Placer gold settings within an alpine glaciated environment, Granite Creek, Yukon (NTS 105M/14)

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Abstract

Alpine glaciers from cirques of Granite and Albert creeks have deformed and reworked sediments in the Granite Creek valley and deposited locally sourced gold. Placer mining operations in the valley allowed detailed study of sedimentary deposits. The main units identified are from at least two glacial episodes which advanced farther than the previously mapped limits. Thick sequences of advance and retreat outwash blanket the till and represent high energy depositional environments. At least one proglacial lake formed due to ice-damming of lower Granite Creek by the Cordilleran Ice Sheet. We provide a stratigraphic record extending approximately 130 000 years and have correlated alpine till units to MIS 4, which has not been identified elsewhere in central Yukon. Multiple gold-bearing sedimentary units are found in the stratigraphy, representing glacial, interglacial/interstadial, and modern processes. This work highlights processes important to gold concentration that can be applied to other alpine glaciated areas with proximal gold mineralization.

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Introduction

Placer deposits are concentrations of heavy minerals generally formed by fluvial action. In glaciated terrain, placer deposits may underlie or be incorporated into glacial sediments (LeBarge *et al.*, 2002). This can increase the complexity when exploring for the deposits, but also introduce opportunities for increased erosion and concentration of gold-bearing material. This study describes the depositional processes of placer gold deposits in an alpine glaciated environment in central Yukon. We utilized extensive placer mining excavations to identify sedimentary units and reconstruct the glacial history of Granite Creek valley. We identified glacial, interglacial and modern placer-forming environments, and key gold-bearing units. The result is a composite stratigraphic log representing all units found in the upper Granite Creek basin with relative gold concentrations, and glacial models which demonstrate the mode of deposition. Results of this work can be applied to other alpine environments in the Cordillera that host gold mineralization.

Location and Physiography

The study area is in Granite Creek in central Yukon, approximately 400 km north of Whitehorse (Fig. 1). The Ecoregion is the Yukon Plateau-North (Smith et *al.*, 2004) and the physiographic region is the Stewart Plateau, though the adjacent Wernecke Mountains to the north are in very close proximity (Mathews, 1986). The area is part of the Omineca morphological belt, which is dissected by the Tintina Trench. Glacial landforms on the northeastern part of the belt include rounded hills and U-shaped valleys (Smith et *al.*, 2004). The study area is within the Gustavus Range, which includes Mount Hinton and several other summits around 2000 m in elevation (Fig. 2). There are cirques throughout the range, which either drain southward into Granite or Keystone creeks, or northward into Duncan, Lightning or Faith creeks. The headwaters of Granite Creek drain the eastern side of Mount Hinton and empty into Roop Lakes.

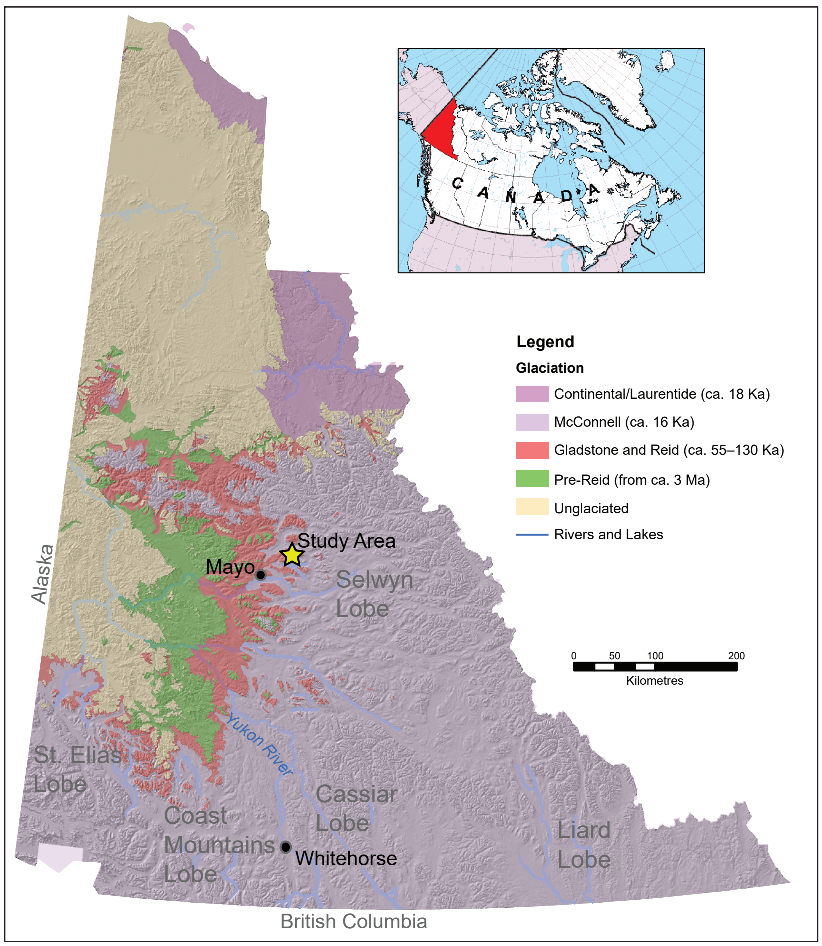

Figure 1. *Glacial limits map modified from Duk-Rodkin (1999).*

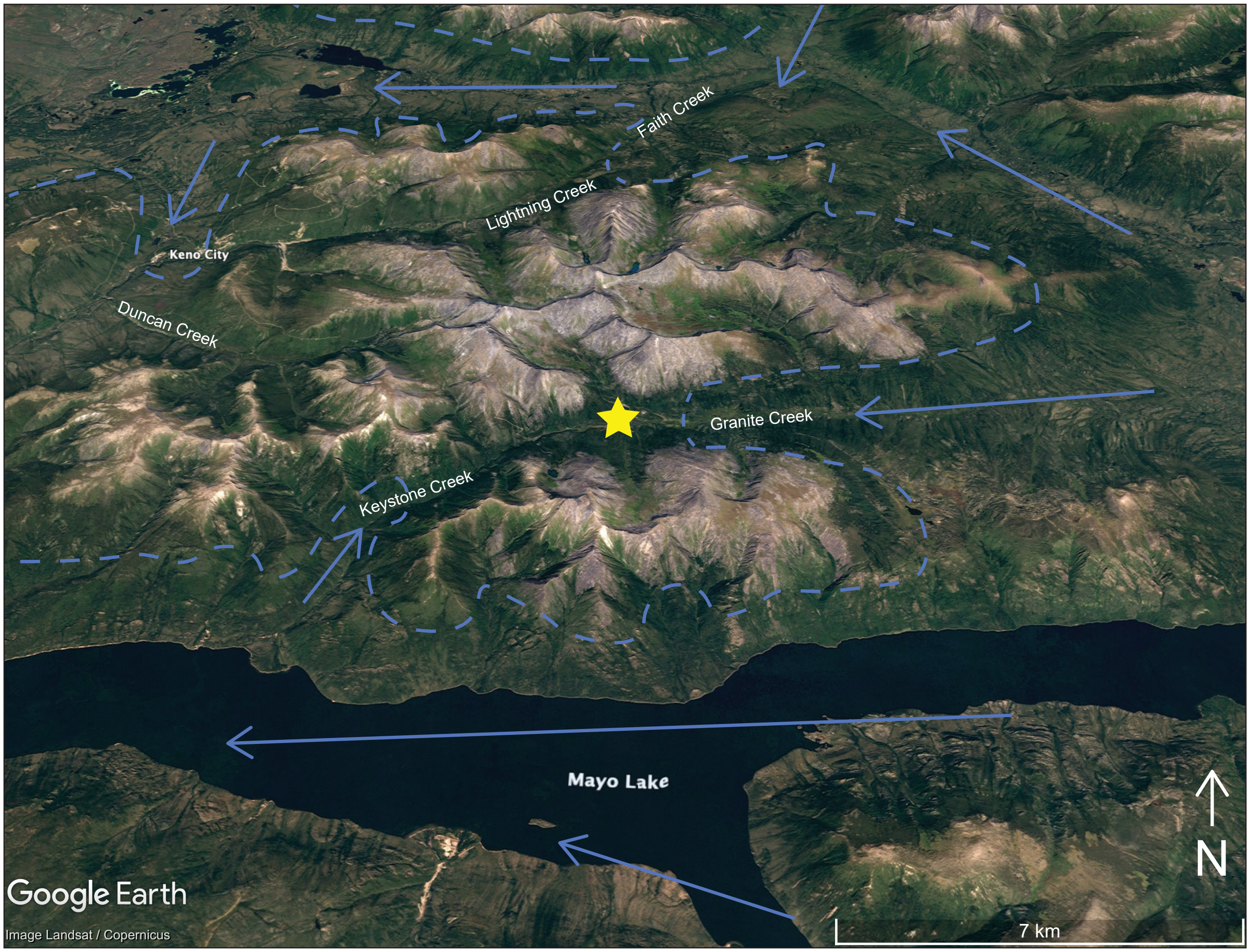

Figure 2. *Location map from Google Earth showing location of field camp. Ice flow direction is indicated with blue arrows and approximate MIS 2 glacial limit is shown with dashed blue line.*

Glacial History

The Yukon Plateau-North region in central Yukon was glaciated by the Selwyn Lobe of the Cordilleran Ice Sheet (CIS), which flowed west-northwest during Marine Isotope Stage (MIS) 2 (Table 1; Bond, 1999). As in the rest of Yukon, glaciers were largely topographically controlled, with widespread nunataks (Jackson et *al.*, 1991). Glaciers emanated out of upland areas such as the Selwyn Mountains and local cirques. Of the exposed limits in central Yukon, each subsequent glaciation was less extensive than those prior (Fig. 1; Bostock, 1966; Jackson et *al.*, 1991; Smith et *al.*, 2004). Yukon glaciations have previously been considered coherent advances, but Ward et *al.* (2008) challenged the synchrony of the penultimate glaciation across Yukon. Terrestrial cosmogenic nuclide-dated boulders at the mapped penultimate limit in southwestern Yukon were MIS 4, while Old Crow Tephra found in deglacial sediments along the Pelly River dates the penultimate surface to MIS 6. This indicates that the penultimate glacial limit is not synchronous across the territory.

Bond (1999) completed glacial limits and surficial geology mapping in the Mayo region and identified McConnell and Reid-age moraines in the Granite Creek study area. Ice flow of the CIS was dominantly west in central Yukon during the McConnell Glaciation (Bond, 1999). In Granite Creek, the Selwyn Lobe of the CIS terminated 1 km east of the divide with Keystone

Table 1. *Alternating warm and cool periods of Earth's climate derived from oxygen isotope data. These climatic periods, which control glacial and non-glacial processes of the Northern Cordilleran Ice Sheet (NCIS), are referenced throughout the paper.*

Marine Isotope Stage (MIS)	Temperature	NCIS Name	Age (years B.P.)
1	warm	Holocene	11 700 to present
2	cool	McConnell	29 000 to 11 700
3	warm	Interstadial	57 000 to 29 000
4	cool	Gladstone	57 000 to 71 000
5	warm	Interglacial	71 000 to 130 000
6	cool	Reid	130 000 to 191 000

Creek (Bond, 1998) based on moraines and ice-contact features. The age of MIS 2 deglaciation was confirmed by terrestrial cosmogenic nuclide dating (Ward and Bond, unpublished data). Alpine glaciers from upper Granite and Albert creeks terminated in the Keystone-Granite pass area, just beyond the limit of the CIS (Bond, 1999). Reid glacial deposits around Granite Creek are confined to higher elevations and pre-Reid deposits are sparse and occur as erratics on stable surfaces at elevations of 1615 and 1645 m (Bond, 1999, 1998). During the Reid glacial advance, ice followed regional drainages and flowed west, like the McConnell Glaciation. The lower Granite Creek valley was a conduit for ice advancing from the east (Bond, 1998). The MIS 4 Gladstone Glaciation had not been identified at the time of previous surficial geology and glacial limits mapping.

Regional Bedrock Geology

Central Yukon is underlain the extensive Neoproterozoic to Paleozoic Selwyn basin (Roots, 1997). Regional bedrock geology of the Mayo area is composed the following sedimentary sequences: Upper Proterozoic–Lower Cambrian Hyland Group metasandstone, conglomerate, siltstone, shale and phyllite, which underlie Selwyn basin strata; Ordovician Road River Group siltstone and chert; Devonian Earn Group coarse chert-pebble conglomerate, sandstone, siltstone, with minor dark grey to black limestone and chert; and Mississippian Keno Hill Quartzite (Roots, 1997). Read *et al.* (2021) separated the Keno Hill Quartzite into two members: the Basal Quartzite Member is composed of quartzite, graphitic shist, and sericite and chlorite schist; and the overlying Sourdough Hill Member is composed of quartzite, alternating schist, limestone, grit and chlorite. Two regional thrust sheets, the Robert Service and Tombstone, are located just south and north of the study area, respectively (Fig. 3). The Roop Lakes stock lies east of the study area and is associated with the Tombstone-Tungsten magmatic belt (Murphy, 1997; Mair *et al.*, 2006).

