Surficial geological mapping of the central Kluane Ranges (parts of NTS 115G/1, 2, 3, 7 and 115B/15, 16), southwestern Yukon

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Ackerson, C.M, Ward, B. and Kennedy, K., 2021. Surficial geological mapping of the central Kluane Ranges (parts of NTS 115G/1, 2, 3, 7 and 115B/15, 16), southwestern Yukon. *In:* Yukon Exploration and Geology 2020, K.E. MacFarlane (ed.), Yukon Geological Survey, p. 157–176.

Abstract

Surficial geological mapping in the central Kluane Ranges was undertaken to better understand the distribution and character of surficial materials. Upland surficial materials in the area are dominated by near-source bedrock derivatives. Valley bottom settings, including Shakwak trench and Duke River valley, are characterized by broad open valleys with thick deposits of Quaternary sediment. Permafrost is discontinuous in the study area and its character is affected by slope and aspect, topography and material texture. Mass wasting processes in the study area include rock fall and avalanches, debris flows and avalanches and active layer detachment slides. The distribution and character of surficial materials has significance for soil geochemical sampling programs and infrastructure and implications for mineral exploration and developments are addressed.

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Introduction

This paper presents preliminary results from 1:50 000-scale surficial geological mapping undertaken in the central Kluane Ranges in 2020 (Fig. 1). Emphasis is placed on describing the character and distribution of surficial materials within the map area. Mapping (currently in progress) will also identify glacial limits that will be placed into the stratigraphic framework of the Kluane Ranges.

The Kluane district has both placer (Kennedy and van Loon, 2017; Bond and van Loon, 2018) and bedrock mineral potential (Israel *et al.*, 2006). In the central Kluane Ranges, placer claims exist along the entirety of Bock's Creek and most of Nines Creek and its largest tributary (Fig. 1). There are also several active aggregate quarries along the Alaska Highway in the study area and there is potential for further aggregate development in fluvial fan deposits.

Bedrock mineral exploration in the Kluane district focuses primarily on nickel-copper-platinum group elements (PEG) in Triassic ultramafic rocks (Israel et *al.*, 2006) with several mineral showings and prospects located within the mapping area (Fig. 1). Porphyry and skarn intrusion-related mineralization exists throughout this region and has been shown to be associated with the Kluane Ranges suite (Kennedy and van Loon, 2017).

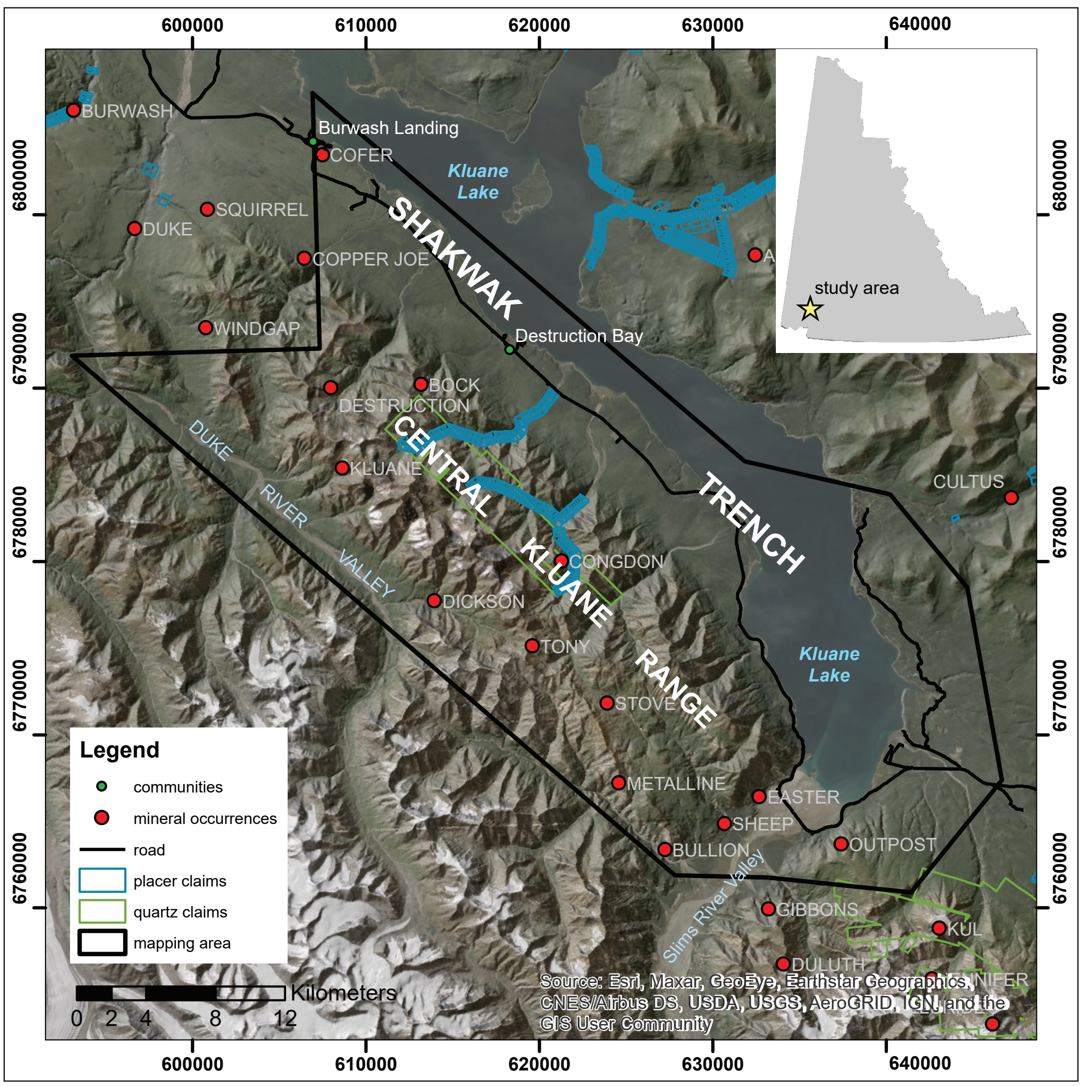

Figure 1. *Location map of the central Kluane Ranges study area and locations of mineral occurrences, placer claims, and quartz claims.*

In addition to the surficial mapping project, work on active layer detachment slides is being undertaken to investigate temporal changes to frequency and magnitude and a possible relation to climate warming. Heavy rainfall in August 2020 triggered landslides that crossed the Alaska Highway south of Ä'äy Chù (Slims River) and resulted in a highway closure. The same precipitation event is also thought to have initiated large active layer detachments at the confluence of Arch Creek and the Donjek River (Fig. 2). Work related to mass wasting is ongoing and will be published at a later date.

Figure 2. *Active layer detachment slides at the confluence of Arch Creek and Donjek River. Helicopter (circled) for scale. The initiation zone is ~150 m vertically above the toe and the track is ~500 m long. These active layer detachment slides are quite large with respect to others seen in this region.*

Physiography and bedrock geology

The Kluane Ranges and the southwestern Kluane Lake area are part of the northeastern Coast Mountain Belt. The Kluane Ranges span 30 km and are part of the front ranges of the St. Elias Mountains, which are some of the highest mountains in North America, with peaks exceeding 5000 m above sea level (a.s.l.). This region is characterized by rapid uplift resulting in steep valley walls sculpted by repeated glaciations. Much of the map area is mountainous terrain with bedrock commonly exposed in canyons, along ridges, summits and upper slopes. Lower slope positions and valley bottoms have thick and more varied deposits of surficial materials. Kluane Lake occupies Shakwak trench, a 10–15 km wide valley that trends northwest-southeast and parallel to the Denali fault. The Duke River fault parallels the Duke River Valley at the western margin of the map area (Fig. 1).

Bedrock in the study area is complex and variable consisting of volcanic, granitic, metamorphic and uplifted oceanic and terrestrial sedimentary rocks (Israel *et al.*, 2006; 2010; Israel and Cobbett, 2008; Colpron *et al.*, 2016). The study area predominantly lies within the Wrangellia Insular terrane which was accreted onto the continent in Early to Middle Jurassic. It is composed of mafic and ultramafic oceanic and island arc rock. Overlapping the Insular terrane rocks are Upper Jurassic to Lower Cretaceous muddy sandstones of the Dezadeash Formation. The Paleocene to Oligocene aged Amphitheater Formation is composed of poorly consolidated conglomerate and sandstone with some interbedded coal seams (Greene *et al.*, 2004; Israel *et al.*, 2006). Andesitic and basaltic volcaniclastic and tuff rocks from the Miocene aged Wrangell volcanic rocks are positioned stratigraphically above and interbedded with the Amphitheater Formation (Israel *et al.*, 2006).

