Surficial Geology and Glacial History of the Macmillan Pass Area

Prepared for

Fireweed Zinc Ltd.

December 8, 2018

December 8, 2018

Dr. Jack Milton

Chief Geologist

Fireweed Zinc Ltd.

1020-800 West Pender Street

Vancouver, BC V6C 2V6

Dear Dr. Milton,

Re: Surficial Geology of Fireweed Zinc's Macmillan Pass Project

Enclosed is a report describing our interpretations of the ice flow history, type and character of surficial materials and implications for the surficial geochemical sampling, near-surface permafrost distribution and drift thickness for Fireweed Zinc Ltd.'s Macmillan Pass Project in the Selwyn Mountains. It includes maps and data submitted separately as four appendices.

I appreciate the opportunity to work with you in this fascinating area in Yukon and help advance your exploration efforts. Should you have any questions or require additional information, please feel free to contact me via phone or email.

Sincerely,

Dr. Derek Turner, Ph.D. P.Geo

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1 Introduction

1.1 Scope of Work

Drs. Turner and Ward were retained by Fireweed Zinc Ltd. (Fireweed) to complete a surficial geology map of their Macmillan Pass project area (Fig. 1). The scope of work included high resolution mapping of medium to high priority areas (1:5,000 and 1:10,000), 1:50,000-scale mapping of the surrounding area, near-surface permafrost distribution mapping in five areas of interest outlined by Fireweed, and a review of the Quaternary geology of the Macmillan Pass area. A strategic field program was designed to ground truth the surficial geology map, investigate ice flow indicators and test near-surface permafrost conditions in priority areas. Accompanying this report are maps of the surficial geology (terrain) (Appendix A), near-surface permafrost in priority areas (Appendix B), geochemical dispersal distance map (Appendix C) and a compilation of field work site locations (Appendix D).

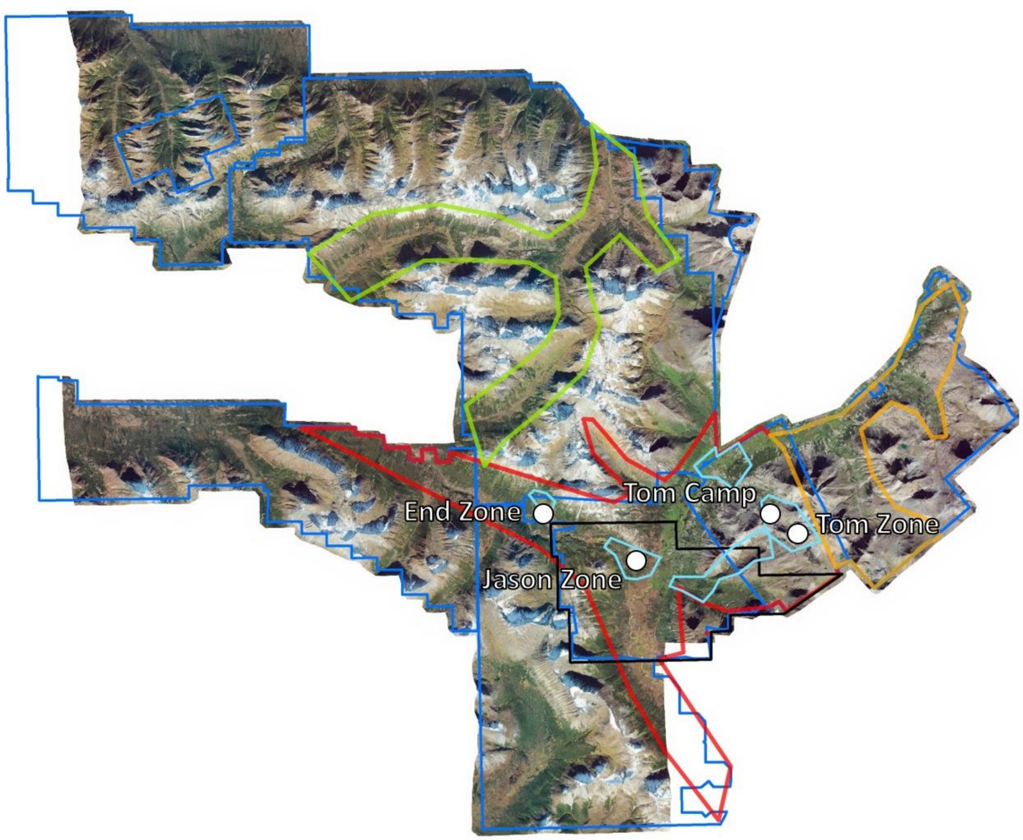

***Figure 1:** Study area for the Macmillan Pass surficial geology mapping. Detailed mapping was completed at 1:10,000 scale for three priority areas, shown in order of priority from medium (green), high (orange) and highest (red). Regional mapping at 1:50,000 scale was completed for the surrounding area within Fireweed Zinc Inc.'s claims (dark blue). Areas of interest for permafrost distribution mapping are shown in light blue.*

1.2 Bedrock Geology

MacMillan Pass lies within the Selwyn Mountains. These mountains formed as part of the Selwyn Basin, a late Proterozoic deep marine basin with active deposition through to the Middle Paleozoic (Goodfellow, 2007). The lithology of the Selwyn Basin includes late Proterozoic continental sediments, Cambrian to Ordovician carbonates, Ordovician to Devonian chert and shale of the Road River Group and Devonian to Mississippian shale, chert and turbidites of the Earn Group (Goodfellow, 2007; Arne and McGarry, 2018). Subsequent faulting, folding and thrusting occurred from the mid-Paleozoic to the Mesozoic. Local intrusion of quartz monzonite occurred in Macmillan Pass in the Cretaceous.

The Selwyn Basin hosts multiple large SEDEX zinc-lead-silver deposits, including the Faro, Grum and Vangorda deposits, several deposits in Howard's Pass and the Tom and Jason deposits in Macmillan Pass (Arne and McGarry, 2018). Mineralization was discovered in Earn Group rocks on the Tom Property in Macmillan Pass in the early 1950's, with current exploration efforts by Fireweed including Tom, Jason, Jerry, End Zone, Mac and BR.

1.3 Regional Glacial History

The Selwyn Mountains were glaciated multiple times by the northern Cordilleran Ice Sheet (CIS) from the latest Pliocene to the late Pleistocene. The northern CIS was composed of semi-independent ice lobes emanating from the St. Elias, Coast, Cassiar and Selwyn Mountains that merged to form a continuous ice sheet (Hughes *et al.*, 1969). The Selwyn Mountains were the largest centre of ice accumulation (Jackson *et al*., 1991), with ice spreading west to central Yukon over more than 300 km (Duk-Rodkin, 1999).

The Selwyn lobe likely grew in stages (Davis and Mathews, 1944; Jackson *et al.*, 1991). Initially, ice expanded from local cirques as alpine glaciers. As the ice thickened, these glaciers merged to form a continuous ice sheet that initially flowed southwest across the Selwyn Mountains from an ice divide to the east. At its maximum, ice thicknesses exceeded 2000 m in accumulation areas of the Selwyn Mountains, covering most peaks except the highest, which protruded as nunataks (Jackson *et al.*, 1991). Most of the Selwyn lobe was strongly topographically controlled, flowing according to underlying valley orientation. The source area in the Selwyn Mountains was one possible exception to this, with evidence in nearby Howard's Pass indicating that with continued growth of the northern CIS, the ice divide migrated across the Selwyn Mountains and ice flowed across lower peaks to the north (Turner *et al.*, 2008).

As the ice thinned, it became increasingly topographically controlled again, with valley glaciers following local valley orientations. Deglaciation of the Selwyn Mountains was mostly by stagnation and downwasting, with ice melting in place, rather than by frontal retreat into source areas (Jackson *et al*., 1991; Turner *et al*., 2008). Evidence for this includes kame and kettle topography in valley bottoms, high elevation deltas and terraces and a lack of recessional moraines in valley bottoms.

1.4 Methods

The surficial geology and terrain of the Macmillan Pass area was completed following the Guidelines and Standards to Terrain Mapping in British Columbia (RIC, 1996). Terrain codes follow the Yukon terrain classification system outlined by the Yukon Geological Survey, which is based on the Terrain Classification System for British Columbia (Howes and Kenk, 1997). Textures were only included for polygons that were field checked.

Terrain mapping was completed using a combination of aerial photograph analysis and LiDAR, orthophotography, satellite imagery and exploration data provided by Fireweed. High resolution digital scans of aerial photographs were obtained through the National Air Photo Library. These images were then turned into stereo models by IGI Consulting Inc. Terrain mapping of the priority areas outlined by Fireweed was conducted at a scale of 1:10,000-scale, except in the area of LiDAR coverage where it was completed at 1:5,000-scale. The surrounding area within the Fireweed property was mapped at 1:50,000-scale.

Field work was conducted by Dr. Turner between August 11th to 15th, 2018 using foot and truck-supported traverses based out of Tom Camp. Helicopter and drone surveys provided additional information. A total of 91 sites were examined and described in detail. At each of these sites, the texture, type of surficial material, surface expression and any significant geomorphic processes were noted (Appendix D). Representative photographs of material types and processes were also taken at each site.

2 Results

2.1 Surficial Materials

Seven surficial materials were observed in the field. The general character of each of these materials is discussed below. The likelihood of each material having near-surface permafrost is also discussed. The definitions of some material types are taken from Howes and Kenk (1997).

The dominant soils observed in the study area are Regosols in areas of recently-weathered bedrock (Orthic Regolsols) and active floodplains (Cumulic Regosols) and Cryosols where there is evidence of relatively shallow (<1 m) active layers (Static Cryosols) or cryoturbation (Turbic Cryosols). Some Brunisols were also observed in well drained areas that do not have near-surface permafrost.

A creamy white to light grey tephra of varying thickness was observed across the study area (Fig. 2). This is likely from the eastern lobe of the White River Ash. This layer is approximately 1185-1168 years old (Lerbekmo, 2008; Jensen *et al*., 2014) and is a useful stratigraphic marker for recent deposition in the study area.

2.1.1 Bedrock

The bedrock in the study area is a combination of shale, conglomerate, sandstone, igneous intrusive rocks and several other lithologies. Bedrock is more prevalent on steeper slopes and local convexities, where other materials are relatively thin. The proportion of bedrock to colluvium varies downslope, with increasingly more colluvium towards the base of the slope (Fig. 3). On moderately steep slopes, there are typically patches of colluvium or till covering any bedrock outcrops. On more gentle surfaces at higher elevations, undulating bedrock outcrops are mixed with thin remnant till veneers (Fig. 4). Some lithologies

Figure 2: a) Typical exposure of White River ash preserved in organics in the South Macmillan River valley; b) Close up of White River ash.

are expressed as more weathered bedrock, rather than solid rock, due to extensive frost shattering since deglaciation.