Deformation and Mineralization

Regional deformation began in the Middle Jurassic to the Early Cretaceous resulting in upright and overturned folds. The Robert Service thrust displaced Hyland Group rocks, and Tombstone thrusting resulted in shearing and foliation. The 93 ± 3 Ma Tombstone intrusions are composed of undeformed granite and granodiorite (Mair *et al.*, 2006; Roots, 1997). The Basal Quartzite Member identified by Read *et al.* (2021) is the host rock for most of the mineralized veins. Read *et al.* (2021) studied the geology of mineralized veins near Keno Hill, just northwest of Granite Creek and in similar rocks. They note that there are five stages of faulting, two associated with vein faulting. Vein faults are longitudinal and formed between 89 and 68 Ma, transverse vein faults formed afterwards. Rare indicators of oblique-left normal to dip-slip movement are visible in veins exposed at the surface. Their model

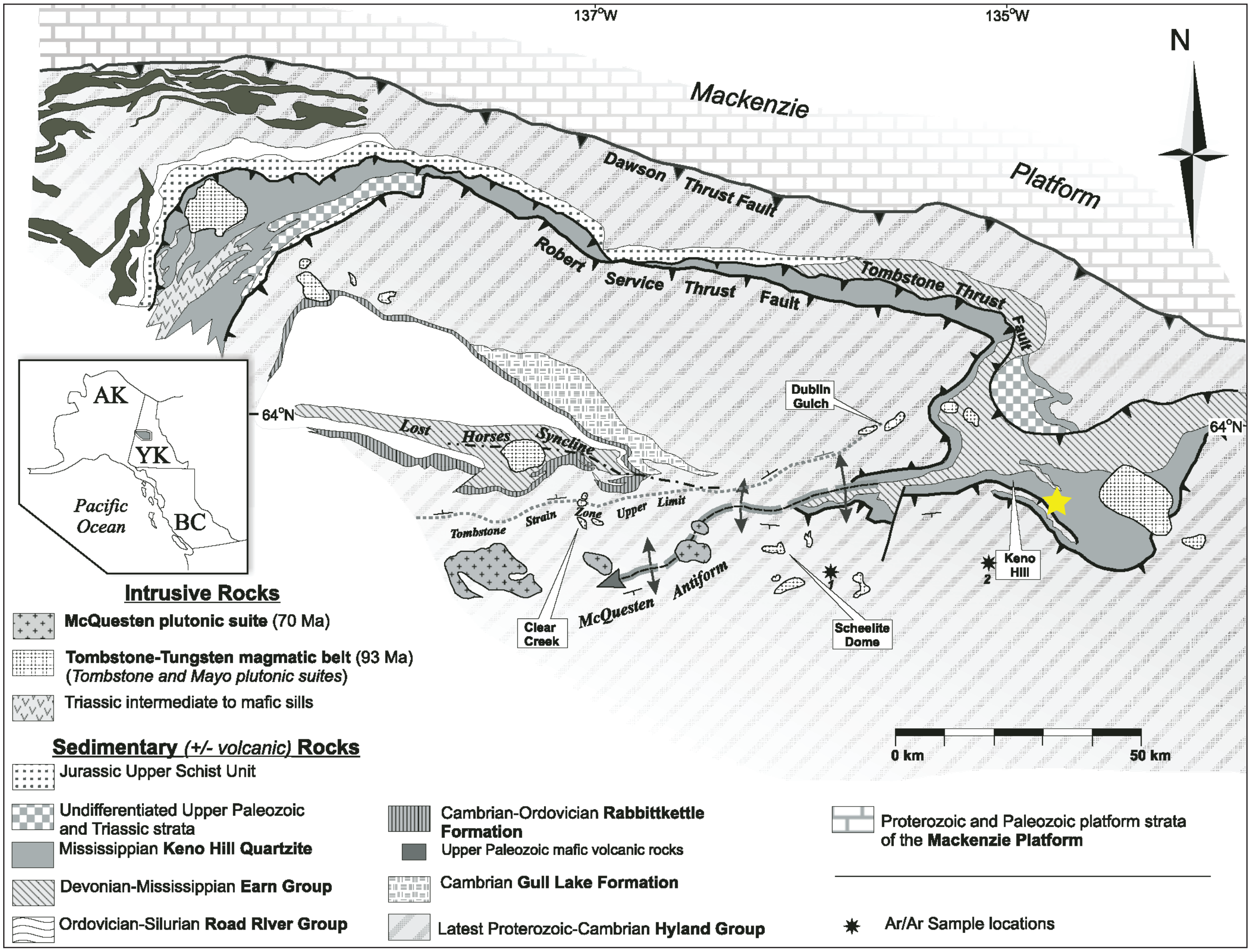

Figure 3. *Regional geology map modified from Mair et al. (2006). Study area is shown with star.*

for mineralization, built on Boyle (1965), reported faults dip steeply in competent quartzite and gently or moderately in schist in Keno Hill Quartzite. Read et *al.* (2021) note that open space for mineralization depends on direction of fault movement, and this period may have allowed formation of open space for veins. Long east-northeast striking longitudinal veins contain early phase mineralization, which is thought to be the source of gold, as well as late phase mineralization either as cemented brecciated zones or thin, secondary veins parallel to early veins (Reid, 2021). Late phase veins are short north-northeast striking transverse veins with late-stage mineralization.

Mining and Exploration

Mining in the Mayo area began with the discovery of placer gold on the Stewart River in 1883 and Duncan Creek in 1901, prompting the establishment of the Mayo townsite. Lead and silver discoveries were made in the Keno region by 1906 and were staked by 1919; development followed soon after (MacDonald et *al.*, 1990). Activity continued throughout the 20th century, increasing with rising gold prices. Between 1978 and 2021, the Mayo Mining district produced 192,815 crude ounces of placer gold. Additionally, there have been many silver-lead-zinc mines in the Keno area, with the main operator being the United Keno Hill Mines. Keno Hill was once Canada's second largest producer of silver (LeBarge *et al.*, 2002). During the summer of 2021, four placer operations were actively mining in the Granite Creek area, and one mineral exploration project was ongoing in the Granite Creek cirque targeting the hardrock gold veins. Since 2015 Granite Creek has produced 16,393 crude ounces of placer gold.

Placer Gold Development

Placer-forming environments in the Mayo region are characterized by LeBarge *et al.* (2002) and grouped into modern, interglacial, glacial and periglacial settings. Modern placers are Holocene-age deposits usually found in floodplains, alluvial terraces, fans, fan-deltas and gulches. These are the most targeted environment for placers. Buried interglacial placers are similar to modern deposits in that they are commonly found in alluvial deposits such as plains, fans and terraces, and also in reworked gulch deposits. In glaciated terrain, placer deposits commonly form during interglacial periods and are most commonly preserved at the margin of glaciers where deposition dominates erosion. Interglacial placers are commonly buried by periglacial, colluvial or glacial deposits. Glacial placers are less common, but can be found in till and outwash material, especially where glaciers reconcentrate interglacial material, or erode mineralized bedrock. Periglacial placers form outside the glacial limit where weathering and erosion dominate, where paleoplacers are reworked, or where mineralized bedrock is eroded. Deposition occurs as periglacial fans, floodplains, or colluvial deposits (LeBarge *et al.*, 2002).

Methods

Desktop Mapping

Preliminary mapping consisted of using scanned 1:20 000 air photos obtained from the Energy, Mines and Resources Library in Whitehorse, and a stereoscope to map surficial geology. A series of polygons were created and included surficial material, expression, and any processes or modifiers. Polygon labels followed the method described in Howes and Kenk (1997) and modified for Yukon.

Field Mapping

Field mapping took place in the summer of 2021. Surficial geology field sites were accessed using a pickup truck on mining roads or by foot traverse. Landform sedimentology relied on soil pits, mine cuts and natural exposures to document characteristics. At each field site the following information was collected: location, measurements of the pit/exposure, landform, geomorphic processes, sorting, texture, abundance of clasts, colour, and soil horizons. Photos were taken and sketches made at each site.

Stratigraphic and Sedimentological Data

Granite Creek stratigraphic sections were logged at placer mining excavations, road cuts and stream cuts (Fig. 4). Detailed information collected includes unit thickness, grain size, texture, colour, bedding, contacts, proportion of clasts and matrix, clast lithology and rounding, fabric, and presence of structures or organics. Fabrics consisted of a minimum of 25 clasts where possible, and were plotted as contoured data on an equal area Schmidt net (Table 2). A site map is included in Figure 4 showing locations of excavations.

Results

Stratigraphy: Unit Descriptions

A composite section of units found in the study area of upper Granite Creek is shown in Figure 5. There are 16 units representing a particular depositional environment derived from a total of 12 sites. In the absence of dating control, age estimates and correlation of units are based on stratigraphic position with Unit 1 being the oldest unit.

Unit 1: Weathered bedrock

Unit 1 is weathered grey to black phyllite and quartzite bedrock of the Mississippian Keno Hill Formation. The bedrock surface is undulatory and only exposed in sections GRC-02N, GRC-03A, GRC-03H and GRC-04W (Fig. 6). The bedrock is fractured, folded and foliated, and hosts mineralized quartz veins that are the primary source of placer gold at Granite Creek.

Table 2. *Till clast fabric details. Locations and stereonet plots shown in Figure 7.*

Section Number	Lithostratigraphic Unit	Clasts Measured	Global Mean Trend (°)	Global Mean Plunge (°)	Eigenvalue	Apparent Ice Flow
GRC-01W	Unit 5	25	20	3.2	0.579	Southwest
GRC-01W	Unit 3	23	143	14.6	0.673	Southeast
GRC-01S	Unit 11	15	309	16.6	0.609	Southeast
GRC-02W	Unit 2	14	117	10.4	0.588	Southeast
GRC-02S	Unit 11	15	236	5.4	0.641	Southwest
GRC-03A	Unit 11	15	359	1.4	0.687	North
GRC-04E	Unit 5	25	139	9.2	0.682	North

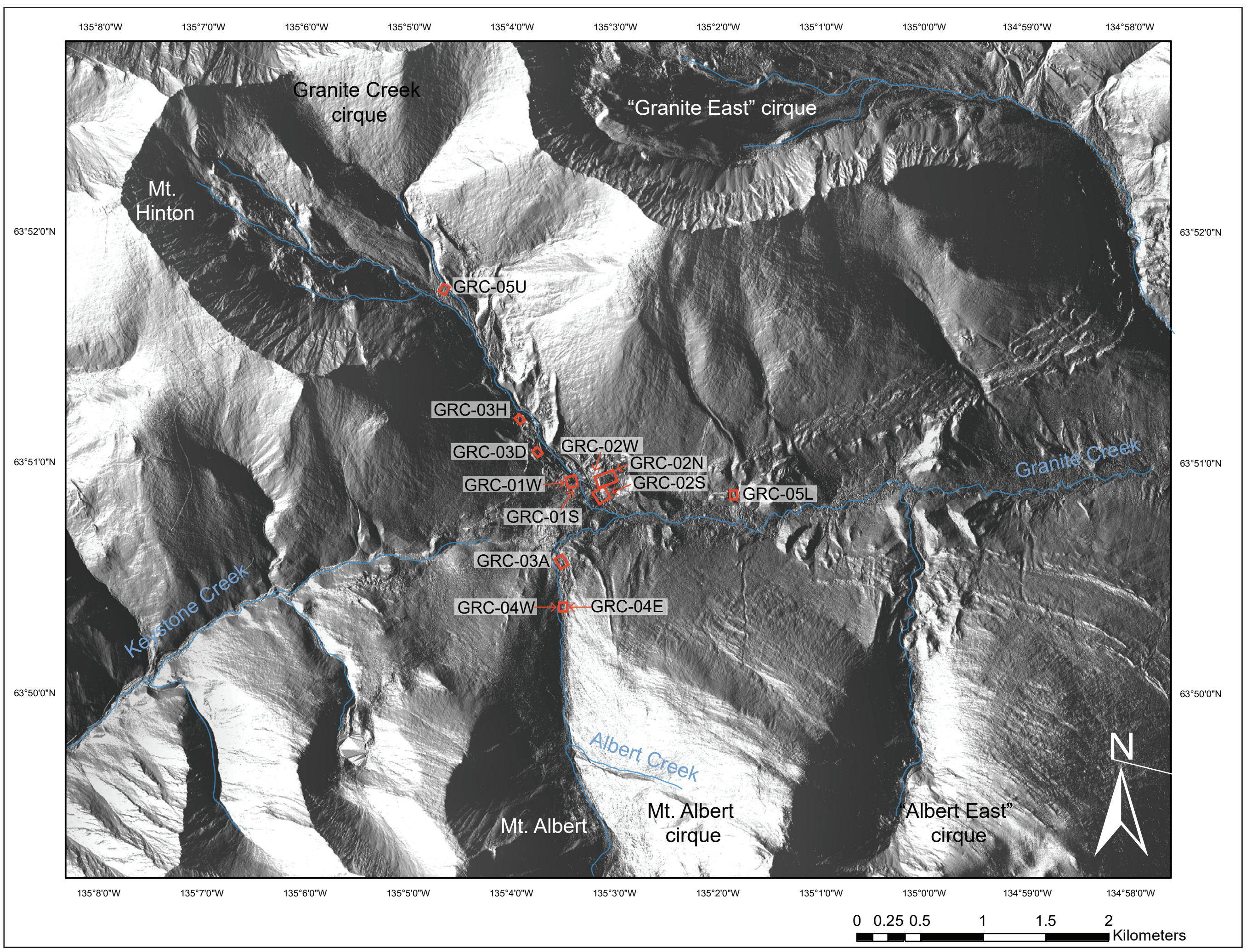

Figure 4. *Lidar imagery showing placer excavation locations, cirques, named mountains and creeks in the study area.*

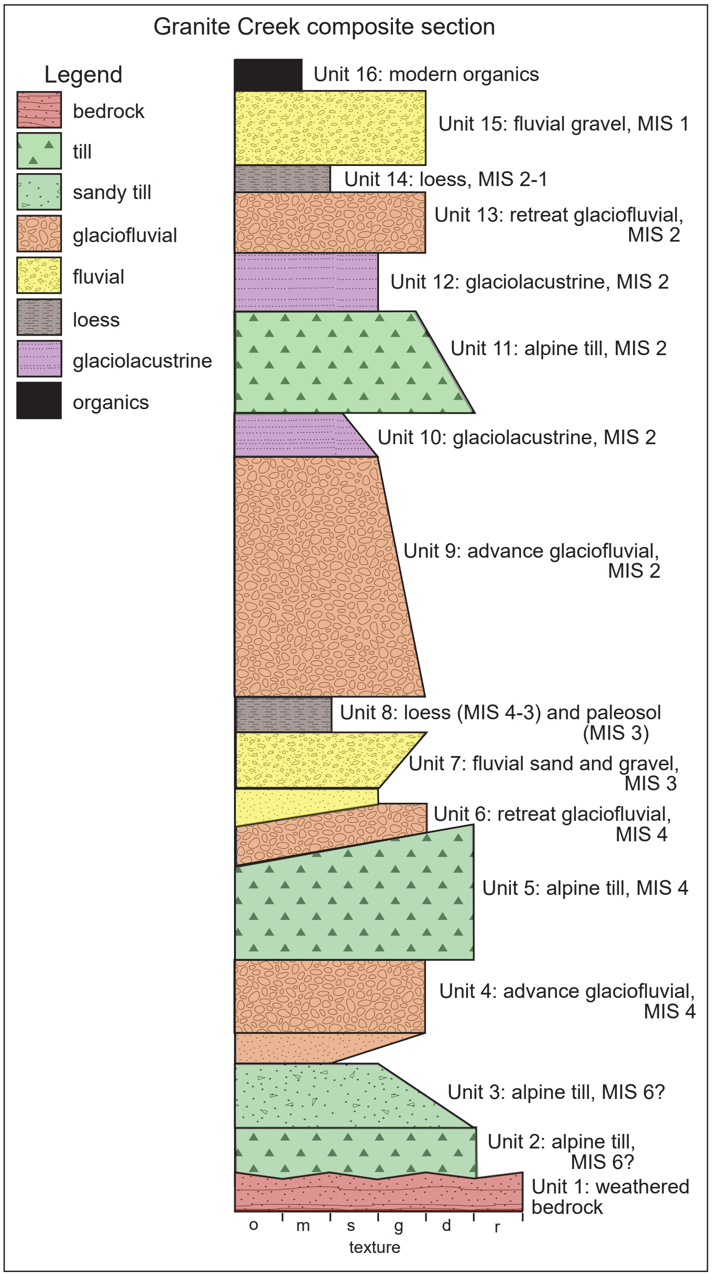

***Figure 5.** Composite stratigraphic log illustrating all units found in the upper Granite Creek basin.*

Veins contain fine to coarse-grained quartz, milky white quartz, or quartz breccia. Mineralized zones are highly oxidized.

