Preliminary stratigraphic and geotechnical investigations of the glaciolacustrine and loess deposits around the city of Whitehorse (NTS 105D/11), Yukon

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ABSTRACT

This paper presents the preliminary results of a study investigating the stratigraphy and basic geotechnical properties of the surficial geology deposits observed in the bluffs around the city of Whitehorse. A total of eleven sections were examined on both the east and west banks of the Yukon River. Representative stratigraphic units were analysed for grain size distribution; deposits ranged in size from silt and clay to coarse gravel. Most of the observed sediments represent the glaciolacustrine depositional environment of Glacial Lake Laberge with the exception of a loess unit exposed near the top of the sections. Consistency indices of seven silt and clay-rich samples collected in the bluffs surrounding Whitehorse indicate a low plasticity comparable with other Canadian loess units and the glaciolacustrine bluffs around Kamloops and in the Elk Valley of British Columbia. The soil unconfined compressive strength was estimated using a pocket penetrometer and the dry silt and clay-rich units were found to have strength estimates up to two orders of magnitude greater than the sand-rich units.

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INTRODUCTION

During the last glaciation, large glacier-dammed lakes formed during ice sheet advance and retreat phases (*e.g.,* Teller, 1987; Eyles and Clague, 1991; Bednarski, 2008). Several urban areas of Canada are built on the deposits left behind by these glacial lakes; examples of these developments can be found in Whitehorse (Bond *et al.*, 2005); Prince George (Tipper, 1971); Kamloops (Fulton, 1965); Kelowna (Paradis, 2009); Edmonton (Fredlund and Dahlman, 1971); Calgary (Osborn and Rajewicz, 1998); Regina (Mollard *et al.*, 1998); and Winnipeg (Matile, 2004). Glaciolacustrine deposits have commonly been associated with slope instability and geotechnical problems (*e.g.,* Evans, 2003). In Kamloops, glaciolacustrine deposits are prone to piping erosion and slope failures (Evans and Buchanan, 1976; Lum, 1979), while landsliding in glaciolacustrine sediments due to river undercutting and agricultural irrigation has long been affecting railway lines in the Thompson River Valley (Clague and Evans, 2003; Eshraghian *et al.*, 2007; and Bishop, 2008). Hungr *et al.* (2001) also noted the collapse of a glaciolacustrine bluff near Kelowna that resulted in a dry silt flow which blocked a nearby highway.

This study focuses on the surficial deposits of the area in and around the city of Whitehorse (Fig. 1), where silt bluffs associated with the glaciolacustrine deposits represent a distinct component of the city's landscape (Fig. 2). The objectives of this study were to describe the stratigraphy in the bluffs around the City of Whitehorse; to characterize the basic geotechnical soil properties of the various identified stratigraphic units; and to compare the results with previously published data from similar studies in other Canadian cities.

PHYSIOGRAPHY, CLIMATE AND BEDROCK GEOLOGY

The study area is part of the Yukon Southern Lakes Ecoregion (Smith *et al.*, 2004) and has a physiography characterized by rounded summits and broad valleys. The climate of the ecoregion is arid due to its location in the rain shadow of the St. Elias and Coast Mountains (Smith *et al.*, 2004). Monthly average temperature and precipitation for Whitehorse Airport are presented in Figure 3. The total precipitation for the year averages 267 mm water equivalent (Environment Canada, 2010). Whitehorse is situated within the sporadic discontinuous permafrost zone as defined by Heginbottom *et al.* (1995). Mougeot (1997 and 1998) highlights that the permafrost distribution around the city of Whitehorse is not well understood; however, at other locations in the Yukon where fine-grained sediment tends to be ice-rich, there can be significant impacts on slope stability. For example, Glacial Lake Laberge glaciolacustrine sediments, which contain ice-rich permafrost, occur beneath and adjacent to the Alaska Highway in the Takhini River Valley, 40-50 km west of Whitehorse in an area of active slumping (Burn, 1998; Huscroft *et al.*, 2004).

The bedrock geology underlying the Whitehorse area consists of Upper Triassic limestone to the east of the Yukon River, and mid-Cretaceous plutons to the west ranging in composition from granodiorite to diorite and tonalite (Hart and Radloff, 1990). To the south, outcrops of Pliocene Miles Canyon Basalt are exposed on the downstream side of the Yukon River dam and upstream at Miles Canyon (Hart and Villeneuve, 1999).

PREVIOUS WORK

GLACIAL LAKE LABERGE

The Whitehorse area was glaciated by the Cassiar lobe of the Cordilleran Ice Sheet. The accumulation zone for this lobe was largely to the south of Whitehorse in northern British Columbia. Ice-flow was directed northwestward and reached a minimum thickness of 1350 m in the Yukon River valley near Whitehorse (Bond, 2004). Deglaciation was punctuated with frontal standstills and possible re-advances, which resulted in the deposition of recessional moraines and larger areas of stagnation moraine. A significant standstill occurred near the north end of Lake Laberge that resulted in the damming of the Yukon River valley. The glacial lake, informally called Glacial Lake Laberge, reached elevations of 716 m (Horton, 2007), 88 m above the modern level (628 m) of Lake Laberge. In the past, the name Glacial Lake Champagne has been used to describe the glacial lake that deposited the sediments exposed in the bluffs around the city of Whitehorse (*e.g.,* Barnes, 1997; Mougeot, 1997 and 1998), but current usage of the term is now restricted to the glacial lake west of Champagne, Yukon that drained north via the Nordenskiold River divide (Bond, 2004). Glacial Lake Laberge expanded with the southward recession of the ice sheet. A standstill in the recession occurred at Whitehorse and resulted in deposition of the Chadburn Lake moraine complex (Chadburn phase; Bond, 2004). At that time, the glacial lake shoreline was at 705 m (Fig. 4; Horton, 2007). It is likely that much of the glaciolacustrine

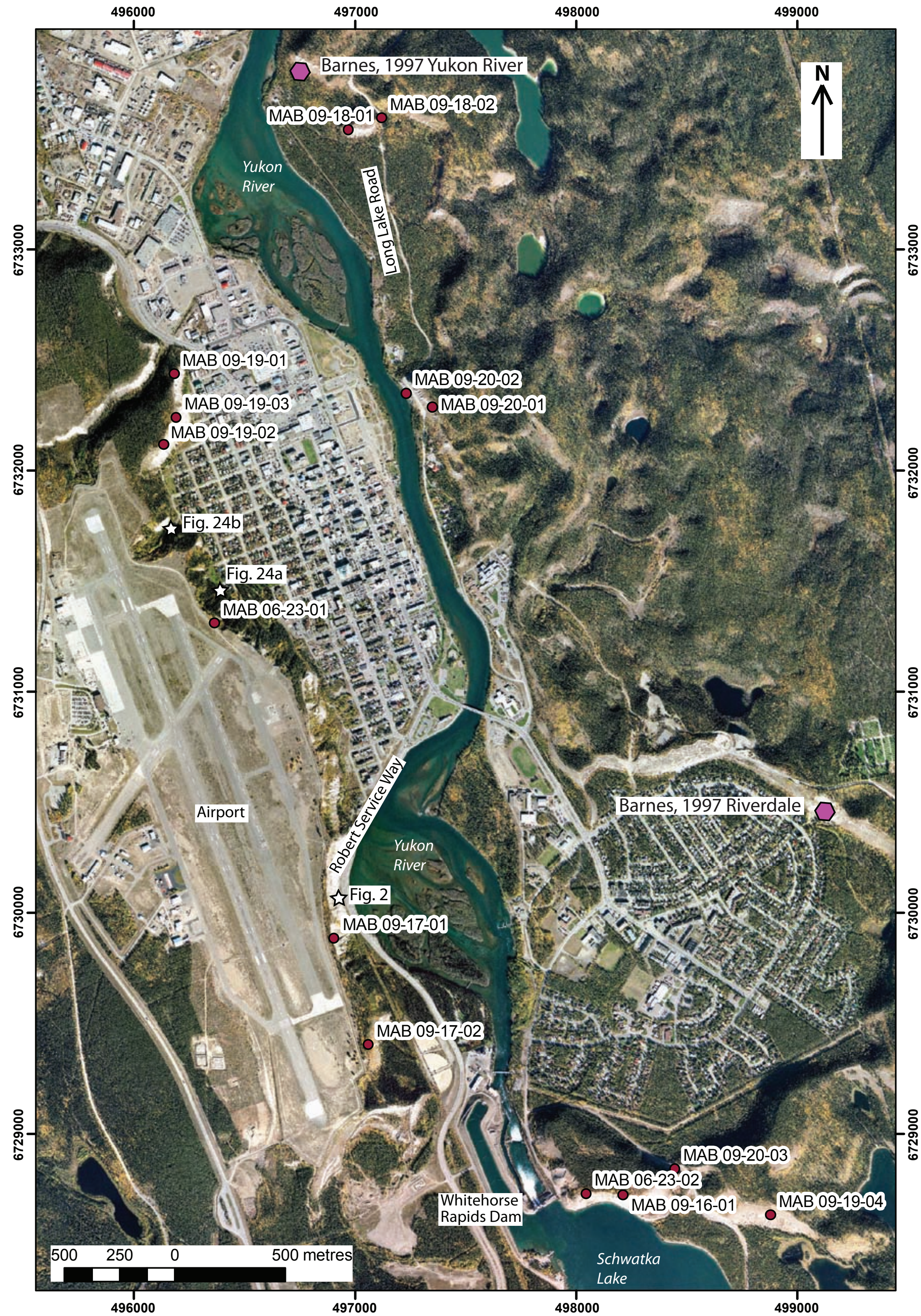


Figure 1. *Study area including the following locations:* ***1)*** *sections examined in this study;* ***2)*** *sections studied by previous authors; and* ***3)*** *photographic sites included in this report.*