Valley bottoms typically have sufficiently thick surficial materials to prevent exposure of rock. However, in some valleys, such as near End Zone, meltwater erosion scoured down to bedrock, leaving only a thin veneer of other materials covering bedrock terraces. Conventionally, bedrock is not mapped as being below other surficial materials as it is assumed to underlie all other materials. Any polygon with a label indicating thin material in valley bottoms (e.g. *Mv*, a thin veneer of till) without any stratigraphic relationship indicates shallow depth to bedrock in these locations.

Although soil samples of bedrock or weathered bedrock is not possible, smooth ridges with geomorphically stable tops can have thin veneers of fine-grained residual material that has weathered directly from the underlying bedrock. This material is well-suited for geochemical sampling and has a low transport distance. Exposed bedrock typically does not have near-surface permafrost.

2.1.2 Till

Till is sediment deposited directly by glacial ice without significant modification by other agents of transportation. It is typically poorly to very poorly sorted with a variety of clast sizes and degrees of rounding. Till can be deposited subglacially as basal lodgement till, or as sub- or supraglacial meltout or ablation till. Lodgement till forms from erosion and deposition at the base of the ice. Meltout till forms as ice melts and material falls out. Ablation till is similar to meltout till, but typically occurs at the margin or on top of the ice, rather than at the base. Lodgement till can be distinguished from the other types by being highly consolidated, containing glacially-eroded clasts with striations, facets, lee-end fractures and/or keels, and, most diagnostically, the presence of fissility. One possibly diagnostic property of lodgement till in the study area is a high clay content, which would potentially be washed out of meltout or ablation till during deposition. The difference between lodgement and meltout till can be significant, as lodgement till will

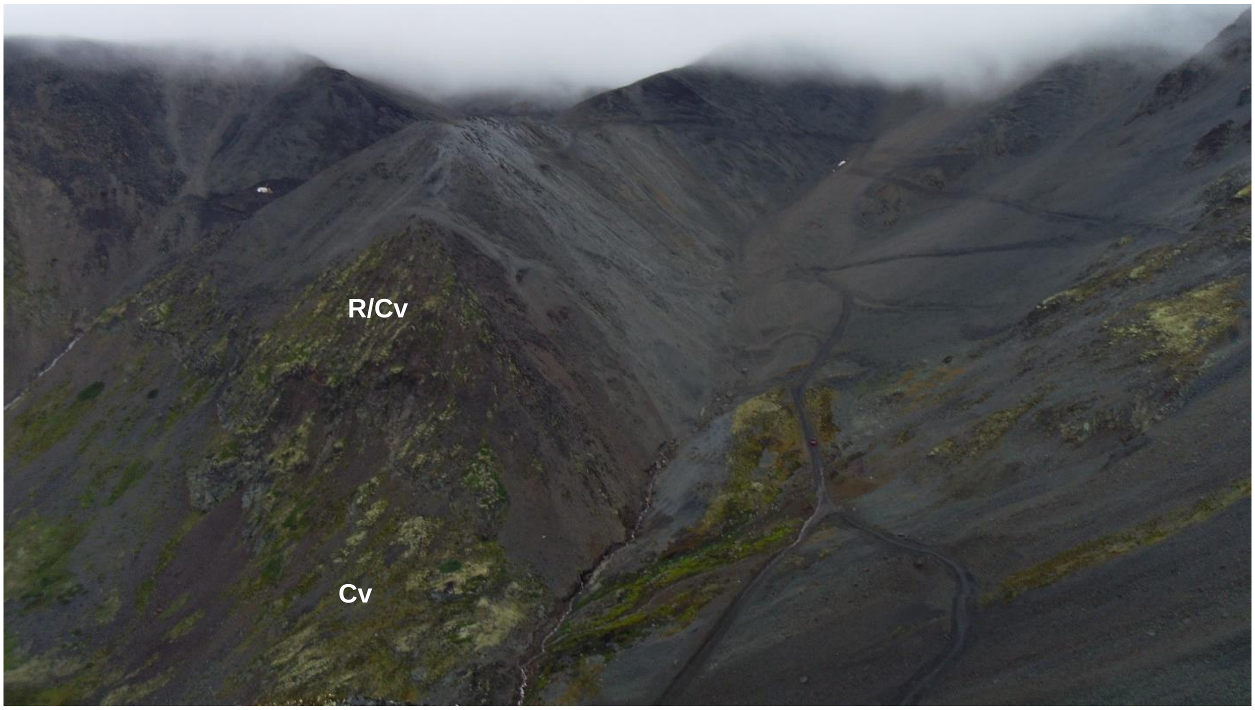

Figure 3: Typical distribution of colluvial veneer (Cv) and exposed bedrock (R) on steep slopes at Tom Zone.

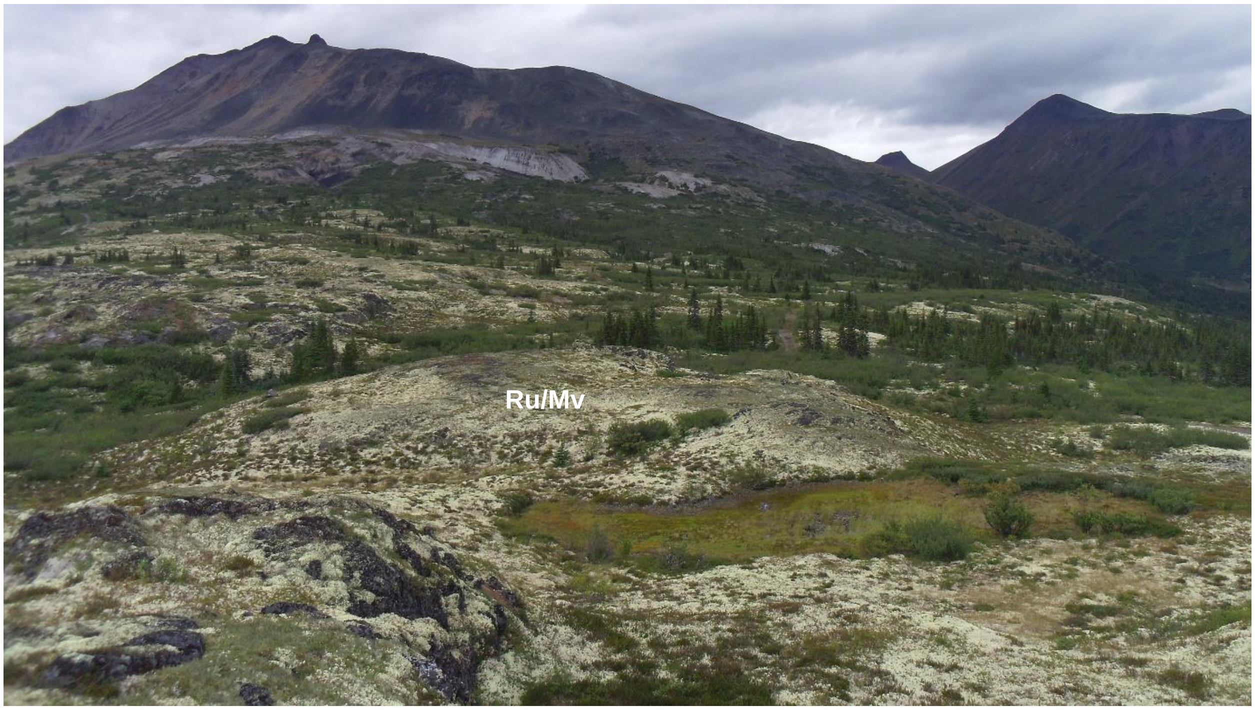

Figure 4: Undulating rock outcrop and till veneer at Jason Zone.

transport geochemical anomalies a relatively short distance, according to ice flow directions. Ablation till may incorporate material that has travelled further, making it a less reliable sample medium.

Lodgement till in the South Macmillan River Valley is best exposed on mid-slope positions and along river exposures below glaciofluvial material. At one such valley-bottom location (at the *'junk yard'*), highly consolidated, clay-rich till with strongly-expressed fissility underlies roughly 3 m of glaciofluvial sandy gravel (Fig. 5). The dark grey colour of the till likely results from clay weathering of shale (Fig. 6). This may be a useful property for soil samplers to observe when looking for C-horizons in lodgement till. Due to the high clay content, lodgement till may also be expressed at the surface by frost boils, although this is not necessary indicative of lodgement processes. One such location is the ridge below Tom Camp, where variably thick till was likely transported <3 km (Fig. 7). The till along this ridge above 1350 m also contains abundant locally-derived clasts.

Till is the study area is expressed mostly as veneers and blankets on lower valley slopes. In a few smaller tributary valleys, remnant moraines deposited during a small re-advance during or after deglaciation persist on valley sides. An example of this is near Tom Camp, where two small ridges running perpendicular to the valley orientation are likely remnant moraines.

Exposures of till along the South Macmillan River and along the road leading to End Zone can also be used to track ice flow directions. Intrusive lithologies in till in the South Macmillan River valley at the southern edge of the study area support ice flow interpretations of flow down valley towards the south from plutons to the north. The lack of intrusive erratics between End Zone and Jason suggest that ice did not flow east along this valley, but instead likely flowed west along the current topographic profile. More observations of intrusive clasts in till would be a useful data set to further refine ice flow reconstructions.