Unit 2: Alpine till, MIS 6

Unit 2 is an overconsolidated black diamict with abundant clasts of local quartzite and phyllite, and only found in section GRC-02N. This unit is discontinuous and has a variable thickness of 0.5–1.5 m, filling in undulations in bedrock at the base of GRC-02N. Clast content averages 30%, with 80% pebbles and 20% cobbles. Clasts are subangular to subround. The matrix is silty sand. The lower contact is undulatory and sharp with bedrock below. Gold values were subeconomic.

Unit 2 is interpreted as being MIS 6 alpine till due to stratigraphic position below MIS 4 till and fabric indicating flow out the Granite Creek cirque (Fig. 7).

Unit 3: Alpine till, MIS 6

Unit 3 is a discontinuous, silty, overconsolidated olive brown to beige diamict with abundant round to subround clasts. This unit, found only in GRC-01W, is discontinuous and has a thickness of 0–3 m. Clast content is highly variable and averages 35%, with 20% pebbles, 75% cobbles and 5% boulders. The matrix is medium sand with some thin silt beds found under boulders. Clasts are subround to round. The clast lithology of Unit 3 is dominantly quartzite, but 10 highly weathered granitic pebbles and cobbles were found in section GRC-01W. The lower contact was not exposed. This unit contains low amounts of gold.

This unit is interpreted as being till due the presence of erratics and clast fabric indicating flow out of the Granite Creek cirque. The presence of weathered granitic erratics suggests that this unit reworked sediments deposited by the retreat of the CIS during an older glaciation. Granite bedrock is not present in the upper Granite Creek basin and erratics originate from the Roop Lakes Pluton, approximately 20 km to the east. The age is interpreted as MIS 6 due to its stratigraphic position underlying inferred MIS 4 till at location GRC-01, however it is possible that this deposit is from an older glaciation or an earlier phase of the MIS 4 advance.

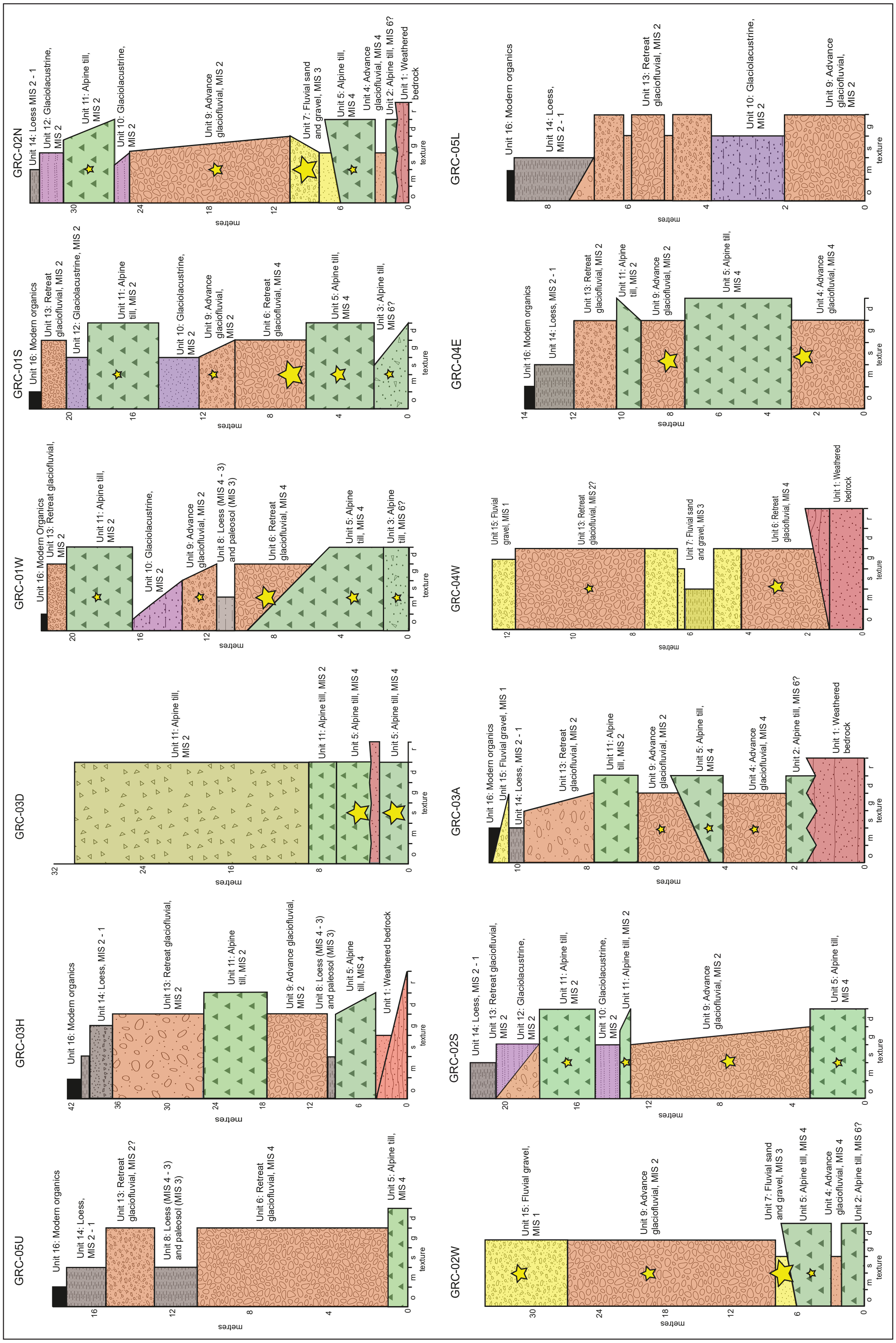

Figure 6. *Key stratigraphic sections, locations in Figure 4. Relative size of yellow star correlates to relative gold value.*

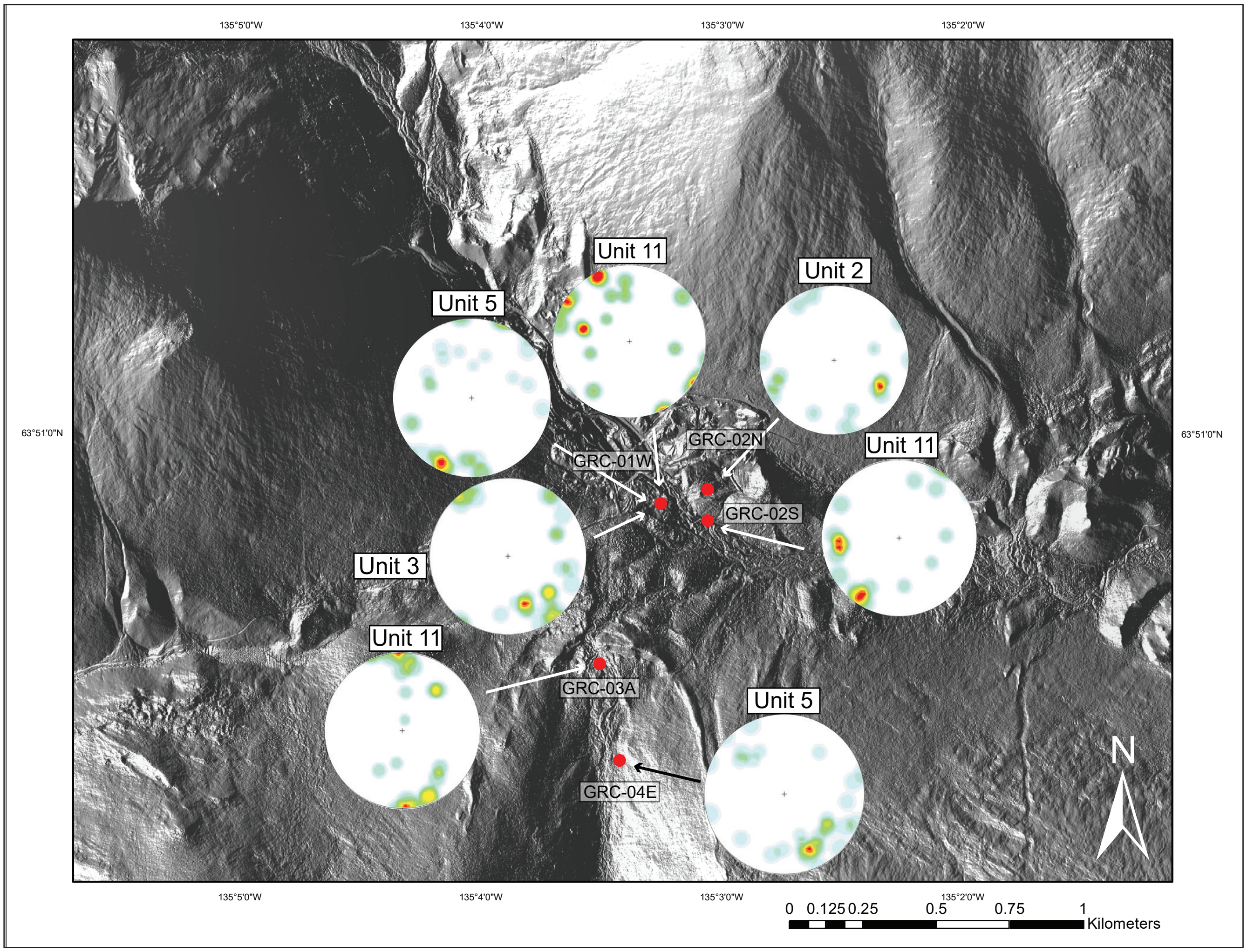

__Figure 7.__ Clast fabrics with unit number and section location.

Unit 4: Advance glaciofluvial, MIS 4

Unit 4 is a horizontally bedded, fine-grained, oxidized sand that grades into coarse, moderately sorted gravel. The unit is laterally discontinuous and found at GRC-02N, GRC-04E and GRC-03A. The unit is at least 2 m thick, but only exposed in the base of the excavations. The sand is fine grained and laminated, and gradually coarsens upward into subround to round gravel having a clast content averaging 75%, with 90% pebbles and 10% cobbles. In some locations, there is a sharp contact between the sand and coarse gravel, which has a clast content averaging 80%, with 35% pebbles, 45% cobbles and 20% boulders that are subangular to subround. The matrix is medium sand with some fine sand. The lower contact is undulatory and interstratified with Unit 2. This unit is gold-bearing at location GRC-04.

The unit is interpreted as being advance outwash gravel due to the coarsening upward sequence and stratigraphic position below Unit 5, interpreted to be MIS 4 age till.

Unit 5: Alpine till, MIS 4

Unit 5 is an oxidized, overconsolidated, matrix-supported diamict. This unit is 1–3 m thick and laterally continuous, and present at locations GRC-01W, GRC-01S, GRC-02N, GRC-02S, GRC-04E, GRC-03H, GRC-03A and GRC-03D. Clast content is variable and averages 35%, with 45% pebbles, 40% cobbles and 15% boulders. Clasts are subangular to subround. The matrix is variable, ranging from silt with some fine sand to medium sand with some fine sand. The clast lithology is dominantly quartzite, phyllite and diorite, with rare granite. Intraclasts of sand and glaciotectonized sandy silt beds were found at GRC-01W and GRC-01S. The lower contact is variable as the unit is found overlying till (GRC-01), bedrock (GRC-02N and GRC-03H) and advance gravel (GRC-04, GRC-03A).

Unit 5 is interpreted as being MIS 4 alpine till due to stratigraphic position, glaciotectonized forms, and till fabric which indicates flow out of a Granite Creek cirque. This unit may contain reworked outwash from the CIS due to presence of at least one granitic boulder. Unit 5 contains a variable amount of gold depending on what was reworked by the alpine glacier. Near the mouth of the Granite Creek cirque (GRC-05D), Unit 5 contains fluvially rounded boulders and oxidized bedrock fragments including vein quartz, suggesting nearby erosion of stream gravel and mineralized bedrock. In these settings Unit 5 contains high amounts of gold. More distal to the mouth of the cirque, Unit 5 contains lower amounts of gold suggesting limited incorporation of mineralized bedrock or enriched stream gravel.