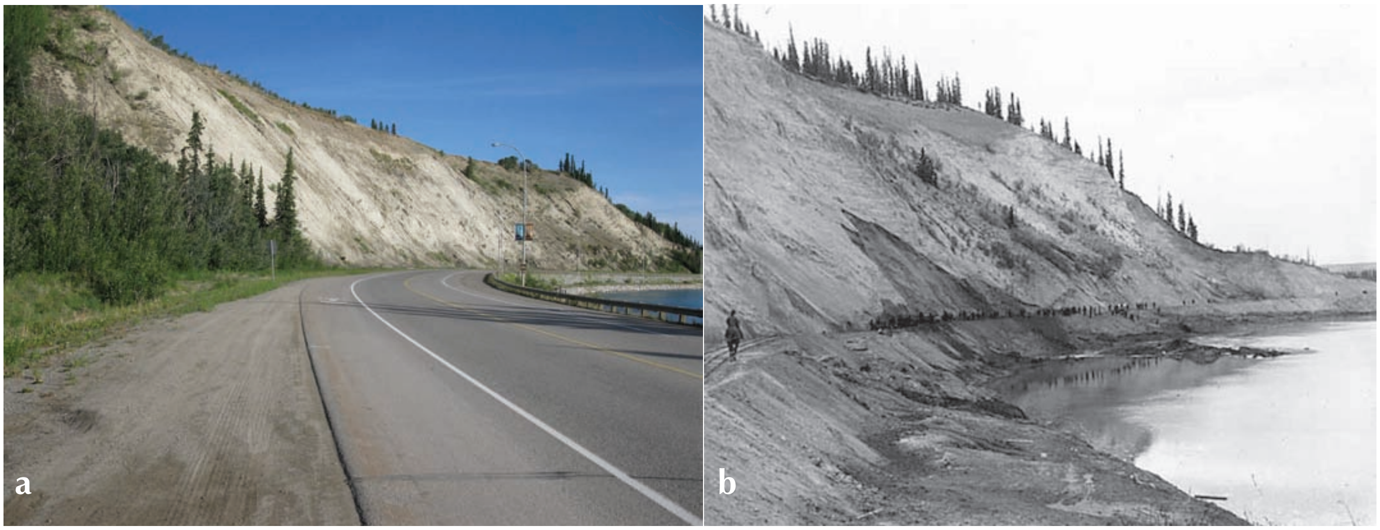


Figure 2. (a) *View of a silt bluff at the southern end of town along Robert Service Way, where the road is confined between the base of the bluff and the Yukon River;* ***(b)*** *photo taken at the same location, ca. 1900, where a minor landslide was being cleared from the railroad track (historical photo by H.C. Barley Fonds from the Yukon Archives, #5416).*

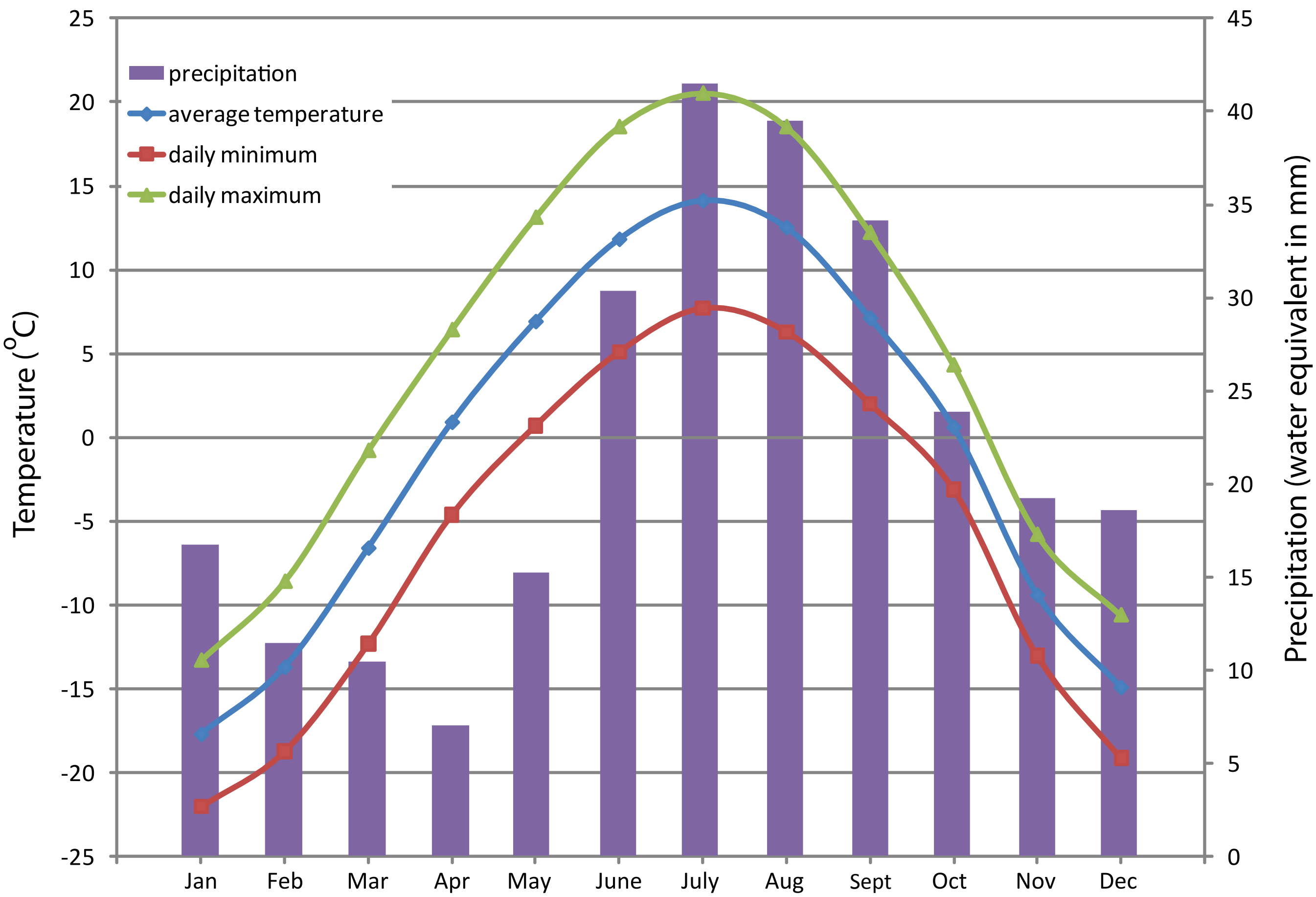


Figure 3. *Average temperature and precipitation recorded at the Whitehorse airport (data from Environment Canada, 2010).*

sedimentation in the Whitehorse area occurred at this time. With continued erosion of the outlet, the glacial lake became shallower and the southern shoreline began migrating northward. This regression continued through the Holocene, causing a drop in base-level for the Yukon River near Whitehorse (Wolfe *et al.*, 2011). The Yukon River has responded to this base-level fall by eroding into Late Wisconsin glaciogenic units and Pliocene basalts in the Yukon River valley bottom.

The glaciolacustrine sediments are well exposed in the city of Whitehorse. Much of the glaciolacustrine deposits on the eastern side of the valley are kettled, suggesting the glacial lake sediments were deposited supraglacially on stagnant ice (*e.g.,* Ward and Rutter, 2000). In contrast, the glaciolacustrine surface on the western side of the valley forms a plain without kettles (Fig. 5). This plain is capped by medium-grained fluvial sand that was likely deposited in a deltaic environment (shallow basin) as the glacial lake regressed northward (Bond, 2004). This sand unit is continuous northward and merges with the contemporary sandy delta at the south end of Lake Laberge. In the early Holocene, the sand cap was reworked into the Whitehorse dune field (Wolfe *et al.*, 2011).

