

Geologic Hazards and Risk Assessment, Yale, BC

For
Rick McDermid
Manager of Development Approvals
Fraser Valley Regional District
tel 604-702-5000

By
Pierre Friele
Cordilleran Geoscience
PO Box 612
1021 Raven drive
Squamish, BC
V8B 0A5

March 9, 2010

Table of Contents

1.0 Introduction.....	1
2.0 Objectives and Methods.....	1
3.0 Geologic Hazard and Risk Tolerance	2
4.0 Environmental Setting	2
4.1 Physiography.....	2
4.2 Human Settlement.....	4
4.3 Geology	4
4.4 Glaciation.....	4
4.5 Climate and Hydrology.....	5
5.0 Landforms at Yale.....	5
5.1 Yale Tunnel Wall.....	5
5.2 Spirit Cave Steeplands	5
5.3 Outwash Terrace	6
5.4 Yale Creek Watershed	6
5.5 Yale Creek Alluvial Fan	7
5.6 East Flank of Gordon/Yale Creek Divide.....	8
5.7 Kuthlalth Landslide Headscarp.....	9
5.8 The South Yale Blockfield.....	10
6.0 Geological Hazard Assessment.....	13
6.1 Background Data Compilation	13
6.2 Earthquake	15
6.3 Fraser River Floods.....	16
6.4 Tributary Creek Floods and Debris Flows.....	17
6.4.1 Tributary creek floods.....	17
6.4.2 Tributary creek sediment floods and debris flows.....	18
6.4.3 Ice jam floods.....	19
6.5 Fragmental Rockfall.....	19
6.5.1 Spirit Caves steeplands	19
6.5.2 Mary Anne Creek steeplands	19
6.5.3 Yale Tunnel wall.....	20
6.6 Rock Avalanche	20
6.6.1 Graveyard Creek landslide.....	20
6.6.2 Spirit Caves Cliff	20
6.6.3 Kuthlalth landslide	21
6.7 Instability on Escarpment Slopes.....	21
6.8 Snow Avalanche	21
7.0 Yale OCP Hazard Mapping	22
8.0 Recommendations.....	22
9.0 Acknowledgements.....	28
10.0 Closure	28
11.0 References.....	29

1.0 Introduction

The Fraser Valley Regional District (FVRD) manages geologic risk for the village of Yale (Fig. 1) following BC Provincial floodplain mapping Bylaw No. 0681 (2005) and terrain hazard mapping prepared by Thurber (1987). These two documents are contradictory, in that the floodplain map shows the main area of town to be subject to alluvial fan hazards, while the Thurber report does not. On the basis that there are two applicable, but inconsistent bylaws, and that there are newly identified rock avalanche hazards (Savigny and Clague 1992) that need to be documented and adopted into policy, QCD (2008) has recently recommended FVRD conduct a review and update of geological hazards and risk management policies for Yale. This study addresses that recommendation.

2.0 Objectives and Methods

The ultimate objective of this study is to provide an updated, comprehensive geologic hazard assessment and risk management report and hazard/risk map that may be adopted for geologic risk management for the village of Yale Official Community Plan (OCP). Specific issues identified by FVRD that require assessment are 1) resolution of the alluvial fan hazard affecting downtown Yale; 2) identification and assessment of rock avalanche hazards; and 3) discussion of the origin and hazard implications of large angular boulders found throughout the OCP study area.

The area of interest includes the Yale OCP study area and terrain in the immediate vicinity that could produce hazards affecting Yale, such as the Yale Creek watershed and steep bedrock slopes above the town.

The scope of work for this project includes a search and review of any journal articles, contract reports, field-trip guides, and academic theses that might pertain to geologic hazards at Yale, and review of air photos covering the study area on file with FVRD. Geotechnical reports and air photos on file with FVRD were examined January 20-21, 2009 in the Chilliwack office.

This report is a compilation and assessment of existing data, aided by fieldwork, as described below. Hazard estimation (i.e., frequency/magnitude/intensity of impact) of landslides and floods affecting the OCP area is based on judgment. Peak flood estimation for design purposes is beyond the scope of this report.

Field work in the Yale vicinity, and pertaining to the hazard assessment herein, includes detailed terrain mapping of South Yale blockfield and Kuthlalth basin on June 19 and October 8-9, 2003; collection of rock samples for lithological analyses from boulders on the South Yale blockfield, Kuthlalth colluvial cone and Trans Canada Highway road cuts on September 27-28, 2007; and detailed terrain mapping in the OCP study area January 22-23, 2009.

The polygons on the revised Yale hazard map were delimited in the field, with the aid of handheld GPS, 1/5000 scale base map, and airphotos (BC79140:94-96; BC79128: 258-260). For each polygon, hazards affecting and associated frequency are assigned, and mitigation measures are described. Refer to Cave (1993) for management responses appropriate to proposed development type.

3.0 Geologic Hazard and Risk Tolerance

Hazard is defined by the Canadian Standards Association (CAN/CSA-Q850-97) as “a source of potential harm, or a situation with a potential for causing harm in terms of human injury damage to health, property, the environment, and other things of value, or some combination of these”. Landslide hazard includes but is not limited to estimating (1) likelihood or probability of occurrence of a landslide or (2) factor of safety of a slope, then combining the results with some estimate, either empirical or analytical, of landslide runout (APEGBC, 2008).

Hungr (MoE 1999) proposed the following hazard probability classification system (Table 1). This report refers to hazard levels in Table 1, but hazard map labeling follows convention previously developed by Bob Gerath (Thurber/QCD) and FVRD. The approaches are combined whereby Significant Hazard equals $>1/100$ per annum; Potential Hazard equals $<1/100$ per annum; No apparent hazard equals no hazard identified.

Table 1. Qualitative landslide hazard frequency categories (MoE 1999).

Qualitative frequency	Annual return frequency	Comments
Very high	$>1/20$	Hazard is well within the lifetime of a person or typical structure. Clear fresh signs of hazard are present.
High	$1/100$ to $1/20$	Hazard could happen within the lifetime of a person or structure. Landslides are identifiable from deposits and vegetation, but may not appear fresh.
Moderate	$1/500$ to $1/100$	Hazard within a given lifetime is possible, but not likely. Signs of previous events may not be easily noted.
Low	$1/2500$ to $1/500$	The hazard is of uncertain significance.
Very low	$<1/2500$	The occurrence of the hazard is remote.

Table 1 categories cannot be equated to the qualitative hazard ratings applied by Golder (2008) to terrain polygons in the vicinity of Yale. The hazard ratings used by Golder (2008) are derived from forest industry and described terrain response to logging-related disturbance, and they are not associated with a specific return frequency.

A problem with landslide risk assessment in certain cases is the uncertainty associated with hazard estimation. Unlike river flooding, which occurs regularly and may have a detailed historical record of flood discharge and stage (water level), landsliding occurs stochastically, deposits may not be well preserved and/or studied in detail, and as a consequence future events are not readily predicted or their occurrence is uncertain.

The Local Government Act requires a statement that the land is safe for the use intended. However “safe” is not defined by the legislation. To fill this deficiency, FVRD has adopted the risk tolerance framework prepared by Cave (1993) that is used herein.

4.0 Environmental Setting

4.1 Physiography

Yale (Fig. 1) marks the southern extent of the Fraser Canyon, a 2000 m deep, 75 km long gorge cut through the Coast Mountains by the Fraser River. Through the Fraser Canyon,

the valley sides consist of steep bedrock walls that confine the river, which is 100-400 m wide and fraught with rapids. From Yale on downstream the valley widens to about 1-km and the valley floor supports confining terraces, alluvial fans and isolated floodplain areas. Yale is developed on the west bank of the Fraser River at the mouth of Yale Creek.

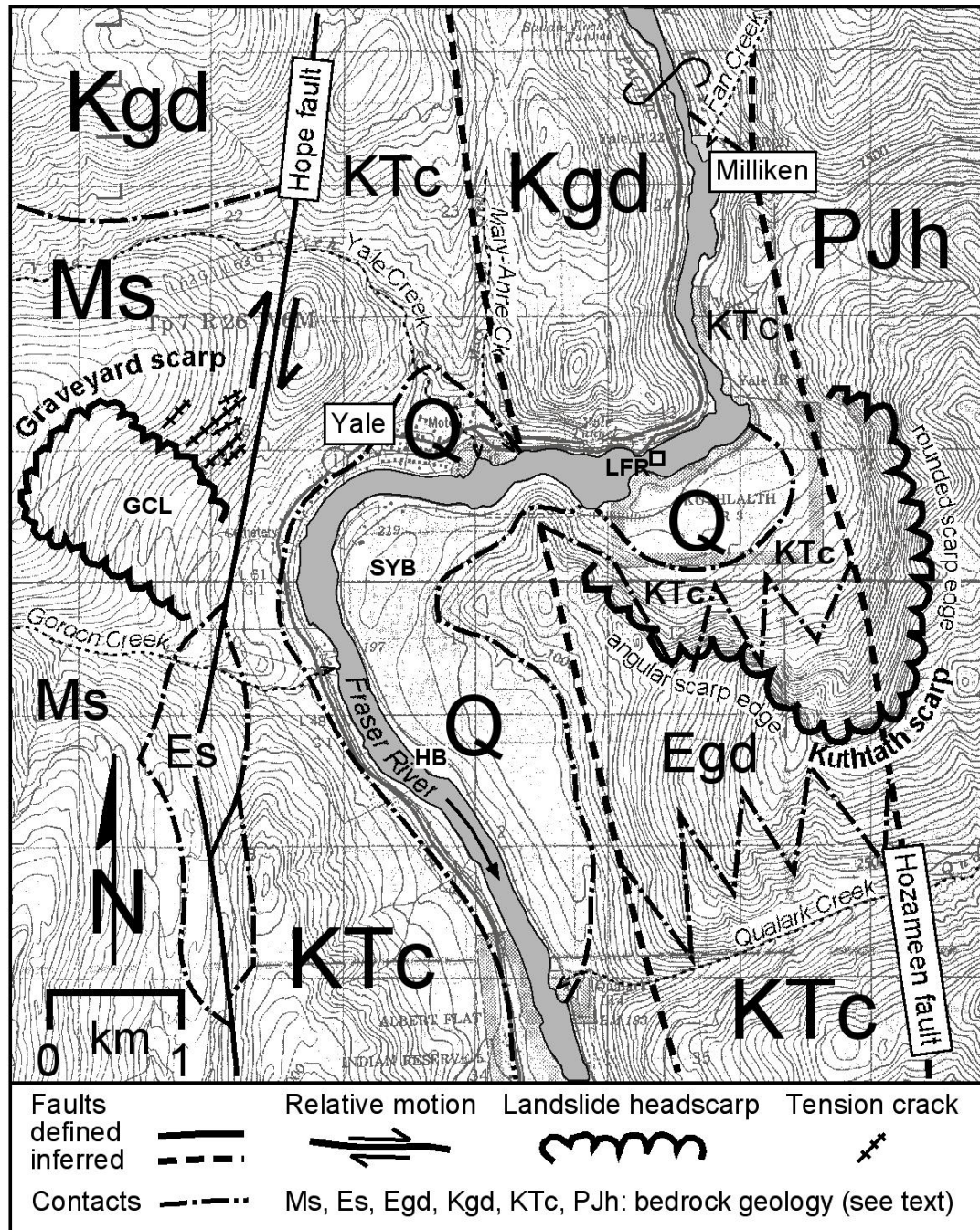


Figure 1. Geology of Yale and vicinity. SYB, South Yale blockfield; GCL, Graveyard Creek landslide; Kgd & Egd, granodiorites; KTc, Custer gneiss; Ms, Settlers schist; PJh, Hozameen Complex; Es, sedimentary rocks; Q, Quaternary deposits.