Unit 6: Retreat glaciofluvial, MIS 4

Unit 6 is a coarse, poorly sorted gravel with sandy matrix. This unit is discontinuous and may be in direct contact with MIS 2 advance gravel in some locations suggesting an unconformity is present, or that it is beyond the limit of alpine glaciation. This unit is found in GRC-01W, GRC-01S and GRC-04W. Thickness is 0.5–2.5 m, and exposures are poor due to sloughing of excavation walls. Clast content averages 75%, with 15% pebbles, 45% cobbles and 40% boulders. The matrix is silty sand. The lower contact is sharp and undulatory.

The unit is interpreted as being deglacial gravel due to its stratigraphic position, lack of organics and sorting.

Unit 7: Fluvial sand and gravel, MIS 3

Unit 7 is a finely bedded sand grading into a coarse oxidized gravel with manganese staining. The unit is 0.5–3 m thick and laterally discontinuous, found only in GRC-02N, GRC-02S and GRC-04W. Gravel matrix is medium to fine sand and averages 15%. Clasts are subround to subangular and 30% pebbles, 40% cobbles and 30% boulders. The lower contact at GRC-02N is sharp and the unit dips steeply toward the east, consistent with flow out of the Granite Creek cirque.

The unit is interpreted as fluvial gravel likely deposited during MIS 3 due to its oxidation and stratigraphic position. This unit contains high concentrations of placer gold.

Unit 8: Loess (MIS 4-3) and paleosol (MIS 3)

Unit 8 is thin, 0.25–1.25 m thick, discontinuous, oxidized silt with some sand, has crude horizontal bedding, and is mottled. This unit is laterally discontinuous and found only in GRC-0W1 and GRC-03H. It has approximately 15% pebbles incorporated in the top 0.75 m. At location GRC-01W, the lower contact is sharp, and is draped over Unit 5, which may be a buried MIS 4 alpine moraine. Oxidation and mottling within the loess is gradational and extends into the underlying morainal sediment.

This unit is interpreted as MIS 4 and 3 loess with a paleosol formed during MIS 3. The lower 0.5 m in GRC-01 was sampled for optically stimulated luminescence dating. Results are pending.

Unit 9: Advance glaciofluvial, MIS 2

Unit 9 is a coarse gravel that fines upward into interbedded sand and gravel that interfingers with Unit 10. This unit is laterally continuous and is found in nearly all sections, and has a thickness of 5–15 m. Matrix content is highly variable but averages 15% and consists of sand and some silt. Clasts are subround to subangular and consist of 40% pebbles, 45% cobbles and 15% boulders. The clast lithology is dominantly quartzite, gabbro and phyllite. Imbrication indicates flow out of alpine cirques. The lower contact is undulatory.

This unit is interpreted as being an advance glaciofluvial gravel due to the stratigraphic position interfingering with glaciolacustrine sands above. This unit contains moderately economic amounts of gold that is distributed throughout the section.

Unit 10: Glaciolacustrine, MIS 2

Unit 10 is a horizontally bedded to deformed and glaciotectonized silty to medium sand. This unit is undulatory due to erosive till which deforms the unit and is found toward the top of most excavations located near the Granite-Keystone creek pass area. Thickness is highly variable and ranges from 0–4 m. Clasts are rarely found but some cobbles are present. The advance glaciofluvial gravel below interfingers with this glaciolacustrine sand.

This unit is interpreted as being glaciolacustrine sand deposited when the Cordilleran Ice Sheet advanced up lower Granite Creek and impounded the drainage. This interpretation was made based on the sedimentology of the unit, stratigraphic position below Unit 11 which is interpreted as being MIS 2 alpine till and surficial geology mapping of the CIS terminal moraines that block the drainage. Additionally, no organics were found in this unit and some dropstones were observed. This unit is folded and faulted by the overlying alpine till.

Unit 11: Alpine till, MIS 2

Unit 11 is an overconsolidated, very dark grey, matrix-supported diamict. This unit is 0.25–2 m thick, laterally continuous, and is found in most excavations. Clasts are subangular to subround and average 35%, with 45% pebbles, 40% cobbles and 15% boulders. The clast lithology is dominantly local quartzite and phyllite. Some vertically oriented clasts are present. Matrix is highly variable but predominantly silty sand. The lower contact is variable, undulatory and erosive. Till fabrics are consistent with flow out of respective cirques.

This unit is interpreted as being MIS 2 alpine till due to its lateral extent, fabric, local clast content and overconsolidation. This unit contains low amounts of gold, however values may increase closer to the Granite Creek cirque where the till is in contact with bedrock and more completely eroded pre-existing sediment.

Unit 12: Glaciolacustrine, MIS 2

Unit 12 is a 1–3 m thick, continuous, horizontally bedded, silty sand to medium sand. This unit is laterally continuous and found at locations GRC-02N, GRC-02S and GRC-01S. Clasts are rare, but some pebbles are present in the top of the unit as it grades into a soil in some locations. The lower contact is sharp and undulatory, draped over Unit 11.

This unit is interpreted as glaciolacustrine sand deposited after the alpine glaciers began to retreat and the CIS still blocked the drainage. This is based on stratigraphic position above Unit 11 alpine till, sedimentology of the unit, its extensive nature and lack of organics.

Unit 13: Retreat glaciofluvial, MIS 2

Unit 13 is a coarse, moderately sorted, clast-supported gravel. The unit is laterally continuous and is found at most locations. Thickness is 0.25–1.5 m. Clast content is highly variable but averages 75%; 45% pebbles, 35% cobbles and 15% boulders. Some crude imbrication is found indicating flow out of Granite Creek cirques. The matrix is variable but averages fine to medium sand. Clasts are subround to subangular. Lithology is dominantly local phyllite, quartzite and diorite. The contact is variable and ranges from gradational to sharp and undulatory when in contact with Unit 11.

This unit is interpreted as retreat glaciofluvial gravel deposited by outwash from melting alpine glaciers. The interpretation is based on its texture, lack of sorting, stratigraphic position and crude imbrication. This unit may contain Holocene gravel at the top of the unit as it is difficult to differentiate in some locations. Unit 13 contains economically low amounts of gold.

Unit 14: Loess, MIS 2-1

Unit 14 is 0.25–3 m of massive to crudely stratified, oxidized silt and fine sand. This unit is laterally continuous and is found at the top of most exposures in Granite Creek valley where preservation allows.

The lower contact varies from being sharp, to being intermixed with colluvium. At some locations, this unit is in direct contact with overlying organic material forming the A horizon. Where this occurs, B horizon oxidation is present within the unit. The lower contact is variable, ranging from gradational to sharp.

This unit is interpreted as being loess deposited following MIS 2 glaciation due to its texture and massive structure.

Unit 15: Fluvial gravel, MIS 1

Unit 15 is a poorly sorted, clast-supported gravel. The unit is restricted in extent and found at locations GRC-02W, GRC-03A, GRC-03H. Thickness is 0.5–5 m. This unit is thickest at lower elevations and generally thinner closer to the cirque. Clast content averages 80%, with 30% pebbles, 50% cobbles and 20% boulders. Clasts are subround to subangular. Lithology within the gravel is dominantly phyllite and quartzite. The lower contact is erosional.

This unit is interpreted as being Holocene fluvial gravel due to its proximity to modern Granite Creek and stratigraphic position. This unit contains moderate amounts of gold at GRC-02W and becomes more enriched toward the lower contact.

Unit 16: Modern organics

Unit 16 is modern organics that range in thickness from approximately 0.25–0.5 m. This unit is composed of modern soil horizons and vegetation. The organics are commonly stripped from excavations during preparation and set aside for reclamation.

Location Descriptions

GRC-01 (GRC-01W and GRC-01S)

GRC-01 is inside the maximum limit of the Granite Creek alpine glacier during the last glaciation (MIS 2). Two walls of this section were logged; GRC-01W (Fig. 8) and GRC-01S (Fig. 9). Modern Granite Creek flows just east of the excavation. Units are shown in Fig. 6. Many of the laterally continuous units are present in this section, but this is the only location where Unit 3 was found. It is interpreted that this unit reworked a recessional deposit from the retreat of the CIS. This excavation contains glacial and interstadial sediment extending back to the MIS 6 Reid Glaciation. The lowermost units consist of till from this time frame and are overlain by outwash and till from the ensuing MIS 4 Gladstone Glaciation. The MIS 4 glacial sediments are capped by a veneer of loess that contains a paleosol likely from the MIS 3 interstadial warm period. This unit is overlain by MIS 2 glacial sediments that include alpine till and glaciolacustrine material from the damming of Granite Creek by the CIS. These units are illustrated in a southwest to northeast cross section that intersects GRC-01, Granite Creek, and GRC-02 (Fig. 10).

GRC-02 (GRC-02N, GRC-02W and GRC-02S)

GRC-02N (Fig. 11) and GRC-02W (Fig. 12) are at the confluence of alpine glaciers and near the MIS 2 CIS limit. This location is southeast of GRC-01. Section GRC-02W differs from GRC-02N and GRC-02S (Fig. 13) because it includes the Holocene fluvial gravel and the unconformity associated with its deposition. In this location some preceding glacial units have been reworked. GRC-02S is located farther south on the toe side of a potential ice stagnation complex from the CIS. Units are shown in Figure 6. The base of the excavation intersected a steeply dipping bedrock surface only visible in the northwestern corner. The lowermost units consist of sediment from the Reid Glaciation, which infill bedrock undulations. These units are overlain by alpine till from the Gladstone Glaciation and are also gold-bearing. In the northeastern corner, the richest gold-bearing unit is an interstadial fluvial gravel from MIS 3. Overlying this gravel is a thick, gold-bearing, advance McConnell glaciofluvial gravel which fines into interbedded sand and gravel. In the northeastern corner, discontinuous retreat glaciofluvial gravel overlies the MIS 2 till. Glaciolacustrine sand, subeconomic gold-bearing till and loess cap the exposure (Fig. 10).

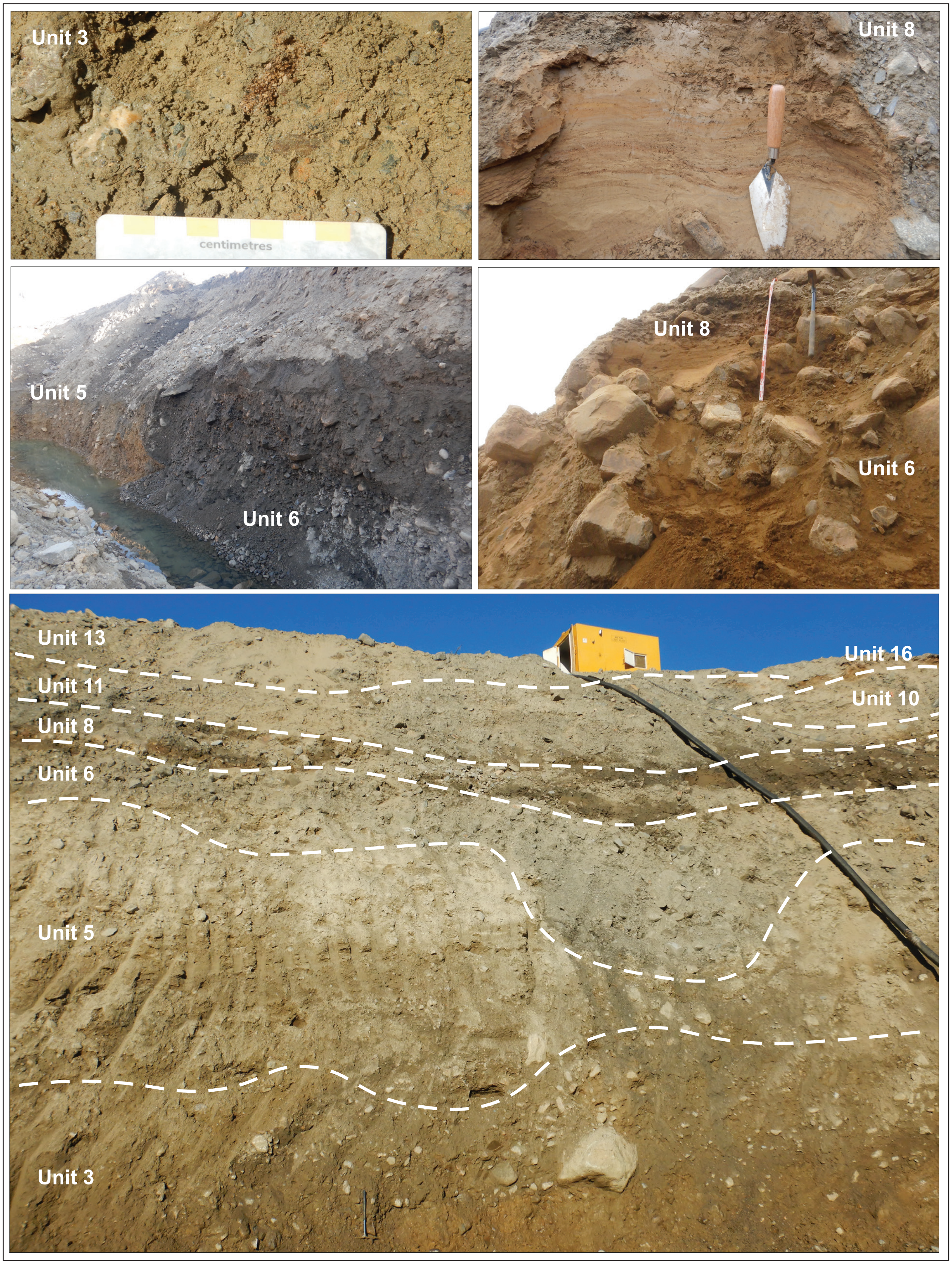

Figure 8. *Main stratigraphic units at GRC-01W.*

Figure 9. Main stratigraphic units at GRC-01S.