At the southeastern end of the study area bedrock consists of Kluane schist. These metamorphic rocks consist of muscovite, biotite and quartz-rich schist. This schistose rock can also be found under the Ruby Range batholith situated on the east side of Kluane Lake (Israel *et al.*, 2010). The Ruby Range batholith is dominantly composed of quartz-diorite, tonalite and granodiorite and is located east of Kluane Lake in the Ruby and Nisling ranges (Israel *et al.*, 2010).

Glacial history

Yukon was repeatedly glaciated by the northern part of the Cordilleran Ice Sheet during the Quaternary. The northern Cordilleran Ice Sheet consisted of quasi-independent ice lobes rather than a coherent ice sheet (Jackson *et al.*, 1991). The study area was affected by the St. Elias Lobe. Stratigraphic studies have recognized five glacial advances in southwestern Yukon but there were likely additional unrecognized earlier advances (Turner, 2014; Turner et *al*., 2016; Cronmiller, 2019). Uplift of the St. Elias Mountains in the Miocene is thought to have created a precipitation barrier east of the St. Elias Mountains in southwestern Yukon (Foster et *al*., 2010). This is thought to have caused Late Pliocene and Pleistocene ice to initiate in these mountains and flow north-northeast into the Shakwak trench (Fig. 3; Hughes et *al*., 1969; Duk-Rodkin 1999).

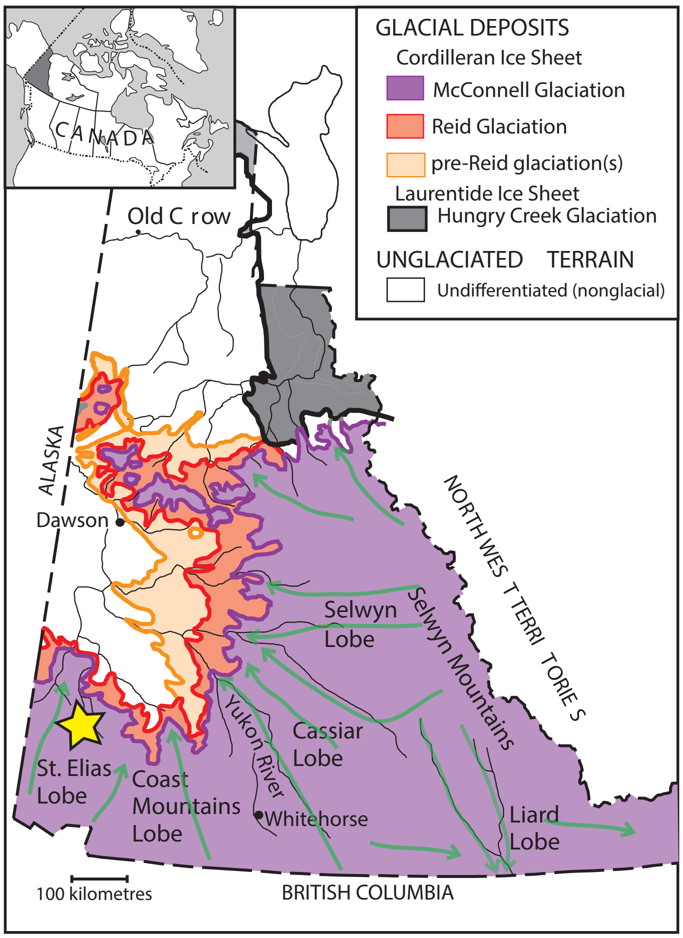

Figure 3. *Map of Yukon showing ice flow directions and approximate extents of glaciations during the Pleistocene. The study area (marked with a yellow star) is approximately 200 km west of Whitehorse. Modified from Ward et al. (2007) after Duk-Rodkin (1999).*

Regional glacial and interglacial terminology exists for southwestern Yukon, but most researchers now place this into the framework developed for central Yukon. Denton and Stuiver (1967) identified and named three glaciations in southwestern Yukon, from oldest to youngest, the Shakwak, Icefield and Kluane; these glaciations are separated by interglacial intervals termed the Silver, Boutellier and Slims interglacials. Turner et *al*., (2016) confirmed these results and identified two additional glaciations. Evidence for these glaciations was obtained from five units interpreted as till in stratigraphic sections along Silver Creek (Turner et *al*., 2016). The Boutellier interval, below the Kluane till and above the Icefield till, is dated to Marine Isotope Stage (MIS) 3 (~60–30 ka) (Denton and Stuiver, 1967; Lowdon et *al*., 1970; Turner et *al*., 2016). This constrains the Kluane till to MIS 2 which, correlates to the McCauley till (Rampton, 1971) from the Snag-Klutlan area and the McConnell glaciation from central Yukon.

Ages of older tills are not well constrained. The next youngest till in southwestern Yukon is from the Icefield glaciation (Denton and Stuiver, 1967). The Icefield glaciation is correlated to the Mirror Creek (Rampton, 1971) and Gladstone (Ward et *al*., 2007) glaciations from the Snag-Klutlan and Aishihik areas, respectively. The Gladstone glaciation has been dated to MIS 4 with ^{10}Be on deglacial erratics (Ward et *al*., 2007). The Shakwak glaciation is correlated to central Yukon's MIS 6 Reid glaciation (Turner et *al*., 2016). The two oldest tills are considered pre-Reid. A loess unit above the younger of the two tills is dated to at least 320 ka using infrared-stimulated luminescence dating indicating MIS 10 or older deposition (Turner et *al*., 2016). Only two glacial limits have been mapped in southwestern Yukon, in contrast to other areas where the pre-Reid is much more extensive.

Surficial materials

A combination of foot, truck and helicopter traverses were used to examine the surficial geology of the study area. Texture, surface expression, contacts between surficial materials, and geomorphic processes were described during traverses. Where present, depth to permafrost was noted along with slope position and aspect. These data were used to develop an interpretation of the genesis of the material and to assign terrain polygon labels using a modified version of the Howes and Kenk (1997) Terrain Classification System for British Columbia (YGS, 2020).

Till

Till is material directly deposited by glacier ice without significant modification. Till deposits in the study area are variable but are all matrix supported (Fig. 4a). Clast sizes range from pebble to large boulders (>1 m). Clasts are dominantly subround with fewer subangular and round shapes. Clast content ranges from 10–40% (20–30% is dominant) and clasts are polymictic, representing a broad range of rocks transported by the St. Elias Lobe. The matrix is dominantly sandy silt, but can be clayey silt and silty sand as well. The source area and depositional environment influence the variability. Subglacial till is commonly over-consolidated with subhorizontal fissility.

Till is preserved on gently sloping surfaces and benches on mid to lower slopes both in the central Kluane Ranges and in Shakwak trench. It is also present in section on bluffs along Kluane Lake, where it usually occurs at the base of the stratigraphy. In the central Kluane Ranges, till is commonly overlain by loess and is discontinuous on mid-elevation slopes due to reworking by gravitational processes and surface water.

Glaciofluvial

Glaciofluvial materials are deposited by braided rivers in close proximity to an ice margin. They typically comprise moderately sorted, moderately to well-stratified silty-sandy gravel. Fining-upward grading from boulder dominated to cobble, and even pebble dominated, is common (Fig. 4b). In the canyons and valleys of the central Kluane Ranges, glaciofluvial materials are typically poorly preserved in isolated pockets; there are some glaciofluvial terraces present above Sheep and Bouillon creeks. In Shakwak trench there are extensive glaciofluvial deposits visible in section along the bluffs of Kluane Lake. Clast content is variable but is generally 60–80%. At the south end of Kluane Lake, hummocks, discontinuous ridges and kettle lakes form ice stagnation topography composed primarily of glaciofluvial gravel.

Glaciolacustrine

Glaciolacustrine materials are deposited in or along the margins of glacial lakes and include ice rafted debris. These sediments are observed in sections along the bluffs of Kluane Lake and in the Duke River area. They are dominantly well-stratified, laminated to thinly bedded sand, silt and silty clay. Drop stones (ice rafted debris) and soft sediment deformation structures including faulting are common (Fig. 4e). Sections with diamict containing rip up clasts and pebble gravel layers and lenses were noted along and near Kluane Lake.

Weathered bedrock

Weathered bedrock is the product of *in situ* mechanical and/or chemical weathering of bedrock leading to decomposition or disintegration mainly as a result of strong periglacial processes coupled with weak or faulted bedrock. There is extensive weathered bedrock in the study area, particularly in the northwestern part of the map area and at higher elevations. Deposition of weathered bedrock occurs primarily on flat or gentle slopes. The northwestern part of the mapping area is characterized by poorly consolidated bedrock such as the Wrangell basalt and Amphitheater Formation conglomerate (Fig. 4d), resulting in widespread weathered bedrock. Texture varies with respect to the initial lithologic characteristics and degree of mixing with loess and/or till by periglacial processes, such as cryoturbation and frost heave.