4.2 Human Settlement

As the upstream extent of navigable water on lower Fraser River, Yale is a natural location for human settlement. First Nations have occupied the area for at least 9000 years as demonstrated by archaeological sites at South Yale and Milliken (Haley 1996; Mitchell and Pokotylo 1996).

The modern settlement of Yale (unincorporated) was founded in 1848 by the Hudson's Bay Company as Fort Yale. In its heyday (Photo 1) it was the largest city west of Chicago and north of San Francisco, with a typical population of between 5000-8000, peaking at 15,000 during the height of the gold rush (1858-1888). Following the completion of the Canadian Pacific Railway in 1885 the importance of the town diminished and the population steadily declined. Yale experienced a revival after 1950 with the completion of the Trans Canada Highway, but went into decline again after 1986 with completion of the Coquihalla Highway. Today it is a small hamlet with a population of 186 people residing in 74 dwellings, including the Yale Indian Reserve (Canada Census 2006).

4.3 Geology

The Fraser River at Yale forms the boundary between two major geologic provinces in the Canadian Cordillera, the Coast belt to the west and the Intermontane belt to the east. The parent rocks in both belts are derived from accreted island-arc terranes (Monger and Price 2000), but the Coast belt underwent high-grade, regional metamorphism during the mid-Cretaceous to Tertiary mountain building event, while the Intermontane belt only experienced low-grade metamorphism.

In the vicinity of Yale (Fig. 1), high-grade rocks of the Coast Belt are represented by the Settler's Schist (Ms) and Custer Gneiss (KTc); while, low grade rocks of the Intermontane belt are represented by Hozomeen Complex (PJh). Rocks of both belts are cut by younger granitic (Kgd, Egd) intrusives. At the boundary between the Coast and Intermontane belts are a number of thrust faults. These have been offset by the younger transform fault, the Hope Fault. None of the faults are considered active (Monger and Journeay 1994).

4.4 Glaciation

During the preceding 2-3 millions years of the Pleistocene Epoch the Coast Mountains were extensively glaciated numerous times. At the end of the last, or Fraser Glaciation, as late as 11,000 ^{14}C yr BP, the lower Fraser River in the vicinity of Hope (Fig. 1) was occupied by a valley glacier (Clague et al. 1997), and stagnant ice may have remained for a few hundred years thereafter. By 11 000 ^{14}C yr BP, sea-level had fallen to less than 30 m above sea level (asl) in the Fraser River lowland (James et al. 2002), and the marine strandline stood somewhere just west of Hope. Thus, the Fraser River began incision to modern sea-level by no later than 10,500 ^{14}C yr BP. This deglacial history places a maximum age of about 10,500 ^{14}C years ago for complete deglaciation of the Yale area.

4.5 Climate and Hydrology

Climate is transitional between Coast and Interior. At Hope, the closest long-term weather station, winters are cool but not cold, with average monthly temperatures staying above freezing; summers are warm with average monthly temperatures reaching 18-19 °C in July and August. Average annual precipitation is 2000 mm with 7% falling as snow. The precipitation peak occurs between October and April, and rainfall exceeding 75 mm/24hr is expected in these months. Extreme rainfalls have exceeded 100 mm/24 hr in all months from Oct-Feb, with a maximum of 173 mm/24 hr in November 1990. Due to orographic effects precipitation (rain and snow) might be expected to be slightly more extreme at Yale.

The Fraser River drains a large portion of southern British Columbia, having a watershed area of 217,000 km² measured at Hope. The flow regime is dominated by snowmelt, with a freshet peak reaching 10,000 m³/s and winter flows falling to 500 m³/s. Fall rains may produce a secondary peak typically about 3000 m³/s. In the vicinity of Yale, the river is 200-400 m wide with seasonal water level fluctuations on the order of 10-15 m. In contrast, tributary creeks in the Yale area have a mixed runoff regime with annual floods being driven by spring snowmelt (freshet), fall rain and fall/winter rain-on-snow. Yale Creek was gauged for a few years in the 1930s with an annual peak flood discharge of up to 100 m³/s recorded.

5.0 Landforms at Yale

5.1 Yale Tunnel Wall

From Mary-Anne Creek extending east about 1500 m distance along the Trans Canada and CPR corridor is a steep bedrock cliff and talus complex with 400-600 m of relief directly above the Fraser River (Fig. 1). Bedrock and associated talus consist of competent granodiorite. Here the canyon is exceedingly narrow where the Fraser River is forced through a 50-m wide gap at Lady Franklin Rock. Both the highway and railway lines required tunneling to navigate this reach. Historic rockfall has caused interruption of the old Cariboo Road, the Trans Canada Highway and CPR, most recently in 1979 (Septer 2006).

5.2 Spirit Cave Steeplands

Between Yale and the Hope fault to the west (Fig. 1) is a bedrock knoll rising to 615 m elevation (Photo 2). Bedrock underlying the knoll consists of Custer gneiss. Due to its proximity to the Hope fault the bedrock is altered and highly fractured. The southeast face of the knoll overlooking Yale is underlain by steep rock and scattered colluvial veneer derived from fragmental rockfall.

A significant feature on the slope is a 300 m wide, 150 m tall bedrock bluff lying between 350-500 m elevation. This feature is referred to as Spirit Caves bluff. The steep slopes below the wall are mantled with rockfall colluvium; with rubble-sized material higher up the slope and boulder sized material near the toe. At the foot of the slope is the outwash terrace described below. Thurber (1987) and Golder (2008) have mapped rockfall hazard on the Spirit Caves steeplands. Golder (2008) indicates a moderate rockfall potential.

For much of the length of the outwash terrace there is a trench 3-4 m deep and about 10-m wide following the foot of slope. The south end of this feature (WP151-

WP155) has been exploited by an access road, but the north end appears natural and it is partially filled with boulder-sized blocks derived from rockfall. The origin of the trench is uncertain, but if natural it is then likely a product of fluvial erosion during the deglacial period. There is no evidence of rockfall material blanketing the outwash terrace surface beyond the trench. Thus, the trench forms a rockfall catchment. It appears that in the time since the formation of the outwash terrace, that is since the deglacial period some 10,500 ^{14}C yr BP, there has not been a large rockfall or rock avalanche event from the wall, only minor fragmental rockfall.

5.3 Outwash Terrace

Directly to the west of Yale below the Spirit Caves steep land there is a 100-200 m wide terrace standing at 150-160 m elevation (Photo 1). On an east-west profile, this surface is convex, the first 100-m adjacent to the hillside being more-or-less level, then increasing to 30-50% slope, then finally breaking to 70% slope immediately above the town. In a north-south profile, the surface extends from Yale Creek about 1000 m to All Hallows Creek, with an average surface gradient of approximately 2% slope.

The terrace is interpreted to be a glacial outwash feature (Thurber 1987). BGC (1994) suggested it may have formed as an ice-contact, or kame terrace, but this is not certain. The existence of a similar terrace on the east side of Fraser River between Hill's Bar and Qualark Creek suggests it might represent a remnant of a broad outwash surface, or sandur, developed at the mouth of the Fraser Canyon. If so, the feature has since been dissected by Fraser River. In either case the deposit is most certainly deglacial in age, having formed some 10,500-12,000 ^{14}C yr BP.

The upstream end of the terrace is sharply truncated by Yale Creek, and the north facing escarpment slope is steep and gullied. At the downstream end the terrace narrows, until a point 200 m north of All Hallows Creek where it is completely removed by erosion exposing hummocky bedrock topography south of All Hallows Creek.

The terrace is composed of granular pebble/cobble gravels with rounded clasts of mixed lithology, including various silicates, plutonics and shale. A conspicuous feature is the inclusion of a significant proportion, perhaps 1-5% by volume, of matrix-supported, angular boulders and megagravel of gneissic lithology (Photos 3-5). Large angular fragments up to 10-m diameter occur.

5.4 Yale Creek Watershed

Yale Creek drains an east-facing basin, 11 km long and 2.5 to 4 km wide, with a watershed area of 37 km². The majority of the basin is underlain by Settlers Schist, with only a small slice of the headwater and the steep south facing slopes at the mouth underlain by quartz diorite (Monger 1989).

The upper basin forms a broad U-shape with moderate to moderately steep sidewalls mantled by till. In contrast the lower basin is a narrow V-shape with steep rocky slopes descending directly into Yale Creek.

In the middle part of the valley, where the channel steepens, the creek becomes incised in glacial deposits and slumping of channel sidewalls is evident in several places on air photos. The steep south facing slopes along the lower basin support several snow avalanche slide tracks that impact Yale Creek, while the steep sidewalls are subject to

moderate to high potential for rock fall and debris slides that would directly impact Yale Creek (Thurber 1987, Madrone 2005, Golder 2008).

Madrone (2005) indicates that there is no post-logging landslide activity from clearcut areas (open slope slides) within the basin, but there are numerous failures associated with old roads. In particular they suggest that the October 2003 regional storm triggered numerous road-related failures that resulted in direct sedimentation to Yale Creek.

The watershed has been extensively logged and there are plans for new blocks in the immediate future (YA203, YA106; Madrone 2008). According to the MoF watershed assessment (Madrone 2005) there is 37km of road with a road density of 1 km/km². The effective clearcut area is 15% and proposed new logging is expected to increase this to 18%. The combined effect of new road construction and harvest is not expected to have an adverse affect on watershed hydrology (Madrone 2005).

To provide access to proposed logging, the YA1000 FSR mainline will be upgraded according to prescriptions provided by Madrone (2008). The YA1000 mainline enters Yale Creek at 600 m elevation just above a midslope break, with steep slopes running 200 m directly to the creek below and moderately steep slopes above. The YA1000 FSR section from stations 2+561-3+193 m crosses a steep rock slope descending directly into Yale Creek. The river undercuts the slope and there is evidence on air photos of four individual hectare-sized instabilities along the toe of slope. This road section supports both unstable fill, partially supported on rotten crib logs and stumps, and an unstable cutslope with “daylighting” structures and active rockfall. Rollerson (pers. com. 2008) indicated that the cutslope instabilities were deep seated and extended as much as 30-40 m upslope of the crest of the cutslope. Fillslope or cutslope failures from this road section could impact Yale Creek.

5.5 Yale Creek Alluvial Fan

At the mouth of Yale Creek and inset into the outwash terrace previously described is the Yale Creek alluvial fan. This feature was described as a “paraglacial fan” (see Church and Ryder 1972) formed within a few thousand years of deglaciation by Bell (1980), Pacific Hydrology Consultants (1981) and BGC (1993/1994). The fan apex, located at the Albert Street bridge over Yale Creek, stands at 110 m elevation, with the fan surface descending at an average 7% slope, to about 60 m elevation at Front Street along the Fraser River. Front Street itself stands about 8–10 m above the normal annual high water mark defined by the vegetation trimline, or “natural boundary” of Fraser River.

The proximal portion of the Yale fan (80-110 m asl) has a bouldery surface and appears channeled by flows from Yale Creek. Closer to the Fraser River there is a series of north-south benches, apparently Fraser River cut terraces. On the right bank of Yale Creek just upstream of the highway is a small terrace inset within the main fan. Boulders on the main fan surface are primarily gneissic, with some granodiorite stones present. Matrix sediments contain schist, representative of the Settler’s schist underlying the Yale Creek watershed. A core log described during drilling of the Yale water system was interpreted to contain 25-m of bouldery and gravelly fan deposits overlying 43-m of glacial drift (interbedded till, gravel, and silt/sand), overlying till at the base of the hole (Pacific Hydrology 1981).