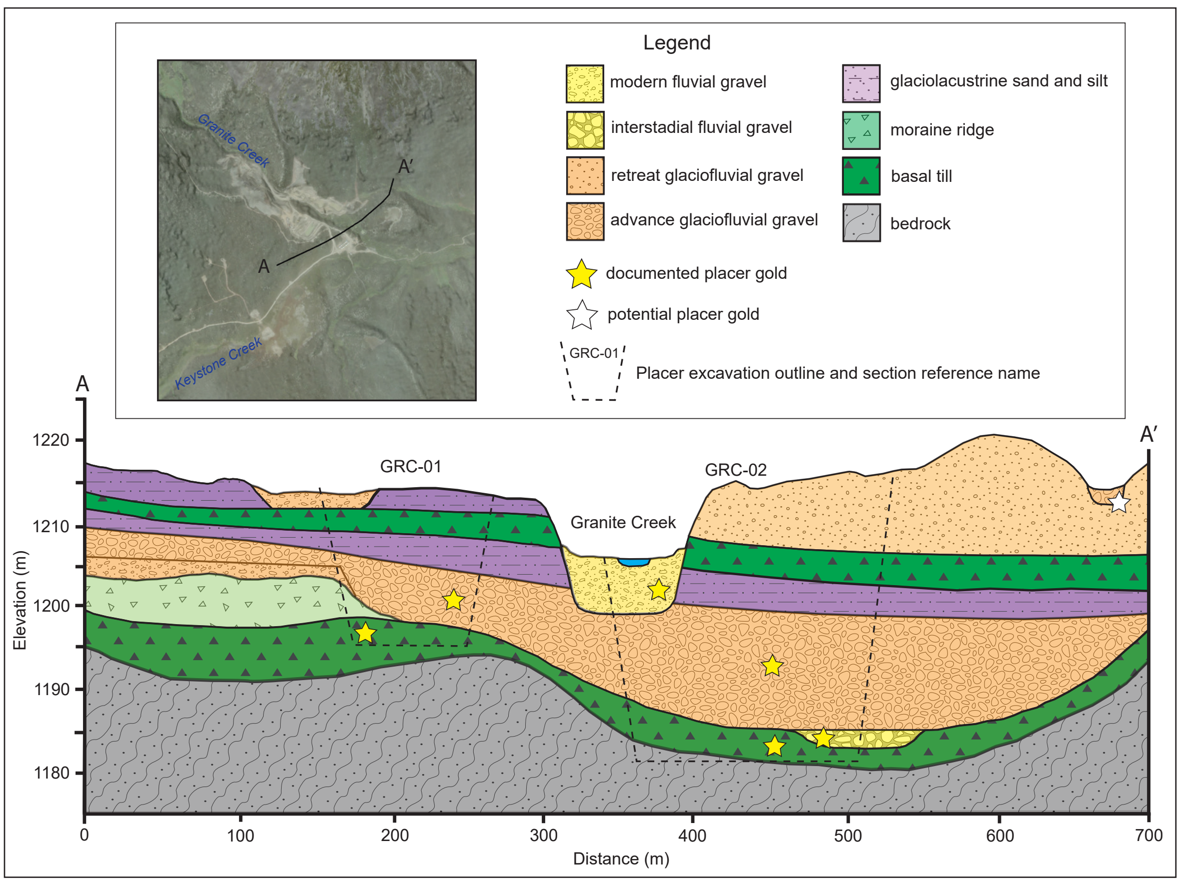

***Figure 10.** Simplified units in cross section at exposures GRC-01 and GRC-02. Transect is roughly southwest to northeast.*

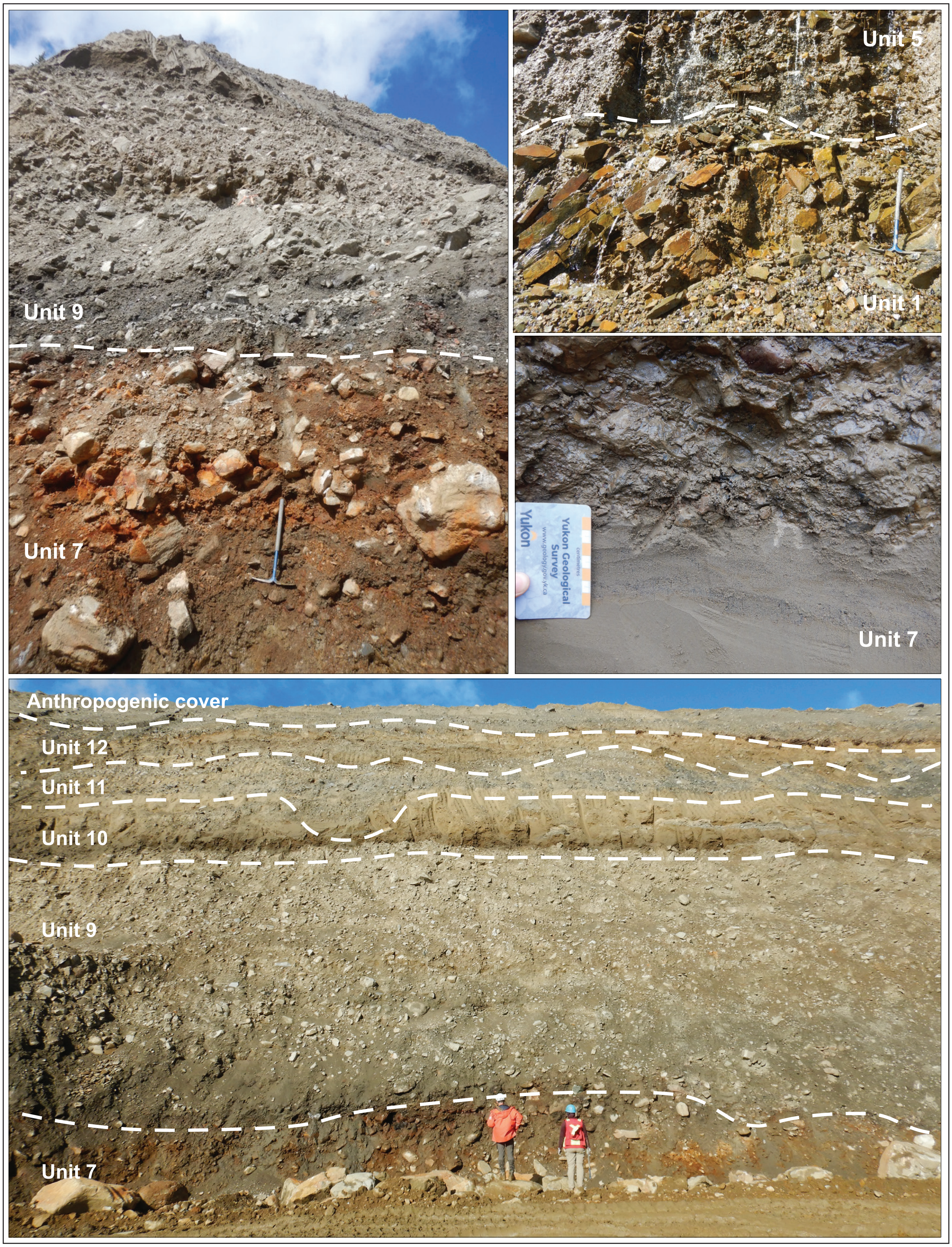

Figure 11. *Main stratigraphic units at GRC-02N.*

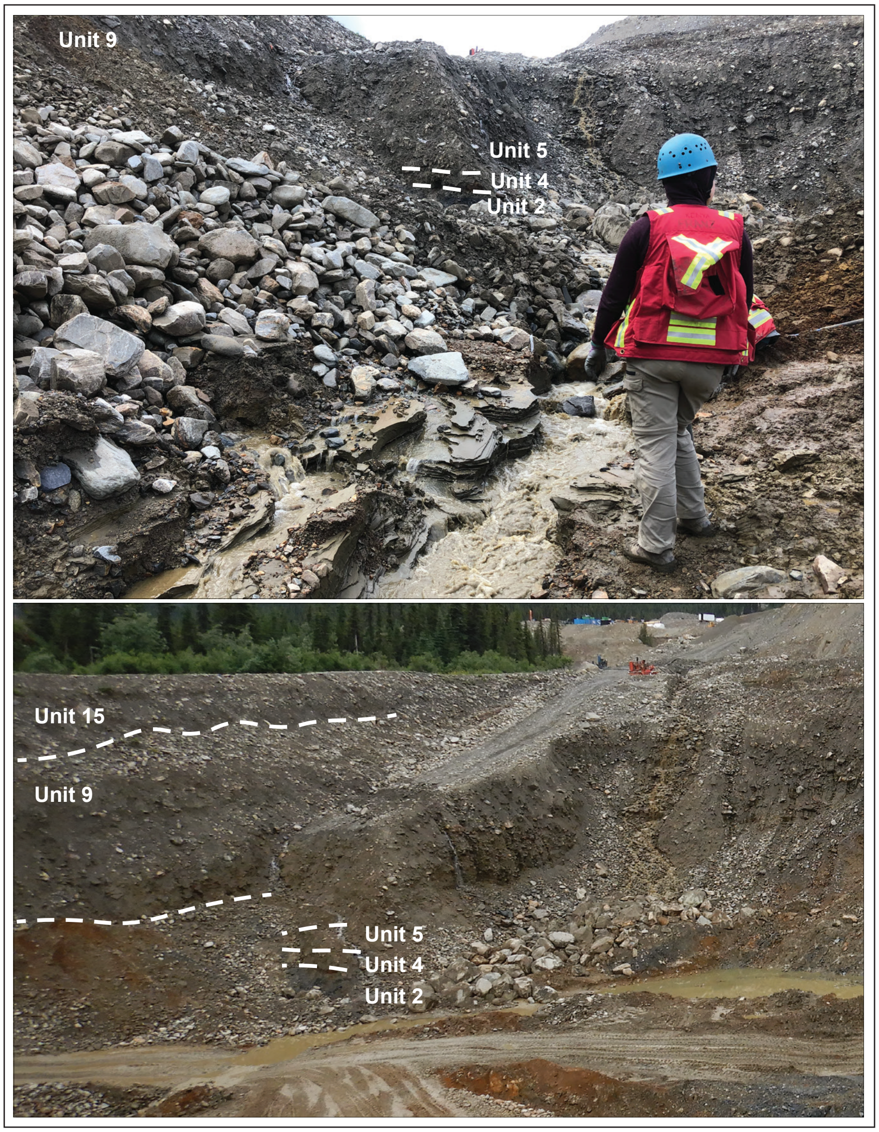

Figure 12. *Main stratigraphic units at GRC-02W. The view in the lower photograph is to the northwest.*

GRC-03D and GRC-03H

GRC-03H (Fig. 14) is just west of modern Granite Creek, up-valley of a recessional moraine formed by the Granite Creek alpine glacier. GRC-03D (Fig. 15) is just south of GRC-03H. Units are shown in Figure 6. The lowermost unit at GRC-03H is highly weathered and presumably altered bedrock overlain by MIS 4 age alpine till, which is also found in GRC-03D. At GRC-03D this unit is thicker, consisting of basal till that contains thrusted sheets of bedrock. Both contain high economic concentrations of placer gold, likely due to nearby mineralized veins in the valley bottom. GRC-03D is the original discovery pit excavated in 2017. At this site only MIS 2 basal till is present overlying the MIS 4 till. At GRC-03H, the MIS 4 till is overlain by interstadial sediments correlating to MIS 3, followed by advance gravel and till from MIS 2. Modern organics and thick loess overlie the MIS 2 deposits.

GRC-03A

GRC-03A is inside the prominent recessional moraine from the Albert Creek cirque glacier (Fig. 16), just west of modern Albert Creek. This location would have been an outwash fan during advance and retreat of alpine glaciers, and close to paleo-streams formed during interglacial periods. Units are shown in Figure 6.