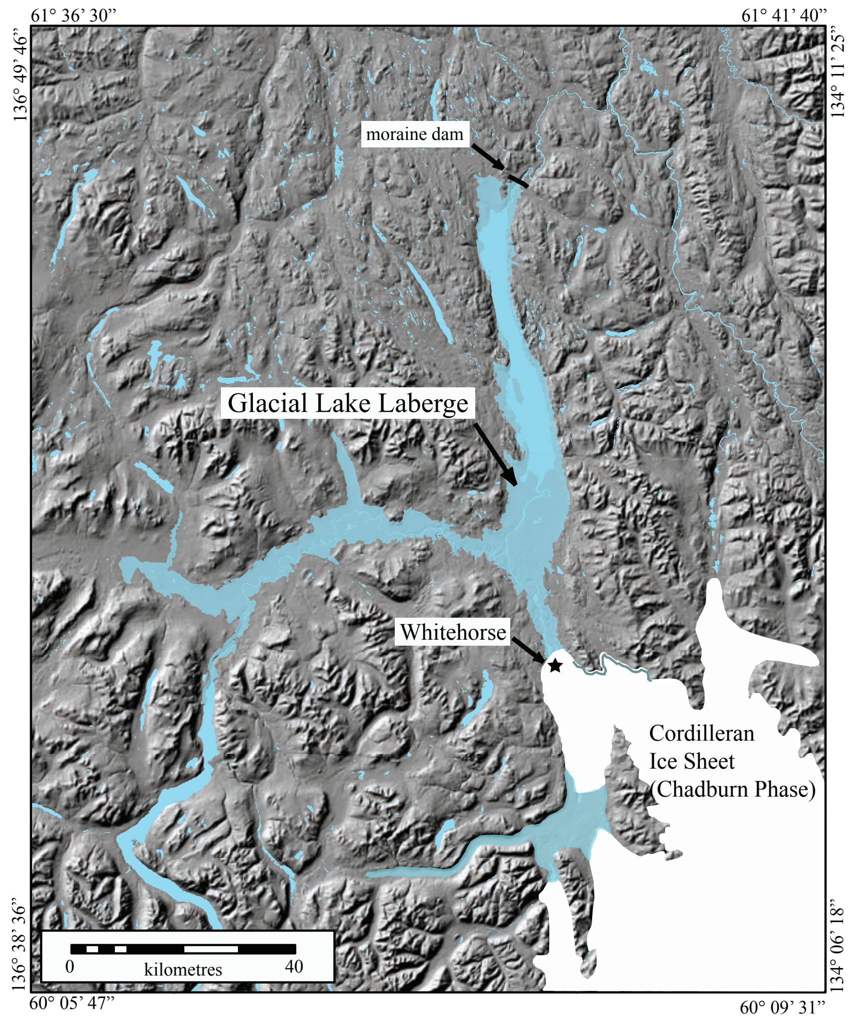


Figure 4. *Map of the Yukon River valley depicting Glacial Lake Laberge at its maximum extent (705 m a.s.l.).*

Figure 5. *A view to the west over Whitehorse showing the glaciolacustrine surfaces remnant from Glacial Lake Laberge. The hummocky and kettled terrain in the foreground is glaciolacustrine sediment that was deposited over stagnant ice and moraine. This is in contrast to the glaciolacustrine plain on the west side of the Yukon River (see airport).*

CURRENT INVESTIGATION

The sediments exposed in the bluffs were described at five main locations (including a total of 11 sections and 3 field stations where general observations were made) in and around the City of Whitehorse: Robert Service Way, Schwatka Lake, Downtown Whitehorse, Long Lake Road South, and Long Lake Road North (Fig. 1). The information observed at each section is summarized in geotechnical logs (Figs. 6 to 15) which include a stratigraphic column, a lithological description, and field estimates of the plasticity, water content, Unconfined Compressive Strength (UCS), and colour (Munsell).

OBSERVATIONS ON THE STRATIGRAPHY AND SEDIMENTOLOGY

The two main stratigraphic units observed are a horizontally laminated silt and clay (Figs. 9, 11, 12, 14, and 16a) and a fine to coarse sand that may or may not be horizontally laminated, cross-bedded or interbedded with silty-sand units (Figs. 6, 7, 8, 9, 10, 11, 13, 14, 16b and 16c). The silt and clay-rich unit exhibits rhythmic layering of light and dark lamination, which likely represents suspension settling; colour changes are due to varying silt and clay abundance (Smith and Ashley, 1985; Ashley, 2002). Convolute laminae in interbedded silt and fine sand units are observed at station MAB 09-16-01 (Figs. 6 and 16b). Convolute laminae have previously been reported in glaciolacustrine deposits and are interpreted to be the result of turbid underflow currents and subaqueous fan settings (*e.g.,* Ashley, 2002; Bennett *et al.*, 2000) which cause soft sediment deformation loading during slumping. Crossbeds and climbing ripples have been attributed to turbidity currents in glacial lakes by Shaw and Archer (1978). Rip-up clasts of silt and clay in a medium to coarse sand bed were observed at station MAB 09-16-01 (Figs. 6 and 16c), which are also characteristic of turbidity currents. Similar features were described by Barnes (1997) at his Riverdale section (Fig. 1).

A distinct unit comprising weak red (2.5YR 5/3) silt mixed with some fine sand was observed in the upper parts of sections MAB 09-16-01, MAB 09-19-01 and MAB 09-19-02 (Figs.1, 6, 10 and 11) and has been interpreted by Barnes (1997), Mougeot (1998) and Bond *et al.* (2005) as loess from reworked glaciolacustrine deposits. These aeolian deposits are commonly referred to as 'cliff-top deposits' (David, 1972) and are the result of wind eroding material in the sections and depositing it on top. A tephra layer and several buried organic horizons are associated with the loess layer (Fig. 17). Based on stratigraphic position, the tephra has been interpreted by Barnes (1997), Mougeot (1997) and Smith *et al.*, (2004) to be White River Ash, which has been dated at ~1150 years BP (Clague *et al.*, 1995). The observed buried organic horizons have also been recognized by Smith *et al.* (2004) as the remnants of large forest fires, but could also represent paleosols not necessarily associated with forest fires. This study represents the first time that 8 buried organic horizons are reported at a single location.

A series of stratigraphic units defined as gap-graded (bimodal), polymictic, well rounded pebble gravel with minor cobbles in a silt and clay matrix were observed only at station MAB 09-20-02 (Figs. 15 and 18). A possible depositional environment for these coarse units could be from melt-out of stranded ice in a lacustrine environment (Mougeot, 1998), resulting in the deposition of large clasts within a fine matrix, while still preserving the horizontal contacts above and below the unit. These units are bounded above and below by silt and clay-rich units that do not contain coarse fragments. These units are exposed just above the level of the Yukon River, and as such, represent the lowest topographic elevation exposure visited in this project; it is unclear however from this study if it also represents the lowest stratigraphic level.

GEOTECHNICAL CHARACTERISTICS

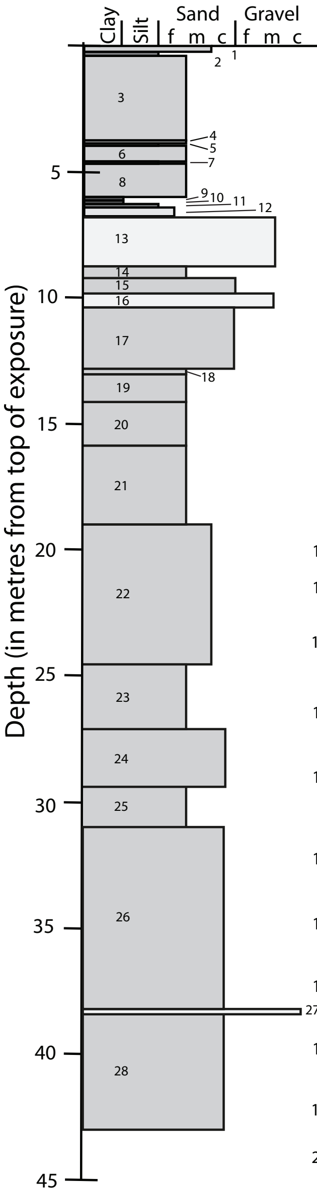
GRAIN SIZE DISTRIBUTION

The grain size distribution of sixteen samples was determined using a stack of ten sieves with openings varying in size from 37.5 mm (#1½) to 0.075 mm (#200). The samples were initially dried in an oven for 24 hours at 100°C after which the soil clumps were broken using a pestle and mortar before being put through the sieve stack. The grain size distribution of four samples containing more than 30% silt and clay was further analysed using a hydrometer, according to the method defined in ASTM (2007). The grain size distributions are presented in Figure 19, demonstrating a wide range of sediment grain sizes associated with the glaciolacustrine environment. The weak red (2.5YR 5/3) fine sand and silt of sample MAB 06-23-0-01 (Fig. 20a) is representative of the grain size distribution and appearance of loess from wind-reworked glaciolacustrine deposits. The clayey silt of sample MAB 09-17-02-01 (Fig. 20b) represents lacustrine deposition in calm water. The cross-bedded coarse to fine sand of sample MAB 09-17-01-03 likely represents underflow current deposition (Fig. 20c), whereas the coarse gravelly

Schwatka Lake section 1
MAB 09-16-01

UTM
0 498 212
6 728 722

Elevation: 755 m a.s.l.



	Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
1	medium to fine sand and silt, laminated	frictional	dry	<25	2.5Y 4/2	N/A	rooting zone for grass
2	silt, weak lamination	very low	damp	<25	5Y 4/2	MAB RV-01	
3	silty fine sand, massive, poorly graded	very low	damp	85	5Y 4/2	N/A	
4	clayey fine sand, poorly graded	low to medium	dry	85	2.5Y 5/3	N/A	
5	clayey and sandy silt, poorly graded	low	dry	79	5YR 2.5/1 organic	N/A	two organic and one tephra layers
6	silty fine sand, massive, poorly graded	frictional	dry	55	2.5Y 4/2	N/A	discontinuous reddish organic layer
7	clayley silt, organic-rich	medium	dry	82	10YR 2/1 (dark)	MAB RV-02	organic layer red colour 7.5YR 5/4
8	silty fine sand, weak lamination, poorly graded	very low	dry	84	2.5Y 4/2	MAB RV-03	small pockets of reddish soil
9	silty clay, massive	medium	dry	84	10YR 2/1	N/A	organics present
10	silty clay, massive	medium	dry	112	7.5YR 3/2	MAB RV-04	no organics present
11	clayey silt, massive	low	dry	235	2.5Y 4/3	N/A	discontinuous tephra
12	silty fine sand, laminated, poorly graded	frictional	dry	110	2.5Y 5/2	N/A	diffuse but continous tephra layer 5 cm at top
13	sandy cobbly gravel, coarsely bedded, well graded	frictional	dry	S3 - S4	N/A	MAB RV-05	polylithic rounded clast
14	silty clay and fine sand, interbedded, moderately well graded	clay layer medium to high	dry	clay: 390	clay: 2.5Y 5/2 tephra: 2.5Y 6/2	N/A	top 5.8 cm thick tephra; occasional cobble
15	fine to coarse sand, weak bedding of coaser fraction, poorly graded	frictional	damp	30	N/A	N/A	
16	sandy cobbly gravel, coarsely bedded, well graded	frictional	dry	S3	N/A	N/A	polylithic rounded clast
17	fine to coarse sand, laminated, poorly graded	frictional	damp	<25	N/A	N/A	
18	silty clay and fine sand, interbedded	clay: medium; sand: frictional	damp to moist	clay: 60 sand: <25	clay: 2.5Y 5/2 sand: 2.5Y 3/2	N/A	clay dried out as blocky peds
19	silty fine sand, cross-bedded	low	damp	105	2.5Y 5/2	N/A	
20	silty clayey fine sand, horizontally laminated, poorly graded	medium	dry	375	2.5Y 6/3	N/A	some convolute lamination
21	clayey silt and clayey silty fine sand, horizontally laminated, poorly graded	sand: medium; clay: medium to high	damp	<25	2.5Y 5/3	MAB RV-06	
22	fine to medium sand, cross-bedded, poorly graded	frictional	damp	30	2.5Y 6/2	N/A	
23	silty clay and fine sand, horizontally laminated, poorly graded	low to medium	damp	190	5Y 5/3	N/A	
24	silty fine to coarse sand, poorly graded	frictional	damp	40	N/A	N/A	clay rip-up clasts
25	clayey silty fine sand, horizontally laminated, poorly graded	medium	damp	190	2.5Y 5/2	N/A	
26	fine to coarse sand, horizontally laminated, poorly graded	frictional	damp	<25	N/A	N/A	
27	sandy cobbly gravel, weak layering, well graded	frictional	dry	S3-S4	N/A	N/A	rounded polylithic clast
28	fine to coarse sand, massive	frictional	dry	335	N/A	N/A	

Figure 6. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-16-01 (see Fig. 1 for location).*

sand of sample MAB 09-16-01-05 (Fig. 20d) is interpreted as the proximal part of a large turbidite. An overall fining-upward stratigraphic sequence is illustrated in Figure 20: coarse deposits at the bottom of the section, followed by a sandy unit, which is in turn overlain by a laminated silt and clay unit, and finally capped by a loess unit. This sediment package suggests that the glacier which dammed the valley became progressively more distal to the Whitehorse area.

PLASTICITY

The plasticity of selected soil samples was investigated by determining the liquid and plastic limits of the soil component passing through a sieve having openings of 0.425 mm (#40). The liquid limit (LL) corresponds to the water content at the point at which the remoulded soil starts behaving as a liquid, while the plastic limit (PL) corresponds to the water content at the point at which the soil stops behaving plastically. The plasticity index (PI) is defined as PI = LL- PL and represents the water content range over which the soil behaves plastically (Craig, 2007). The liquid limit was determined using a cone penetrometer, whereas the plastic limit was derived by rolling a wet soil sample into a thread on a frosted glass plate until it crumbled (see Smith, 2006 for details on the methodology).

The results of the seven tested Whitehorse-area samples are plotted on Figure 21 along with published test results from other glaciolacustrine and loess deposits from other areas in Canada. The Whitehorse samples exhibited a low plasticity behaviour that was similar to the range of values reported by Evans and Buchanan (1976) for samples from the Thompson River Valley, and the plasticity of Canadian loess deposits (Sweeney and Smalley, 1988). The low plasticity is attributed to the low clay content (<20% by weight) of the samples collected in this study, as well as those collected by Evans and Buchanan (1976). The high plasticity samples from Mollard *et al.* (1998), Eshraghian *et al.* (2007), and Bishop (2008), all contain 40-80% clay by weight.

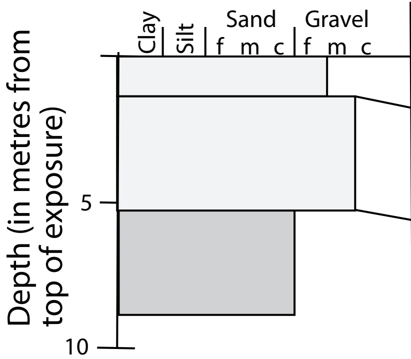
Another factor that can influence the plasticity is the clay mineralogy. Mougeot (1994) reported on the clay mineralogy of four samples collected in the Takhini River valley and at the confluence of the M'Clintock River and the Yukon River. X-ray diffraction (XRD) analyses demonstrate that the most common minerals were kaolinite (25-50%) and illite (40-50%), and lesser amounts of montmorillonite (0-20%) and chlorite (10-15%). Very few of the plasticity data from the literature presented in Figure 21 have accompanying clay mineralogy analyses. Two exceptions are the samples from the Elk Valley region, which are kaolinite and illite-dominated (George, 1986), and the sample from Regina, which contained up to 55% montmorillonite (Mollard *et al.*, 1998). The low montmorillonite content of the Whitehorse-area samples makes them more comparable to the Elk Valley samples.

SOIL STRENGTH

The Unconfined Compressive Strength (UCS) of the soil was estimated using a pocket penetrometer (model EI29-3729 by ELE). The pocket penetrometer is intended to test cohesive (silt and clay-rich) soils; in this study it provides a simple field estimate of frictional (sand-rich) soil strength. To account for the variability associated with the small area sampled during the test, an average of 5 measurements are reported in the geotechnical logs (Figs. 6 to 15). When weak soils (≤5 kPa) were encountered, an adapter foot was used to distribute the force over a larger area. The values listed next to each stratigraphic unit in Figures 6-15 demonstrate that a wide range of strength values was observed even within one section. Figure 22 illustrates that overall, the dry silt and clay-rich units had higher strength estimate values than the sand-rich units. Where a high strength value was observed for the sand-rich units, these results could be attributed to the presence of silt and/or clay cement, as recorded in the lithological description in Figures 6-15. This is consistent with the general expectation that a 'clean', non-cemented dry sand would not have significant cohesive strength. The relationship between soil strength and grain-size distribution may also be demonstrated by field observations whereby the silt and clay-rich units tend to be preferentially exposed in sub-vertical cliffs, while the sandier units tend to be covered in talus. The density of the gravel-rich units (Figs. 6 and 14) was estimated using the field assessment categories listed in Table 1. The observed density categories varied between loose (S2) to the boundary between compact and dense (S3-S4).

Schwatka Lake section 2
MAB 09-20-03

UTM
0 498 447
6 728 840
Elevation: 681 m a.s.l.