Yale Creek is incised within the fan, and between the apex and highway/CPR corridor it has downcut to bedrock. Freeboard along the escarpment of the main fan surface ranges from 10-20 m on the south bank (with the exception of a low point at the Albert St. bridge at apex where it is 5-6 m), and 13-15 m along the north bank of Yale Creek. Freeboard of the small inset terrace above the highway is 9-10 m above Yale Creek.

The channel itself is about 40-m wide at river level, and has a trapezoidal shape, with 70-80% sloping sidewalls formed in bouldery sediment and rock. Thus, assuming a minimum freeboard of 10-m, the cross sectional area of the incised channel exceeds 400 m². The fan apex is an exception, with considerably less available cross sectional area. There the freeboard on the right (townside) bank is only about 5.5 m and the channel is 14-m wide. The bridge reduces the available opening to 4-m tall by 14-m wide, or 56 m².

From the Canadian Pacific Railway to Fraser River there is an active fan, with a surface 4-m above Yale Creek. This area is occupied by Yale Town IR 1 and is not part of the Yale OCP area.

5.6 East Flank of Gordon/Yale Creek Divide

On the east flank of the Gordon-Yale Creek divide (Fig. 1) is a moderately steep (50-70%) hillside underlain by Settler's schist and lesser granodiorite (Monger 1989). From Gordon Creek to the head of All Hallows Creek this slope is about 2.2 km wide with 900 m of vertical relief extending to 1000 m elevation. The southern half of the slope is concave in vertical and horizontal cross section, with the horizontal concavity up to 120-m in depth at midslope. Immediately to the north, the slope is straight in vertical and horizontal profile and cut by a series of bedrock lineaments extending parallel with the slope contours.

Savigny and Clague (1992) described the entire hillside as an ancient, immediate post-glacial landslide, referred to herein as the Graveyard Creek landslide. They suggested the southern portion may have failed catastrophically and blocked the Fraser River, while the northern half was described as a sagging slope, perhaps buttressed by the knoll forming the east bank of All Hallows Creek.

Terry Rollerson (Golder 2008) has conducted a reconnaissance investigation of the Graveyard Creek landslide, traversing the roads that climb up the bowl (YA1100 FSR) and access Yale Creek (YA1000 FSR). He described the southern portion as being underlain by fragmental bedrock debris, primarily schist with rare granodiorite, and lacking a cover of till (pers. com. 2008), and on that basis agreed with the interpretation that the slope represents a post-glacial landslide (Golder 2008). On the slope north of the bowl the lineaments (airphotos 30BCC02033:62, 63) consist of large tension cracks (see Plate 26, Golder 2008) indicative of a sagging slope, or *sakung*. However, on the basis of topographic observations, Rollerson does not agree that the knoll west of All Hallows Creek buttresses the sagging slope (pers. com. 2008).

In contrast, Madrone (2008) indicated that the terrain between 300-800 m elevation within proposed blocks YA202 and YA204, is covered by a mantle of till and colluvium. The existence of till on the landslide would indicate a potential preglacial initiation age. Thus, the age of the Graveyard Creek landslide remains uncertain.

As originally noted by Savigny and Clague (1992), there are no landslide deposits below about 110 m elevation. Above this, the slope is underlain by angular debris derived

from Settlers Schist. Below 110-m elevation the slope is underlain by hummocky bedrock (Custer gneiss) with discontinuous colluvial veneer of gneiss and schist.

The absence of landslide deposits below 110-m could indicate the slide did not propagate below this elevation, or that the toe has been removed by erosion. Considering the former, either the travel distance was limited or there was a glacier margin at about 110-m elevation and the slide deposited on ice. If removed by river erosion, then the landslide age is constrained by the age of the floodplain surface when the river stood at 110 m elevation. Two dates from the immediate locality constrain the age of river grade. Wood at 90 m elevation in Gordon Creek raised fan deposits yielded an age of 7490 ± 70 ^{14}C yr BP (McNeely and Clague 1996), while an age from charcoal in a hearth under a rockshelter at South Yale yielded an age of 5900 ^{14}C yr BP (Haley 1996). Thus, it can be concluded that the rockslide had limited travel or that it occurred before 7500 ^{14}C yr BP (8500 calendar years) and has since been removed by ice and/or by Fraser River.

A series of small creeks drain this slope, All Hallows Creek, Graveyard Creek and an unnamed creek. All have small drainage basins, flow in incised channels with gradients $>25\text{-}30\%$, and have been noted to be subject to periodic debris flow by locals (Thurber 1987). Golder (1998, Figure 16, Appendix III) mapped the headwaters of these channels as having a moderate and high rock avalanche, debris flow and rockfall hazard. In contrast terrain within Blocks YA202 and YA204 were mapped as supporting low hazard by Madrone (2008). The lower reaches of these creeks, between the hydro right-of-way and the Highway, are confined in bedrock channels, while between the Highway and CPR, in the Yale Cemetery, there is an apron of colluvial debris composed of Settlers Schist indicating flood and debris flow source upslope.

5.7 Kuthlalth Landslide Headscarp

The Kuthlalth landslide scar (Fig. 1; Photo 7) is located on the east side of the Fraser River about 2-km upstream of Yale. It is a northwest facing bedrock amphitheatre, 2000 m wide with 1000 m relief. Bedrock consists of granodiorite, Custer Gneiss, and the Hozameen Complex (Fig. 1). The amphitheatre is filled with a debris cone extending from 400 m elevation to river level. The debris consists of a mix of locally derived granodiorite, gneiss and pelitic rocks. The southern part of the cone is truncated by a paleochannel raised about 10-m above river level.

The “missing volume” or the amount of rock exhumed from the entire Kuthlalth headscarp is 1.5 km^3 . However, the northern rim of the headscarp is rounded suggesting it has been glacially eroded, and must predate the last, or Fraser glaciation, as suggested by Bell (1980). Only the southern half of the headscarp supports an angular scarp edge, indicating post-glacial rockfall and rock avalanche activity may have occurred. The “missing volume” encompassed by the angular headscarp is less than 0.5 km^3 .

The debris apron filling the floor of the amphitheatre does not contain a blocky deposit suggestive of a large post-glacial rock avalanche. Either such a deposit has been eroded by Fraser River, or a large rock avalanche has not occurred. Small rockfall and debris flow events are common. The CNR has been blocked by debris flow several times (Septer 2006; Table 3). Airphotos (BC78100:194; BCB91080:33) indicate that recent debris flow activity was initiated by a small rockfall event.

5.8 The South Yale Blockfield

The blockfield (Fig. 2) extends from South Yale, 1.5 km south to Hill's Bar, and is about 500 m wide. It lies between 75-110 m asl. The surface is characterized by a preponderance of 2-5 m diameter subround boulders and 5-15 m diameter angular blocks scattered in clusters separated 5-15 m apart (Fig. 5). The block-field is channeled by the Fraser River, with two relict paleochannels separated by a flat-topped ridge, coined the South Yale Ridge (Borden 1961) rising 10-20 m above the paleochannels flanking either side. The steeper (>40%) sidewalls of the ridge are blanketed with a boulder lag. The northwest side of the ridge descends gently (6%) to a lower terrace level at 65 m asl.

The main paleochannel (Fig. 2) lies to the east of the South Yale ridge and is about 200-300 m wide and 20-m deep (see inset cross section, Fig. 2). This channel has a smooth floor with a gradient of about 0.005 m/m. A few megagravel blocks project from the paleochannel floor, but they are less abundant than on the channel sidewalls and adjacent debris surfaces.

The east sidewall of the main paleochannel has a moderate (10-20%) slope rising to a defined slope break. This break consists of a scarp crest at about 100-105 m elevation. East of the sidewall crest is a blocky bouldery debris terrace at 105-110 m elevation. This level is bounded by a steep (70%) sloping escarpment that rises to the highest, outwash terrace level at 170 m elevation.

Antiquus (2008) conducted numerous exploratory shovel tests and eight 1x1 m excavations (TUs 1-6, 9; Fig. 3) on the north end of South Yale Ridge, on either side of the main paleochannel. These 1x1 m test units, excavated in 10 cm layers and terminated between 0.5 to 1-m depth, reveal that the T2 surface sediment consists of about 0.5 to 1-m of silty sand overlying gravelly sand with rounded pebbles and cobbles. Angular and subround blocks and boulders protrude into and project from the sandy gravel and overlying silty sand. The capping silty sand along the margins of the main paleochannel and on South Yale Ridge contains cultural artifacts throughout, while the gravelly sand is culturally sterile (Antiquus 2008). Radiocarbon dates from cultural horizons have yielded a minimum surface age of 5900 ± 130 ^{14}C yr BP (SFU-238; Haley 1996).

There are no natural or artificial sections through the deposit, but drill core (6" from Barber drill; log provided by Coast Mountain Geological; Chris Basil, pers comm., 2003) revealed 5-m of gravel overlying a 3-m thick layer of boulders, which in turn overlies gravel at 70 m elevation. Interstratified gravel and sand extend down to 13-m elevation where the hole was terminated in "pyritic shale gravel" (Coast Mountain Geological; Chris Basil, pers comm., 2003).

Approximately 65 subround to round boulders and angular megagravel blocks were sampled for lithology at 10 different stations distributed across the T2 debris surface (Fig. 2). All were gneissic and classified as Custer Gneiss. This is in agreement with observations made by Greg Brooks (pers. comm., 2007).

The origin of the South Yale blockfield remains enigmatic. The debris at South Yale was described as a large landslide deposit by British Columbia historian BA McKelvie (1889-1960)(cited on p. 146 in Paterson 1979). Greg Brooks of the GSC suggested that the South Yale blockfield could be a postglacial rockslide deposit (cited in McNeely and Clague 1996); Friele (2003) has speculated that the deposit represents a large, post-glacial landslide from Kuthlalth headscarp. In contrast, Swondell (1973) in a report commissioned by Irvine (1973) suggested the deposit originated as glacial

outwash. Although apparently on file at the Victoria office of Thurber Engineering, I have not been able to acquire for review a copy of the Swondell (1973) report.

The bouldery and blocky character of the surface morphology of the deposit seems characteristic of a large debris flow evolved from rock avalanche upstream. The uniform lithology (Custer gneiss) of the boulders and blocks supports a colluvial rather than glacial mechanism. There is gneiss in the Kuthlalth headscarp, and the south portion of the headscarp has an angular crest. Both these observations are consistent with a landslide source at Kuthlalth headscarp. There are no other candidate landslide headscarps near Yale.

Yet certain features and relationships do not support the landslide hypothesis. If a large landslide filled the valley from 70-110 m elevation then

- 1) why, asked Brooks (in McNeely and Clague 1996), is there no evidence for backwater inundation in the Milliken archaeological site excavated by Borden (1961, 1965, 1968);
- 2) it is questionable that the angular portion of the Kuthlalth headscarp could have produced a landslide large enough to cause valley wide inundation from Kuthlalth IR to Hills Bar, an area of $5.5 \times 10^6 \text{ m}^2$ (with an apparent thickness of 20-40 m, the deposit would have a magnitude of 10^8 m^3); and
- 3) why are there no relict deposits in the Kuthlalth bowl at the base of slope; is it likely that Fraser River completely removed all evidence of such a major post-glacial landslide?

From a sedimentologic viewpoint, while it is acknowledged the surface has been washed and channeled by Fraser River, why is the matrix material from test pits outside the defined channels (Antiquus 2008; Qualark Resources) not uniform lithology, angular and very poorly sorted (i.e., diamictic), as expected for rock avalanche or debris flow deposits. In most places where test pits have been dug they reveal matrix materials consisting of rounded silty, sandy, pebble-cobble gravels of mixed lithology, as expected for upstream sources on Fraser River.