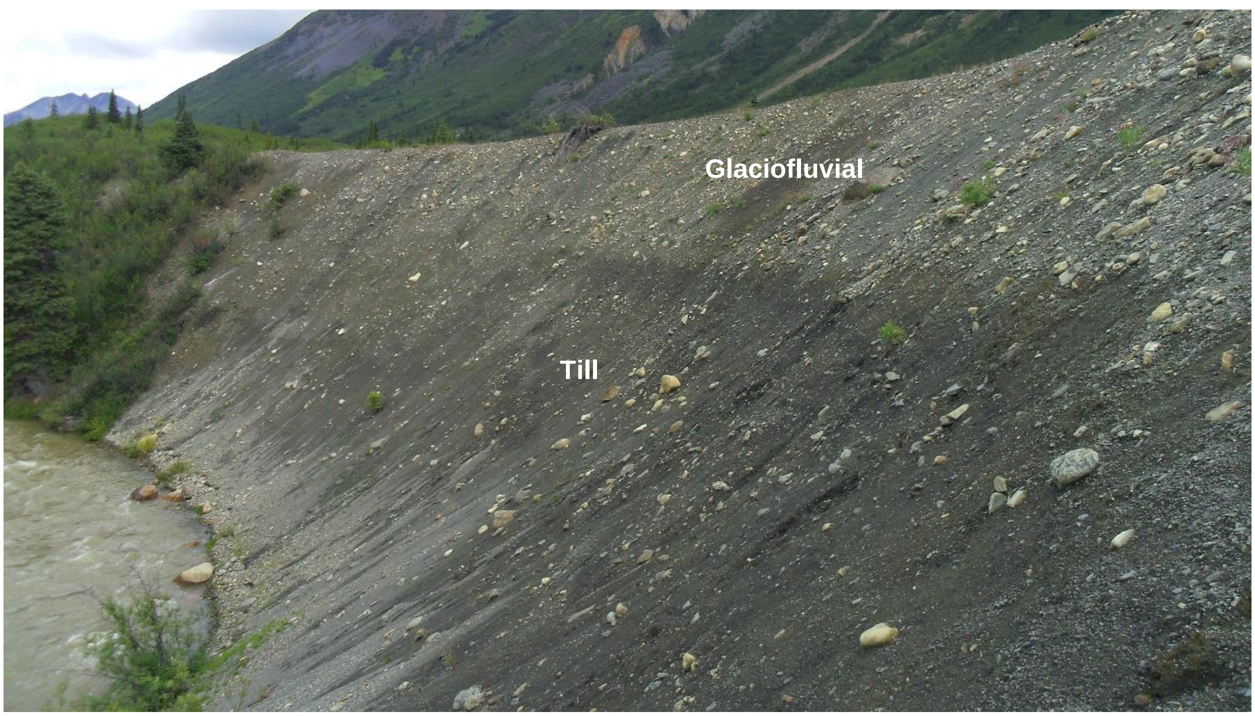

Figure 5: Thick till underlying glaciofluvial sediment exposed along the South Macmillan River.

Figure 6: Glaciofluvial sediment overlying till in Figure 4.

The distribution of near-surface permafrost in till is highly dependant on the texture of the till matrix, slope aspect and thickness of the material. Fine-grained till on north-facing slopes is undergoing periglacial sheetwash (*-Xs*), indicative of shallow frozen ground.

Figure 7: Frost boils in till veneer along a spur near Tom camp.

2.1.3 Glaciofluvial

Glaciofluvial sediment is deposited directly by glacial meltwater either in front of, or in contact with, glacial ice. In the study area, it is relatively course grained and varies from well to poorly sorted with clast sizes ranging from pebble to boulder. It is also generally well drained, either massive or stratified and contains a mix of subangular to well rounded clasts, depending on transport distance (Fig. 8).

Thick accumulations of glaciofluvial deposits fill many of the valleys in the study area and are exposed extensively along the Canol Road (Fig. 9). These deposits likely formed late during deglaciation as ice stagnated and melted, forming ice marginal terraces, crevasse fills and kames (Fig. 10). Kames form as depressions in the ice fill with glaciofluvial sediment. As the ice melts, these former depressions are expressed as hummocks filled with sand and gravel (Fig. 11). Heavily incised terraces and hummocks flank the valley sides in the South Macmillan River valley well above the current valley floor. Near Tom Camp, a glaciofluvial terrace filled with mostly local lithologies probably formed adjacent to ice in the main valley. Two large crevasse fill deposits filled with glaciofluvial sediment are exposed near the southern boundary of the project area along the Canol Road. Glaciofluvial sediment is also commonly deposited in large paraglacial fans that form where unconsolidated sediment in tributary valleys was transported to larger valley floors during or after deglaciation. These fans can be incised by Holocene drainage to form terraces at higher elevations inset by more modern fans.

Figure 8: Thick, bedded glaciofluvial sand and gravel exposed in the side of a hummock (FGh). Exposure is ~3 m high.

Figure 9: Incised glaciofluvial hummocks (FGh) on the east side of the South Macmillan River valley near Jerry Zone.

Figure 10: Glaciofluvial terraces and hummocks (FGth), formed by meltwater during deglaciation.

Figure 11: Example of a glaciofluvial hummock (FGh) with distinctive well drained surface and caribou lichen.

Clast lithologies in glaciofluvial material in the South Macmillan River valley contain a mix of shale, conglomerate, sandstone and intrusives, suggesting that most of the glaciofluvial sediment in this valley is not locally sourced. Glaciofluvial sediment is therefore considered a poor sample medium, as geochemical signatures are often diluted, and transport histories of any anomalies are poorly constrained. There are a few possible exceptions to this, such as the southern of the two crevasse fill deposits, which contains an abundance of angular, locally-sourced clasts that may have a shorter transport distance. The drainage of glaciofluvial materials makes them generally less likely to host near-surface permafrost.

2.1.4 Glaciolacustrine

Glaciolacustrine sediment is composed mostly of clay, silt and fine-grained sand deposited into lakes in association with glacial ice. These deposits are typically stratified and well sorted, with the only clasts being dropstones melted out from localized ice bergs calving off the ice front. Its fine grain size and poor drainage commonly results in thin active layers and ice-rich permafrost in these deposits. Glaciolacustrine sediment is a poor geochemical sample medium, due to its long and unpredictable transport history.

Although no glaciolacustrine sediment was mapped in the project area, lakes were likely dammed at both the northern and southern boundaries. A lake was likely blocked by stagnant ice directly north of the project area. This interpretation is supported by a large delta at the northern boundary (Fig. 12) and poor drainage along throughout this valley, due to the likely fine grain size of the material here. Near-surface permafrost is likely pervasive in this area.

Figure 12: Large delta immediate north of the study area. The delta and the poor drainage indicate that a lake was dammed in this valley, with meltwater entering the lake from the south.

Glaciolacustrine sediment was only observed in the field within the priority areas in one location (*18DT014*), exposed below thick peat accumulations in a palsa (Figs. 13, 14). Similar smaller palsa hummocks elsewhere in the South Macmillan River valley may also overlie glaciolacustrine deposits, as their formation is linked to sediment with poor drainage. However, they may also form on more poorly drained alluvial sediment, such as overbank silt deposited during flood conditions. Some of these hummocky organic deposits were mapped as being stratigraphically overlying glaciolacustrine if they resembled the palsas where this relationship was observed.

Isolated glaciolacustrine deposits are common in kame and kettle topography, caused by local ponding of small lakes by hummocky glaciofluvial deposits and melting glacial ice. Exposures of small glaciolacustrine deposits in Howard's Pass (Turner *et al.*, 2008) indicate that these can form as fine-grained hummocks where lakes developed next to ice, as part of larger glaciofluvial depositional complexes, or on the flanks of eskers.

Previous mapping of the South Macmillan River valley interpreted large exposures of glaciolacustrine sediment at the surface on the west side of the valley, near the southern edge of the study area (Morison *et al*., 1981). This interpretation may have been based on erosional patterns in the clay-rich till in this area, which can be similar to the erosion of glaciolacustrine sediment. It may also have been based on extrapolation from interpreted glacial lakes to the south. In either case, no glaciolacustrine material was observed in this area.

There could be glaciolacustrine sediment buried in the South Macmillan River valley stratigraphically below the observed glaciofluvial sediment and till, although this was not observed in any stratigraphic exposures along the river or Canol Road. There is one ~1.7 km long stretch of the valley, approximately 5 km north of

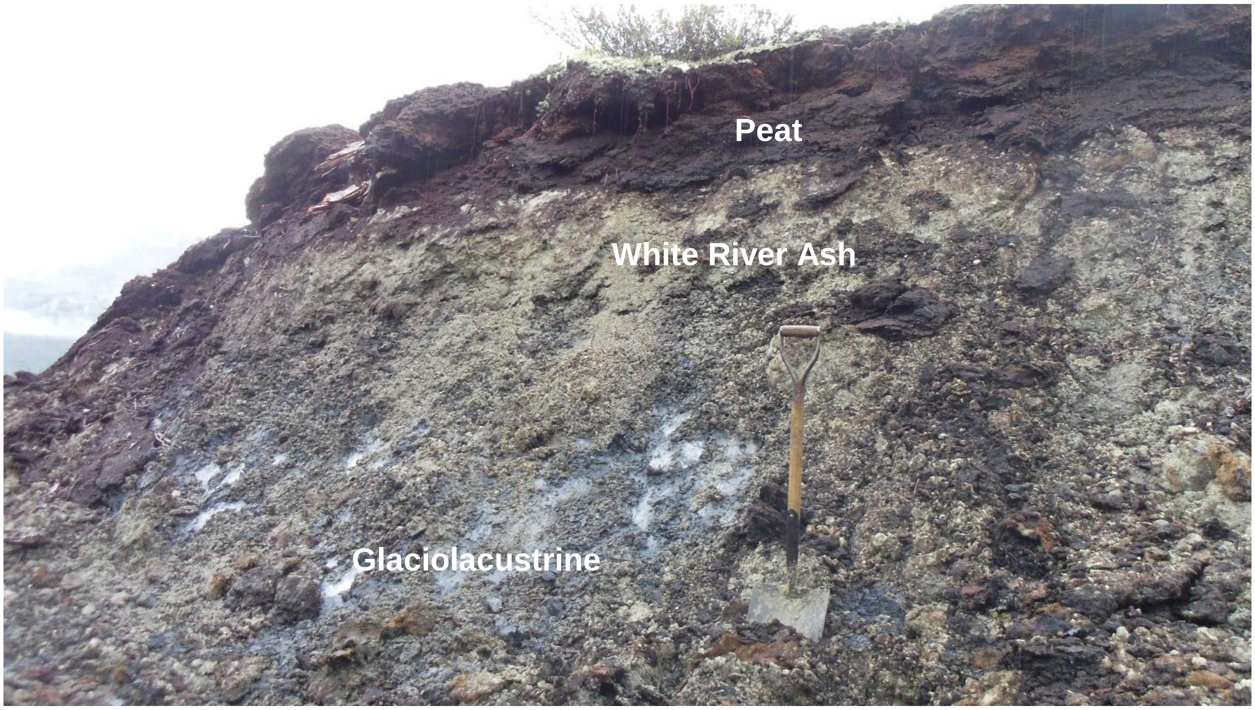

***Figure 13:** Exposure into the side of a peat palsa, near the Tom Camp airstrip. The bottom 2 m are dark grey glaciolacustrine sediment, underlying ~70 cm of White River Ash and 50 cm of frozen peat. Shovel is ~1.5 m.*