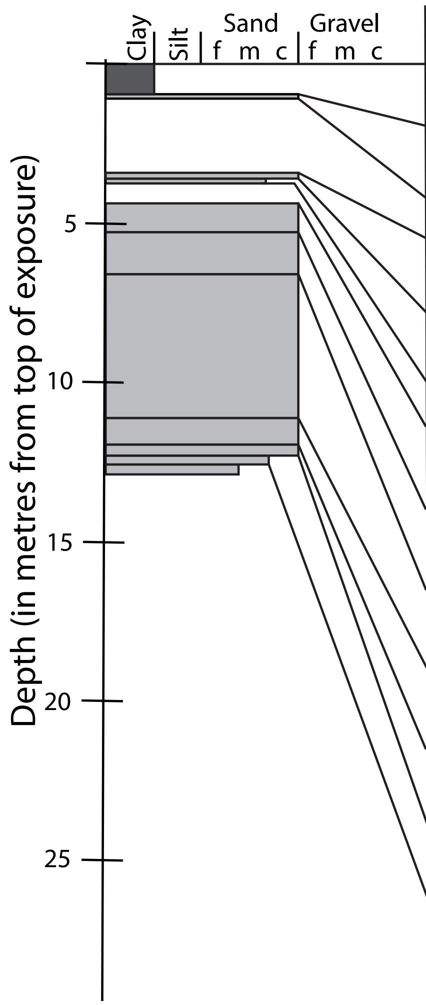


Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
interbedded fine to medium sand and fine gravel	frictional	damp	32	N/A	N/A	
interbedded fine sand with some silt, fine gravel and sandy medium gravel	frictional	gravel: damp sand: moist	17	N/A	N/A	polymictic rounded loose gravel
fine to coarse sand, horizontally laminated and minor cross-stratification	frictional	damp	13	N/A	N/A	

Figure 7. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-20-03 (see Fig. 1 for location).*

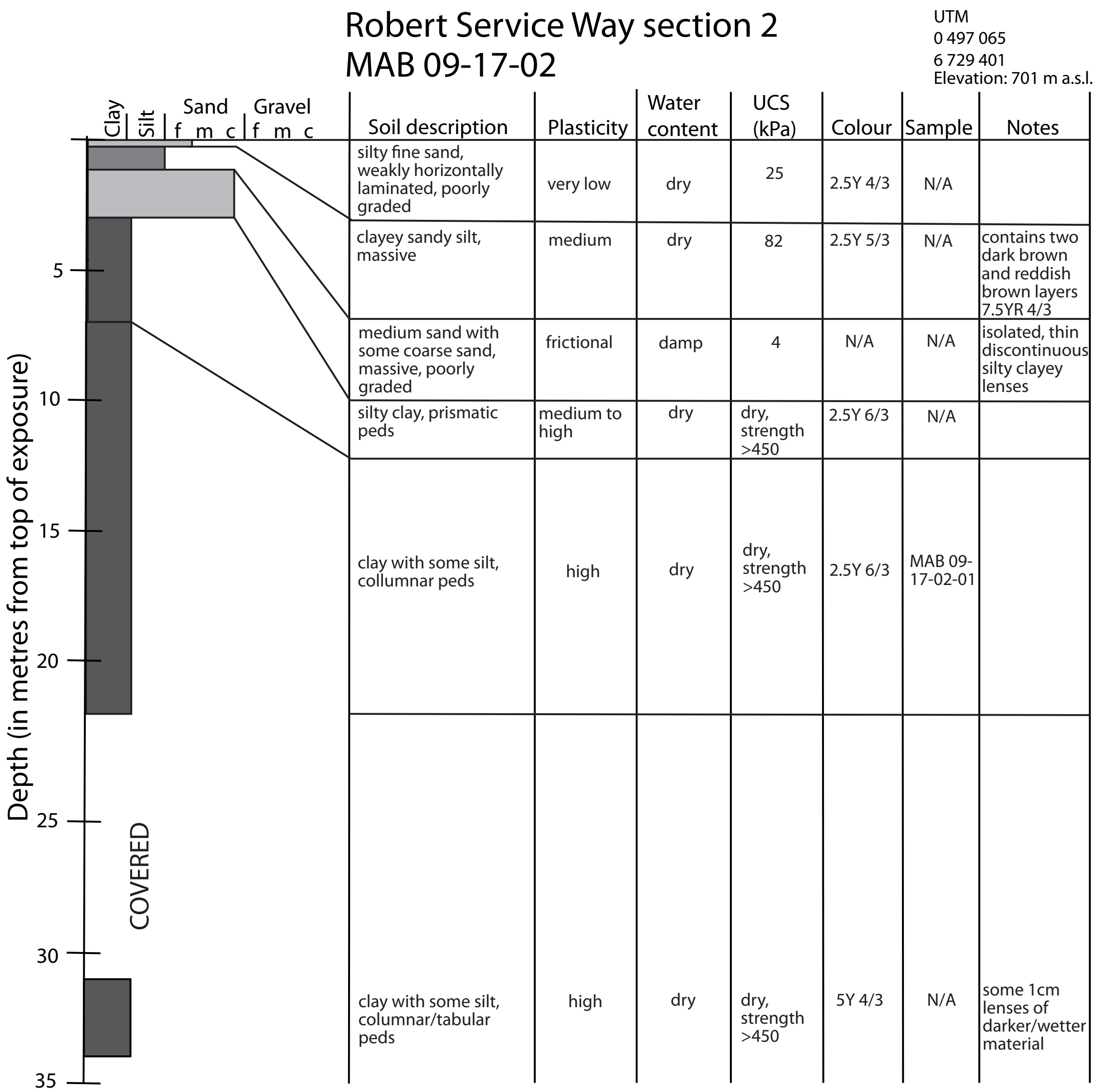
Robert Service Way section 1
MAB 09-17-01

UTM
0 496 906
6 729 884
Elevation: 674 m a.s.l.



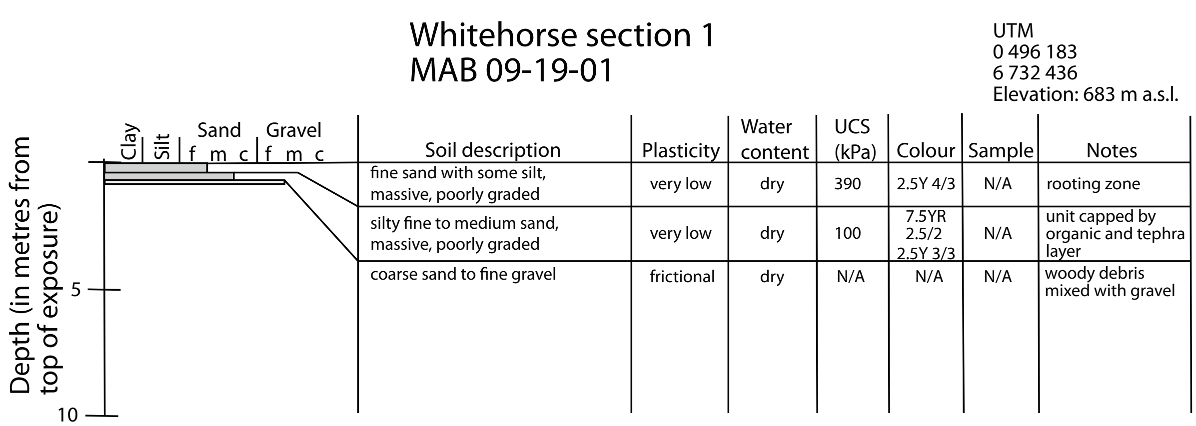
Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
silty clay, massive	high	wet	16	2.5Y 4/3	MAB 09-17-01-01	
medium to coarse sand, massive, poorly graded	frictional	moist	7	2.5Y 3/3	N/A	
COVERED						
coarse sand and some gravel, massive, poorly graded	frictional	damp	9	N/A	MAB 09-17-01-02	
silty fine to medium sand, horizontally laminated	frictional	damp	42	2.5Y 3/2	N/A	
COVERED						
medium to coarse sand, horizontally laminated, poorly graded	frictional	damp	26	N/A	N/A	
medium to coarse sand, dipping laminae, poorly graded	frictional	damp	11	N/A	N/A	
medium to coarse sand, horizontally laminated, poorly graded	frictional	damp	21	N/A	N/A	
medium to coarse sand, cross-bedded, poorly graded	frictional	damp	23	N/A	MAB 09-17-01-03	
coarse sand, cross-bedded, poorly graded	frictional	damp	22	N/A	N/A	
clayey fine to medium sand, massive, poorly graded	low to medium	dry	425	2.5Y 4/4	N/A	reddish layer present on either side
clayey fine sand, weak horizontal lamination, poorly graded	medium	dry	195	2.5Y 4/3	N/A	

Figure 8. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-17-01 (see Fig. 1 for location).*



Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
silty fine sand, weakly horizontally laminated, poorly graded	very low	dry	25	2.5Y 4/3	N/A	
clayey sandy silt, massive	medium	dry	82	2.5Y 5/3	N/A	contains two dark brown and reddish brown layers 7.5YR 4/3
medium sand with some coarse sand, massive, poorly graded	frictional	damp	4	N/A	N/A	isolated, thin discontinuous silty clayey lenses
silty clay, prismatic peds	medium to high	dry	dry, strength >450	2.5Y 6/3	N/A	
clay with some silt, collumnar peds	high	dry	dry, strength >450	2.5Y 6/3	MAB 09-17-02-01	
clay with some silt, columnar/tabular peds	high	dry	dry, strength >450	5Y 4/3	N/A	some 1cm lenses of darker/wetter material