Fluvial

Fluvial sediments are composed of stratified sand and gravel, with a minor silt component. They occur in, and adjacent to, modern drainages including fan settings

Figure 4. *Examples of the surficial materials encountered in the mapping area are:* ***(a)*** *till;* ***(b)*** *glaciofluvial;* ***(c)*** *lacustrine (from pit on Kluane Lake beach);* ***(d)*** *weathered bedrock;* ***(e)*** *glaciolacustrine;* ***(f)*** *loess (eolian);* ***(g)*** *fluvial;* ***(h)*** *colluvium. Measuring tape units are in centimetres and both shovel and pick handles are ~1 m long.*

(Fig. 4g). These deposits are dominantly moderately-sorted, however, lenses and layers of well-sorted sand and gravel are also present. Clast size ranges from pebble to boulder with pebble being dominant. Steep and confined channels are characterized by coarser fluvial deposits. Clasts are dominantly round to subround. However, some fans proximal to source have dominantly subround to subangular clasts. The majority of these deposits are limited to narrow bedrock-constrained channels and small fans. However, in the Duke River valley and Shakwak trench large fans prograde into broad, open valleys.

Lacustrine

Lacustrine sediments are primarily located at the margin of Kluane Lake as raised beaches. Lacustrine sediments are moderate to weakly stratified sand, pebble gravel with a sandy matrix, and openwork pebble gravel (Fig. 4c). Berms of lacustrine beach sediment up to 2 m high can be found several hundred metres inland from the shore. Clast lithology is variable as many clasts have a history of glacial transport, and are dominantly round to subround, although tabular clasts are present.

Colluvium

Colluvium is material transported by gravity-driven processes including rapid processes such as rock fall, debris flows and avalanches, and slow processes such as solifluction and creep. These deposits have variable texture and composition due to the variability in process and sediment source. At higher elevations blocks from rock fall are dominant while finer grained sediments can be found on gentler slopes where slow mass movement processes are prevalent. On lower slopes colluvium is commonly a diamict, deposited by rock avalanches, debris flows and debris avalanches (Fig. 4h) or loose blocky angular fragments from accumulated rock fall. These deposits can be high in silt and/or clay if sourced from sediments with fine-grained matrix, fine-grained glaciolacustrine sediments or if mixed with significant quantities of loess. In areas of Wrangell basalts colluvium typically has a higher content of fines (silt and clay).

Eolian

Although generally too thin to map, loess or windblown silt is the most widespread sediment throughout the study area (Fig. 4f). During glacial and deglacial times loess is generated by katabatic winds blowing over recently deglaciated or unvegetated surfaces, entraining silt and fine sand and depositing it downwind. There are both paleo and modern loess deposits in the central Kluane Ranges. Paleo loess deposits in the study area formed from katabatic winds at the end of the last glaciation. Modern loess deposits are typically confined to the southern part of the map area and originate primarily from katabatic winds blowing down Ä'äy Chù Valley.

Stratigraphy

Stratigraphic sections were divided into units based on material type and texture. Unit descriptions include texture, structures, weathering and contacts between units. With a paucity of well exposed sections, the majority of stratigraphic correlations are based on manual excavations through slopewash sediments. As a result, contacts and units could be unintentionally omitted. This adds uncertainty to the stratigraphy in the study area. For the purpose of stratigraphic correlations, the study area has been divided into three main areas: Shakwak trench, Duke River, and the central Kluane Ranges.

Shakwak trench

Lewis Creek north (CA203201)

This section is located on the upper part of a bluff overlooking Kluane Lake just south of Lewis Creek (Fig. 5). The section is ~22 m high (Fig. 6).

Unit 1 is a stratified, clast supported sandy gravel ≥1 m thick. The lower contact of unit 1 is covered. Bedding is defined by stratification of pebble-cobble gravel and granule-pebble gravel. Beds range from 2–10 cm thick and dip 8–10° to the NW. Finer beds composed of small pebbles are dominantly openwork and clasts have silt and clay coatings. Some medium to very coarse sand matrix partially infills the interstices between

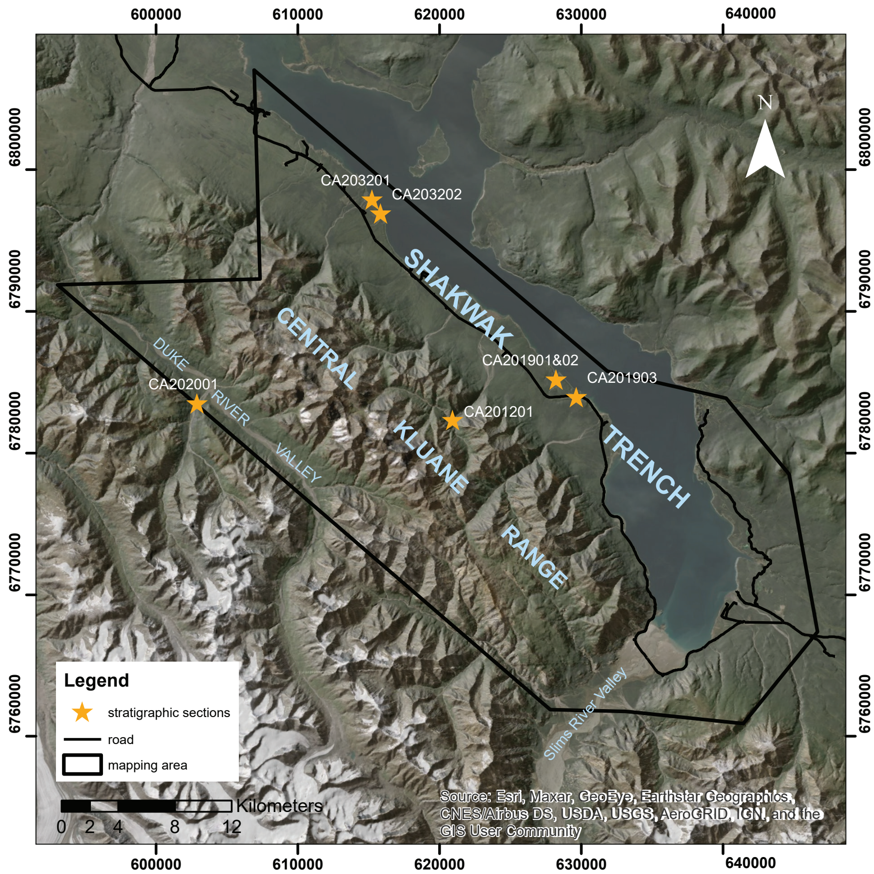

Figure 5. Location map of stratigraphic sections.

clasts that are dominantly subround. Clast content in the finer beds is ~90–95%. Coarser beds are matrix supported pebbles and small cobbles with a 70–80% clast content. The matrix in these beds is coarse to very coarse sand. Unit 1 is interpreted as advance outwash as ice moved northwest down Shakwak trench, based on stratigraphic position (below till) and inclined bedding interpreted to represent deposition into water.

Unit 2 is a stratified diamict ≥1.2 m thick, that is fissile and has an abrupt, irregular, inclined, nonconformable lower contact. The two layers observed in this diamict are differentiated by clast content and matrix. However, clast shape and size, and features such as facets and striations are the same between beds. The lower bed is ≥30 cm thick with a fine sandy silt matrix and 30–40% clasts. The upper bed is ≥90 cm thick with a very fine to fine sand matrix and 20–25% clasts. The two beds are separated by an abrupt contact. Clasts are dominantly pebble-sized but range up to 30 cm in diameter and are dominantly subround with abundant faceted and striated clasts. Unit 2 is interpreted as till due to its stratigraphic position, texture, and the presence of striated and faceted clasts. Variation between the upper and lower till layers in this unit could represent till deposited during advance (lower) and retreat (upper) phases of glaciation.

Unit 3 is a laterally discontinuous deposit of silty organic material 0.05–0.08 m thick with a clear subhorizontal, irregular, unconformable lower contact. This unit is dominantly fibric organics with silt and has a medium brown colour when freshly exposed. Unit 3 is interpreted as a paleosol based on the abundance of fibric organics and stratigraphic context. This implies a period of subaerial exposure between Units 2 and 4.

Unit 4 is ≥0.45 m of laminated and finely bedded silt and sand with an abrupt, irregular, inclined (~8° to the NW) lower contact. This unit is composed of fine beds and laminations of medium sand fining upward to very fine sand and is capped by a 2 cm bed of silty medium sand. Soft sediment deformation structures such as flame structures, convolute bedding, and dish structures are present. Unit 4 is interpreted as a lacustrine deposit based on texture, bedding, and soft sediment deformation. Its stratigraphic position above a paleosol indicates this unit was deposited during a non-glacial period.

Unit 5 comprises massive silt with tephra. The unit is ≥0.8 m thick with a gradational, horizontal lower contact. It has a 3–5 cm thick bed of tephra ~30 cm from its base. This unit is dominantly massive silt with minor very fine sand. The upper 30–40 cm has a well developed soil. The tephra comprises medium to coarse sand sized particles with a black-and-white speckled colour like salt-and-pepper. Unit 5 is interpreted as eolian loess and tephra. The tephra is assumed to be White River Ash deposited approximately 1200 years ago (Jensen et *al.*, 2014). The tephra in the loess indicates significant windblown sediment deposits have occurred in this region in the last 1200 years.