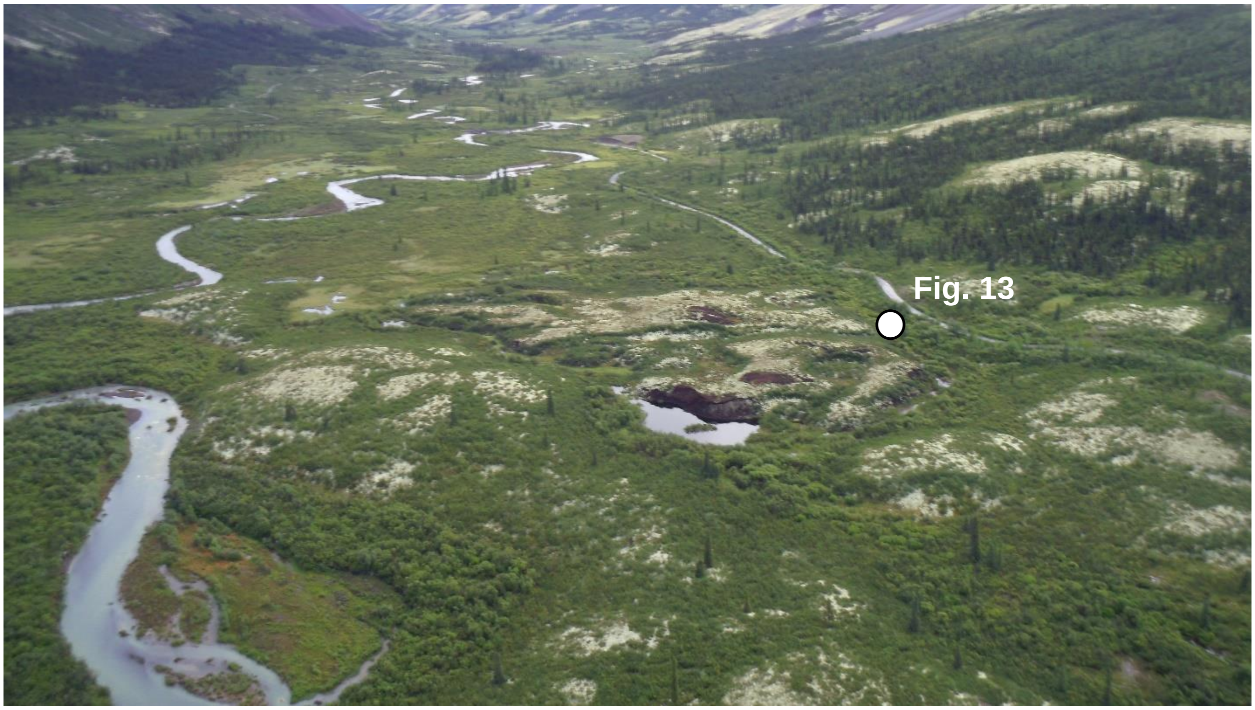

***Figure 14:** Aerial view of peat palsas developed above small pockets of glaciolacustrine material in the South Macmillan River valley.*

the Tom Camp air strip, that could have buried glaciolacustrine sediment. This section of the river is braided, with little vegetation covering exposed gravel bars. This change in river drainage from the typical sinuous drainage pattern is likely from a reduced gradient in this area. Our interpretation is that this area was locally dammed by the glaciofluvial deposits to the south during or after deglaciation, resulting in a relatively flat surface. Therefore, although this area is mapped as being an active fluvial polygon, it is possible that it is underlain by thicker accumulations of ice-rich glaciolacustrine sediment.

2.1.5 Colluvium

Colluvium is material that is transported down-slope by gravity-driven processes. Typically, colluvium is poorly sorted, unconsolidated diamict with an abundance of angular to subangular clasts of local lithologies. Colluvium in the study area sourced from shale is dark in colour, has abundant angular shale clasts and can have a clay- and silt-rich matrix. However, if the parent material for the colluvium is another surficial material besides bedrock, the resulting colluvium will inherit its properties. For example, till deposited as lateral moraines on valley sides can be transported by both slow and rapid mass movements into toe slope or valley bottom positions. The resulting colluvium would then contain glacially-eroded clasts of erratic lithologies. In these cases, colluvium can be distinguished from till by its lack of consolidation, surficial expression and slope position.

Colluvium has several surficial expressions in the study area. Most commonly, it occurs as thin veneers or thicker blankets on valley sides (Fig. 15). Thinner colluvium is more common on steeper slopes or areas with local convexities such as the sides of ridges or spurs. Thicker colluvium is more common in concavities, lower slope positions, and in aprons, fans and cones[1] where mass movement processes are active (Fig. 16). These processes include rapid mass movements, such as rock slides (-*Rr*), rock falls (-*Rb*), debris flows (-*Rd*), and slow mass movements. These slower slope failures include solifluction lobes (-S) and rock (frost) creep (-*Fg*) caused by periglacial processes, typically on north-facing slopes (Fig. 17). Many north-facies cirques currently have rock glaciers in them. These typically consist of large blocks of frozen colluvium that slowly flow due to periglacial processes. There are also a few large slumps emanating from north-facing cirques that are interpreted to have transitioned into large rock glaciers connected from the cirque to the valley floor (Fig. 18).

The potential for a larger bedrock instability along the slope across the valley from the planned Tailings Management Area was identified during the mapping. Multiple large tension cracks were interpreted from the LiDAR data along this slope (Fig. 19). These features should be investigated further to confirm that they are tension cracks, especially if tailings infrastructure is developed in this area.

[1] Fans and cones were mapped as being colluvial if the dominant process was interpreted to be a rapid mass movement event. If the dominant process was interpreted to be a creek or stream, it was mapped as fluvial.

Figure 15: Incised colluvial blanket (Cb), illustrating the thickness and texture of these materials in toe-slope positions.

Figure 16: Examples of colluvial cones with active rock slides (Cc-Rr).

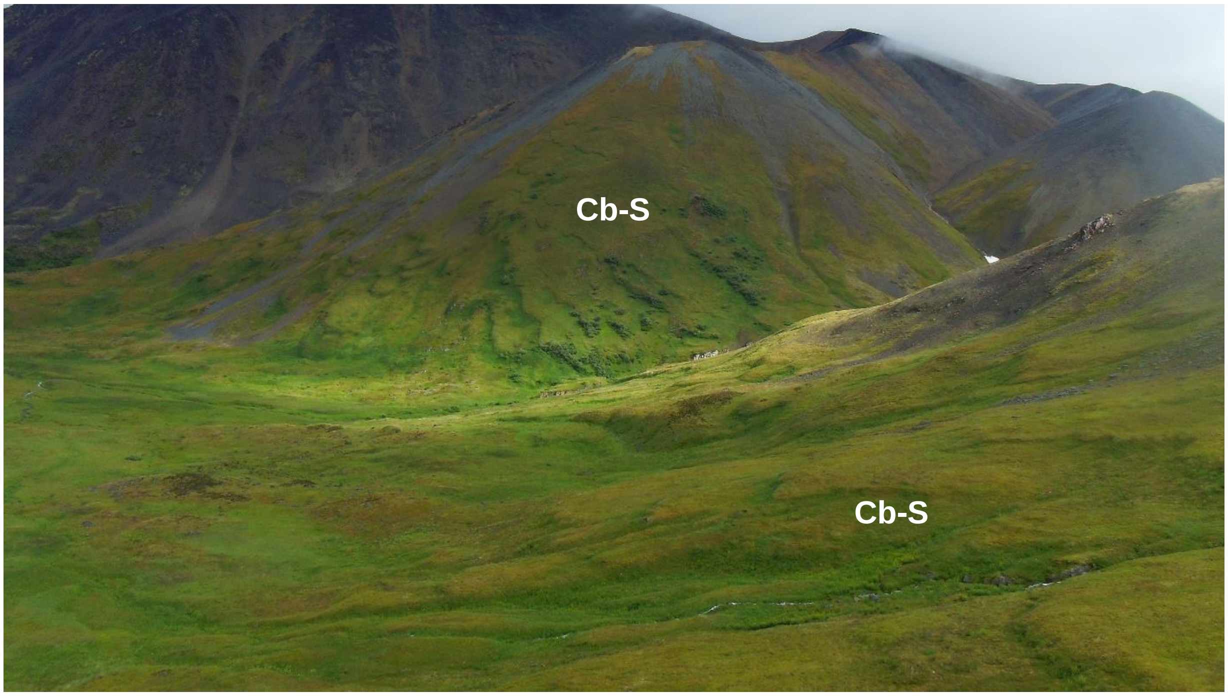

Figure 17: Solifluction lobes composed of colluvium (Cb-S), created by the slow downslope movement of material over a frozen substrate.

Figure 18: Large periglacial slump with active debris flows (Ccrh-ZFgRud).

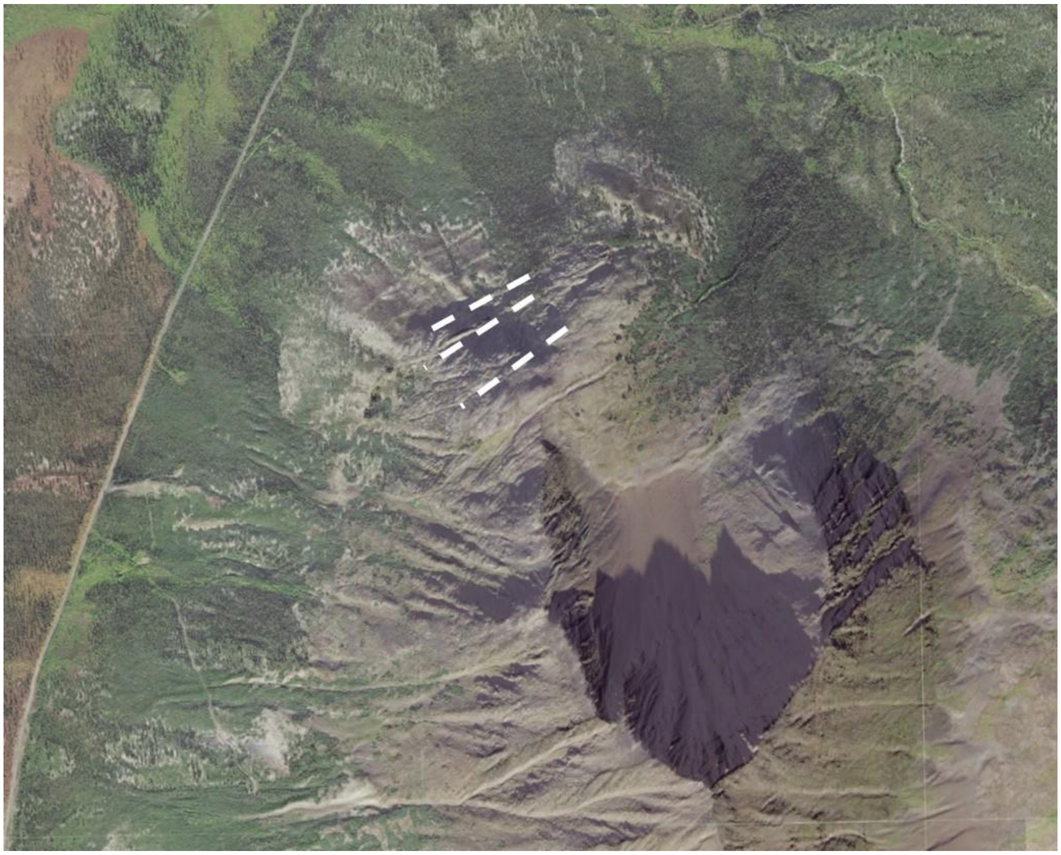

Figure 19: Possible tension cracks mapped (-Rk) near the Canol Road, south of Tom Camp.