The alternate hypothesis suggesting the deposit originates from glacial outwash cannot be rejected at this point. The observation that large gneiss blocks occur as matrix supported stones in low abundance (1-5% by volume) in the outwash deposit on the west side of Yale raises the possibility that the boulder and block accumulations forming the South Yale block field are derived by the process of winnowing gravel from a former outwash sandur filling the valley, and the accumulation of a lag of large non-transportable boulders and blocks on abandoned terraces and channel sidewalls. By this hypothesis the source of the gneissic blocks would be rockfall or rock avalanche during the deglacial period from nearby slopes underlain by Custer gneiss.

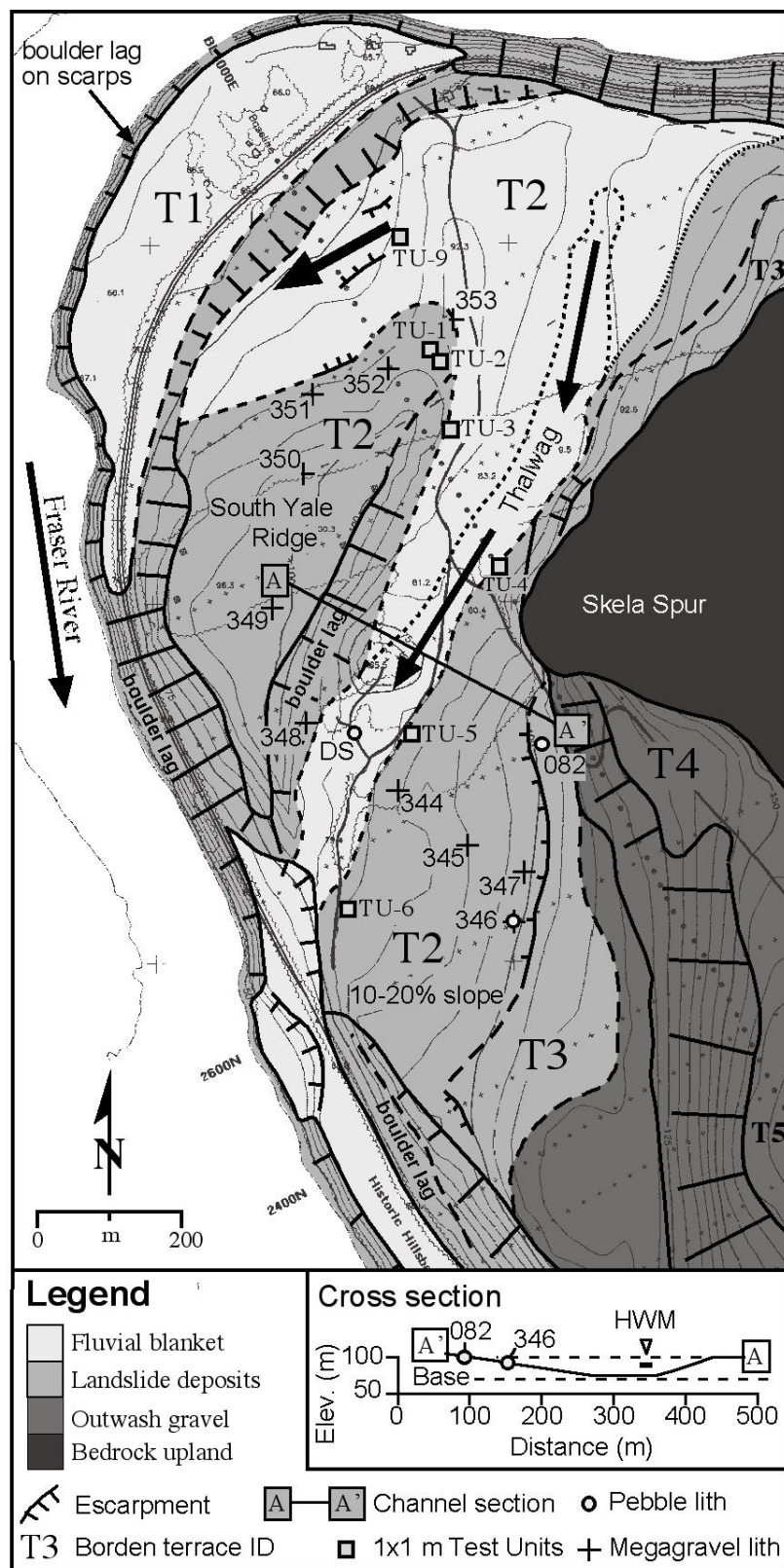


Figure 2. Geomorphic map of the South Yale blockfield. Materials mapped as landslide deposits may represent fluvial lag from Fraser River incision into outwash gravel. The origin of these materials is uncertain.

6.0 Geological Hazard Assessment

6.1 Background Data Compilation

Background reports describing the geological hazards in the vicinity of Yale include geotechnical reports on file with FVRD (Table 2), a detailed compilation of historical floods and landslides for southwestern BC as reported in media and other available documents (Septer 2007; Table 3), a study of rockfall incidence along the CNR (Peckover and Kerr 1977), a terrain hazard and landslide incidence assessment for the Fraser Canyon (Bell 1980), reconnaissance mapping of large landslides and bedrock lineaments in the lower Fraser River valley (Savigny and Clague 1992), a geotechnical and natural hazard assessment of the Interior to Lower Mainland transmission project conducted for BCTC (Golder 2008), and comprehensive review of Fraser River flood hydrology at Hope (NHC 2008). This information and observations from field-work are compiled and discussed in the following sections.

Table 2. Main conclusions from hazard assessments for Yale on file with FVRD.

Report File No.	Author/Year	Landform/Area	Conclusions
71	Thurber 1987	Gordon Creek subdivision	Bedrock benches with Gordon Creek fan on north end of parcel. No hazards affect housing.
77	Thurber 1987	Front Street Terrace	Minor terrace instability possible, otherwise no issues.
80	Thurber 1987	Yale OCP study area	Rockfall, alluvial fan, Fraser River fan, steepland slope hazards in various polygons.
125	Thurber 1990	All Hallows/ Graveyard Creek	Alluvial fan hazards identified on Graveyard Creek. Rockslide identified by Wayne Savigny is not considered a hazard to residential development.
238	BGC 1993/94	Yale Creek alluvial fan	Yale Creek alluvial fan considered a relict feature greater than 6000 years old. Yale creek is incised 15-20 m in the deposit, and development on the fan surface not subject to alluvial fan hazards. Granitic boulders thought to be lag from incision into kame terrace deposit whose surface stands at 165 m elevation.
394	QCD 2008	Graveyard Creek landslide	Graveyard Creek landslide now recognized as a potential hazard.

Table 3. Historic flood and landslide events, Yale and vicinity, 1865-2005 (Septer 2007).

Year	1865	Event	Location	Hazard/Consequence
1865	Nov 11-12	Rain	Fraser River tributaries.	Extensive road and bridge damage.
1866	May-June	Freshet	Yale	Water level reached 15-m above high water mark at Yale.
1871	June	Freshet	Yale	Water level higher than in 1866.
1876	June	Freshet	Lower Fraser River	Largest flood on record. Flooding and damage to buildings at Yale and Gordon Creek.
1882	June	Freshet	Lower Fraser River	Water level 33 cm higher than in 1876. Yale suspension bridge endangered; Flooding of railway; Cariboo Road washed out.
1894	May-June	Freshet	Lower Fraser River	The Great Flood of '94, with 33 day flood peak. At Yale water level 62.5 cm higher than 1882.
1921	Dec 9-12	Rain-on-snow	Fraser River tributaries	Mudflow covering CNR tracks at Yale
1935	Jan 20-27	Ice storm, rain-on-snow, ice jam flooding.	Fraser River and tributaries	At Yale, 2.4-2.7 m of snow fell during a 36-hour period.
1949	Nov-Dec	Rain-on-snow	Fraser River tributaries	Trans Canada and CPR bridges at Gordon Creek washed out.
1950	Feb 5-8	Rain-on-snow, avalanches	Lower Fraser River region	Snow slides near Yale stopped CNR mainline railway traffic for two weeks.
1953	Jan 9-16	Rain-on-snow	Lower Fraser River region	1-2 m snowfall followed by rapid thaw and rainfall. Numerous washouts on both rail lines.
1954	Nov 17-21	Rain-on-snow	Fraser River tributaries	A washout at Yale Creek bridge held up traffic for several hours on November 21.
1975	Nov 29-Dec 8	Rain-on-snow, earthquake.	Fraser Canyon	A 15 m deep mudslide near Yale blocked the CNR tracks (Kuthlalth IR).
1977	Nov 1	Rain-on-snow	Fraser Canyon	At Yale, a mudslide covered the Trans Canada Highway and CPR.
1979	Dec 4	Rain	Fraser Canyon	Yale Tunnel rockslide blocks highway and CPR tracks.
1980	Dec 23-27	Rain-on-snow	Fraser Canyon	Highway and CPR tracks washout out at Gordon Creek. CN washed out (Kuthlalth IR?).
1990	Nov 6-13	Rain-on-snow	Fraser Canyon	Rockslide blocked the Trans-Canada Highway north of Yale
2005	Oct 11	Rain	Fraser Canyon	Rockslide onto CPR tracks causes train derailment.

6.2 Earthquake

According to the Geological Survey of Canada, Yale is outside the area affected by ground motions from Cascadia subduction zone earthquakes. However, it may be affected by large crustal earthquakes, such as the Lake Chelan, Washington earthquake that occurred on December 14, 1872 (Fig. 3). The magnitude of the Lake Chelan earthquake has been estimated at 7.4. The exact location is uncertain, but it appears to be about 100 km or more south of Hope. At Yale the shaking was strong enough to frighten people and cause them to run out of buildings (i.e., Modified Mercalli Intensity VII). A frequency analysis of seismic hazards for Yale (49.5646 °N 121.4254 °W)(<http://earthquakescanada.nrcan.gc.ca>) is presented in Table 4.

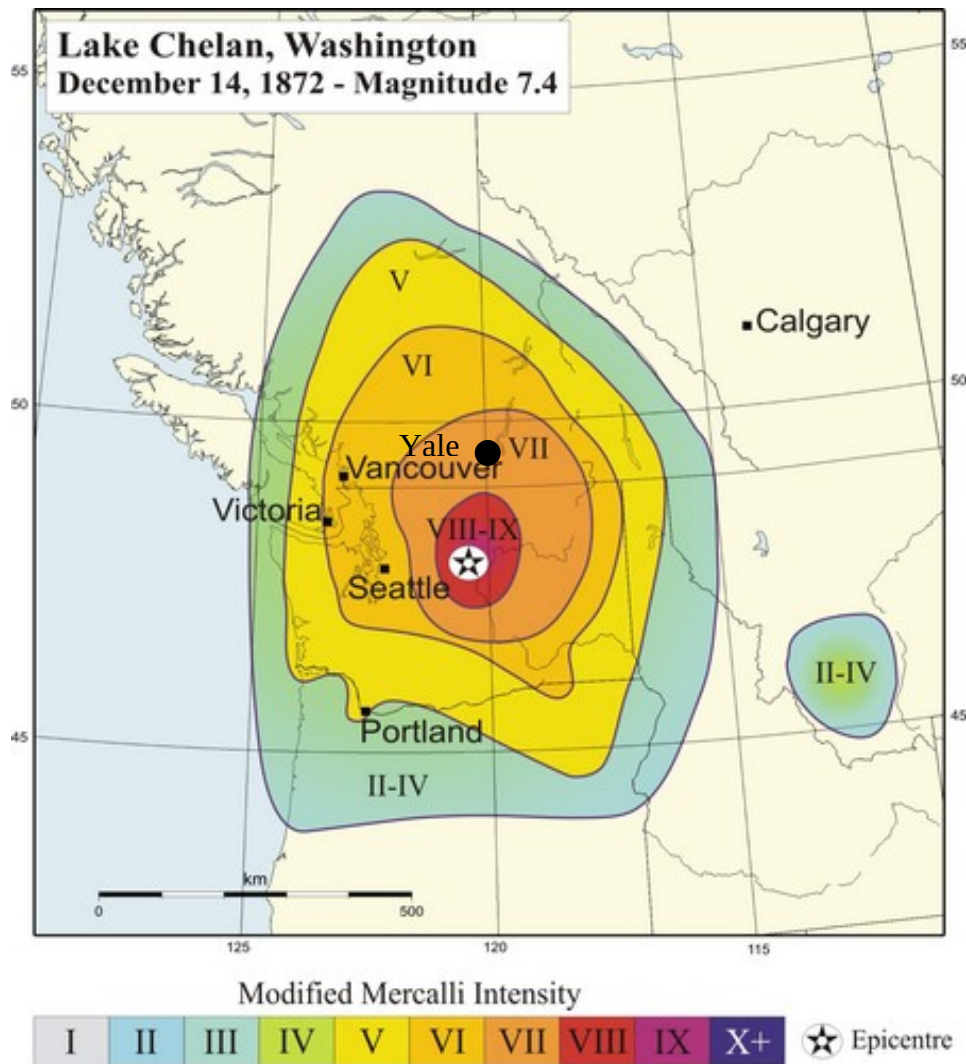


Figure 3. 1872 Lake Chelan crustal earthquake. Yale experienced the shaking, but no significant damage (i.e., Mercalli Intensity Zone VII).