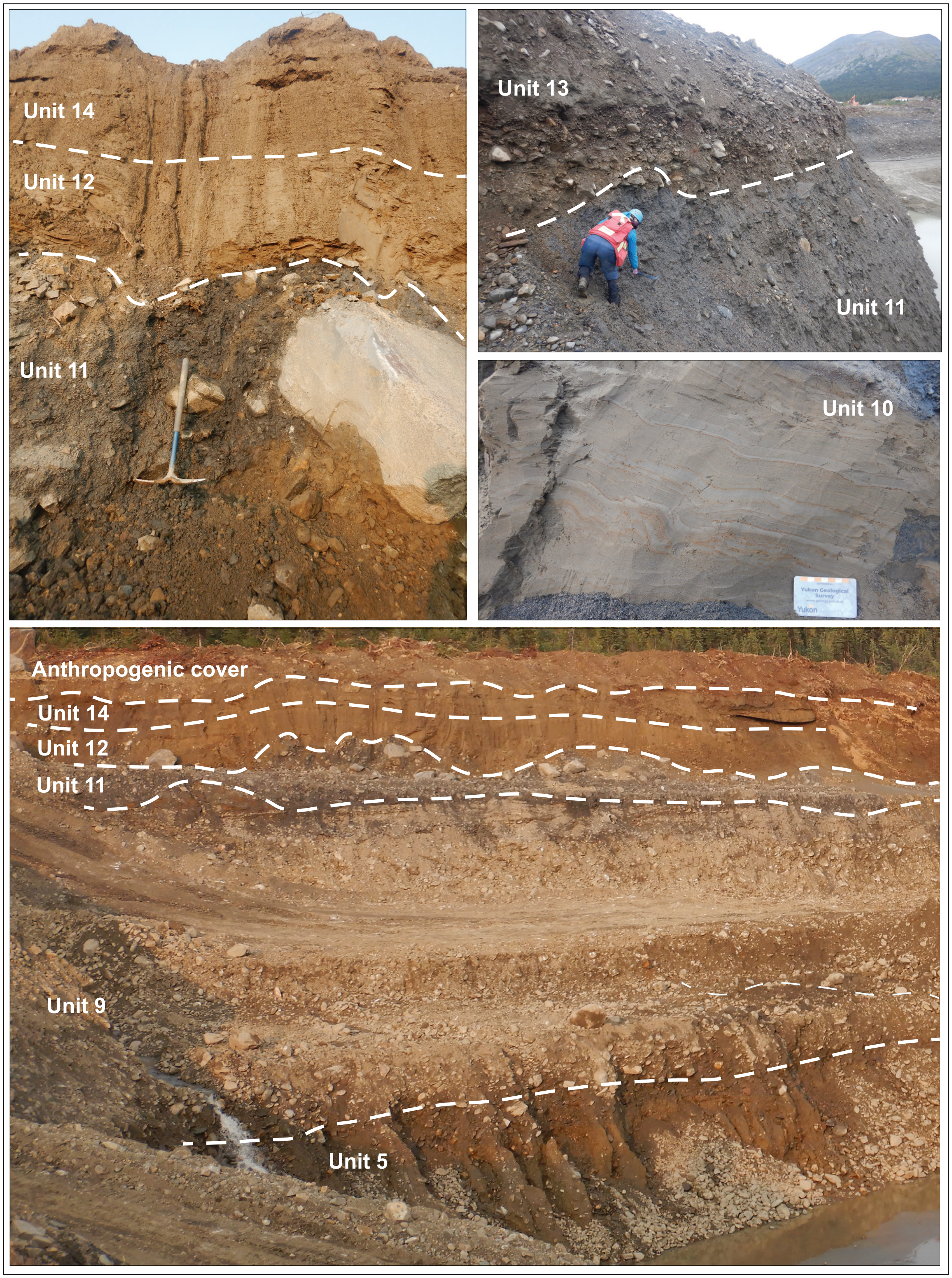

Figure 13. *Main stratigraphic units at GRC-02S.*

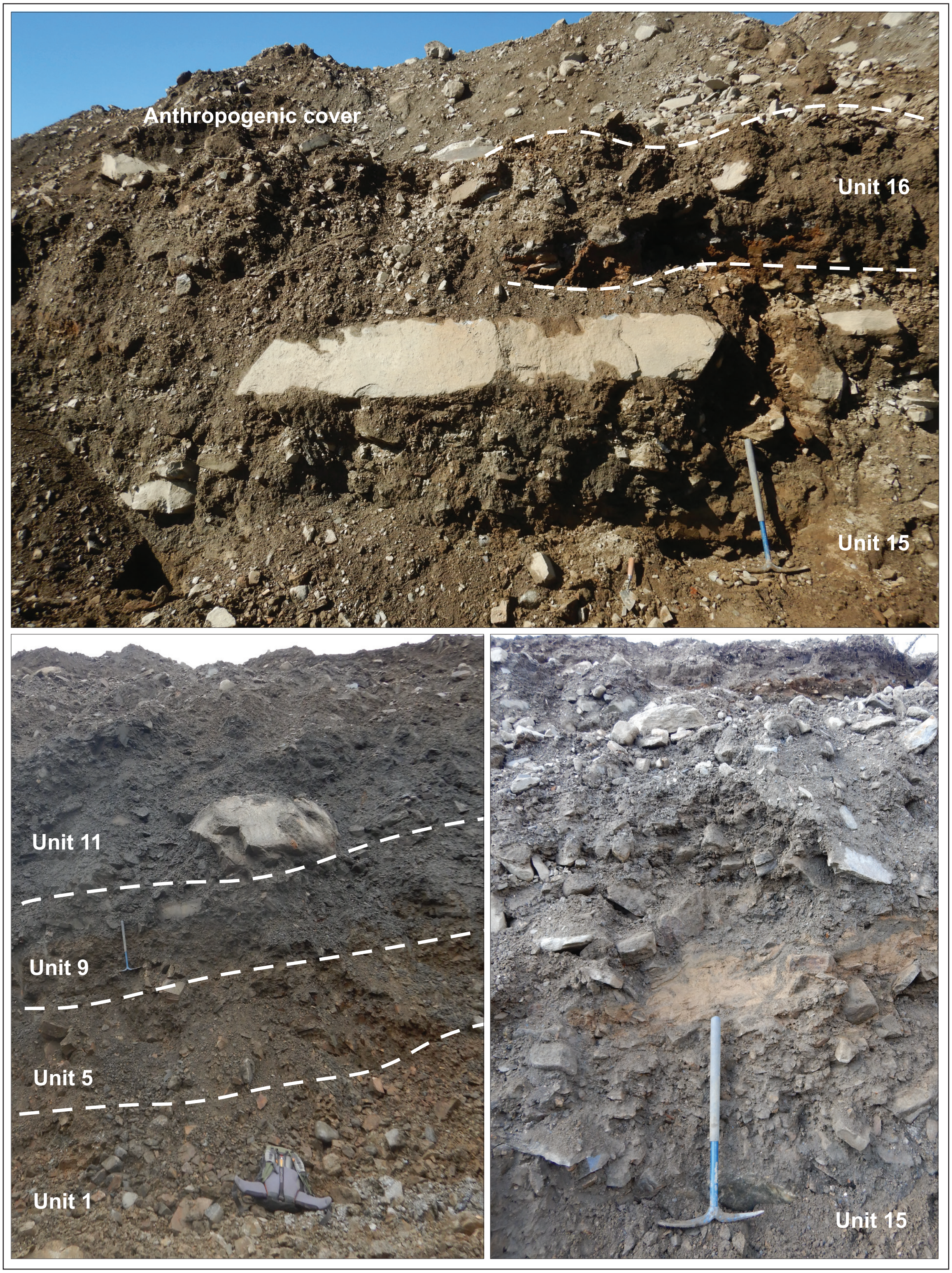

Figure 14. *Main stratigraphic units at GRC-03H.*

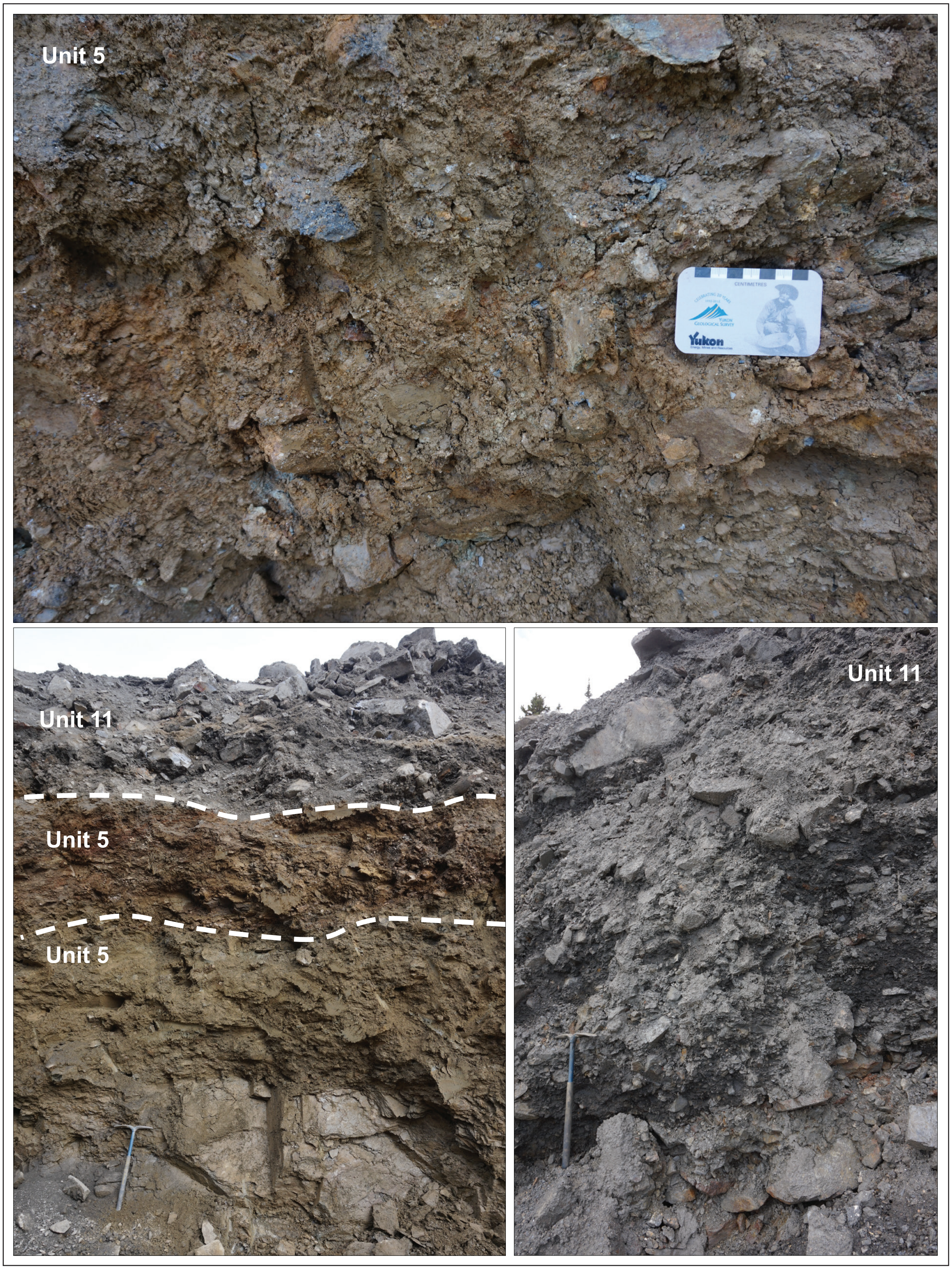

Figure 15. *Main stratigraphic units at GRC-03D.*

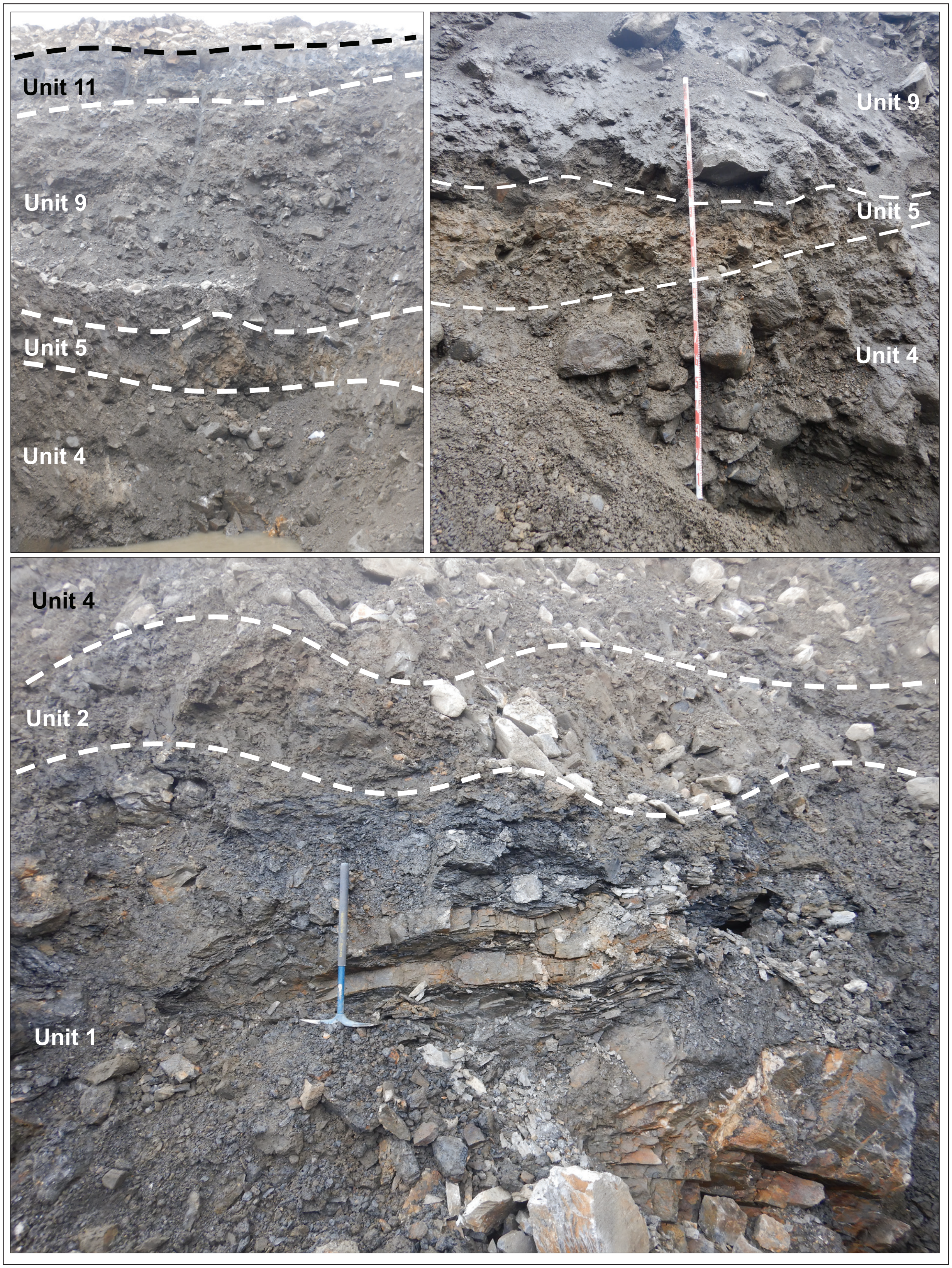

Figure 16. *Main stratigraphic units at GRC-03A.*

Bedrock outcrops on the north and west sides of the excavation and is not found in the rest of the cut. Discontinuous till inferred to be MIS 6 Reid overlies the bedrock and is unconformably overlain by a gold-bearing, yet not economic, advance gravel and till sequence from MIS 4. The next glacial units consist of an advance gravel, till and retreat gravel of MIS 2 age, which also contain low economic values of gold. Thick loess, fluvial gravel and organics overlie the glacial deposits. Gold values are generally low in this deposit, however, could be economic with greater through-put capacity in a wash plant.

GRC-04E and GRC-04W

GRC-04E and GRC-04W are up-valley of the prominent Albert Creek alpine moraine, and to the east of the modern creek. Two walls of this section were logged: GRC-04E (Fig. 17) and GRC-04W (Fig. 18). Units are shown in Figure 6. The units found on each wall of the excavation differ greatly due to the proximity of the modern creek that likely would have been inundated with outwash during glacier advance and retreat, resulting in variable erosion and deposition. Bedrock outcrops on the west wall and is not found on the east wall. Advance gravel and till of MIS 4 age are preserved on the east wall and contain some gold though the absolute values are not known. Deglacial MIS 4 gravel is found on the west wall and overlain by fluvial sand and gravel likely deposited in the MIS 3 interstadial. These units have potential for placer gold. None of the till units were preserved in the west wall, closest to the present creek. Advance gravel containing some placer gold, till and retreat gravel inferred to date to MIS 2 are found on the east and west walls. Fluvial gravel caps the sequence on the west wall and thick loess overlies the sequence on the east wall.