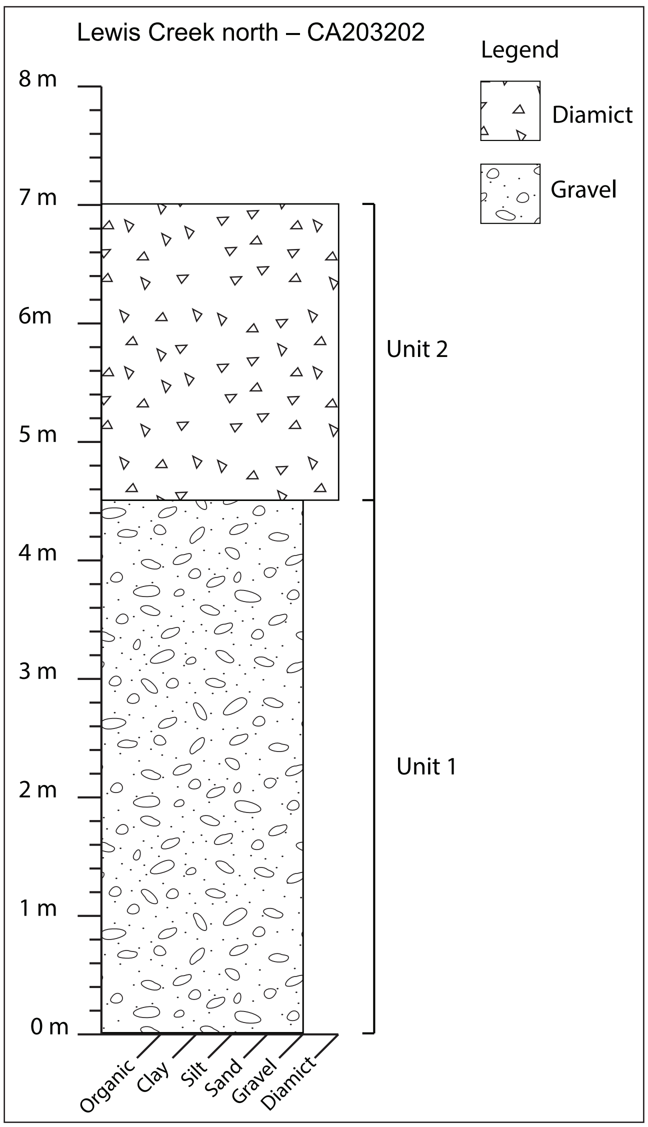

Figure 6. *Stratigraphy of sediments observed in section along bluffs on the western shore of Kluane Lake (Lewis Creek north - CA203201).*

Lewis Creek south (CA203202)

This section is exposed in bluffs along Kluane Lake between Destruction Bay and Lewis Creek (Fig. 5). The section is ~20 m high with two units exposed in the lower 7 m of the section (Fig. 7).

Unit 1 is a ≥4.5 m-thick, moderately consolidated, stratified gravel. Poorly sorted pebble-cobble beds are dominantly matrix-supported with silty medium to very coarse sand, and include some clast-supported lenses and beds. Beds are separated by clear, inclined (~8° to the NW), planar contacts, commonly with laminated silt beds (2–3 cm thick) along bedding planes. Bedding ranges from 15–100 cm thick and matrix supported beds are generally thicker than clast supported beds and lenses. Unit 1 is interpreted as subaqueous outwash deposited in front of a glacier advancing northwest along Shakwak trench. This is based on the unit's stratigraphic position below till, inclined bedding, and interstratified silt representing quiet water deposition.

Unit 2 is a ≥2.5 m thick stratified diamict. The lower contact appears sub-horizontal, although it is poorly exposed. The matrix is dominantly silt with some very fine to medium sand. Clasts comprise 30–40% of the unit, and are dominated by pebbles with lesser amounts of cobbles and boulders. Clasts are commonly faceted, striated, and fractured. Unit 2 is interpreted as till deposited during the last glaciation based on texture, clast features (striations, facets and fractured clasts), and stratigraphic position. Silt partings indicate this may be a flow till deposited at the ice margin.

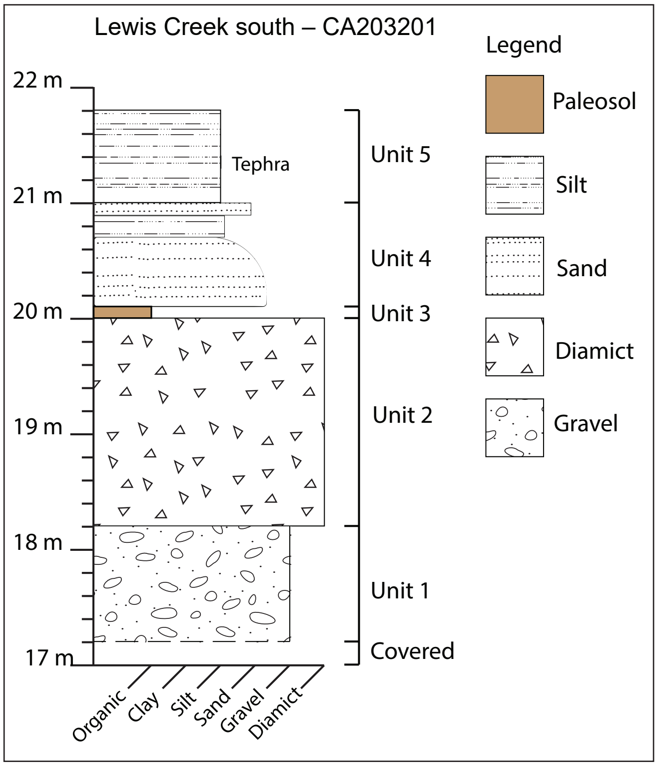

Figure 7. *Stratigraphy of sediments observed in section along bluffs on the western shore of Kluane Lake (Lewis Creek south - CA203202).*

Dutch Harbour (CA201901 & CA201902)

These sections are located on the south side of Dutch Harbour on the west shore of Kluane Lake (Fig. 5). The CA201901 section is ~15 m high with only the upper ~1 m well exposed; thus the majority of descriptions were from manually-excavated exposures. Site CA201902 is located in a small landslide scar several hundred metres south-southwest of site CA201901.

Unit 1 (Fig. 8) is light grey brown, weakly-stratified, unconsolidated diamict with a covered lower contact. There are silt partings less than 1 cm thick separating the layers of diamict that are laterally continuous for at least several metres. Unit 1 has a fine sandy-silt matrix (60–70%) supporting subround, striated, and faceted clasts ranging from pebble (>50%) to boulder (<5%) in size. Elongate and anvil-shaped clasts are present, some with infrequent vertical to subvertical orientations. Clasts are polymictic. This unit has undergone chemical weathering resulting in many disintegrating clasts. Unit 1 is interpreted as flow till deposited in an ice marginal glaciolacustrine environment during deglaciation of Shakwak trench. This is based on stratigraphic context (below glaciofluvial and glaciolacustrine sediment), texture, clast features (striations, facets and anvil-shape), and interbedded silts.

Unit 2 comprises ≥0.8 m of laterally discontinuous sand. The unit displays horizontal planar stratification and a gradational, irregular, horizontal, lower contact. Overall, laminae and beds range from 0.5–5 cm and coarsen upward from very fine sand to very coarse sand and pebbles. Lenses and blebs of Unit 1 are present in the lower 15–20 cm of this unit. Unit 2 is interpreted as a glaciolacustrine deposit from the end of the last glaciation based on horizontal bedding, texture, and stratigraphic context (above till and below glaciofluvial deposits). The reverse grading is interpreted to represent deposition from a sediment flow in a subaqueous environment.

Unit 3 is a stratified sandy gravel that is ≥1.4 m thick with a nonconformable (erosive), sharp, inclined (toward the north-northwest) lower contact at site CA201901 and covered lower contact at site CA201902. Matrix supported beds, 5–20 cm thick, are interbedded by openwork pebble gravel beds with some 5–10 cm diameter cobbles. These beds have an apparent dip of ~5° to the northwest. This unit has a dominantly coarse sand matrix with some medium sand and a clast content of 70–75%. Clasts are dominantly pebbles with some cobbles and have a subround shape. Many elongate clasts display a vertical to subvertical orientation. Unit 3 is interpreted as a glaciofluvial gravel deposited during deglaciation of Shakwak trench based on texture, inclined beds, and an erosive lower contact over till.