2.1.6 Fluvial

Fluvial, or alluvial, sediment is transported and deposited in fans, rivers and streams. It is typically composed of stratified, well sorted, fine- to coarse-grained sand and gravel. In larger rivers, such as the South Macmillan River, these grain sizes are commonly interbedded with organic beds and silt deposited during overbank flooding conditions (Fig. 20). Fluvial clasts can range from well rounded to subangular, due to the abundance of shale in the area. The depth of fluvial sediment varies. In steeper areas, it may occur as a veneer or blanket as thin as 1 m. The South Macmillan River valley has exposures showing >3 m of fluvial deposition. Thicknesses of fluvial sand and gravel are likely significantly higher in the braided portion of the South Macmillan River, northeast of the Tom Camp airstrip. Fluvial deposits typically have deep active layers due to their high permeability. However, rivers in wider valleys with broader floodplains will have significant fine-grained sand and silt and buried organics that can have ice-rich, near-surface permafrost.

Holocene fluvial fans can be distinguished from glaciofluvial and paraglacial fans deposited during and immediately after deglaciation based on their size and location. Some of these larger, older fans have since been incised by modern streams, producing a fluvial fan at their base (Fig. 21).

***Figure 20:** Thick accumulations of silt, sand and gravel in the floodplain of the South Macmillan River valley, near the Tom Camp airstrip. The depth of the White River Ash indicates approximately 2-3 metres of deposition on this floodplain in the past ~1200-1150 years.*

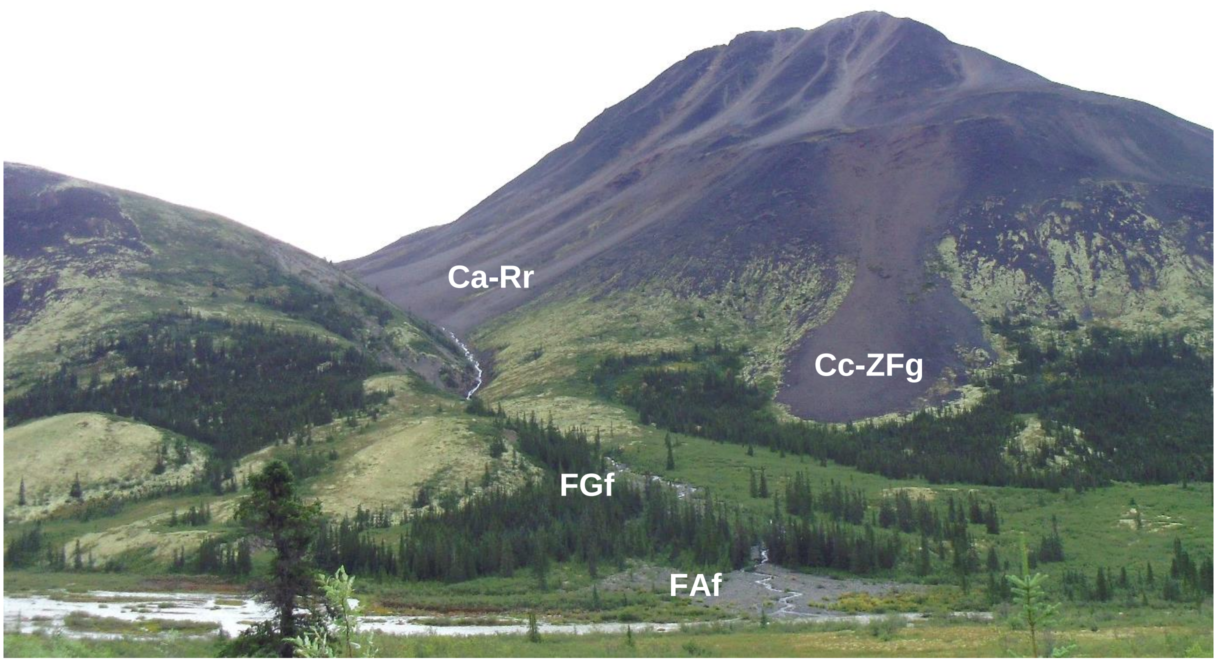

***Figure 21:** Paraglacial fan (FGf), with an active fluvial fan depositing at its toe (FAf). Above the fans are a colluvial apron with active rock slides (Ca-Rr) and a colluvial cone formed by periglacial rock creep (Cc-ZFg).*

Some of the tributary streams and rivers that drain into the South Macmillan River valley have iron-cemented fluvial deposits armouring their bed. In some cases, such as near Tom Camp, these creeks have incised through their fans in small canyons, reaching the bedrock below.

2.1.7 Organic

Organic materials are a mix of mineral and organic matter that form from the accumulation of decomposing vegetative matter. Organics in the study area are mostly fibric to mesic and occur as veneers, blankets and plains in flat or gently-sloping, moderately to poorly drained areas (Figs. 22, 23). They typically have shallow active layers, with near surface permafrost being common. Evidence of this in organics in the South Macmillan River valley includes widespread thermal erosion features, such as drunken spruce, beaded drainage and thermokarst ponds (Fig. 24).

Thick organic deposits were observed in palsas east of the Tom Camp airstrip overlying glaciolacustrine sediment (Fig. 14). One palsa had over 3 m of fibric organics exposed, with >30 cm thick segregated ice lenses, capped by up to 1 m of White River Ash (Fig. 13). These palsas grow from frost heave due to faster and deeper freezing in the palsa compared to the surrounding area. Their formation in this area may be related to the underlying glaciolacustrine sediment, with the resulting poor drainage causing more rapid and deeper freezing than in the surrounding fluvial and glaciofluvial sediment. Once palsas begin to grow, thinner snow packs in winter cause less insulation, resulting in even greater frost heave. Thermal collapse of the peat palsas in Macmillan Pass and in neighbouring areas due to increased temperatures and active layer deepening has increased in recent decades and will likely continue in the near future (Kershaw, 2003; Mamet *et al*., 2017).

Figure 22: Examples of valley-bottom organics in the South Macmillan River valley, mapped as an organic plain (Op; left) and an organic blanket (Ob; right).

Figure 23: Organic veneer above till and shallow bedrock on a gentle slope near End Zone.

Figure 24: Drunken spruce trees, indicative of thermal erosion of near-surface permafrost.

2.2 Geochemical Dispersal Distances

Two of the most direct uses for a terrain map for mineral exploration is to help plan future geochemical sampling surveys and to interpret material types of previously-collected samples. To facilitate this, we created a Geochemical Dispersal Distance map based on the terrain mapping (Appendix B). This map ranks polygons into six categories based on the dispersion distance of surficial materials from their source. These categories were then coloured to help visualize their distribution. Because this map is a derivative of the terrain map, it carries the same level of precision and any other associated limitations. Care should be taken to not ‘zoom in’ past the appropriate map scale.

The key variable in creating this map is an interpretation of the relative transport distance of the dominant surficial material in a polygon (Table 1). Materials that are more likely to reflect nearby bedrock (e.g. bedrock itself, thin colluvium) were assigned short transport distances. Materials with long transport distances are those that are from outside of the immediate valley, or potentially outside of even neighbouring valleys (e.g. glaciofluvial, glaciolacustrine). These were given the same rank as materials that do not reflect the geochemical signature of underlying bedrock (*i.e.* organics). Till and colluvium were broken into categories based on thickness (veneers; blankets and thicker expressions). Till veneers are more likely to have shorter transport distances compared to till blankets or thicker till expressions.

There is abundant glaciofluvial sediment in the South Macmillan River valley. Most of this sediment was likely reworked by meltwater after being transported by glacial ice. Evidence for far transport distances in this material type includes the abundance of well rounded intrusive clasts throughout the South Macmillan River valley, even well away from potential source areas for these lithologies. However, in some cases, glaciofluvial sediment is likely more locally-sourced. For example, the small glaciofluvial terrace on the south side of the valley near Tom Camp, and the southern crevasse fill complex in the main valley. Both of these examples contain mostly smaller and angular shale clasts, likely reflecting a more local valley source. However, the finer fraction of these deposits may have been extensively reworked from beyond the local source and have therefore been considered to have long transport distances.

Table 1: Relationship between primary surficial material type, geomorphic expression and interpreted geochemical dispersal distances.

Geochemical Dispersal Distance	Example Material Types and/or Expressions
Long transport distances or not reflective of bedrock geochemistry [6]	FG, O
Moderately long transport distances [5]	FAp
Moderate transport distances [4]	FAf, Mb, Mh
Moderately short transport distances [3]	Mv, Cb, Cc
Short transport distances [2]	Cv
Residual soil or rock [1]	R, Rh

2.3 Interpreted Surficial Material Thicknesses in the South Macmillan River Valley

One of the goals of this project was to help Fireweed understand possible surficial material thicknesses in the South Macmillan River valley. To help achieve this, three cross sections were broadly interpreted using the LiDAR and DEM data and any other available subsurface data and stratigraphic observations (Figs. 25-28). These are extrapolations of bedrock depths using the assumption of a U-shaped topography typical of glacially-scoured valleys. The profiles therefore carry significant error, should only be used as an initial approximation of drift thickness and require more subsurface data to confirm.

Interpreted thicknesses of surficial materials of ~50 m is supported by: 1) rotary drill data with sediment thicknesses up to ~20 m on valley sides; and 2) preserved records of drill core in valleys in nearby Howard's Pass that contain similar thicknesses (Turner *et al*., 2008). However, some valleys in Howard's Pass also contained incised paleo-valleys inset into broader valleys where surficial material thicknesses are significantly greater than would be expected using a U-shaped topography. Conversely, local bedrock highs could result in much thinner drift than expected.

The three cross sections below were selected to show three different drift thicknesses and stratigraphic relationships. The first profile (Fig. 26) represents the possible stratigraphy in the valley in the southern portion of the study area. The glaciofluvial fill is less extensive and likely thinner here compared to further north. The underlying till is extensively exposed along the western side of the valley and was observed in multiple locations stratigraphically a few metres below the glaciofluvial material along the South Macmillan River. This till has active sheet washing (*-Xs*) that indicates the presence of near-surface permafrost. The east side of the valley has thick glaciofluvial ridges and hummocks, possibly produced by crevasse fill into melting ice during deglaciation. Road exposures in these ridges with angular clasts of local lithologies support the interpretation of supraglacial infill from the surrounding valley walls.