GRC-05L and GRC-05U

These are two separate, abandoned excavations from previous mining operations. GRC-05L (Fig. 19) is in the path of a former meltwater channel from the CIS, inferred from geomorphic position and mapping. GRC-05U (Fig. 20) is inferred as being in the path of a former outwash channel that may have drained a temporary glacial lake in the Granite Creek cirque. Units are shown in Figure 6. Operators at Granite Creek report that gold values in these excavations were not economic. From the lack of placer gold concentrations and geomorphic position, we interpret that these locations were areas of deglacial outwash erosion and deposition that did not rework sediment containing significant gold concentrations. At GRC-05L this is understandable because CIS morainal sediment, which contains very low quantities of placer gold was reworked. At GRC-05U, till that was reworked by the outwash must be sufficiently depleted in placer gold as well.

Discussion

Glacial and Interglacial History

Phase 1

Phase 1 (Fig. 21) represents modern and interglacial periods. In these environments, fluvial erosion and deposition is a common process, and is efficient at concentrating placer gold from surrounding surficial sediment and the bedrock. Within the study area this includes Unit 7 fluvial sand and gravel and Unit 15 modern fluvial gravel. Modern Granite Creek is a proxy for the size of creeks during interglacial periods. Interglacial deposits are not as voluminous as glacial outwash deposits due to the low discharge and velocity of these creeks, which transport less sediment than glacial advance or retreat meltwater environments. The source of material being eroded will impact the placer gold grades in these deposits. In addition, the length of time that the fluvial placers have to develop and concentrate heavy minerals will also impact their grades. Periglacial processes such as frost shattering and cryoturbation, associated with the subalpine and alpine environment of the study area, also liberates bedrock into the valley bottom, which can then be reworked by fluvial activity or incorporated into advancing glaciers.

Phase 2

Phase 2 represents the onset of glaciation. Alpine glaciers respond more quickly to the colder temperatures and advance prior to the arrival of the ice sheet into the area. Alpine glaciers erode bedrock, including mineralized veins in the Granite Creek cirque.

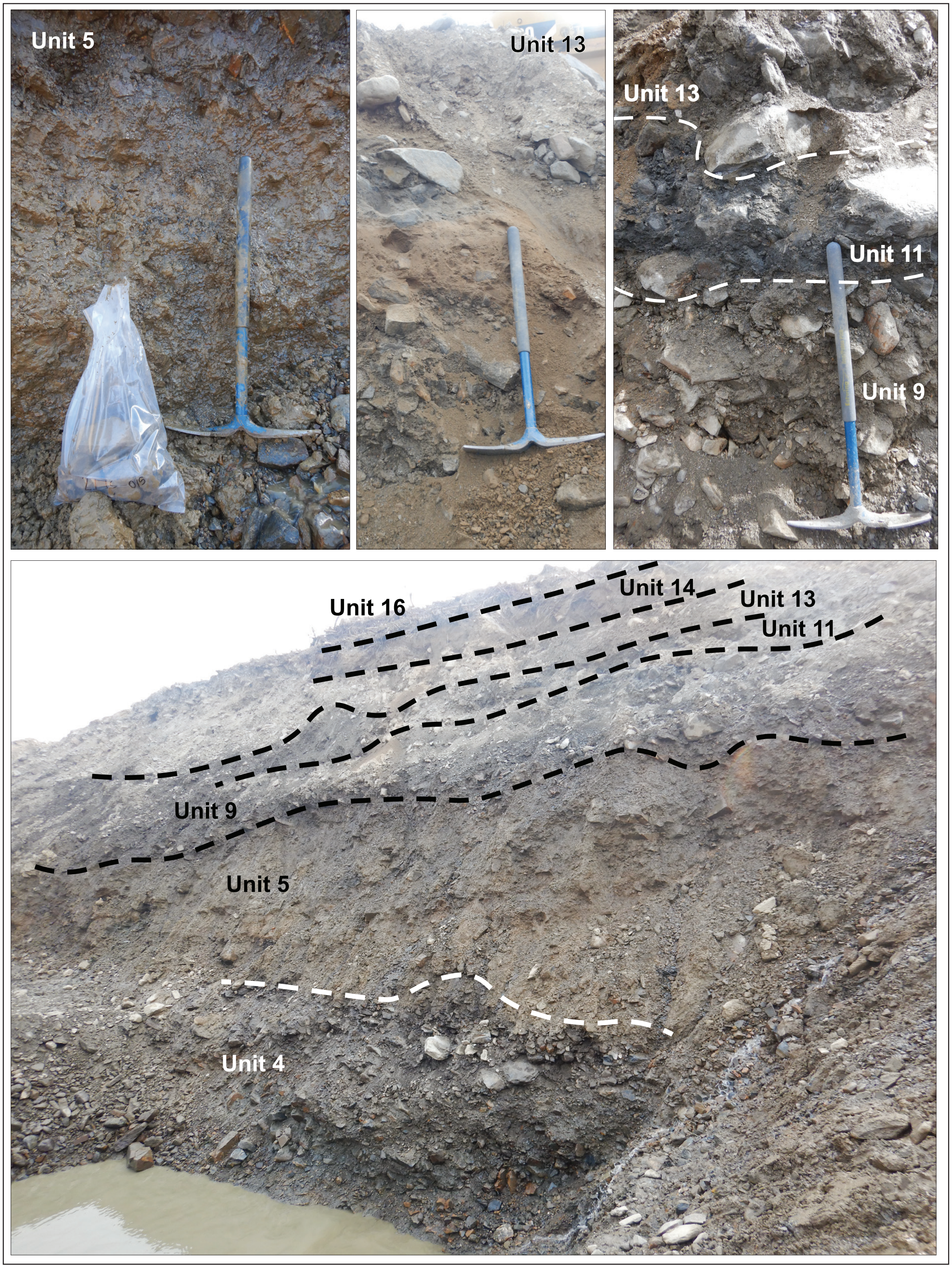

Figure 17. *Main stratigraphic units at GRC-04E.*

Figure 18. *Main stratigraphic units at GRC-04W.*

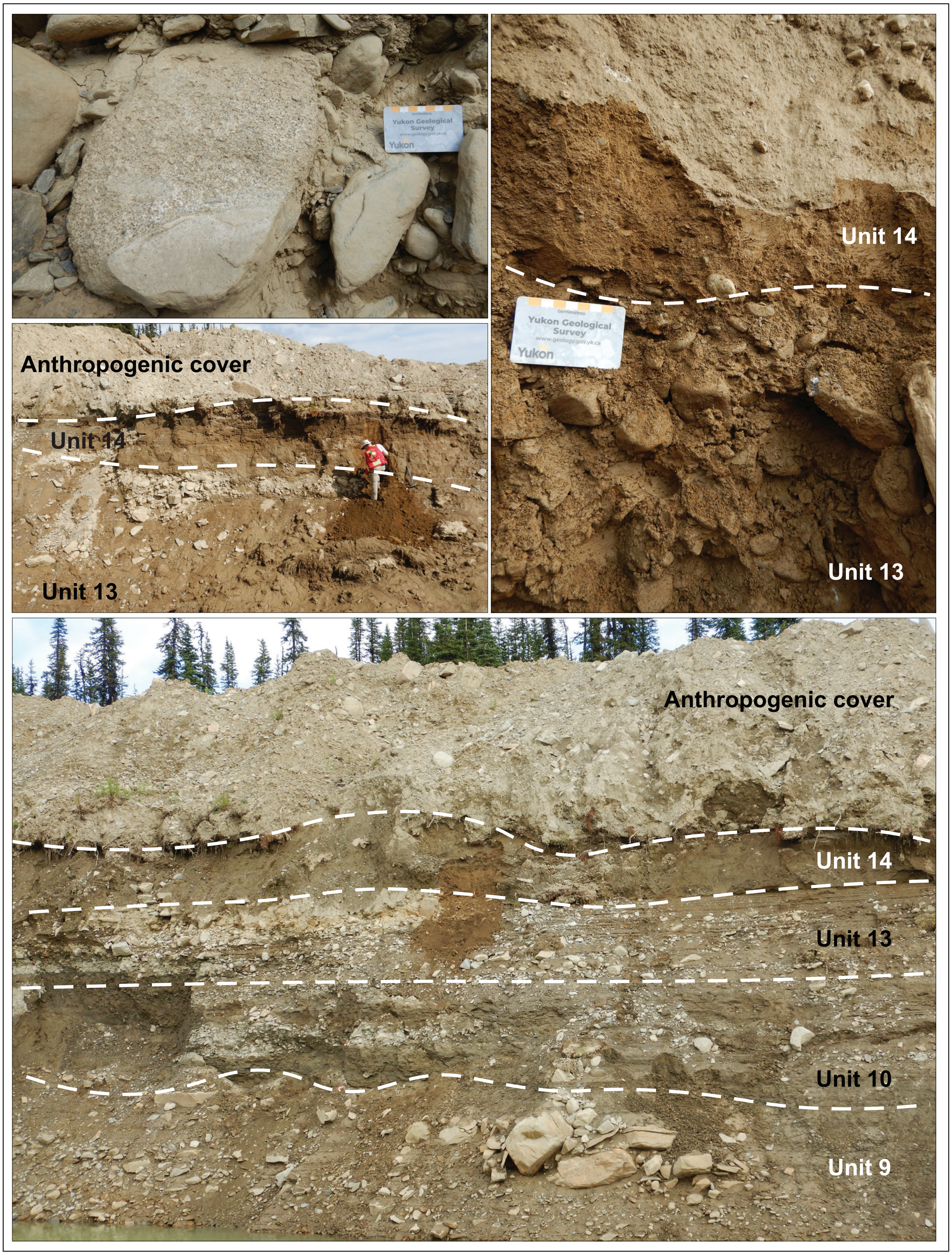

Figure 19. *Main stratigraphic units at GRC-05L including a granite boulder (top left corner) due to the proximity of the CIS MIS 2 moraine.*