Figure 9. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-17-02 (see Fig. 1 for location).*

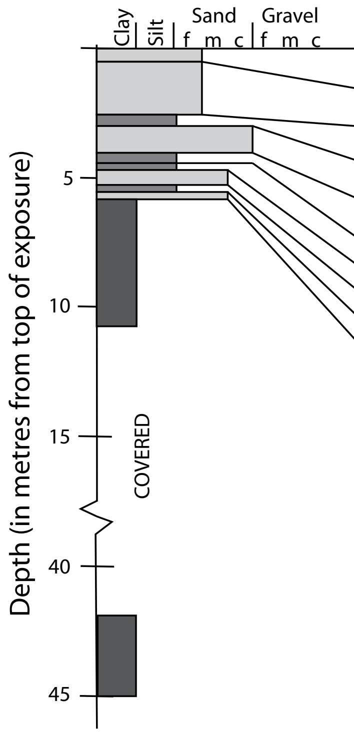


Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
fine sand with some silt, massive, poorly graded	very low	dry	390	2.5Y 4/3	N/A	rooting zone
silty fine to medium sand, massive, poorly graded	very low	dry	100	7.5YR 2.5/2 2.5Y 3/3	N/A	unit capped by organic and tephra layer
coarse sand to fine gravel	frictional	dry	N/A	N/A	N/A	woody debris mixed with gravel

Figure 10. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-19-01 (see Fig. 1 for location).*

Whitehorse sections 2 and 3
MAB 09-19-02 and MAB 09-19-03

UTM 0 496 135, 6 732 116, Elevation: 683 m a.s.l. | UTM 0 496 191, 6 732 239, Elevation: 683 m a.s.l.

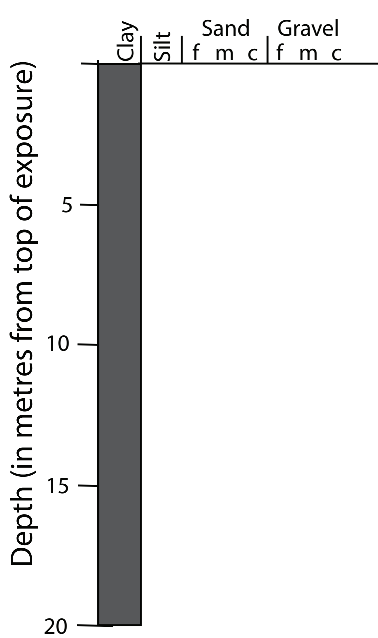


Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
silty fine sand, weak horizontal laminae	very low to low	dry	400	2.5Y 4/3 10YR 3/3	N/A	2 buried organic horizons, 1 tephra
fine sand and silt, weak horizontal laminae	very low	dry	67	2.5Y 4/3	N/A	6 buried organic, horizons
sandy silt	very low	damp	110	10YR 3/6	MAB 09-19-02-01	
silty fine to coarse sand, massive	very low	damp	65	2.5Y 4/4	MAB 09-19-02-02	
interbed of clayey silt and fine sand, horizontal to cross-laminae	medium	damp	117	2.5Y 4/4	N/A	
clayey sandy silt	medium	damp	267	2.5Y 4/4	N/A	
medium sand	frictional	damp	22	N/A	N/A	
clayey silt	medium	damp	95	2.5Y 4/3	N/A	
fine to medium sand	very low	damp	90	5Y 4/2	N/A	
silty clay, laminated	high	dry	>450	5Y 4/2		
silty sandy clay, massive	high	dry	>450	2.5Y 5/3	N/A	5 buried organic horizons and 1 tephra, may represent slump block or draped stratigraphy

Figure 11. *Composite geotechnical logs of stratigraphy and soil properties observed at station MAB 09-19-02 and MAB 09-19-03 (see Fig. 1 for location).*

Long Lake Road section 1
MAB 09-18-01

UTM 0 496 970, 6 733 541, Elevation: 659 m a.s.l.

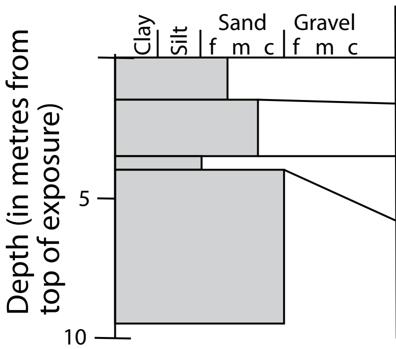


Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
silty clay, horizontally laminated	medium to high	dry	>450	5Y 4/2	MAB 19-18-01-01	only one unit observed in section; columnar structures present as a result of weathering; thickness of vertical section estimated

Figure 12. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-18-01 (see Fig. 1 for location).*

Long Lake Road section 2
MAB 09-18-02

UTM
0 497 121
6 733 593
Elevation: 645 m a.s.l.

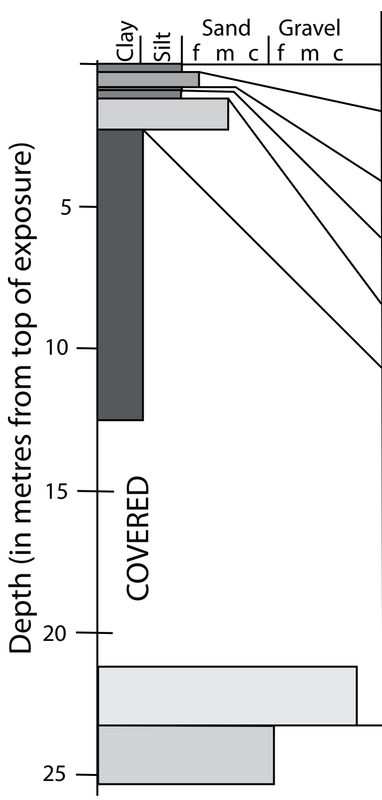


Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
silty fine sand, dipping laminae, poorly graded	low	dry	42	2.5Y 3/3	N/A	two buried organic horizons
silty fine to medium sand, dipping laminae, poorly graded	very low	dry	22	2.5Y 4/2	N/A	discontinuous tephra at top of unit
sandy silt, dipping laminae	very low	dry	252	2.5Y 4/4 7.5YR 3/3	N/A	centimetre-scale pieces of charcoal present in unit
interbedded silty fine sand and medium to coarse sand, cross-bedded, poorly graded	very low frictional	dry	122 for silty fine sand	2.5Y 4/3	N/A	general fining-downward sequence

Figure 13. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-18-02 (see Fig. 1 for location).*

Long Lake Road section 3
MAB 09-20-01

UTM
0 497 350
6 732 286
Elevation: 676 m a.s.l.

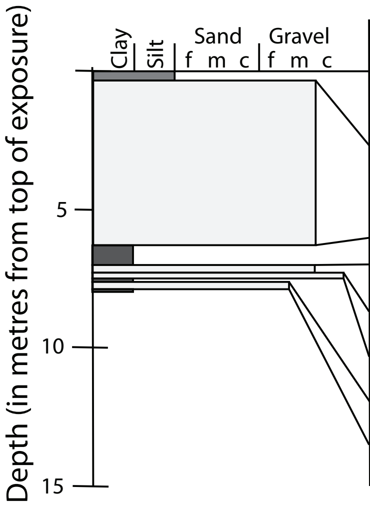


Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
sandy silt, massive	low	dry	270	10YR 3/2	N/A	1 burried organic horizon and tephra
silty fine sand, massive	low	dry	185	2.5Y4/3	N/A	1 burried organic horizon
silt with some fine sand, massive	low	dry	67	10YR 3/3	N/A	1 burried organic horizon
clayey sandy silt, massive	low	dry/ damp	184	2.5Y 4/4	N/A	
gravelly fine to medium sand, weak bedding, moderately well graded	frictional	dry/ damp	16	N/A	N/A	
clay with some silt, horizontally laminated	high	dry	>450	2.5Y 5/2	N/A	
sandy coarse gravel with some cobbles, horizontally bedded, moderately well graded	frictional	dry	S2	N/A	N/A	
gravelly coarse sand, horizontally bedded, poorly graded	frictional	dry	S2	N/A	N/A	

***Figure 14**. Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-20-01 (see Fig. 1 for location).*

Long Lake Road section 4
MAB 09-20-02

UTM
0 497 232
6 732 348
Elevation: 622 m a.s.l.