The Hope and adjacent faults are believed inactive (Monger and Journeay 1994) and earthquakes associated with fault rupture are not considered as potential landslide triggers. This is a significant point considering the close spatial association of fault earthquakes and landsliding (Harp et al 2003).

Building design (2005 National Building Code) must consider 1/2475 per annum seismic hazard (Table 4). Seismic engineering is beyond the scope of this report. In that the geologic record integrates landslide response from past earthquakes, the landslide hazards discussed below implicitly consider earthquake triggering.

Table 4. National Building Code interpolated seismic hazard values for firm ground.

Frequency	Seismic acceleration (g)				
	0.2	0.5	1.0	2.0	PGA
1/2475 per annum	0.623	0.461	0.273	0.151	0.280
1/500 per annum	0.317	0.226	0.129	0.071	0.151

6.3 Fraser River Floods

In the 19th century, between 1865 and 1900, six freshet floods were reported to have caused flooding at Yale (Table 3). The record states the 1866 flood reached 15-m above the high water mark, and that floods in 1871, 1876, 1882 and 1894 all exceeded the level of the 1866 flood. In the 20th century freshet floods were not mentioned in the historical record at Yale. The lack of Fraser River flood impact in the 20th century may be due to a combination of environmental and social factors: freshet peaks may have not been as high as in the late 19th century (NHC 2008), and more importantly, after experiencing several floods, housing and important buildings were likely relocated above the flood level.

FVRD Bylaw 0681 (2005) states that the designated flood construction level is 6-m above the natural boundary. The natural boundary is taken as the elevation on the floodplain separating non-vegetated shoreline from vegetated floodplain. At Yale below Front Street the natural boundary is 50-m elevation. Therefore, at 60 m elevation Front Street is above the existing FCL.

The historic record states that in 1866 the flood level was 15-m above the highwater mark, and that subsequent 19th century floods, including the flood of record in 1894, exceeded it. For the 1882 flood the record states that between the No. 1 and No. 2 tunnels, the water encroached upon the railway and the track had to be shifted; while in 1894 the flood level was said to be some 65 cm higher than in 1882. Based on maps supplied by FVRD the track between the #1 and #2 tunnels is between 60-61 m elevation. However, the precise elevation in 1882 is not known.

Several questions are raised by these observations: 1) was the cited 1866 high water mark equivalent with the natural boundary; 2) was Front Street flooded in the 19th or 20th century; and 3) is the rule-of-thumb FCL of 6-m above the natural boundary of Fraser River appropriate at Yale.

A comprehensive review of Fraser River flooding at Hope (NHC 2008) concluded that the 1894 flood, with a discharge of 17,000 m³/s, represented a 500-year return event; while the 1948 flood, with a discharge of 15,200 m³/s, represented a 200-year return event. Thus, with no large tributaries between the towns, 15,200 m³/s would “approximate” the appropriate design flood flow at Yale.

6.4 Tributary Creek Floods and Debris Flows

6.4.1 Tributary creek floods

Yale Creek and other similarly sized drainages in the vicinity have not been adequately gauged. Available annual flood peak data from Water Survey Canada (Table 5) indicate fall and fall/winter flood peaks exceed freshet peaks by 200%-300%. Based on unit area discharges ($\text{m}^3/\text{s}/\text{km}^2$; Table 5), fall/winter peak floods for Yale Creek (37.3 km^2), Mary-Anne Creek (2.8 km^2) and Gordon Creek (13.3 km^2) would be on the order of $100 \text{ m}^3/\text{s}$, $8 \text{ m}^3/\text{s}$, $36 \text{ m}^3/\text{s}$, respectively. For small drainages ($\sim 1 \text{ km}^2$) such as All Hallows and Graveyard creeks peak discharges of $5 \text{ m}^3/\text{s}$ are reasonable.

Table 5. Unit area discharge for drainages $<100 \text{ km}^2$ near Yale.

Creek	Drainage Area (km^2)	Years of Record	Annual Peak Freshet ($\text{m}^3/\text{s}/\text{km}^2$)	Annual Peak fall/winter ($\text{m}^3/\text{s}/\text{km}^2$)
Yale	37.3	1934-1936	0.6 – 0.8	0.2 – 2.6
American	32.4	1934-1936	--	1.4 – 1.6
Nicolum	77.7	1912-1936	0.14 – 1.11	0.1 – 2.7
Norrish	78.2	1984-2006	--	0.8 – 1.7

An approximate estimate of the 100-year and 200-year return floods for Yale Creek at the apex is provided by application of Gumbel distribution to the annual flood peak record for Norrish Creek (1985-2006), a lower Fraser River tributary with a drainage area less than 100 km^2 . The respective discharge estimates are $115 \text{ m}^3/\text{s}$ and $125 \text{ m}^3/\text{s}$. Assuming a flood velocity of 2-3 m/s, designated floods for bridge design (100-year) and community planning (200-year) would occupy cross sectional areas of 40 m^2 and 60 m^2 , respectively.

At the Yale Creek fan apex, the available bankful capacity, defined by right bank (townside) freeboard, is about 14 m wide by 5.5 m tall, or 77 m^2 . However, the FSR bridge on Albert Street restricts the available opening to 14-m wide by 4 m tall, or 56 m^2 . Thus, the FSR bridge may be only marginally sufficient for the 100-year event, and may not be sufficient for the 200-year flow. Should the bridge restrict flow and cause right bank overtopping, it is most-likely that, given the slight adverse grade on Albert Street for 50-m to a rock throughcut, flood water would disperse off the road and back into the channel, and would not affect areas further south on the relict fan surface underlying Yale.

Farther downstream between the apex of Yale Creek fan and CPR, the channel floor is 30-40 m wide and freeboard exceeds 9-m. Thus, the incised channel provides ample capacity to contain normal hydrologic floods. The first Trans Canada highway bridge was washed out in 1954 (Table 3). It is not known if the existing bridge is a exact replacement or if it provides greater capacity than the original. Presently, the Trans Canada Highway and CPR bridges provide 17-18 m wide spans with 5-m clearance, for a capacity of $85\text{-}90 \text{ m}^2$. These appear more than adequate to pass the 200-year flood. There have been no recorded washouts of these existing structures.

In 1999, to offer some protection against Fraser River and Yale Creek flooding, an ad hoc berm was constructed around the Church Street portion of Yale Town IR 1. The degree of protection offered by this structure has not been quantified (David Sanders (KWL), pers comm., 2009).

6.4.2 Tributary creek sediment floods and debris flows

Drainage basin ruggedness (i.e., basin relief divided by the square root of basin area) may be used as a predictor of potential sediment flood or debris flow activity. Basins with ruggedness >60% may be prone to debris flow activity; while basins with intermediate ruggedness values of 30-60% may be more prone to sediment flood activity (Wilford et al 2005). Gentle basins with ruggedness <30% typically experience water floods only. On this basis it may be concluded that All Hallows and Graveyard Creeks, with basin ruggedness >80%, are subject to potential debris flow activity; Gordon and Mary-Anne Creeks, with intermediate ruggedness of 40-50%, may be affected by sediment flood activity; while Yale Creek is gentle and most likely to be affected by floods only.

However, specific topographic conditions may cause exceptions to these general patterns. For example, where potentially unstable and unstable terrain directly connected to the channel exist near the mouths of larger more gentle basins, landslides from this terrain may impact the main channel causing temporary blockage with potential for sediment flooding or debris flow propagation downstream. These topographic conditions exist on Yale, Gordon and Mary-Anne creeks so sediment flood and or debris flow activity might be expected to reach the fans of each creek. Rain and rain-on-snow events have caused mudslides to interrupt the road and railway at Gordon Creek (1949, 1977?, 1980; Table 3).

The capacity of the incised Yale Creek channel just upslope of Trans Canada Highway is about 30-m wide by 10-m deep, or 300 m². Assuming a bankful debris flow with a velocity of 8 m/s, this yields a peak debris discharge of 2400 m³/s. Using the relation between debris flow magnitude and peak discharge for granular debris flow (Jakob and Bovis 1996), this is equivalent to a debris flow with a magnitude of about 400,000 m³. Thus, it would require an exceedingly large event to produce bankful debris discharge along Yale Creek between the fan apex and the Trans Canada Highway, and consequently this seems a very unlikely event.

Within the Yale OCP area, Mary-Anne Creek breaks from confined channel to valley flat. The creek on the valley flat is not confined. Sediment floods and debris flows could affect Mary-Anne Creek floodplain.

Anecdotal accounts (Thurber 1987) support the occurrence of debris flow activity on All Hallows/Graveyard creeks. The break in slope on the vertical profile of these channels occurs at or just upslope of the BC Hydro right-of-way. Between the BC Hydro right-of-way and Trans Canada Highway, or between 130-100 m elevation, the three channels are confined in rock channels 2-5 m deep and adjacent terrain is dominated by irregular rock topography. Despite moderate confinement, there is a potential for debris flow avulsion in this area. However, since Fraser River abandoned this elevation sometime prior to 5900 yr BP, the absence of significant debris cover suggests debris flow avulsions have been uncommon. Below Trans Canada Highway, the Yale cemetery is located in an east sloping sediment apron consisting of rubbly gravel comprised of angular schist debris, indicating a debris source upslope west of Hope fault. The grounds of the All Hallows RV Park have been excavated into the north side of this apron leaving a 2-4 m tall scarp down to the RV site. A future debris flow reaching the highway could affect this site.

6.4.3 Ice jam floods

An additional hazard is ice jam flooding caused by rapid thaw and heavy rain following a prolonged period of cold. This type of weather occurred once in the 20th century, in 1935 (Table 3). This winter, the recent flood cycle (Jan '09) that followed a prolonged cold mobilized large ice blocks on Yale Creek (Photo 6), although no associated flooding occurred.