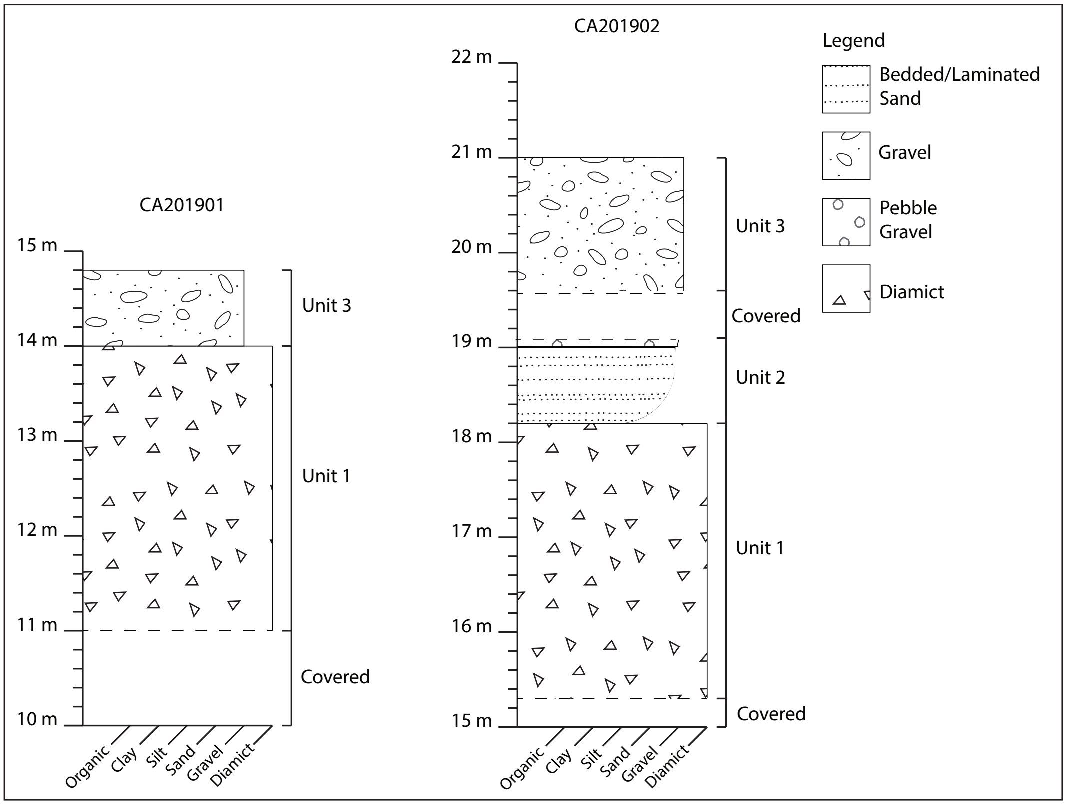

Figure 8. *Stratigraphy of sections at Dutch Harbour (CA201901 and CA201902).*

Goose Bay (CA201903)

This site is located near Goose Bay off the Alaska Highway in a cut for the pipeline (Fig. 5). Three units were observed and are described below (Fig. 9).

Unit 1 is a weakly stratified diamict ≥1.2 m thick that has a covered lower contact. Horizontal to subhorizontal beds are separated by sandy-silt and silt partings with horizontal to subhorizontal fissility. The matrix is a light greyish brown and is dominantly silt with some sand. Clast content is 30–40% and clasts are subangular to subround. Clasts are dominated by pebbles but can be up to 50 cm in diameter and many are faceted and striated. Clasts are polymictic with sedimentary, granitic, porphyritic volcanic and schistose present. Unit 1 is interpreted as a flow till from the margin of an ice sheet in Shakwak trench at the end of the last glaciation due to its texture, faceted and striated clasts, and interbedded silt and sandy silt.

Unit 2 is a ≥0.55 m thick stratified sandy pebble gravel that pinches out to the west (possibly thickening in the opposite direction) with an abrupt, irregular, inclined (apparent strike and dip = 20°/310°) nonconformable (erosive) lower contact. Beds are dominantly horizontal to subhorizontal openwork gravel interbedded by matrix supported sandy gravel beds up to 10 cm thick. Clasts are dominantly subround fine pebbles. Unit 2 is interpreted as a glaciofluvial outwash gravel deposited during deglaciation of Shakwak trench based on its stratigraphic position (above till) and the presence of an erosive lower contact. The apparent dip of the beds could indicate this unit was deposited in a subaqueous environment.

Unit 3 is interbedded silt and pebbly sand ≥1.7 m thick with an abrupt, conformable lower contact. It is dominated by horizontal to subhorizontal laminations of silt and clayey silt with sand and pebbly sand and sandy pebble gravel laminations, beds, and lenses. Silt and clayey silt laminae are dominantly fine (≤0.5 cm) sandy laminae are coarse (≥0.5 cm and <1 cm) and pebbly sand and pebble gravel with a sandy matrix are dominantly finely bedded (≥1 cm and <5 cm). The frequency of the coarser beds increases toward the top of the unit. Silt and clayey-silt layers contain pebble clasts with laminae and beds draped over them.

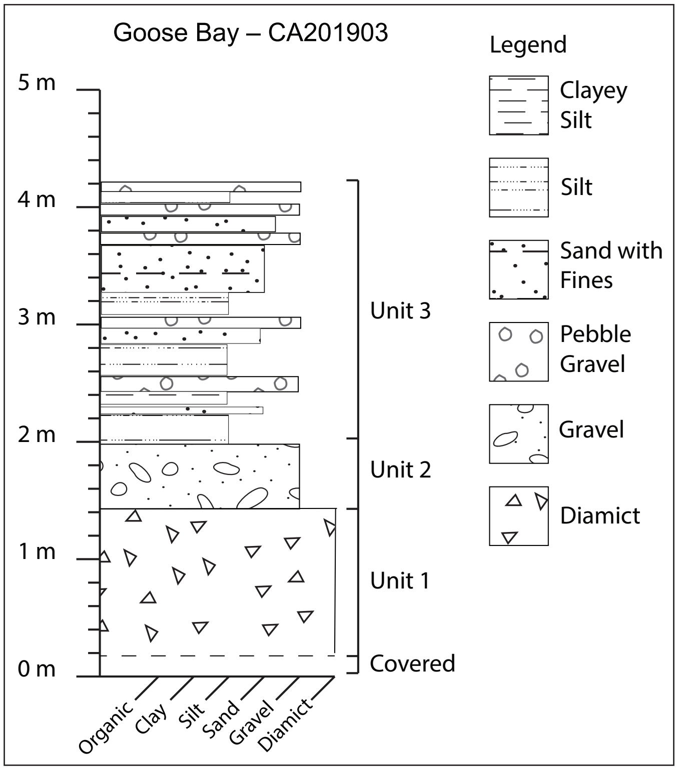

Figure 9. Stratigraphy of sediment in a pipeline cut off the Alaska Highway near Goose Bay (CA201903).

Unit 3 is interpreted as a glaciolacustrine deposit based on texture and the presence of drop stones (clasts draped by silt and clayey silt). The coarser beds could be debris melting out of ice or might represent a more proximal position to the ice front.

Duke River

Grizzly Creek (CA202001)

Located ~500 m upstream of the confluence of Grizzly Creek and Duke River (Fig. 5), the Grizzly Creek section comprises 14–16 m of surficial sediments overlying discontinuously exposed bedrock at creek level.

Unit 1 is a matrix-supported stratified diamict ~5.5 m thick (Fig. 10). It is consolidated and fissile with an irregular lower contact with underlying basalt. Comprising 60–65% of the unit, clasts are dominantly subangular to angular greenstone pebbles, with rare subround clasts of amygdaloidal basalt and fine grained sedimentary rocks. Clasts are dominantly pebble sized with a maximum clast diameter of ~1 m. The matrix of Unit 1 is light greenish–grey fine sand (Fig. 4H) with a dark rusty brown horizon in the upper 60 cm of the unit. Unit 1 is interpreted as a colluvial fan deposit based on stratification and the dominant locally-sourced clast composition of the diamict. The rusty brown colour along the upper contact of the unit is interpreted as subaerial oxidation, but could also have resulted from groundwater movement.

Unit 2 is a ~3.8 m-thick unconsolidated, fissile, matrix-supported diamict with a sharp, planar lower contact. Grey sandy–silt matrix supports 30–40% subround, polymictic pebbles and small cobbles. Some clasts are striated and faceted. Unit 2 is interpreted as till based on its texture and the presence of striated and faceted clasts.