Soil description	Plasticity	Water content	UCS (kPa)	Colour	Sample	Notes
clayey silt with some fine and medium gravel, gap-graded	medium to high	dry	40	2.5Y 6/3	N/A	upper boundary covered by road fill; polymictic gravel
silty fine to medium gravel, gap-graded	medium to high	dry	>450	2.5Y 6/3	N/A	dry strength; polymictic gravel; plasticity of matrix
silty clay	medium	dry	>450	2.5Y 6/3	N/A	dry strength
fine to medium gravel in silty clay matrix, gap-graded	N/A	dry	>450	N/A	N/A	dry strength; polymictic gravel
fine to coarse gravel in silty clay matrix, gap-graded	N/A	dry	dense	N/A	N/A	polymictic gravel
silty clay, horizontally laminated	medium to high	dry	>450	2.5Y 6/3	N/A	dry strength
fine gravel in silty clay matrix	medium to high	dry	>450	2.5Y 6/3	N/A	dry strength
silty clay, massive	medium to high	dry	>450	2.5Y 6/3	N/A	dry strength

Figure 15. *Geotechnical logs of stratigraphy and soil properties observed at station MAB 09-20-02 (see Fig. 1 for location).*

Figure 16. *Photos of some of the sedimentological structures observed in the measured sections:* ***(a)*** *horizontally laminated rhythmite of silt and clay at section MAB 09-19-03;* ***(b)*** *convoluted bedding of fine sand and silt at section MAB 09-16-01;* ***(c)*** *silt rip-up clast in silty, fine to coarse sand at section MAB 09-16-01.*

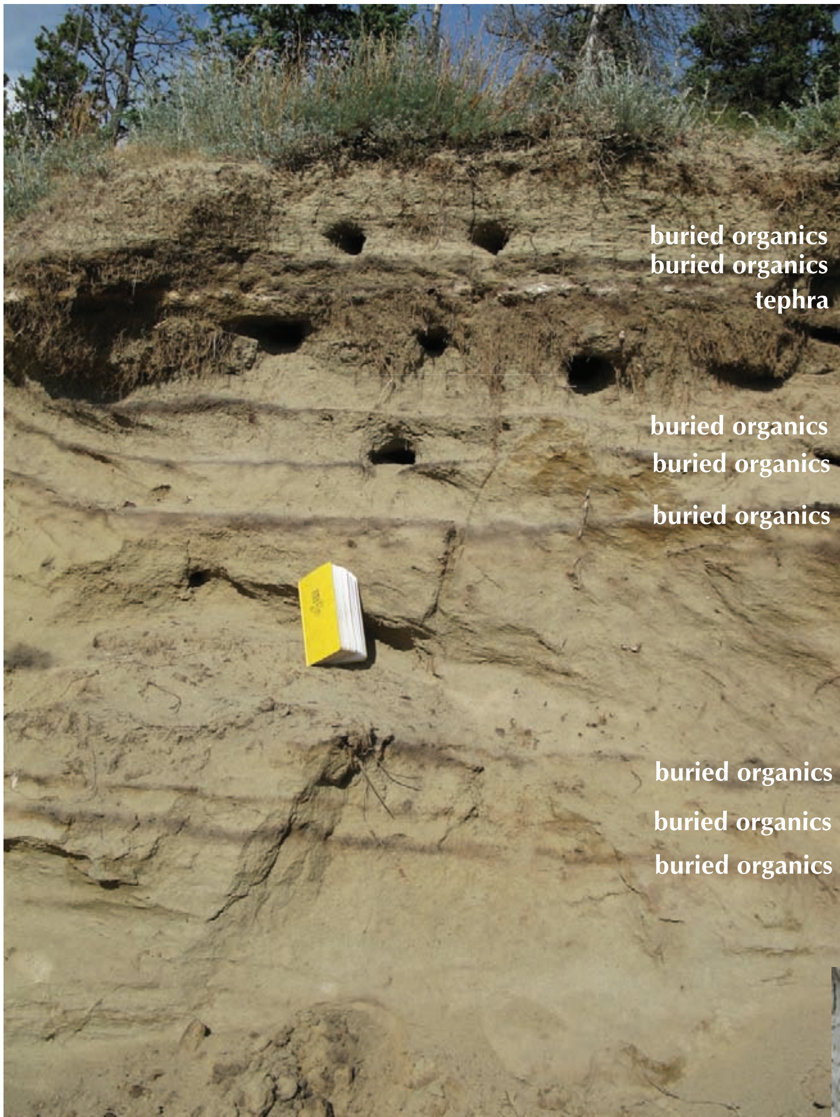


Figure 17. *Multiple buried organic horizons and White River Ash (tephra) in the loess deposit at station MAB 09-19-02.*

Figure 18. *Gap-graded, polymictic, well rounded coarse gravel (including cobbles), in a matrix of silt and clay, at station MAB 09-20-02.*

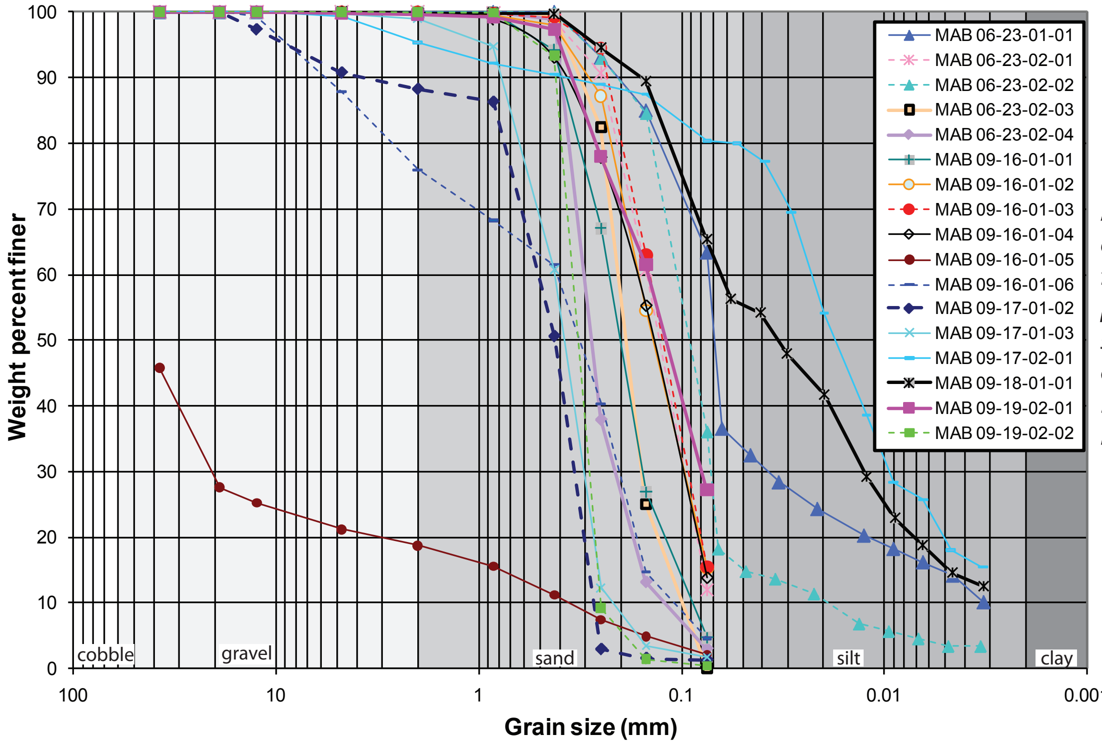


Figure 19. *Grain size distribution curve of percent finer (i.e., weight percent passing through a given sieve size) vs. grain size for samples collected during this study. See Figures 6 to 15 for stratigraphic location of samples and Figure 1 for location of stations.*

Figure 20. *Field photos of selected samples analysed for grain size distribution in Figure19:* ***(a)*** *loess unit of sample MAB 06-23-02-01;* ***(b)*** *laminated silty clay of sample MAB 09-17-02-01;* ***(c)*** *medium cross-bedded sand of sample MAB 09-17-01-03; and* ***(d)*** *sandy gravel of sample MAB 09-16-01-05.*

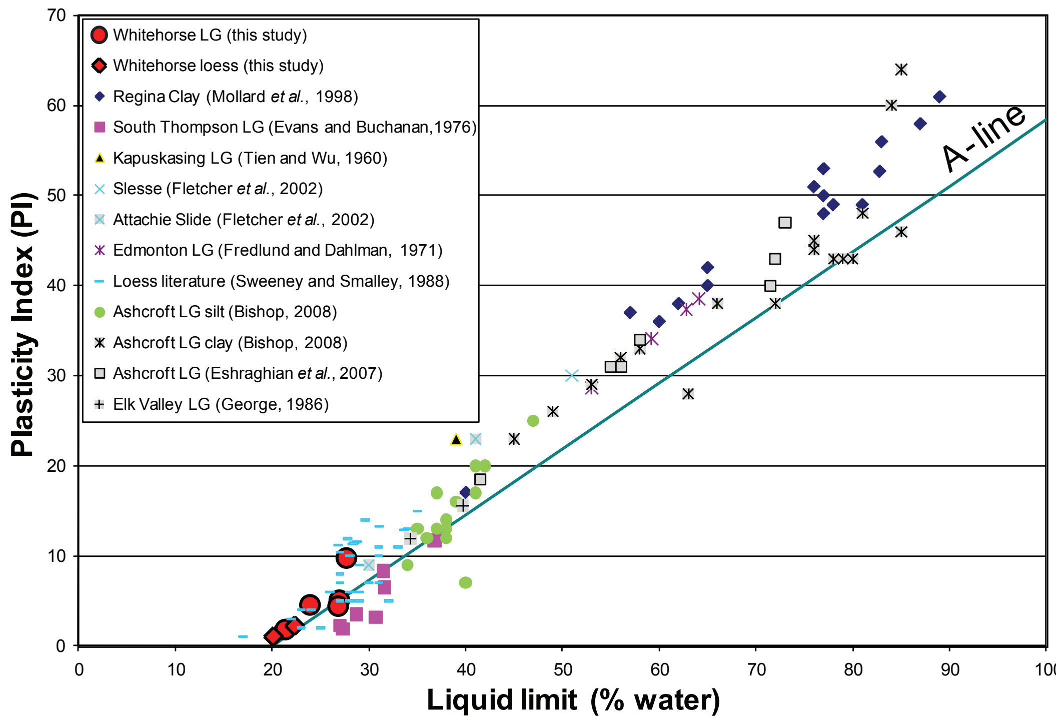


Figure 21. *Plasticity chart comparing samples from this study with plasticity values for samples from other locations in Canada found in the literature. The A-line is an empirical boundary dividing soils with a mechanical behaviour dominated by the presence of clay (above) or silt (below). LG = glaciolacustrine.*