The second cross section is south of Jason Zone (Fig. 27). The dominant surficial materials in the middle of the valley at this point are a mix of fluvial and organic material overlying thick accumulations of glaciofluvial sediment. Till likely underlies the glaciofluvial material, as shown in stratigraphic exposures further south in the valley, although the depth of this contact at this cross section is unknown. This till is partly exposed on the valley sides, where the glaciofluvial fill thins and where it has not been covered by colluvium from the nearby slopes.

The thirds cross section (Fig. 28) represents a more complex stratigraphy in a unique portion of the South Macmillan River valley. The valley here is flat-bottomed and the river is braided. This topography may be a result of local damming of meltwater, possibly by ice or the development of glaciofluvial fans to the southwest, followed by deposition of outwash. The interpreted profile here therefore includes a layer of glaciolacustrine material, although there is no direct evidence of this or till underlying the glaciofluvial outwash. Regardless of the stratigraphy in this portion of the valley, the surficial materials are likely thick here.

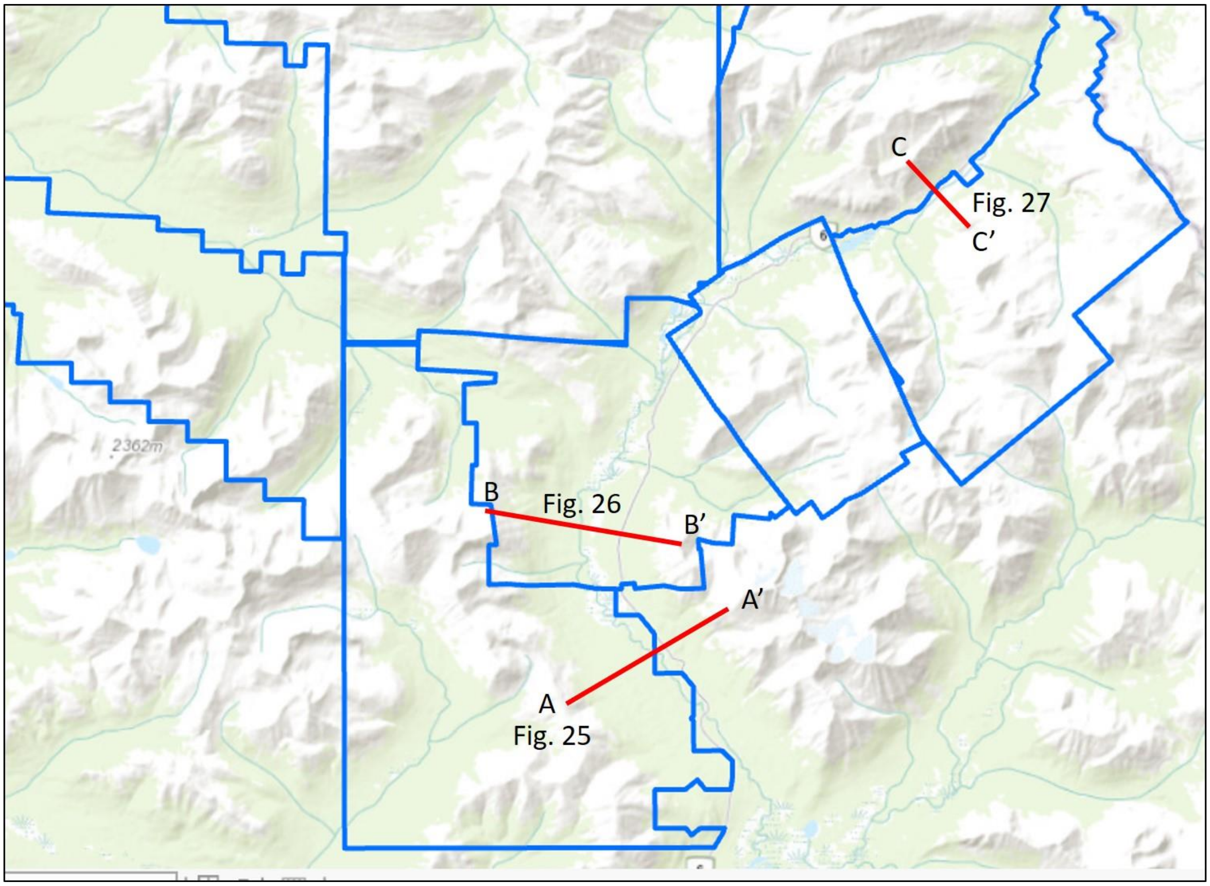

Figure 25: Locations of the topographic profiles shown in Figures 25-27.

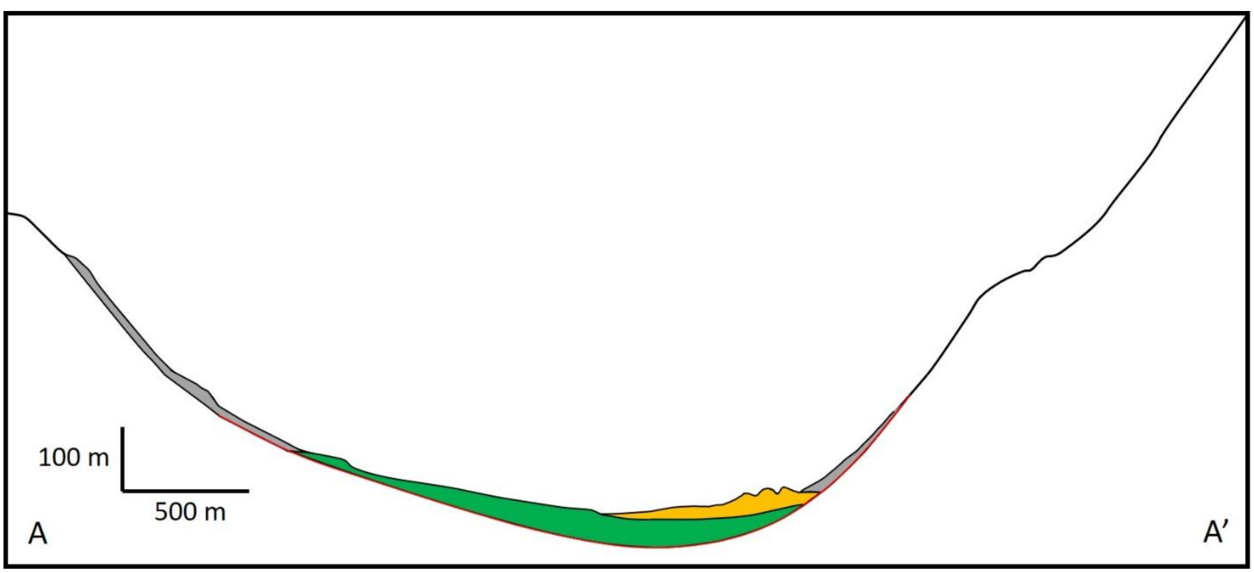

Figure 26: Interpreted cross section of surficial material from A-A’ (see Fig. 25 for location). Till is green, glaciofluvial sediment is orange and colluvium is grey.

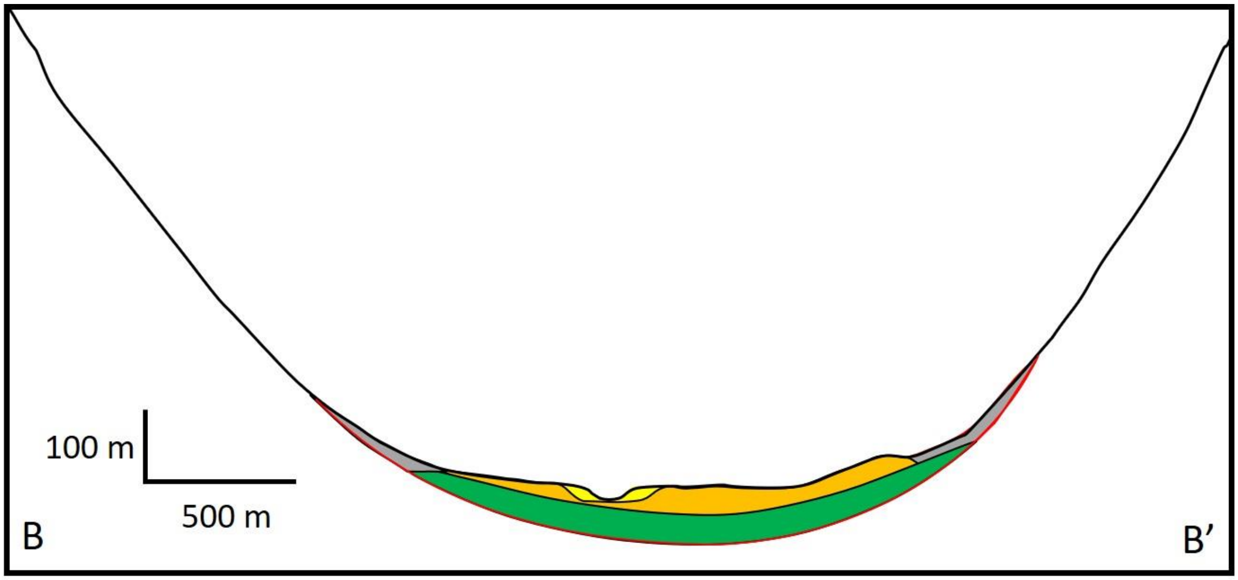

Figure 27: Interpreted cross section of surficial material from B-B’ (see Fig. 25 for location). Till is green, glaciofluvial sediment is orange, colluvium is grey and fluvial sediment is yellow.

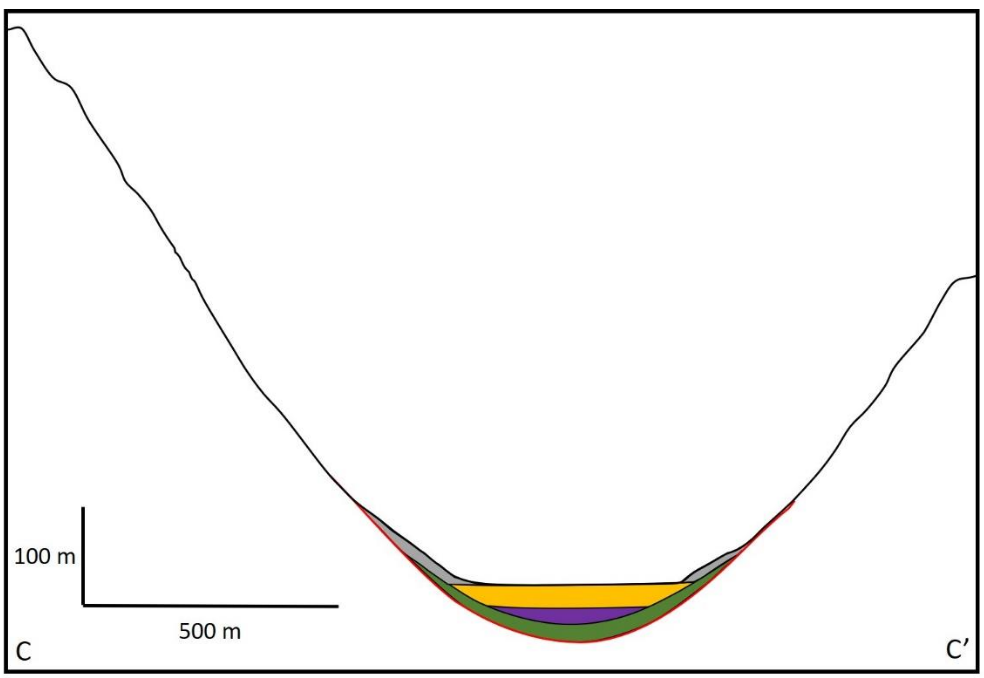

Figure 28: Interpreted cross section of surficial material from C-C’ (see Fig. 25 for location). Till is green, glaciofluvial sediment is orange, colluvium is grey and glaciolacustrine sediment is purple.