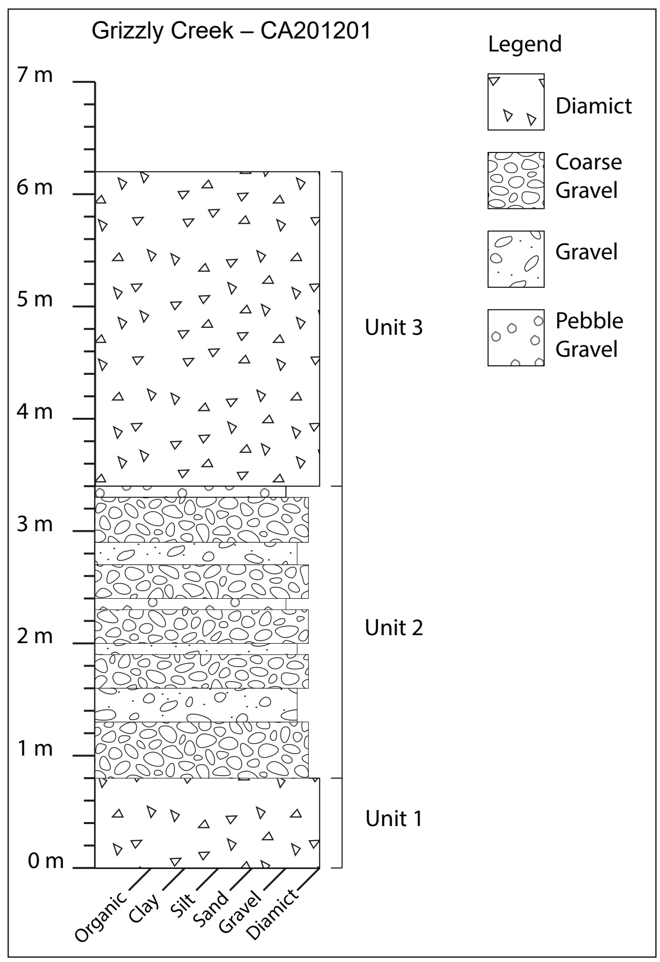

Figure 10. Stratigraphy of sediments at Grizzly Creek (CA202001).

Unit 3 is a ~1.7 m thick matrix-rich diamict with a sharp, irregular, horizontal lower contact. It is fissile, unconsolidated, and has a dark grey silt matrix with a clast content of 10–15%. Clasts are commonly striated and faceted and comprise subround pebbles with rare cobbles. Unit 3 is interpreted as till based on its texture and the presence of striated and faceted clasts. The low clast content could indicate a change in glacier source area.

Unit 4 comprises 40 cm of interbedded silt and sand with a sharp, subhorizontal, planar lower contact. Rare (~5%) round to subround pebbles are draped by clayey-silt to silty fine-sand laminae and beds. Laminae and thin beds (<2 cm) thicken upward to a 25 cm-thick bed of dark grey clayey silt at the top of the unit. Unit 4 is interpreted as a glaciolacustrine deposit based on the texture, stratigraphic context and clasts draped by beds and laminae.

Large striated boulders up to 1 m in diameter are present on the recessive, covered surface above the Grizzly Creek section. No clasts of this size and description with striations were found in the lower units. The presence of large striated boulders at the top of the section may indicate a stratigraphically higher till, or that one of the diamict units lower in the stratigraphy has been draped over the section.

Central Kluane Ranges

Nines Creek (CA201201)

The Nines Creek section (Fig. 11) is characteristic of the sections found in the steep narrow valleys of the central Kluane Ranges. Located at the confluence of Nines Creek and its main tributary (Fig. 5), the section comprises 3 units and is ~6 m high with a sloping upper surface.

Unit 1 is a 0.8 m-thick moderately consolidated diamict with a sandy silt matrix and a covered lower contact. Clasts comprise 60–65% of the unit and are dominantly subround pebbles and cobbles with rare boulders. Unit 1 is interpreted as colluvium deposited by a mass wasting event such as a debris flow or avalanche. The high clast content coupled with an abundance of angular clasts indicate a non-glacial origin.

Unit 2 is a 2.6 m-thick moderately sorted, stratified, cobble-pebble gravel with a coarse sandy matrix. Unit 2 has a sharp lower contact and is interpreted as a high energy fluvial deposit based on its texture and position in the bottom of a bedrock canyon.

Unit 3 is a 2.8 m-thick stratified, silty diamict with a clast content of 65–70% and an abrupt lower contact. Clasts are dominantly angular to subangular and range from boulder to pebble. Bedding in this unit is inclined ~12° to the north-northeast, with the entire unit thinning and fining before pinching out in the same direction.

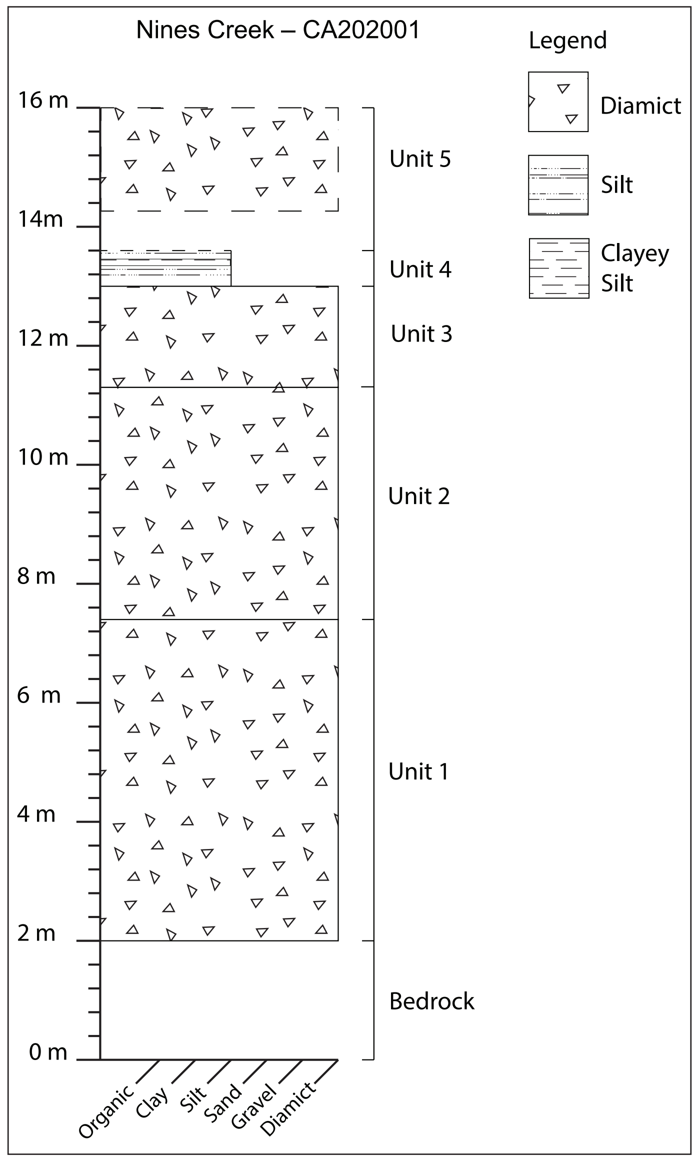

Figure 11. *Stratigraphy of sediments exposed along a river cut on Nines Creek in the central Kluane Ranges (CA201201).*

Unit 3 is interpreted as a colluvial fan deposit based on the high clast content, abundance of angular clasts, and lateral fining. This unit likely formed from successive mass movements originating on the steep slopes above the canyon floor. The lateral fining and thinning of beds in this as the unit pinches out likely indicate a change from proximal to distal position during deposition.

Discussion of regional stratigraphy

The Lewis Creek north section represents ice advancing down Shakwak trench depositing advance outwash sediments. The outwash could have been deposited in a subaqueous environment based on inclined beds but lacks obvious interstratified silt that indicate periods of quiet water deposition to confirm this interpretation. Ice then advances over the site, depositing till. Following deglaciation a paleosol formed and was subsequently buried by lacustrine sediments representing a high stand of Kluane Lake at ~20 m above its current level, which is a higher elevation than previously determined in the Holocene (Clague *et al.*, 2006). Loess and White River ash were deposited over the lacustrine sediments after lake levels dropped.

The Lewis Creek south site represents ice advancing northwest along Shakwak trench depositing advance outwash into a lake. Ice subsequently overruns the site depositing till. Ice advancing out of the St. Elias Mountains or the Ruby Range north of Kluane Lake could have blocked drainage in Shakwak trench to form the lake that ice was advancing into (*cf.* Turner *et al.*, 2016; Cronmiller, 2019).

The Dutch Harbour sections represent ice overrunning the site depositing till during the last glaciation. Then during deglaciation glaciolacustrine sediments were deposited representing a lake occupying Shakwak trench. Finally glaciofluvial outwash gravel was deposited over the glaciolacustrine sediments.

The Goose Bay section represents ice overriding this site depositing till. Outwash gravel documents the initial retreat of ice in Shakwak trench, which is followed by deposition of glaciolacustrine sediments.

The Grizzly Creek section has pre-last glacial sediments (Unit 1 at least) that suggest ice in this area was not erosive enough to remove these sediments. Glaciolacustrine sediment overlying till shows a glacial lake occupied the area during deglaciation. It is possible a readvance occurred depositing another till above the glaciolacustrine sediments but further work is needed to confirm this.