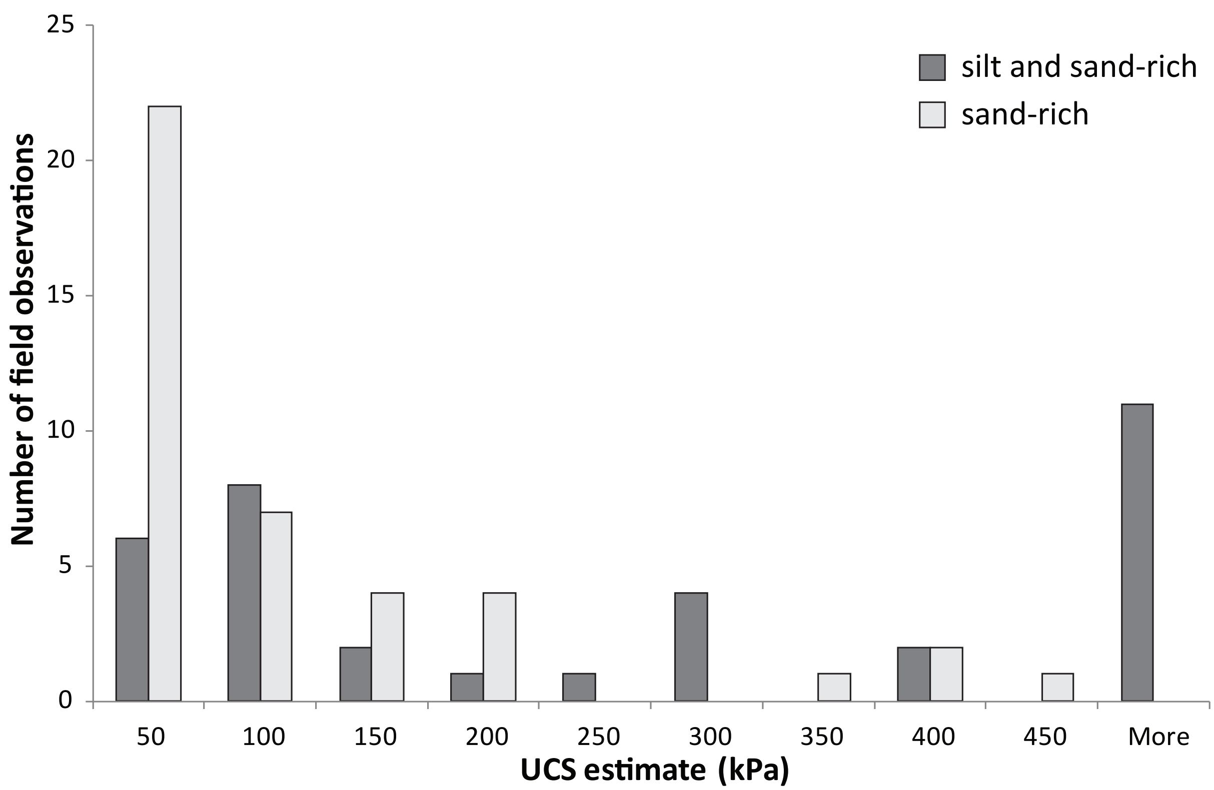


Figure 22. *Histogram of the soil strength estimates obtained from the pocket penetrometer for each of the stratigraphic units in Figures 6 to15.*

Table 1. *Table of soil density class based on field tests (modified from Paddington, 2004).*

Class	Field parameters used in this study to estimate soil density of gravel-rich soils
S1 - very loose	shovel penetrates soil to full length of the blade; easily excavated by hand
S2 – loose	shovel only penetrates soil to half blade length; difficult to excavate by hand
S3 - compact	soil only excavated with shovel with great difficulty; soil excavated without difficulty using pick
S4 - dense	impossible to excavate soil using shovel; pick required
S5 - very dense	soil only excavated with great difficulty using pick

DISCUSSION

Small scale instabilities (such as earth flows and slides (Huscroft *et al.*, 2004, p. 24)) associated with the Whitehorse bluffs have impacted infrastructure (roads, railways and houses) in and around the Whitehorse area (Fig. 2). Their potential hazard has been recognized by the City of Whitehorse which has established geohazard development planning zones, and the City has even purchased properties that are located in high hazard zones (Hopper, 2009). The only obvious sign of active mass movement observed during the period of fieldwork (July 2006 and 2009) conducted for this project, was piping erosion that was noted at station MAB 09-17-02 (Fig. 23); the resulting deposit buried low-lying vegetation with 30 cm of sediment over an area of approximately 20 m by 15 m. To assess the response of the bluffs to the large-scale landscape change due to the raised water table associated with the filling of Schwatka Lake following the construction of the Whitehorse Rapids hydroelectric dam in 1958, aerial photographs from 1950 (A12788-96 to 100; scale 1:15 000) were reviewed. No significant erosion or slope deformation features were observed between the 1950 aerial photographs and the 2006 1-m resolution orthophoto (orthophoto provided by Geomatics Yukon).

The weak strength of the sandy units, and the unvegetated nature of all stratigraphic units in the bluffs, may result in high erosion potential. The low yearly precipitation (Fig. 3) in the Whitehorse region probably minimizes the actual soil erosion; however, as a precaution, sediment erosion control structures such as a series of check dams and interception ditches have been installed at the base of a bluff in downtown Whitehorse (Fig. 24a; see Fig. 1 for location) to facilitate sediment deposition and thereby prevent erosion. In addition, a bio-stabilization attempt was made for the lower section of the bluff by introducing newly planted seedlings (observed during the 2009 fieldwork, Fig. 24b; see Figure 1 for location). Vegetation can increase the soil strength by increasing the root network, and reduce the amount of rainfall reaching the soil and thus moderating surface runoff.

Figure 23. *Photo of piping erosion observed at station MAB 09-17-02.*

Most of the stratigraphic units described in this project were either dry or damp. One sandy unit at station MAB 09-20-03 (Fig. 7) was moist, and one silty clay unit at station MAB 09-17-01 (Fig. 8) was wet. These observations suggest that the heterogeneities of grain size documented in the sections investigated are likely to result in a spatially complex hydraulic conductivity. This could be an important consideration not only for slope stability, but also for contaminant transport (*e.g.,* Soloway *et al.*, 2001).

CONCLUSIONS

Our observations document a larger range of sediment sizes and structures than previously recognized in the Whitehorse area bluffs. This work corroborates the interpretation of previous researchers who noted that the material exposed in the bluffs is dominantly glaciolacustrine sediments associated with Glacial Lake Laberge, which is overlain by a layer of loess. The large range of sediment sizes and structures is evidence for the variety of sediment sources and depositional processes within the glaciolacustrine environment. The loess layer was found to contain up to 8 buried organic/charcoal layers and at least one tephra layer.

This paper provides a first description of the basic geotechnical properties of the glaciolacustrine and loess deposits around the City of Whitehorse. Samples of the fine, horizontally laminated units typically contain less than 20% clay and their mechanical behaviour is predominantly controlled by the high silt content and consequently low plasticity values. These results are comparable to previously reported values for similar deposits in the Canadian Cordillera, including sites near Kamloops and the Elk Valley areas. Most of the units in the Whitehorse bluffs were observed to be dry, but a few were moist or wet suggesting complex hydrogeological conditions. The dry silt and clay-rich units were found to have strengths up to 2 orders of magnitude greater than the sand-rich units. Minor piping erosion of the silt and clay-rich units was observed during 2009 summer fieldwork.

Figure 24. *Examples of the remediation effort completed to reduce erosion of the bluffs in downtown Whitehorse:* ***(a)*** *check dam to reduce flow velocity and encourage deposition; and* ***(b)*** *planting of grass and tree saplings in order to reduce erosion due to overland flow, and to increase soil strength by increasing the root network.*

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