6.5 Fragmental Rockfall

According to Bell (1980), rockfall is the most common mass-movement hazard in the Fraser Canyon, with the greatest frequency associated with cutslopes along railway corridors. In a comprehensive survey of rockfall events affecting CNR in the Fraser Canyon, Peckover and Kerr (1977) clearly demonstrate the seasonality of rockfall and its link to fall and winter precipitation. In the 20th century ten major rain and rain-on-snow events produced rockfall, small slides and tributary floods that caused road and/or rail interruptions near Yale (Table 3), for an average of 1/10 per annum. In 1979 rockfall at Yale Tunnel blocked both CPR and the Trans Canada, and in 2005 rockfall caused a train derailment near Yale.

Steep rock slopes supporting potential rockfall bound the Yale OCP area and therefore potential rockfall impacts are of concern. For discussion, these can be divided into the southeast facing slope between Yale and All Hallows, referred to as Spirit Caves steeplands; the south facing slope between Yale and Mary-Anne creeks; the west facing slope east of Mary-Anne Creek; and the Yale Tunnel wall.

6.5.1 Spirit Caves steeplands

Thurber (1987) and Golder (2008) have mapped fragmental rockfall hazard in the Spirit Caves steeplands. Golder (2008) suggests a moderate hazard, both for the slopes and the cliff area. Direct observation of the toe of slope along the inside edge of the outwash terrace revealed an apparently natural trench that appears to have acted as a rockfall catch. Although the terrace surface has been somewhat modified by human activity, there is no evidence for extensive rockfall deposits beyond the toe of slope on the outwash terrace surface. On the basis of this observation, fragmental rockfall from these slopes does not present a significant hazard to the OCP area to the south and east of the outwash terrace.

6.5.2 Mary Anne Creek steeplands

The south-facing slope west of Mary-Anne Creek has an average angle of about 60% slope and the toe is bounded by the relict Yale Creek fan. No talus deposits were noted at the base of slope on the fan surface. Since the fan is judged to be paraglacial in origin, inactive for more than about 8500 years, the rockfall frequency affecting the toe of slope is very low.

The west-facing slope paralleled by Mary-Anne Creek is also a smooth to undulating bedrock slope broken by short bluffs and supporting localized colluvial veneer. The average slope angle is about 85% slope. There is a talus apron on the lower slope, and the toe is bounded by the active Mary-Anne Creek alluvial fan. Material at the base of slope consists of both recent debris flow and fluvial deposits. During the field traverse a 50-cm diameter angular clast, suspected to be of rockfall origin, was noted 30-

m from the base of slope. Due to the assumed youth of the Mary-Anne Creek fan it is harder to judge the frequency of rockfall from the slopes above.

6.5.3 Yale Tunnel wall

Frequent rockfall affects the entire area beneath the Yale Tunnel Wall (Thurber 1987). All lands at the base of slope are within the rockfall shadow zone (Evans and Hungr 1993).

6.6 Rock Avalanche

6.6.1 Graveyard Creek landslide

Savigny and Clague (1992) and Golder (1998) agree that the Graveyard Creek concave hillslope (airphoto 30BCC02032:112,113) represents a large landslide that may have affected Fraser River and both agree the NE-trending lineaments (air photo 30BCC02033:62,63) represent a sagging slope.

Thurber (1990) did not consider a future landslide a significant risk, but based on discussion with Terry Rollerson, QCD (2008) revised their opinion of the hazard and suggested the potential for a rockslide from the previously failed portion of the site affecting the OCP area downslope was very low, perhaps 1/5000 to 1/10,000 per annum, and the hazard at the northern sakung portion of the site was very low, perhaps 1/2500 to 1/10,000 per annum. Golder (2008) indicates the potential for a future event is real, especially given an earthquake trigger. Golder (2008, Figure 16, appendix III) has mapped portions of the failed area to be subject to high rockfall and/or rock avalanche hazard and the northern sakung area to be subject to a moderate to moderately high potential for slow mass movement. On the basis that little is known about these slopes, Mr. Rollerson was hesitant to assign quantitative probabilities to the qualitative hazard classes (pers. comm., January 6, 2009).

A significant factor in the interpretation of existing hazard is landslide age: did the landslide occur before the last glaciation, or during the period of landscape adjustment during and immediately following deglaciation (the so-called paraglacial period; Church and Ryder 1972), or later under “normal” landscape conditions. With an inferred minimum age of 8500 years old (Section 5.5), the Graveyard Creek landslide is considered paraglacial in origin or older.

However, without detailed geotechnical information (drill hole geology, piezometer & inclinometer data; bedrock geology mapping; kinematic analysis) the existing hazard is uncertain.

If catastrophic failure were to occur the affected area would include All Hallows RV Park and the terrain to the south.

6.6.2 Spirit Caves Cliff

Neither Thurber (1987) nor Golder (2008) mapped a potential rock avalanche hazard for the 300-m wide by 150-m tall Spirit Cave cliff (Photo 2). Airphotos BC79140:94, 95 (~scale 1/10,000) depict the cliff area in detail. On the airphotos there is no evidence of bedrock lineaments at or above the headscarp that would suggest tension cracking and the potential for a larger instability.

However, based on analysis of topographic profiles, in the event of a larger failure, triggered by a large earthquake for example, a rock avalanche of several hundred

thousand to a million cubic metres in volume might be possible. Based on reach angles for events of this size (Scheidegger 1973; Corominas 1996), it is possible that a substantial portion of the town of Yale could be affected. Given the apparent lack of signs of potential instability and the absence of major post-glacial rock avalanche deposits at the toe of slope on the outwash terrace, the potential for rock avalanche from this slope is considered uncertain at this time.

6.6.3 Kuthlalth landslide

The Kuthlalth landslide headscarp (Photo 7) is likely the product of an extended landslide history spanning the Pliocene/Pleistocene. There is an angular, fresh appearing scarp on the southwest side of the headscarp, but there are no known remnant rock avalanche deposits at the foot of slope that may have been derived from a singularly large event. The origin of the South Yale blockfield remains enigmatic. Although fragmental rockfall occurs at the headscarp, which may trigger debris flows that affect CNR. There is no unequivocal evidence for large post glacial rock avalanches that have caused major interruption of the Fraser River with severe downstream affects. The potential for this hazard is considered uncertain.

6.7 Instability on Escarpment Slopes

Bell (1980) stated that landslides on slopes underlain by glaciofluvial or fluvial slopes had the lowest incidence rate within the Fraser Canyon. Golder (2008, Figure 16) shows the escarpment slope on the outwash terrace as having a moderate to high potential for instability, but Golder's (2008) appendix III states "steep slopes appears stable, may be subject to rare debris avalanches, and ravel may occur on nonvegetated or partially vegetated surfaces." The historic photo of Yale (Photo 1) shows what appears to be a slump or slide on the east end of the outwash terrace. This same area appears recently disturbed with a steep access road on airphoto BC79140:94. This apparent slide area could be related to anthropogenic disturbance (placer mining). Evidence of instability is uncertain.

The escarpment slopes bounding the incised channel of Yale Creek are typically steep (70-80%) and underlain by bouldery sediments overlying rock. No active instability was noted. Stream undercutting and scour during large floods could cause local instability and ravel. Setback from top of slope is recommended.

Similarly, the escarpment slope above the Fraser River high water mark, beneath Front Street and CPR right-of-way is typically steep (70-80%) and underlain by bouldery gravels and/or bedrock. No active instability was noted. Stream undercutting and scour during large floods could cause local instability and ravel.

6.8 Snow Avalanche

Although snow avalanche commonly affects transportation corridors in the Fraser Canyon (Table 3), this hazard is not identified as a potential hazard in the OCP area by Thurber (1987) or Golder (2008). On airphotos there are no well-defined snow avalanche tracks reaching from timberline into the OCP area. However, on steepland and escarpment slopes given certain snow conditions and forest clearing, small snow avalanches might occur (see Jones 2002). Site assessment might be required for specific cases at the discretion of the building inspector.

7.0 Yale OCP Hazard Mapping

The landform description and hazard assessment of previous sections provides rationale for the hazard mapping presented on the updated Yale OCP hazard map. The revised OCP map is divided into 23 discretely labeled polygons. For each polygon (Table 6) landforms are described, hazards affecting each polygon are identified, their frequencies estimated, and mitigation measures for approvable developments are described.

8.0 Recommendations

- 1) Adopt the revised Yale Terrain Hazard map as a basis for hazard management within Yale OCP. Refer to Table 6 for details for each polygon. To assess management responses for various types of proposed development within each polygon follow Cave (1993).
- 2) The Fraser River FCL bylaw at Yale should be reviewed. Anecdotal observations on flood levels in 1948 (the 200-year flood; NHC 2008) should be sought, and the existing FCL revised accordingly, if required. Hydraulic analysis of flood level at Yale could be challenging as the site is at the mouth of the Fraser Canyon where flows are severely constricted by Lady Franklin Rock. FRVD may wish to seek funding from the Province for help in revising the FCL.
- 3) On the basis of apparent lack of postglacial catastrophic landslide activity from Spirit Caves cliffs, the areas downslope (Polygons 9-15) are considered to be potentially affected by very low ($<1/10,000$ per annum) catastrophic landslide hazard. However, this hazard estimate is uncertain. Since much of the Yale OCP is in the shadow of this potential catastrophic landslide, any future development proposals that involve changes in zoning or require subdivision, thereby allowing an increase in population density, must be required to conduct a detailed assessment of this hazard and the potential risks.
- 4) The OCP area below the Graveyard Creek landslide (Polygon 3) should be considered subject to very low ($1/2500$ - $1/10,000$ per annum) catastrophic landslide hazard until proven otherwise by more detailed assessment. Since the south end of Yale OCP is in the shadow of this potential catastrophic landslide, any future development proposals that involve changes in zoning or require subdivision, thereby allowing an increase in population density, must be required to conduct a detailed assessment of this hazard and the potential risks.
- 5) Request from MoF that TSA reports for Blocks YA202 & YA204 make specific reference to the Graveyard Creek landslide, confirm that surficial materials mapped are indeed till, and that the authors provide a more specific comment about the potential for logging related instabilities affecting residential areas downslope (Polygon 3). The TSA should acknowledge that there is a much lower tolerance for landslides affecting private property and residential areas (APEG 2008) than for those affecting non-human resources.
- 6) Request from MoF that the TSA reports for blocks YA106 and YA203 comment on the potential for post logging landslides impacting Yale Creek (Polygon 14), causing debris floods affecting Yale Creek debris terraces (Polygon 16), Yale Creek fan (Polygon 15), and Yale Creek paraglacial fan (Polygon 13). The TSA should acknowledge that there is a much lower tolerance for landslides and associated

phenomenon affecting private property and residential areas (APEG 2008) than for those affecting non-human resources.

- 7) Request from MoF that the road upgrade plan for YA1000 FSR, section from stations 2+561 to 3+193 m be assessed and developed by geotechnical specialist, as recommended by Madrone (2008). Specialist should be made aware of potential for cutslope instability extending up to 40-m above road bench.
- 8) Notify INAC and the local band office that the ring dyke surrounding the reserve is not built to a known standard and that they may be vulnerable to floods, ice jam floods and/or debris floods on Yale Creek and Fraser River floods.

Table 6. Terrain Polygon description, map label, hazard assessment, and required mitigation for approvable development. Assess management response according to Cave (1993). For Map label description see Map Legend; Qualitative frequency categories see Table 1. Hazard labels: FR, Fraser River; YC, Yale Creek; GC, Graveyard Creek landslide; SCC, Spirit Cave Cliffs; SCS, Spirit Caves steepland; ES, escarpment slope; OS, open slope; US, upland stream.