In the central Kluane Ranges during the last glaciation, ice initiated in cirques and expanded and flowed down valley and out into Shakwak trench. During deglaciation ice retreated back up the valleys where glaciers still exist in some high elevation cirques and icefields. The Nines Creek section represents post glacial colluviation and fluvial action.

A composite stratigraphic column was developed to help reconstruct the stratigraphy of Shakwak trench (Fig. 12). It is likely that ice advancing out of the Kluane Ranges to the northwest of Kluane Lake blocked north-flowing drainage in Shakwak trench and resulted in a higher than present lake level (Turner *et al.*, 2016). We see a record of this at the Lewis Creek north (CA203201) and Lewis Creek south (CA203202) sections.

Till deposits preserved in the four Shakwak trench sections are interpreted to record glaciers from the St. Elias Mountains and possibly Ruby Range coalescing in and flowing NW up the trench. Outwash gravel at the Dutch Harbour (CA201901 and CA201902) and Goose Bay sites (CA201903) represent a retreating or stagnant ice front. These sites are located along ice marginal meltwater channels, further supporting the interpretation of ice stagnation. Glaciolacustrine sediments at the Dutch Harbour (CA201901 and CA201902) and Goose Bay sites (CA201903) are interpreted to be the result of sediment deposited into a glacial lake occupying Shakwak trench during deglaciation.

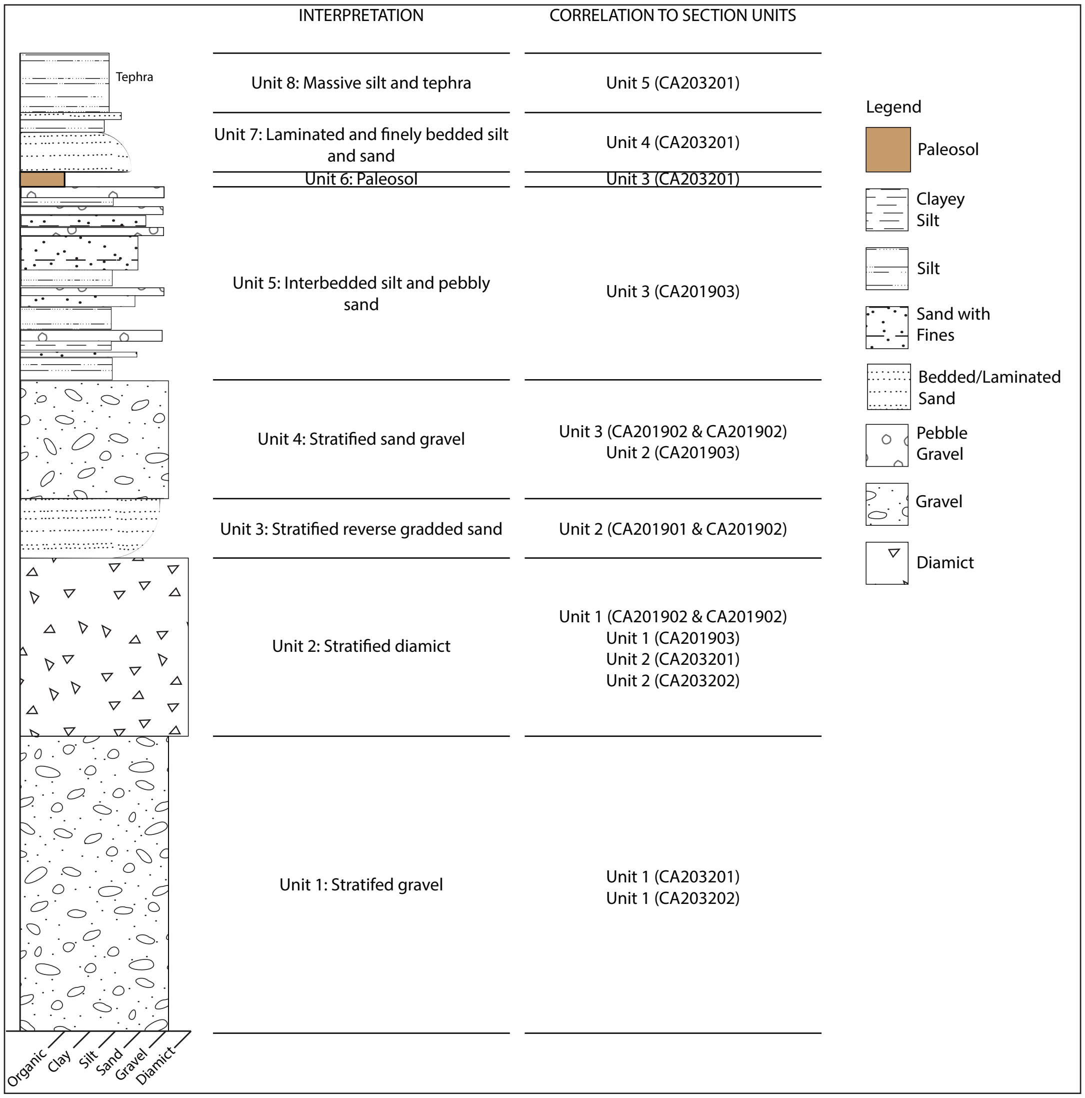

Figure 12. *Compilation of stratigraphy in Shakwak trench from five sites. To the right of the stratigraphic column are unit interpretations and the units that correlate to the individual sections investigated along Shakwak trench.*

Surficial geology landscape model

A general model for the surficial geology of the landscape in the study area has been developed to aid in the discussion of which surficial materials would be expected at each landscape position (Fig. 13). The distribution of surficial materials is primarily controlled by the steepness of slopes and the glacial history in a particular area. The most widespread active modern surficial process is colluviation, or downslope gravitational movement of materials. This, coupled with steep high-energy streams, results in unconsolidated surficial materials that are rapidly moved off-slope. The surficial geology for different landscape positions is discussed below.

Summits, ridges and plateaus

Summits and ridges are predominantly narrow features of bedrock and weathered bedrock. Although, some ridges, especially those at lower elevations, are wider and flatter. The thickness of weathered bedrock is typically <1 m except in the northwest part of the map area where thicknesses >1 m are common.

Loess veneers between 10 and 60 cm thick occur on low angle ridges, summits and plateaus. On plateaus, till blankets (>1 m thick) and veneers (<1 m thick) are common below the loess. Cryogenic mixing of till and loess is indicated by the presence of till clasts in frost boils at the surface. Where loess is present on summits, ridge tops and plateaus, it can dilute the geochemical signature of underlying bedrock and till.

Upper slopes

Upper slopes are located immediately below summit and ridge environments and are typically steep. Rare narrow benches follow bedrock stratigraphy and/or faults. Some of these bench features may be meltwater channels if they are located below the absolute glacial limit of ~1700–1800 m a.s.l. (Kennedy and Ellis, 2020). High slope angles result in rapid downslope movement of weathered bedrock by gravitational processes forming a discontinuous colluvial veneer (<1 m thick) between areas of exposed bedrock. Preservation of glacial sediment is possible on benches if they are below glacial limits. Also, thicker accumulations of colluvium can occur on benches. When soil sampling on upper slopes it should be noted if samples are taken on bench features below glacial limits to account for possible mixing of colluvium with glacial sediments.

Mid-slopes

These slopes are moderately steep. Colluvium accumulates in nearly continuous colluvial veneers (<1 m thick) with localized bedrock knobs protruding through colluvium. Colluvium is commonly loess-enriched on mid-slopes as it is washed off the steep upper slopes by surface water. As with upper slopes, there can be bench features at the mid-slope position and the same sampling considerations should be taken. Care should also be taken to sample materials that are not loess enriched at the mid-slope position to avoid masking till or bedrock geochemistry.