2.4 Near-Surface Permafrost Distribution

Permafrost is defined as ground that is frozen for longer than two consecutive years. The Macmillan Pass area is close to the boundary between the zone of extensive discontinuous permafrost, with 50-90% of the ground underlain by permafrost, and the zone of continuous permafrost (Brown *et al*., 1998). Despite being south of this boundary, deep-lying permafrost is likely pervasive in the study area, except possibly as taliks under standing water bodies and larger rivers. The focus of this mapping was to identify the relative distribution of ice-rich permafrost within a few metres of the ground surface (*i.e.* near-surface) in the surficial material, which may be sensitive to climate change and disturbance during infrastructure development. There is well-documented evidence of widespread regional permafrost degradation in Macmillan Pass and the surrounding areas over the past five decades (e.g. Kershaw, 2003). Some of the palsas within the project area are actively being monitored and measured, giving an invaluable source of data for future infrastructure planning.

Analysis of the distribution of permafrost within the areas identified by Fireweed was completed based on the surficial geology mapping and field investigations, supplemented by high resolution drone footage flown by Fireweed and any available subsurface or regional data. The scale of this analysis is therefore the same as the surficial geology mapping in these areas. Test pit data from the proposed millsite area, collected in late August, 1981 near the Tom Camp air strip (Thompson Geotechnical, 2017), was particularly useful for determining the distribution and character of near-surface permafrost in this area. Soil and test pit observations from previous work can be misleading if they record seasonal freezing of the active layer rather than permanently frozen ground. However, the timing of these test pits in late summer is ideal for evaluating near-surface permafrost conditions in this area.

Four categories of relative likelihood of ice-rich, near-surface permafrost were defined and assigned to each surficial geology polygon:

- **Higher Likelihood** – Definitive evidence of ice-rich, near-surface permafrost.
- **Moderate Likelihood** – No definitive evidence, but contains materials, textures or processes similar to higher likelihood polygons.
- **Lower Likelihood** – Less likely to have near-surface permafrost due to texture and material type, but near-surface permafrost is still possible.
- **Unlikely** – Lowest likelihood of near-surface permafrost due to observations of a lack of permafrost or conditions that are not conducive to the formation of ice-rich ground.

Definitive evidence of near-surface permafrost includes: 1) late-summer soil/test pits or exposures that encountered frozen ground near the surface; 2) evidence of thermal erosion, such as beaded drainage, thermokarst lakes, ribbed fens, sheetwash or drunken spruce trees; or 3) periglacial landforms indicative of relatively thin active layers less than a few metres thick above ice-rich permafrost, such as peat palsas, solifluction lobes or frost boils.

Well drained, permeable materials typically have lower likelihoods of near-surface permafrost. For example, the extensive glaciofluvial material in the South Macmillan River valley, as well as some of the most clast-supported colluvium on the valley sides, have a lower likelihood to have ice-rich permafrost near the surface. An exception to this may be in the millsite area near the Tom Camp air strip, where iron cementation of glaciofluvial sediments has resulted in locally-reduced drainage conditions and increased ice content in these materials.

Poorly drained materials, such as organics and fine-grained glaciolacustrine sediment, have a higher likelihood of near-surface permafrost based on mapped features and field investigations. Fluvial material is a mix of sand, gravel and overbank silt and was not observed in cut bank exposures to have near-surface permafrost in the target areas. However, evidence of thermal erosion in other parts of the valley suggests that this varies, likely dependant on changes in texture and permeability.

Aspect is also an important property in determining the presence of near-surface permafrost in a polygon. An example of this is near Tom Zone, where coarse-grained colluvium on north-facing slopes has active periglacial landforms (e.g. solifluction lobes, rock glaciers), whereas similar material on south-facing slopes does not have shallow permafrost.

2.5 Ice Flow Reconstructions

Ice flow reconstructions typically rely on multiple lines of evidence, such as glacial landforms (e.g. drumlins, crag-and-tails, roche moutonnees), subglacial erosional features (e.g. striations, chatter marks, glacial grooves), meltwater channels, erratic trains and any other data that indicate the direction of ice flow. Below is a preliminary glacial history of the South Macmillan River valley based on the mapping and limited field program. More detailed interpretations would require further field work.

At least three stages of ice flow likely occurred across the project area during the last glaciation (Fig. 29), broadly correlating in style to those described by Davis and Matthews (1944) for the southern Cordilleran Ice Sheet and by Turner *et al.* (2008) for ice growth and decay in nearby Howard's Pass. Initially, alpine ice flowed from local cirques that were strongly controlled by topography (Phase 1). Ice likely flowed into the South Macmillan River valley from multiple directions, including cirques near Tom Zone, merging to form a valley glacier that flowed to the south. A wide, glacially-scoured groove observed at Jason Zone indicates ice flow across this area was approximate to the south (206º; Fig. 30). This valley glacier may have initially also been fed by cirques southeast of End Zone, although no evidence of this ice flow across Jason Zone was observed.

As the valley ice thickened and filled the South Macmillan River valley, ice flowed more independent of topography (Phase 2). At the peak of the last glacial maximum, ice likely exceeded all peaks below roughly 2000 m (Fig. 31). Although flow of the Selwyn lobe at this time was still largely controlled by topography (Jackson *et al*., 1991), ice flow in the Macmillan Pass area may have been more topographically independent, being close to the source of the ice lobe. Near Tom Zone, high elevation conglomerate erratics suggest that ice flow across the massif was to the south (Fig. 32), roughly perpendicular to the orientation of the valleys. However, ice in the valleys themselves may have been more sheltered, without significant geochemical dispersion during this phase. Ice flow at Jason Zone was likely to the west at this time. Evidence for this includes felsic intrusive erratics sourced from across the South Macmillan River valley to the east (Fig. 33) and east-west oriented fine striations cross-cutting the broad groove mentioned above (Fig. 34).

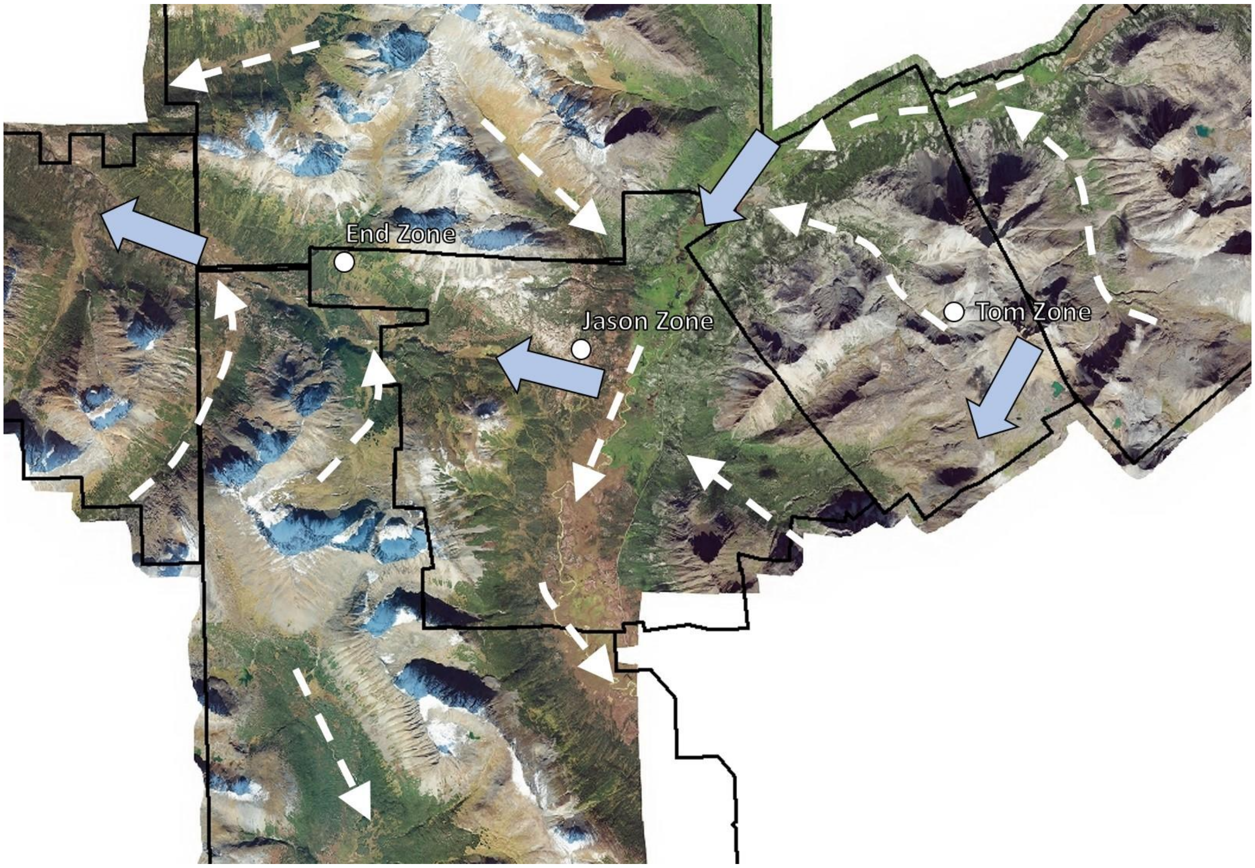

***Figure 29:** Interpreted ice flow directions across the South Macmillan River valley during the last glaciation. Maximum ice flow directions are shown in large blue arrows. Ice flow early and late during glaciation are shown with dashed white arrows.*

***Figure 30:** Glacially-eroded groove in bedrock at Jason Zone oriented towards 206^o. This groove was created early during glaciation and is inset by two sets of cross-cutting striations, a older set towards 228^o and a younger set also oriented 206^o.*

***Figure 31:** View across the South Macmillan River valley from near Tom Camp. Dashed white line indicates the approximate maximum ice surface during the last glaciation. Peaks above this line were likely nunataks projecting above the ice.*