Poly.	Landform description	Map Label	Freq.	Hazard	Mitigation
1	Fraser River active channel within natural boundary.	SH: Fl (F ^A p)	VH	FR flood	No residential development permitted.
2	Steep escarpment slopes, <50-m tall, in Quaternary deposits and minor rock. Affected by Fraser River flooding and escarpment slides.	SH: Fl, Ds, Dss, Ls (F ^G s)	VH M VL VL	FR flood ES slide SCC landslide GC landslide	Infill development must consider Fraser River flood hazard, escarpment slope stability assessment. No zoning changes or subdivision until GC and SCC landslide assessment are completed.
3	Toe of Graveyard/All Hallows slope area. Irregular to benched rock with discontinuous veneer of colluvium from west slopes. Affected by Graveyard Creek landslide, Graveyard and All Hallows Creek flood and debris flows.	SH: Fl, Dfl, Df, Ls (Rak)	H H VL	US flood US debris flow GC landslide	Infill development must consider geotechnical study for floods and debris flow from Graveyard, All Hallows and unnamed creeks. No zoning changes or subdivision until GC landslide assessment is complete.
4	Benchland of Fraser River formed in gravelly Quaternary deposits. Irregular 10-50% sloping surface.	PH: Ls (F ^G b)	VL	SCC landslide	For infill development, no assessment required. No zoning changes or subdivision until SCC landslide assessment is complete.
4a	Subunit of polygon 4, subject to potential rolling rock and slide from escarpment slope above.	PH: Rf, Ds, Dss, Ls (F ^G b)	M M VL	ES rockfall OS slide SCC landslide	Infill development must consider upslope hazard assessment for areas within 30-m of toe of slope. No zoning changes or subdivision until SCC landslide assessment is complete.
4b	Subunit of polygon 4, subject to potential slumping along escarpment slope.	PH: Ds, Dss, Ls (F ^G b)	M VL	ES slide SCC landslide	Infill development must consider slope stability assessment for areas within 30-m of escarpment crest. No zoning changes or subdivision until SCC landslide assessment is complete.

Table 6, continued. Terrain Polygon description, map label, hazard assessment, and required mitigation for approvable development. Assess management response according to Cave (1993). For Map label description see Map Legend; Qualitative frequency categories see Table 1. Hazard labels: FR, Fraser River; YC, Yale Creek; GC, Graveyard Creek landslide; SCC, Spirit Cave Cliffs; SCS, Spirit Caves steep land; ES, escarpment slope; OS, open slope; US, upland stream.

Poly.	Landform description	Map label	Freq.	Hazard	Mitigation
5	Bedrock hillslope, 50-70% slopes. Rockfall from small (<10 m) bluffs with local impact.	PH: Rf, Ds (Rk, Cv)	H M	SCS rockfall OS slide	Infill development must consider slope stability and rockfall assessment.
6	Steep escarpment slopes, <50-m long, in glacial outwash deposits.	PH: Rf, Ds, Dss (F ^G s)	L M	ES rockfall ES slide	Infill development must consider slope stability and rockfall assessment.
7	Quarry in glacial outwash deposit. Affected by rockfall from Spirit Caves steep land.	PH: Rf, Dss (F ^G b)	M L	SCS rockfall ES slump	Infill development must consider slope stability and rockfall assessment.
8	Spirit Caves steep land, 70-80% slopes underlain by rock and discontinuous talus veneer. Possible shallow surface slides.	SH: Rf, Ds (Rs, Cvb)	VH M	SCS rockfall OS slide	Infill development must consider slope stability and rockfall assessment.
9	Moderate to moderately steep slopes in glaciofluvial outwash terrace.	PH: Rf, Dss, Ls (F ^G s)	L M VL	SCS rockfall ES slide SCC landslide	Infill development must consider slope stability and rockfall assessment. No zoning changes or subdivision until SCC landslide assessment is completed.
10	Steep escarpment slopes, 50-100 m long, in glacial outwash deposits.	PH: Rf, Ds, Dss, Ls (F ^G s)	M M VL	ES rockfall ES slide, slump SCC landslide	Infill development must consider slope stability and rockfall assessment. No zoning changes or subdivision until SCC landslide assessment is completed.
11	Glacial outwash terrace surface, smooth gentle slope. Potentially affected by rockfall from Spirit Caves steep land and cliff.	PH: Rf, Ls (F ^G b)	M VL	SCS rockfall SCC landslide	Infill development must consider rockfall assessment. No zoning changes or subdivision until SCC landslide assessment is completed.
12	Spirit Caves steep land, 70-80% slopes underlain by rock and discontinuous talus veneer. Area contains Spirit Caves cliff. Affected by rockfall from cliffs and open slope slides.	SH: Rf, Ds, Ls (Rs, Cvb)	H M VL	SCS rockfall OS slide SCC landslide	Infill development must consider slope stability and rockfall assessment. No zoning changes or subdivision until SCC landslide assessment is completed.

Table 6, continued. Terrain Polygon description, map label, hazard assessment, and required mitigation for approvable development. Assess management response according to Cave (1993). For Map label description see Map Legend; Qualitative frequency categories see Table 1. Hazard labels: FR, Fraser River; YC, Yale Creek; GC, Graveyard Creek landslide; SCC, Spirit Cave Cliffs; SCS, Spirit Caves steepland; ES, escarpment slope; OS, open slope; US, upland stream.

Poly.	Landform description	Map Label	Freq.	Hazard	Management
13	Yale Creek paraglacial alluvial fan. Relict deposit, raised 15-25 m above level of Yale Creek.	PH: Ls (FC ^{1b})	VL	SCC landslide	For infill development, no assessment required. No zoning changes or subdivision until SCC landslide assessment is complete.
13a	Subunit of polygon 13, subject to potential rolling rock from slope above.	PH: Rf, Ds, Dss, Ls (FC ^{1b})	M M VL	ES rockfall OS slide SCC landslide	Infill development must consider upslope hazard assessment for areas within 30-m of toe of slope. No zoning changes or subdivision until SCC landslide assessment is complete.
13b	Subunit of polygon 13, subject to potential slumping along escarpment slope.	PH: Ds, Dss, Ls (FC ^{1b})	M VL	ES slide SCC landslide	Infill development must consider slope stability assessment for areas within 30-m of escarpment crest. No zoning changes or subdivision until SCC landslide assessment is complete.
14	Yale Creek active channel and steep, confining sidewall slopes.	SH: Rf, Ds, Fl, Dfl, Df, Ls (Rs, FC ^{1s})	VH VH VH H VL	ES rockfall ES slide YC floods YC debris flow SCC landslide	Infill development must consider escarpment slides and rockfall, and Yale Creek flood and debris flow assessments. No zoning changes or subdivision until SCC landslide assessment is complete.
15	Yale Creek active alluvial fan. Occupied by Yale Town I.R. 1. Yale Town is protected by an adhoc berm. The degree of protection is uncertain.	SH: Dfl, Df, Fl, Ls (F ^{Af})	H M H VL	YC floods YC debris flow FR floods SCC landslide	Infill development must consider Yale Creek water and debris flood/flow, and Fraser River flood assessment. No zoning changes or subdivision until SCC landslide assessment is complete.

Table 6, continued. Terrain Polygon description, map label, hazard assessment, and required mitigation for approvable development. Assess management response according to Cave (1993). For Map label description see Map Legend; Qualitative frequency categories see Table 1. Hazard labels: FR, Fraser River; YC, Yale Creek; GC, Graveyard Creek landslide; SCC, Spirit Cave Cliffs; SCS, Spirit Caves steep land; ES, escarpment slope; OS, open slope; US, upland stream.

Poly.	Landform description	Map Label	Freq.	Hazard	Management
16	Bouldery debris terraces inset with Yale Creek paraglacial alluvial fan. Surfaces 5-10 m above creek level. Affected by debris floods on Yale Creek. Bridges could block debris and trigger avulsions. Road and rail alignments could channel and/or pond water and debris.	PH: Dfl, Df (FCt)	VL M	SCC landslide YC debris flood	Infill development must consider Yale Creek water and debris flood/flow assessment. No zoning changes or subdivision until SCC landslide assessment is complete.
17	Mary Anne Creek alluvial fan. Affected by water and debris floods. Terrain within 30-m of base of slope may be affected by rockfall.	SH: Fl, Df, Dfl, Rf (F ^A f)	VH H M	MC flood MC debris flow Rockfall	Infill development must consider Mary Anne Creek flood and debris flow assessment. Areas within 30-m of toe of steep land slopes requires rockfall assessment.
18	Steep land, 70-80% slopes underlain by rock and discontinuous talus veneer. Affected by rockfall and open slope slides.	SH: Rf, Ds (Rs, Cv)	H M	Rockfall OS slide	Infill development must consider rockfall and open slope slide hazard assessment.
19	Yale Tunnel Wall. Road and railway corridors at toe of cliffs. Rock cuts increase rockfall hazard. Area south of railway affected by Fraser River floods.	SH: Rf, Fl (Rs, Cv)	VH H	Rockfall FR floods	No permanent habitable buildings allowed.

9.0 Acknowledgements

I would like to thank Bob Gerath for promoting the services of Cordilleran Geoscience; Mike Rousseau (Antiquus) for introducing me to the Yale area; Chris Basil (Coast Mountain Geological) for access to detailed topographic maps and unpublished drill core data for South Yale blockfield; Greg Brooks (GSC) for constructive criticism of an unpublished manuscript on the South Yale blockfield; and Terry Rollerson (Golder Associates) for numerous discussions about Graveyard Creek landslide. All have added greatly to this report, however all conclusions are the responsibility of Cordilleran Geoscience

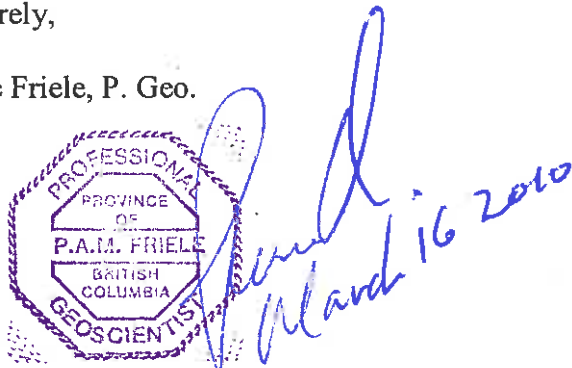
10.0 Closure

This report was prepared for use by Fraser Valley Regional District, including distribution as required for purposes for which the report was commissioned. The work has been carried out in accordance with generally accepted geoscience practice. Judgment has been applied in developing the conclusions stated herein. No other warranty is made, either expressed or implied to our clients, third parties, and any regulatory agencies affected by the conclusions.

Should you have any questions please call.

Sincerely,

Pierre Friele, P. Geo.

A purple ink stamp of a Professional Geoscientist. The stamp is circular with a scalloped edge. Inside the circle, the text reads: "PROFESSIONAL", "PROVINCE OF", "P.A.M. FRIELE", "BRITISH COLUMBIA", and "GEOSCIENTIST". A handwritten signature in blue ink is written over the stamp, and the date "March 16 2010" is written in blue ink to the right of the stamp.