Lower slopes

At the lower slope position a dichotomy exists between valleys in the central Kluane Ranges and Shakwak trench, Duke River Valley and Ä'äy Chùu (Slims River) Valley. Valleys in the central Kluane Ranges are narrow, and the lower slopes are steeper than the lower slopes

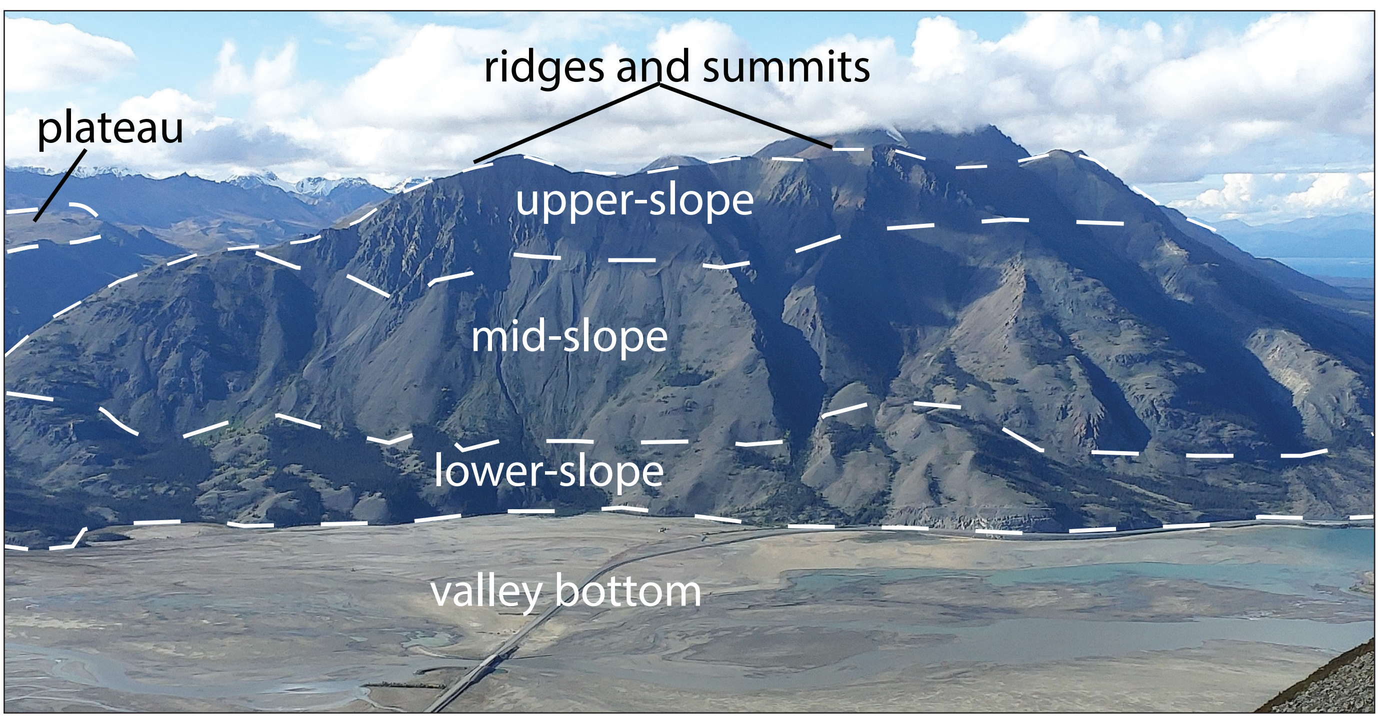

Figure 13. *Surficial geology landscape model superimposed over Sheep Mountain at the confluence of Ä'äy Chù Valley and Shakwak Trench. The valley bottom is the mouth of Ä'äy Chù Valley and the plateau on the left is Bullion Plateau.*

in Shakwak trench and Duke River Valley. Moderate slopes are characteristic of the lower slopes in valleys of the central Kluane Ranges. Thick accumulations of colluvium (>1 m) form nearly continuous aprons. Till and glacial fluvial sediments are rarely preserved at the surface and are typically covered by colluvium. Fluvial sediments can be found in rare pockets perched above the high-water mark.

Conversely, in Shakwak trench and Duke River Valley lower slopes are moderate to gentle. These slopes are characterized by colluvial and alluvial cones and the upper portions of fluvial fans that form thick deposits of colluvium and alluvium. Between fans and cones are thinner colluvial deposits that thicken as slope gradient decreases. There is a higher preservation potential for till on these slopes although it is commonly buried by fans cones and loess.

Geochemical sampling programs should target till where possible or colluvium sourced directly from bedrock. Colluvium derived from glacial sediments would not reflect the bedrock geochemistry and post depositional transport would confound efforts to vector back to the source of an anomaly. An effort should be made to avoid sampling loess and materials enriched by loess.

Valley bottoms

A trichotomy exists between the valley bottoms of Shakwak trench, Duke River and Ä'äy Chù and the valleys in the central Kluane Ranges. These differences can be thought of in terms of stream order. First and second order streams like those in the in the mountains (central Kluane Ranges) are steep and high energy, third and fourth order streams in larger valleys (Duke, Ä'äy Chù) are less steep and lower energy. Finally, Shakwak trench is both a structural basin as well as a higher order fluvial valley bottom.

The valley bottoms of the central Kluane Ranges are much narrower and have steeper gradients than the Duke River and Ä'äy Chù valleys and Shakwak trench. This results in higher energy streams with deeper bedrock incision and more cobble and boulder-rich fluvial deposits. Colluvium is prevalent at the edges of the valleys where it is deposited over fluvial gravel in fans and cones or in aprons between fans and cones. Targets for geochemical sample analysis should be limited to colluvium derived from bedrock or stream sediment samples in first or second order tributaries.

Valley bottoms of Duke River and Ä'äy Chù are characterized by broad braided rivers dominated by coarse sandy gravel. Some glaciofluvial material is preserved in terraces located above bedrock, but valley bottom sediments in these settings are primarily modern fluvial deposits. These sediments are more traveled and therefore more mixed than in higher order streams making them less suitable for geochemical sampling. Samples should be taken from incised streams near the mountain front.

The bottom of Shakwak trench is dominated by broad fans that are aggrading onto the gently-sloped valley sides and floor of the trench. Along the western side of Kluane Lake the dominant surficial materials are fluvial fan sediments and till. Till is more prevalent north of Destruction Bay and in the Burwash Landing area where linear glacial landforms (drumlins and flutes) dominate the landscape. Loess is ubiquitous in broad valley bottoms but is rarely thicker than 50 cm. South of Kluane Lake, ice stagnation topography dominates the landscape (hummocks, discontinuous ridges and kettle lakes). Sediment in this part of the trench comprises thick glaciofluvial and glaciolacustrine deposits with minor till. Streamlined features and thick till deposits suggest significant transport of surficial materials in valley bottom settings like Shakwak trench. Shakwak trench is a poor setting for geochemical sampling and samples should be taken in incised streams near the mountain front.

Geohazards

Permafrost

Permafrost is widespread but discontinuous in the central Kluane Ranges. It is most common on slopes with northeastern and northern aspects and on lower slopes or in valley bottoms. The distribution of permafrost varies widely as does its character (depth, thickness and ice content) based on topography, texture of surficial materials and surface cover. Solifluction lobes, revegetated active layer detachment landslide scars, tilting trees (drunken forest) and thermokarst thaw ponds in the Burwash lowlands are good indicators that permafrost is present. Permafrost is also found in test pits dug where none of these features existed. Permafrost was commonly found 40–50 cm deep, but depths of 10–20 cm occurred where insulating vegetative cover exceeds 10 cm thick. Permafrost was found in a variety of different material types such as fluvial, course and fine-grained colluvium, fibric organics and tephra. Active layer detachment slides are common on the steep slopes in the study area, and are the result of saturated conditions at the bottom of the active layer.

Landslides

This region is characterized by steep valley walls as a result of rapid uplift and repeat glaciations. Steep slopes and highly fractured bedrock result in widespread slope failures such as debris flows and avalanches, rock avalanches and rock fall (Huscroft *et al.*, 2004; Blais-Stevens *et al.*, 2010). Abundant colluvium, outwash, till, and weathered bedrock are easily remobilized into debris avalanches and flows. Large scale landslides in the region have the potential to dam rivers in valley bottoms. This occurred at Vulcan Creek in 2014 in Kluane National Park (Brideau *et al.*, 2019). Lakes that form behind such dams could cause outburst floods if the landslide dam fails suddenly. Landslide hazards pose a risk to existing and future developments and linear infrastructure if mitigating steps are not taken.

Summary

Preliminary surficial geological mapping in the central Kluane Ranges demonstrates the importance of topography in the distribution of surficial materials. Distribution patterns of surficial materials are similar across the mapping area at high elevations. At lower elevations and in valley bottoms, there is variation between the narrow bedrock-controlled valleys of the central Kluane Ranges, the broader semi-confined floodplains of the Duke River and Ä'äy Chù valleys, and the broad Shakwak trench. Introduction of loess can provide additional complexities for soil sampling programs and care needs to be taken to avoid sampling loess where possible. Cryoturbation results in mixing of materials and it is important to recognize its distribution and intensity for accurate and effective analysis of soil geochemical exploration data. The character and distribution of permafrost is affected by slope, aspect, topography and surficial material texture. Permafrost is most common on slopes with north to northeast aspects and in valley bottoms and an average depth of 40–50 cm in the map area. Future infrastructure projects will need to understand the distribution and character of permafrost to avoid instability during and after construction.

Acknowledgments

Funding for this project was provided by Yukon Geological Survey, an NSERC discovery grant to B. Ward, and the Northern Scientific Training Program. Special thanks to Kenya Franz for all the amazing help in the field, Icefield Discovery for providing wonderful accommodations, and Kluane First Nation for supporting our work in their Traditional Territory. Finally, thanks to Derek Cronmiller for completing a thorough review of this paper and providing valuable insights and suggestions on improving the manuscript.

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