***Figure 32:** Chert conglomerate erratic above Tom Camp, transported across the valley from the northeast. Striated clasts and thin till were also observed on this plateau surface.*

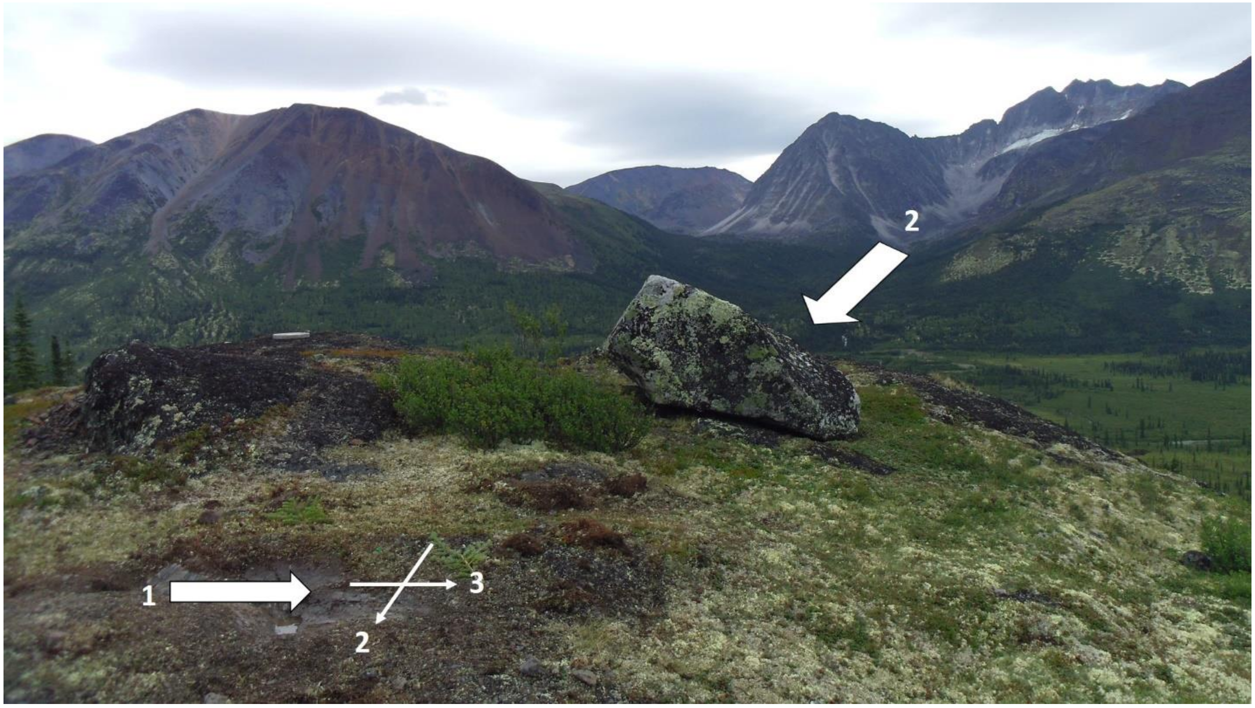

***Figure 33:** Ice flow reconstructions at Jason Zone. Arrows indicate ice flow directions. Numbers denote the interpreted order of ice flow phases. The groove shown in Figure 30 suggests early ice flow to the south-southwest (1). A second ice flow direction is recorded by fine striations cross-cutting the groove and by igneous intrusive erratics sourced from across the South Macmillan River valley in the background (2). A second set of fine striations cross-cutting both the groove and east-west striations shows that late-stage ice flow returned to a valley-parallel orientation (3).*

***Figure 34:** Fine striations in the glacially-eroded groove at Jason Zone. Ice flow direction numbers match those in Figure 33.*

With the onset of deglaciation, thinning ice likely became progressively more topographically controlled (Phase 3) and ice returned to a similar pattern as in Phase 1, with ice flowing south down the South Macmillan River valley. A possible rouche mountinee (Fig. 35) and fine striations oriented north-south cross-cutting both the earlier east-west striations and the broad groove at Jason Zone (Fig. 34) support this interpretation.

Ice flow across End Zone likely continued to the west during this phase, emanating from the cirques to the southeast, between End and Jason zones. No felsic intrusive erratics were observed in the till to the east of these cirques, towards Jason Zone, indicating that ice flow did not move east through this valley during Phase 3. In the valley around the Tom Zone, the thinning ice returned to a valley-parallel ice flow orientation. Two small moraines near Tom Camp suggest that this cirque remained active during initial deglaciation, possibly resulting in minor glacial re-advances in this valley.

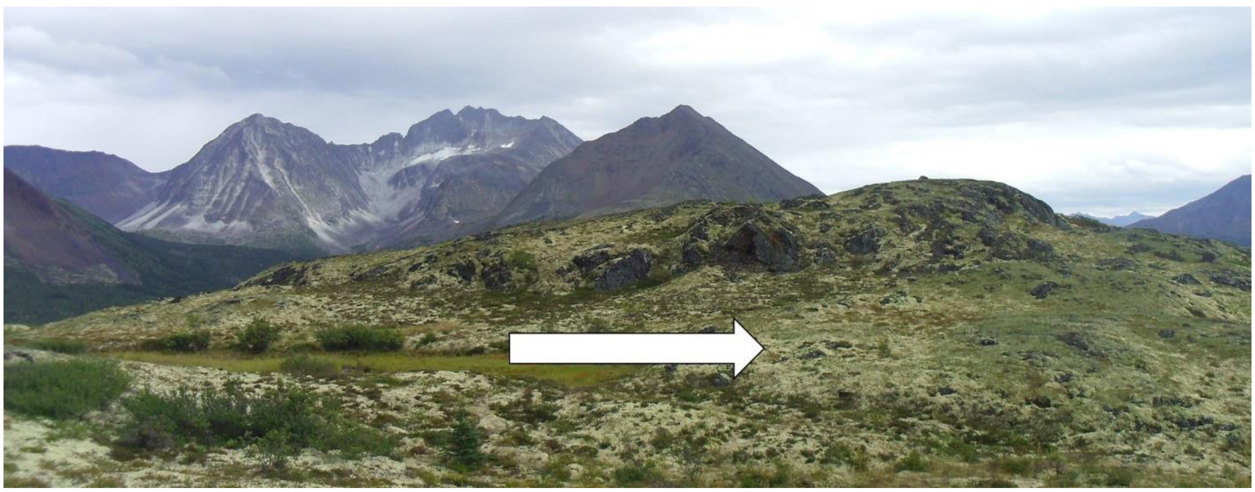

Figure 35: Possible roche moutonnee at Jason Zone, supporting the interpretation of late-stage, valley-parallel ice flow during Phase 3.

Deglaciation across the Selwyn Mountains is marked by rapidly increasing equilibrium lines and wholesale stagnation of the remaining ice (Jackson *et al*., 1991; Turner *et al.*, 2008). Evidence for this includes high elevation deltas and kames, descending meltwater channels, crevasse fills and thick glaciofluvial kame and kettle topography. The South Macmillan River valley has thick accumulations of glaciofluvial sediment, likely deposited as the stagnant ice melted. A large meltwater channel cut though the till cover and into bedrock near End Zone indicates that large volumes of meltwater sourced from melting ice in the South Macmillan River valley flowed across this largely ice-free, higher elevation valley (Fig. 36). Other large meltwater channels were also observed at similar elevations further north in the study area.

There are two large crevasse fill deposits in the south end of the South Macmillan River valley, one of which was filled with locally-sourced material, possibly shedding directly off the adjacent unglaciated valley walls into the open crevasses as the ice melted. With progressive lowering of the ice surface, meltwater incised through this and other glaciofluvial material, creating large terraces and hummocky terrain on the flanks of the valley. Large paraglacial fans also developed where tributary valleys entered the South Macmillan River valley. Local ponding of meltwater late during deglaciation resulted in limited glaciolacustrine deposits. After deglaciation, fluvial deposition, colluviation, periglacial movement and the growth of organics created the distribution of surficial materials that current exists in this valley.

Figure 36: Large meltwater channel eroded into bedrock near End Zone. This channel indicates that the valley was mostly ice free during deglaciation, while ice was still present in the South Macmillan River valley.

2.6 Tom and Jason Zone Geochemical Dispersals

Late glacial ice flow is likely the most significant for determining anomaly dispersion in the study area. The anomalies at the Jason Zone are dominantly valley-parallel, with a more minor dispersal to the west. This directly follows the ice flow history of this area, with the earlier westward dispersion being less significant for exploration than the late phase, valley-parallel dispersion to the south-southwest.

At Tom Zone, the strongest anomalies are found on the ridge ~1.5 km down-valley from Tom Zone. The lack of anomalies between Tom Zone and this ridge is likely due to the amount of erosion and fill in this valley since deglaciation. The steep valley walls have shed most of the till that would have lined the valley walls and the valley floor has been infilled with thick colluvium and, further down-valley, glaciofluvial terraces. The only intact till in this valley is exposed along the more stable ridge, where the anomalies occur. Mineralized erratics have been observed elsewhere in the valley near Tom Camp. These were likely transported from Tom Zone, but then weathered and moved downslope by colluviation.

3 Summary and Conclusions

The primary objective of this work was to provide surficial geology mapping to help guide interpretation of geophysical and geochemical exploration and inform future infrastructure development for Fireweed Zinc Ltd.'s Macmillan Pass project. The following conclusions and recommendations will help Fireweed's continued exploration in these areas:

- Terrain mapping was completed in the defined areas of interest at a scale of 1:10,000, with this scale increasing to 1:5,000 in areas of LiDAR coverage. The surrounding area in the property was mapped at 1:50,000-scale. This mapping is useful for calibrating geophysics data, planning future soil geochemistry surveys, interpreting previously-collected samples and for future infrastructure development.

- Accumulations of till and glaciofluvial material are likely tens of metres thick in the South Macmillan River valley. The glaciofluvial valley fill should be avoided during traditional soil geochemical exploration. This material is far-travelled and could provide false negative results.

- Complex ice flow histories near Jason and Tom Zones were resolved using field observations and measurements of ice flow indicators, including striations, grooves, erratic trains, meltwater channels and roche moutonnees.

- Ice flow orientations align with observed geochemical dispersion at Jason Zone, with an earlier flow to the west during glacial maximum being followed by valley-parallel ice flow towards the south-southwest.

- Geochemical anomalies at Tom Zone are down-valley, to the west. Gaps in this dispersion are likely the result of erosion and subsequent infill with colluvium. Ice flow at higher elevations was likely to the southwest in this area.

- Near-surface permafrost mapping was completed in the areas of interest outlined by Fireweed. Four relative categories of permafrost distribution were established based on the texture, material type, surficial expression and processes active in each polygon.

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