Professional Geoscientist

11.0 References

- Antiquus, 2008. Archaeological impact assessment for a proposed gravel quarry main access road and service yard within the south Yale site (DjRi 7), Yale, BC. Archaeology Branch Permit No. 2003-0158. For Yale First Nation, Hope, B.C., and Lehigh Northwest Materials Ltd., Vancouver, BC.
- APEGBC, 2006. Guidelines for legislated landslide assessments for proposed residential development in British Columbia. APEGBC, Burnaby, BC.
- Bell, A. 1980. Terrain mapping and regional slope stability analyses in the Fraser Canyon, British Columbia. Unpublished M.Sc. thesis, University of British Columbia, Vancouver.
- Blair, T. C., and McPherson, J. G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *Journal of Sedimentary Research* A64: 450-489.
- BGC 1993/1994 Proposed site development, Yale, BC. Letters to Mr Raymond Hatch, March 16, 1993 & February 9, 1994.
- Borden, C., 1961. The Fraser River archaeology project, progress report. National Museum of Canada Anthropology papers.
- Borden, C., 1965. Radiocarbon and Geological Dating of the Lower Fraser Canyon Archaeological Sequence. *Proceedings of the sixth International Congress on Radiocarbon and Tritium Dating*. Pullman.
- Borden, C., 1968. A Late Pleistocene Pebble Tool Industry of Southwestern British Columbia. Pp. 55-69, in *Early Man in Western North America*. C. Irwin-Williams ed. Eastern New Mexico University Contributions in Anthropology 1(4).
- Cave, P. 1993. Hazard acceptability thresholds for development approvals by local government, British Columbia. British Columbia Geological Survey Branch, Open File 1992-15.
- Canada Census 2006. <http://www12.statcan.gc.ca/census-recensement/index-eng.cfm>
- Church, M. and Ryder, J.M., 1972. Paraglacial sedimentation: A consideration of fluvial processes conditioned by glaciation. *Geological Society of America Bulletin*, 83: 3059-3072.
- Clague, J. J., Mathewes, R. W., Guilbault, J. P., Hutchinson, I. and Ricketts, B. D. 1997. Pre-Younger Dryas resurgence of the southwestern margin of the cordilleran ice sheet, British Columbia, Canada. *Boreas* 26:261-278.
- Corominas, J., 1996. The angle of reach as a mobility index for small and large landslides. *Canadian Geotechnical Journal*, 33: 260-271.
- DeScalley, F., Slaymaker, O. and Owens, I. 2001. Morphometric controls and basin response in the Cascade Mountains. *Geographiska Analer* 3:117-130.
- Evans, S.G., and Hungr, O., 1993. The assessment of rockfall hazards at the base of talus slopes. *Canadian Geotechnical Journal*, 30: 620-636.
- Friele, P.A. 2003. The South Yale Ridge landslide and its implications for human settlement of the lower Fraser Canyon, BC. In Program and extended abstracts, International Consortium of Landslides 2nd Annual General Meeting/BOR. – Special Symposium, Vancouver, BC.

- Friele, P.A. and Clague, J.J. 2002. Readvance of glaciers in the British Columbia Coast Mountains at the end of the last glaciation. *Quaternary International*, 87:45-58.
- Friele, P.A. and Clague, J.J. 2005. Multifaceted hazard assessment of Cheekye fan, a large debris flow fan in southwestern British Columbia. Chapter 26 (pgs 659-683) in Jakob, M. and Hungr, O. (eds) *Debris Flow Hazards and Related Phenomenon*. Springer-Praxis, Heidelberg.
- Golder 2008. Geotechnical and natural hazard assessment, Interior to Lower Mainland transmission project. Appendix E in Application for an Environmental Assessment certificate, Interior to lower mainland transmission project, BC Environmental Assessment Office, Victoria, BC.
- Guthrie, R.H. and Evans, S.G., 2007. Work, persistence, and formative events: The geomorphic impact of landslides. *Geomorphology*, 88: 266–275.
- Hallet, D. J., Hills, L. V. and Clague, J. J. 1997. New accelerator mass spectrometry radiocarbon ages for the Mazama tephra layer from Kootenay National Park, British Columbia, Canada. *Canadian Journal of Earth Sciences* 34:1202-1209.
- Haley, S. 1996. The Pasika Complex revisited. In *Early Human Occupation in British Columbia*. Edited by Roy L. Carlson and Luke Dalla Bona. Pp. 51-64. UBC Press, Vancouver.
- Harp, E.L., Jibson, R.W., Kayen, R.E., Keefer, D., Sherrod, B.L., Carver, G.A., Collins, B.D., Moss, R.E., and Sitar, N., 2003. Landslides and liquefaction triggered by the M 7.9 Denali Fault earthquake of 3 November 2002. *GSA Today*, 13(8): 4–10
- Irvine, M. 1973. Report on Salvage Excavations at the South Yale Site (DjRi 7), 1973. Unpublished report on file, Archaeology Lab, Dept. of Anthropology and Sociology, University of BC, Vancouver.
- Jakob, M., and Bovis, M.J., 1996. Morphometric and geotechnical controls of debris flow activity, southern Coast Mountains, British Columbia, Canada. *Z. Geomorph. N.F., Supple.-Bd*, 104:13-26.
- Jakob, M. and Lambert, S. 2007. Effects of climate change on the occurrence of landslides in coastal southwestern British Columbia. *Water Resources Research*. In review.
- James, T.S., Hutchinson, I. & Clague, J.J. 2002: Improved relative sea-level histories for Victoria and Vancouver, British Columbia, from isolation-basin coring. Geological Survey of Canada, Current Research, 2002-A16.
- Jones, A., 2002: Avalanche run-out prediction for short slopes. M.S. thesis, University of Calgary, 125 pp.
- Keefer, D.K., 1984, Landslides caused by earthquakes: *Geological Society of America Bulletin*, v. 95, p. 406-421.
- McNeely, R., and Clague, J.J., 1996. Database of Selected British Columbia Radiocarbon Dates. GSC Open File 3259.
- Mitchell, D. M. and Pokotylo, D. L., 1996. Early Period components at the Milliken site. In *Early Human Occupation in British Columbia*. UBC Press, Vancouver.
- MoE, 1999. Terrain stability mapping, Landslides, hazards, consequences and risks, Ministry of the Environment, Lands and Parks, Victoria, BC, Canada.
- Monger, J. W. H. 1989. Geology, Hope, British Columbia; Geological Survey of Canada, map 41-1989, sheet 1, scale 1:250 000.

- Monger, J.W.H., and Journeay, J.M. 1994. Guide to the geology and tectonic evolution of the southern Coast Mountains. Geological Survey of Canada, Open File 2490.
- Monger, J. W. H. and Price, R. A., 2000. A transect of the Southern Canadian Cordillera from Vancouver to Calgary, Geological Survey of Canada, Open File #3902, 168p.
- NHC 2008. Comprehensive review of Fraser River at Hope flood hydrology and flows scoping study – final report. For BC Ministry of Environment, Victoria, BC.
http://www.env.gov.bc.ca/wsd/public_safety/flood/pdfs_word/review_fraser_flood_flows_hope.pdf
- Pacific Hydrology Consultants Ltd. 1981. Well construction and testing at Yale, for the Yale water system. Reprt for Willis, Cunliffe, Tait & Company Ltd, Chilliwack, BC.
- Paterson, T.W., 1979. Encyclopedia of ghost Towns and Mining Camps of BC, V1. Stagecoach Press Co. Ltd., Langley, BC.
- Peckover, F.L., and Kerr, J.W.G., 1977. Treatment and maintenance of rock slopes on transportation routes. Canadian Geotechnical Journal, 14(4): 487-507.
- QCD 2008. Ancient rockslide and nearby slope hazards, All Hollows Creek area, Yale, BC. Report to Dave Bennet and Rick McDermid , FVRD, April 18, 2008.
- Septer, D. 2007. Flooding and Landslide Events Southern British Columbia 1808-2006. For BC Ministry of Environment, Victoria, BC.
http://www.env.gov.bc.ca/wsd/public_safety/flood/pdfs_word/floods_landslides_south.pdf
- Scheidegger, A. 1973. On the prediction of reach and velocity of catastrophic landslides. Rock Mechanics 5, 231-236.
- Savigny, W., and Clague, J.J., 1992. Technical Tour No. 2: Fraser valley and Fraser Canyon Areas. In Proceeding of GeoHazards '92, *edited by* Byrne, P., Clague, J.J., Gerath, R.F., Hungr, O., Luternauer, J., Naesgaard, E., Savigny, K.W., and Skermer, N. Geotechnique and Natural Hazards, Technical Tours Guidebook, May 7, 1992. The Canadian Geotechnical Society and The Vancouver Geotechnical Society.
- Swondell, D., 1973. Surficial Geology of the South Yale site, BC. Report on File, Thurber Engineering Ltd., Victoria, BC.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J. and Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. Radiocarbon, **40**: 1041-1083.
- Thurber Engineering 1987. Overview of geological hazards in the Yale-Dogwood Valley areas. Report to Peter Cave, Regional District of Fraser Cheam (now FVRD), September 22, 1997.
- Thurber Consultants Ltd.,1990. Yale South Slope Stability Assesment, Yale, BC. Letter to Dr P. Cave, Regional District of Fraser-Cheam. January 4, 1990.
- Wilford, D.J., Sakals, M.E., and Innes, J.L., 2005. Forest Management on Fans – hydrogeomorphic hazards and general prescriptions. Land Management Handbook 57, Ministry of Forests, Victoria.

Annotated Photos

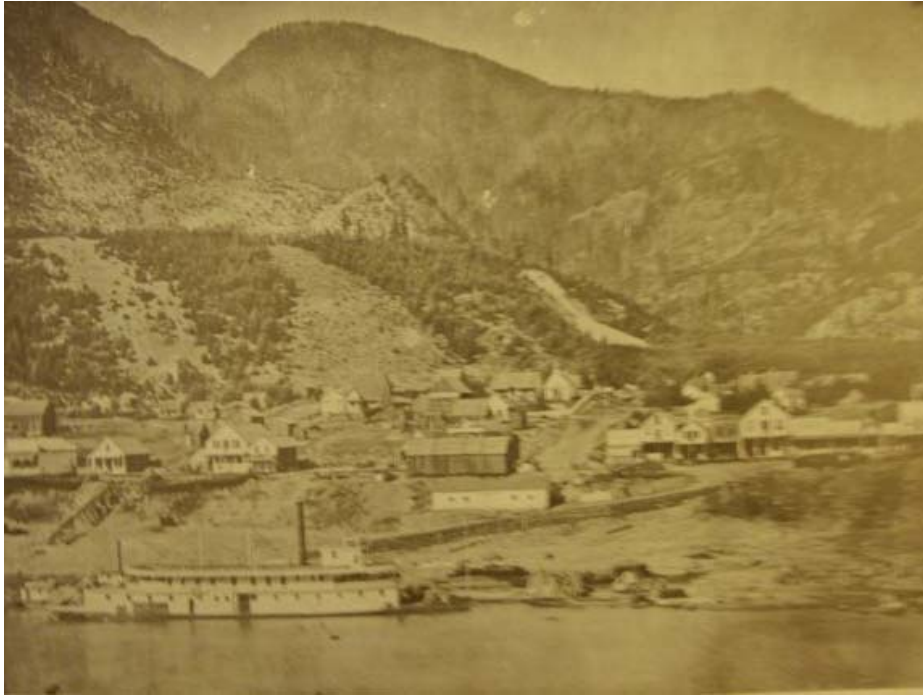


Photo 1. Historic photo of Yale. Note the 160 m elevation terrace behind the town. The white area on the right (east) of the terrace escarpment is a slide scar. The cause of the failure is not known. Note the building on the foreshore below the level of Front Street.



Photo 2. View towards Yale from south of town on the Trans Canada Highway showing the Spirit Caves cliffs that loom above the town. These present a rockfall hazard.



Photo 3. Cutbank on Trans Canada Highway showing 3-5 m diameter gneiss boulders within gravel matrix.



Photo 4. Cutbank in outwash terrace showing 1-2 m diameter gneiss blocks within gravel matrix.



Photo 5. Toe of outwash terrace escarpment showing 10-m diameter block partially imbedded in gravel matrix.



Photo 6. View from CPR bridge down Yale Creek. Note ice blocks on right bank. This indicates a potential ice-jam hazard. The Church Road area of Yale Town IR 1 is considered vulnerable to ice jam flooding.



Photo 7. View up Fraser River from Yale Creek, looking into the Kuthlalth headscarp.