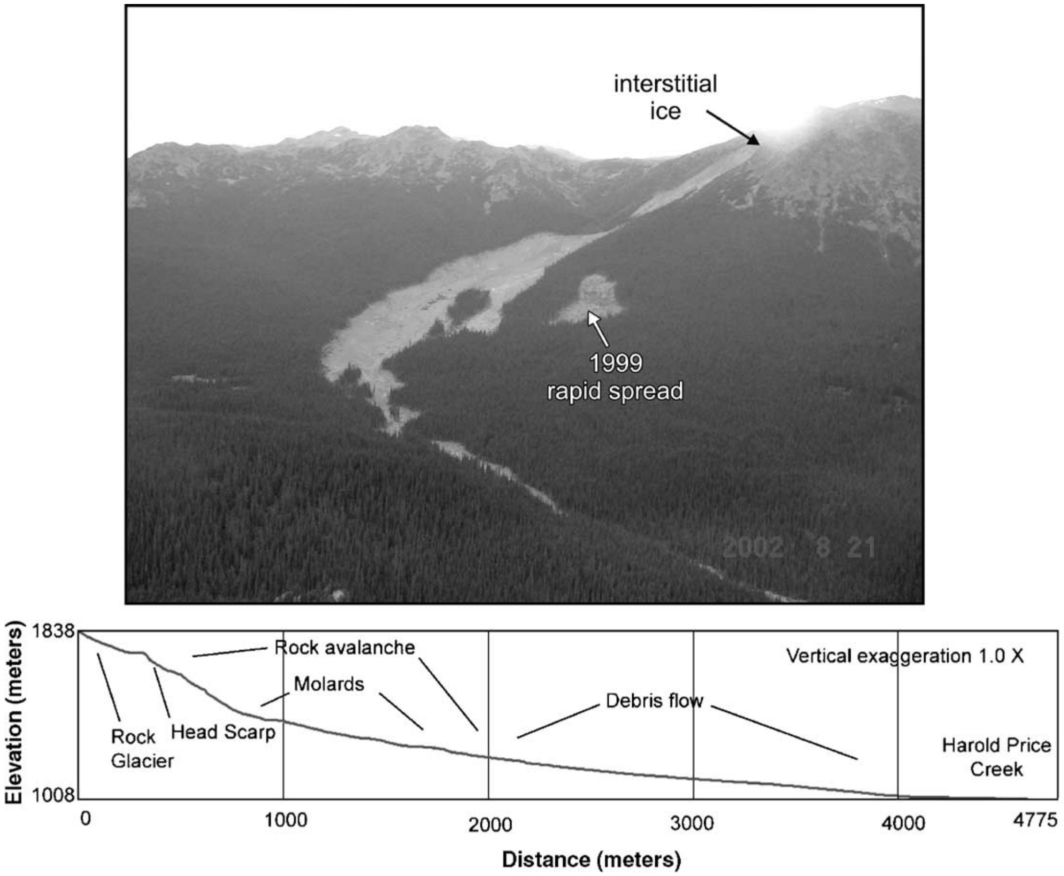


Fig. 26. Top: The 2002 Harold Price rock slide–debris flow. The smaller landslide to the right occurred in 1999. Bottom: profile of the landslide path.

2003). Spatial and temporal clustering of eight large flowslides and other smaller ones in the Buckinghorse River area raise the possibility that they were triggered by melting of permafrost.

The Mink Creek flowslide occurred after nearly a decade of increasing temperature and precipitation. Geertsema and Schwab (1997) provide evidence for an increase in flowsliding 2000 to 3000 years ago in the Terrace area under wetter climatic conditions. Almost all global circulation models predict warmer and wetter conditions in the future for the Terrace area (Geertsema et al., 2006-this issue-a), thus more such landslides may be expected in this area.

Many of the landslides discussed in this paper dammed watercourses. While some of the dams were short-lived, others still remain. The longevity of dams depends in part on the rate of inflow to the impoundment, size and shape of the dam, and its geotechnical properties (Costa and Schuster, 1988). In our data set many large dams on small streams persist, even though lake levels have lowered due to partial incision of the dams. The dams are more likely to persist if they consist of diamicts or blocky rubble. Few dams last for more than a day on significant rivers. Exceptions include the flowslides on the Inklin and Khyex rivers, and the rock slide–debris flow on the Zymoetz River. None of the dams that we have documented failed catastrophically.

Evans and Clague (1999) hypothesized that rock avalanches in glacial environments have greater mobility than those in non-glacial environments (Fig. 8) due to the low friction at the interface of the moving debris and ice. Friction may be further reduced as water films form, and pore pressures develop, at the base of the debris due to frictional heating or compression of snow on the glacier surface. The Chisca rock avalanche (Fig. 10), which ran out on saturated, permanently frozen muskeg, shows similar enhanced mobility (see C in Fig. 8). This suggests that reduction of friction at the base of moving debris through undrained loading of a thin layer of saturated soil in the active layer is similar to that of rock avalanche debris traveling over snow and ice. To our knowledge, this is the first report case of enhanced rock avalanche mobility due to permafrost.

In summary, large landslides are more common in northern British Columbia than previously thought. The landslides are of a range of types and occur in both rocks and soils. The causes and triggers are numerous, but climate warming in recent decades has probably increased the incidence of catastrophic slope failure in northern British Columbia.

Acknowledgements

Richard Franklin, Vanessa Egginton, and Mike Wolowicz drafted most of the figures. Funding for the project was provided by the British Columbia Ministry of Forests and by Forest Renewal British Columbia. Parts of this project were managed by the McGregor Model Forest Association.

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