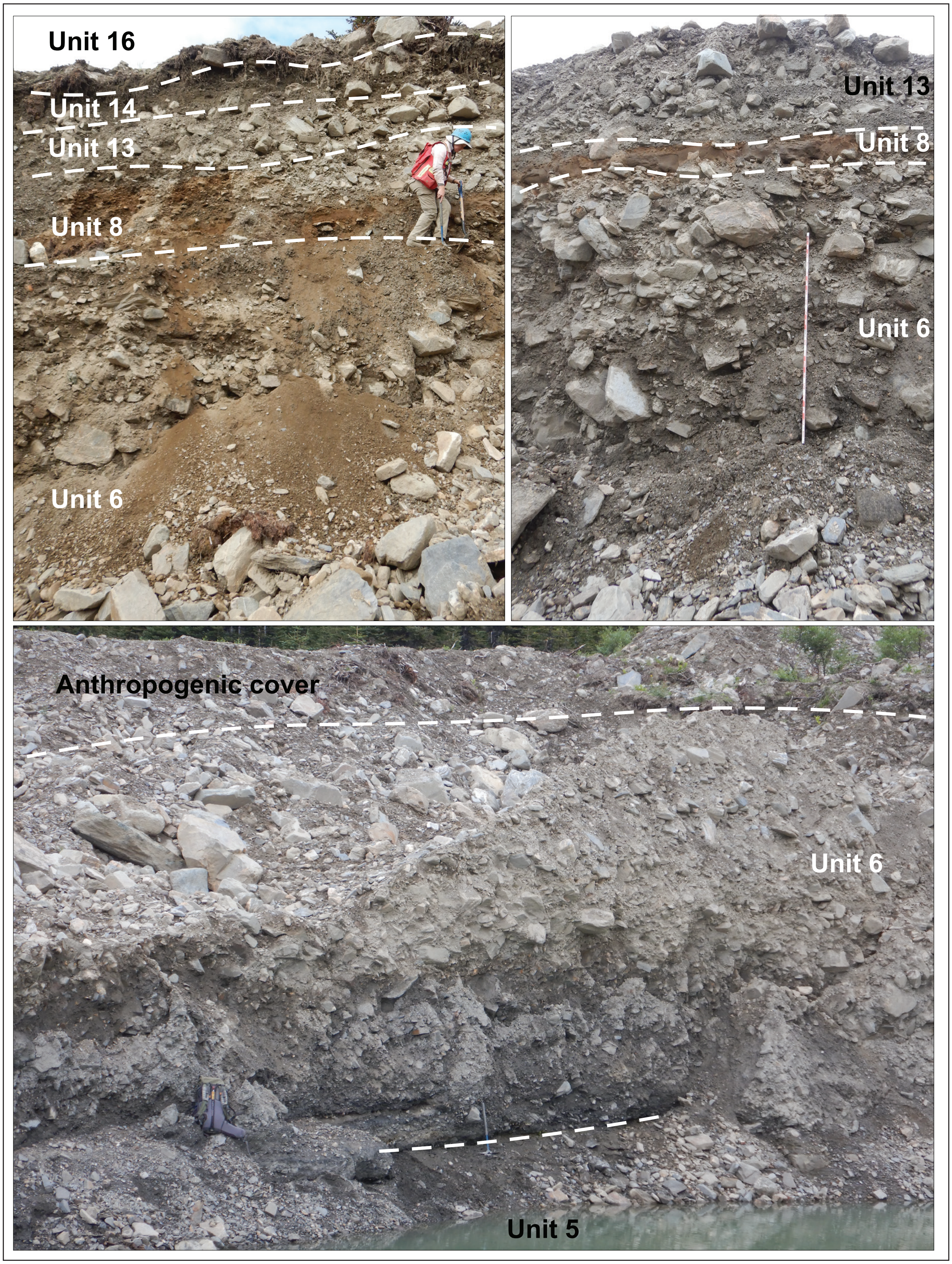

Figure 20. *Main stratigraphic units at GRC-05U.*

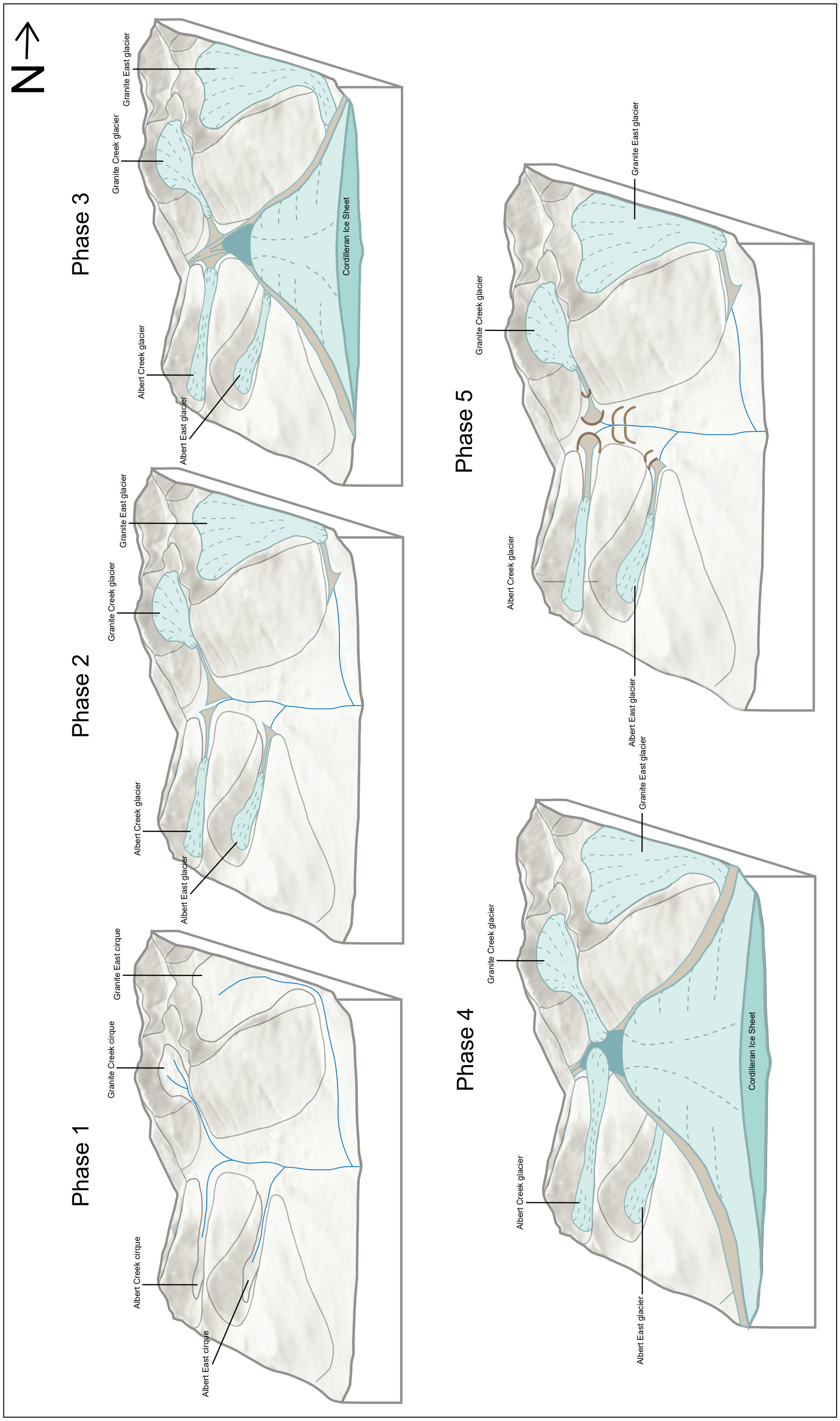

Figure 21. *Block models representing different phases of glaciation in the upper Granite Creek basin. Phase 1: Modern or previous interglacial environment. Phase 2: Onset of glaciation. Phase 3: Cordilleran Ice Sheet advancing up lower Granite Creek. Phase 4: Last glacial maximum (MIS 2). Phase 5: Deglaciation.*

Based on placer gold distribution, mineralized veins are also interpreted to extend into the Mt. Albert cirque. Erosion of these veins and incorporation of gold into till is a significant mechanism for enriching the alpine till. In addition, alpine glaciers erode and incorporate pre-existing gold bearing fluvial deposits. Coarse advance gravel is deposited in outwash fans at the terminus of the alpine glaciers. These deposits are thicker than deglacial deposits due to the aggradational environment associated with their proximity to the advancing ice front. Advance outwash deposits form the thickest placer deposits in the local area. This phase occurs during all glaciations.

Phase 3

Phase 3 represents the presence of the Cordilleran Ice Sheet as it flows up Granite Creek valley, blocking the drainage of Granite Creek and Albert Creek during MIS 2 and MIS 6. In this environment, an ice contact, proglacial lake forms. Meltwater channels form along the margins of the ice sheet. This phase is represented as a coarsening upward sequence in the stratigraphy due to changing base levels as the alpine glaciers and CIS advance. No evidence of this sequence exists for MIS 4, indicating the CIS did not reach the Granite Creek valley or Gustavus Range.

Phase 4

Phase 4 represents the increasing size of the glaciers and glacial lake as the CIS continues to advance up Granite Creek. The drainage changes direction and overtops the divide, flowing west into Keystone Creek. More fine-grained sediment is deposited in the valley. The CIS and alpine glaciers continue advancing into the lake and deform the sand. Topographic representation of the maximum alpine ice position are not preserved likely due to the glaciers terminating into the glacial lake, which would inhibit moraine formation. The prominent moraines visible in the area represent recessional margins. This phase would have occurred during MIS 2 and 6. During MIS 6, the ice sheet would have continued to thicken and eventually flowed through the valley into Keystone Creek.

Phase 5

Phase 5 represents MIS 2 deglaciation. Alpine glaciers retreat, depositing several recessional moraines which indicate that alpine deglaciation was punctuated by significant standstills and potentially readvances. Retreat gravel deposits are thinner and have a finer texture than advance gravels due to the shorter duration of the deglacial phase and reduced outwash flow. Albert and Granite creeks flow east into Roop Lakes after the CIS retreats. Loess blankets the sections, deposited during deglaciation when katabatic winds from the glaciers entrain deglacial sediment, particularly the abandoned glacial lake plain. Fluvial processes downcut into glacial deposits and colluvium from steep slopes accumulate.

Placer Setting landforms

Interglacial Placer Settings

Interglacial placer settings provide some of the most economically viable deposits in Granite Creek due to their high concentration of placer gold. These units include the Unit 7 fluvial sand and gravel deposited during the warm period (MIS 3) prior to the last glaciation, and Unit 15, the modern fluvial gravel (Fig. 10). In the Granite Creek cirque valley, Unit 7 was likely eroded by MIS 2 alpine glacial advance gravel or by the bed of the glacier and reworked into the till. Similarly, this would have occurred during MIS 4 alpine glaciation of the valley when MIS 5 interglacial sediment was reworked. The oxidized fluvial gravel is relatively thin, laterally discontinuous, and only preserved in a few of the sections at Granite Creek. However, there is potential for more deposits in this area due to the sinuous nature of fluvial deposits. Identifying the extent of this unit should be a priority for exploration near GRC-02. Modern fluvial gravel is a second interglacial deposit that contains economic amounts of gold at Granite Creek. Unit 15 modern fluvial gravel was found in sections lower in the valley as well as in upper reaches of Albert Creek. This unit tends to become more enriched toward the lower contact, as the creek reworks and concentrates glacial sediment during fluvial downcutting.

Glacial Placer Settings

Glacial placer deposits comprise the most voluminous gold-bearing deposits at Granite Creek. These units include:

- Unit 4 and 9—advance outwash gravel from the last two glaciations (MIS 2 and 4);
- Unit 5 and 11—alpine basal till (MIS 2 and 4); and
- Unit 13—Retreat gravel, MIS 2

One of the glacial placer settings first discovered in Granite Creek was in a basal lodgement till. In at least one section, lodgement till eroded and thrusted sheets of bedrock, and contained highly economic amounts of placer gold. In this case, the alpine glacier eroded a nearby mineralized bedrock source. Freezing of the glacier onto the bedrock surface, and subsequent plucking and thrusting of the bedrock sheet, can occur near the terminus of a glacier where the ice mass is thinner and not as insulative. In addition to nearby mineralized bedrock, large well-rounded boulders in the till suggest a stream gravel may have also been incorporated into the till. Differentiating between the placer gold-enriched alpine till and the barren till from the CIS can be readily completed by comparing the abundance of foreign versus local material in the till. This can be useful in drilling programs that intersect multiple till units and explain variations in the gold content. However, not all alpine tills contained economic gold concentrations due to the variable distribution of enriched material in the valley. For this reason, detailed exploration drilling is recommended prior to development.

The second glacial placer setting is in advance glaciofluvial gravel, which forms during the onset of glaciation. Advance gravel may rework interglacial deposits that contain economic placer deposits or concentrate large volumes of morainal sediment. These sediments originate as meltwater draining under and alongside the former glacier. In contact with the ice, erosion is common and placer gold is likely carried in high energy streams. Beyond the toe of the glacier, deposition dominates and an outwash fan forms. These deposits are voluminous due to the high input of sediment from the erosional glacial environment and potentially long period in which they develop. Gold concentrates at the contact of competent surfaces such as bedrock or till and is generally dispersed throughout the gravel sequence. As a result, these deposits are important low to moderate-grade bulk tonnage targets.

Placer potential

Placer operations in the upper Granite Creek basin target multiple gold-bearing units in the drainage (Fig. 10). The amount of gold in any one of these units is variable and depends on the mode of deposition, proximity to bedrock mineralization, or previously concentrated placer accumulations. Placer potential is highest in units that form during interglacial/interstadial periods. Recent interglacials spanned periods of time from 50 000 to 30 000 years, which allowed for significant concentration opportunities. Targeting former creek channels or alluvial fans, especially where the gravel is oxidized has the most potential for being economic, depending on thickness of overlying sediments and its gold content. These deposits have the highest preservation potential on the lee side of bedrock highs or in narrow troughs that escaped glacial erosion (Levson and Blyth, 1993). Exploring for these deposits relies on geophysics and drilling to understand their local extent.

Processes that erode mineralized bedrock and deposit it close to the source, such as the formation of alpine till deposits, are found to be enriched in placer gold that is coarse and still retains vein quartz material. Commonly these gold grains are very angular and pristine (Fig. 22). Where bedrock sheets have been thrust into the till, this can be a good indication that erosional processes are occurring nearby and can entrain mineralized bedrock if present. Understanding the structural orientations of mineralized veins in the upper Granite Creek valley bottom will aid in finding new gold-bearing till deposits. The alpine glaciers are also effective at eroding pre-existing stream gravel that contained high concentrations of gold. The presence of well-rounded and water-sculpted boulders in the till provides good evidence of this process.

Figure 22. *Angular gold grains recovered from Granite Creek exposure.*

Glacial meltwater deposits are another potential target. Advance outwash gravel from the alpine glaciers that erodes preglacial gravel or gold-enriched till have high potential, especially when the outwash overlies a competent surface such as bedrock or till. Targeting locations where outwash has eroded into till, which acts as a “false bedrock surface”, have proven to be economic at Granite Creek. These deposits can form very thick units of pay.

In summary, interglacial placer settings are economically viable although discontinuous and low volume, but the potential for more of these deposits exists. Modern fluvial gravel that has reworked and reconcentrated glacial deposits may be preserved in proximity to modern creeks, although they have been largely exploited in recent years in Granite Creek. Glacial placer settings are voluminous and occur as advance outwash, till and retreat gravel. These deposits are the most economic where alpine glaciers erode mineralized bedrock or interglacial placer deposits, resulting in high concentrations of placer gold in till. Advance gravel can contain gold dispersed throughout voluminous deposits and can concentrate on competent surfaces such as till.

There are multiple gold-bearing units at Granite Creek. Exploration programs can benefit from studying the composition of till (local versus erratic material) and employ techniques such as geophysics and drilling to evaluate and map buried economic units. Placer gold concentrations are variable and reflect the complex climatic cycles that have impacted the study area over the past 130 000 years. Future exploration and development in the upper Granite Creek basin will benefit from stratigraphic and sedimentological modeling to understand the mode of deposition of various units. These can be correlated with the 16 units compiled from this study, which will aid in predicting unit continuity across local exploration areas.

Alpine glaciated environments have likely been overlooked in the past, based on the assumption that placer preservation potential is low in areas that have been glaciated multiple times. This study, and the efforts of the Granite Creek mining community, counteracts this assumption. Targeting areas where known high-grade gold veins are present in an alpine glacier-dominated environment would form the basis for exploration.

Conclusion

The glacial history of the upper Granite Creek basin is recorded in a series of interglacial and glacial deposits. The stratigraphy and sedimentology accessed due to extensive placer mining has allowed reconstruction of the geologic history of the last 130 000 years. This sequence is complex and includes interglacial deposits such as fluvial sand and gravel, and a large proportion of glacial deposits such as outwash, glaciolacustrine and till. Glacial material that correlates to an alpine advance during MIS 4 was identified, which has not been found elsewhere in central Yukon. However, no MIS 4 Cordilleran Ice Sheet deposits affected the upper Granite Creek basin, suggesting the advance did not reach the Gustavus Range. The advance of the CIS into the Granite Creek valley during MIS 2 and MIS 6 caused base level changes in the form of ponding and redirection of local drainage to the west.

Placer gold is dispersed throughout the stratigraphy in several units at varying depths and concentrations. Modern, interglacial and glacial placer deposits were identified in several units across the Granite Creek valley. One of the main controls on placer gold content is the material that is incorporated into deposits. The presence of local mineralized gold veins can result in till that is enriched in coarse, nuggety placer gold. Glacial processes that entrain interglacial placer deposits can also be economic and result in concentrations of placer gold at false bedrock contacts. Detailed exploration into these units allow for more targeted exploration into these deep environments. These findings can be extended to other formerly alpine glaciated areas in the Cordillera such as northern BC, or in Alaska.

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