Testing the relationship between the Llewellyn fault, gold mineralization, and Eocene volcanism in northwest British Columbia: A preliminary report

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Abstract

The Llewellyn fault represents a significant geological feature in northwest British Columbia. The fault is at least 100 km long, northwest striking, and steeply dipping. An early ductile history is preserved as foliations, lineations, and local folds in the wallrocks. The fault has a later brittle history, preserved as gouge and multiple fracture sets. Dextral offset related to the brittle deformation overprints earlier ductile fabrics. The quartz-carbonate vein-hosted, past-producing Engineer gold deposit (epithermal, low-sulphidation type) is related to this late brittle deformation. Available geochronological data indicate that the deposit formed in the Eocene (ca. 55-50 Ma). Along the likely extension of the Llewellyn fault to the north in the Yukon (Tally-Ho shear zone) are the Mount Skukum gold deposit and a series of gold deposits at Montana Mountain, also of the low-sulphidation epithermal-type. Both the host volcanic rocks at Mount Skukum (Sloko Group) and gold mineralization are coeval (ca. 55 Ma). Because Mount Skukum gold mineralization is directly related to Eocene volcanism, and Engineer gold mineralization is both spatially and temporally coincident with Eocene magmatism, preliminary comparisons suggest a three-part relationship between large-scale structure, gold mineralization, and Eocene magmatism in northwest British Columbia and southwest Yukon.

Keywords: Llewellyn fault, gold mineralization, Eocene magmatism, Mount Skukum Mine, Engineer Mine

1. Introduction

More than 100 km long, the Llewellyn fault is a major, steeply dipping, northwest-striking structure in northwest British Columbia (Figs. 1, 2; Mihalynuk et al., 1994; 1999). Spatially related to the fault are quartz-carbonate vein-hosted gold-silver and base-metal prospects, including the past-producing Engineer mine (Fig. 2; Mauthner et al., 1996; Millonig et al., 2015). Also spatially related are Eocene volcano-plutonic centres (Fig. 2; Mihalynuk et al., 1999). The Llewellyn fault appears to continue northwest into Yukon (Tally-Ho shear zone, Fig. 2; Doherty and Hart, 1988; Hart and Pelletier, 1989) as indicated by similarities in vein-hosted precious and base-metal deposits and spatially related Eocene volcanic complexes (Doherty and Hart, 1988; Love, 1989; Love et al., 1998).

The spatial relationship between the Llewelyn fault and vein-hosted mineralization supports a structural link, and geochronological data indicate a temporal link between gold mineralization (Engineer and Mount Skukum mines) and Eocene volcanism (Love et al., 1998; Mihalynuk et al., 1999; Millonig et al., 2015). Many of the gold deposits are epithermal (Nesbitt et al., 1986; Walton, 1986; Love, 1989; Mauthner et al., 1996; Mihalynuk et al., 1999; Love et al., 1998; Millonig et al., 2015), although some, like those at Montana Mountain (Fig. 2) are considered mesothermal (Hart and Pelletier, 1989). The apparent relationship between structure, mineralization, and magmatism points to the intrusion-related, epizonal, end-member of the orogenic gold deposit model because such deposits are typically related to first-order crustal breaks and synchronous magmatism (e.g., Goldfarb et al., 2005). To gain a better understanding of the spatial and temporal relationships between the Llewellyn fault, gold mineralization, and Eocene magmatism and the possible connections to the orogenic-style of gold mineralization, we conducted three weeks of field reconnaissance along the trace of the northern segment of the fault in British Columbia. This work included inspecting spatially related gold prospects, past-producing deposits and, where possible, Eocene volcanic rocks in British Columbia and Yukon. This report summarizes this reconnaissance and proposes future avenues of research.

2. Geologic setting

We examined the Llewellyn fault between Engineer Mine and Bennett Lake near the British Columbia-Yukon border and investigated rock units adjacent to the Klondike Highway between the communities of Carcross and Fraser (Fig. 2). Excursions were also made to the past-producing Mount Skukum and Montana Mountain gold-silver mines in the southern Yukon (Roots, 1981; Hart and Pelletier, 1989; Love, 1989). Foot traverses were set out by truck along maintained roads, ATV's on trails (Bennett Plateau and Mount Skukum),

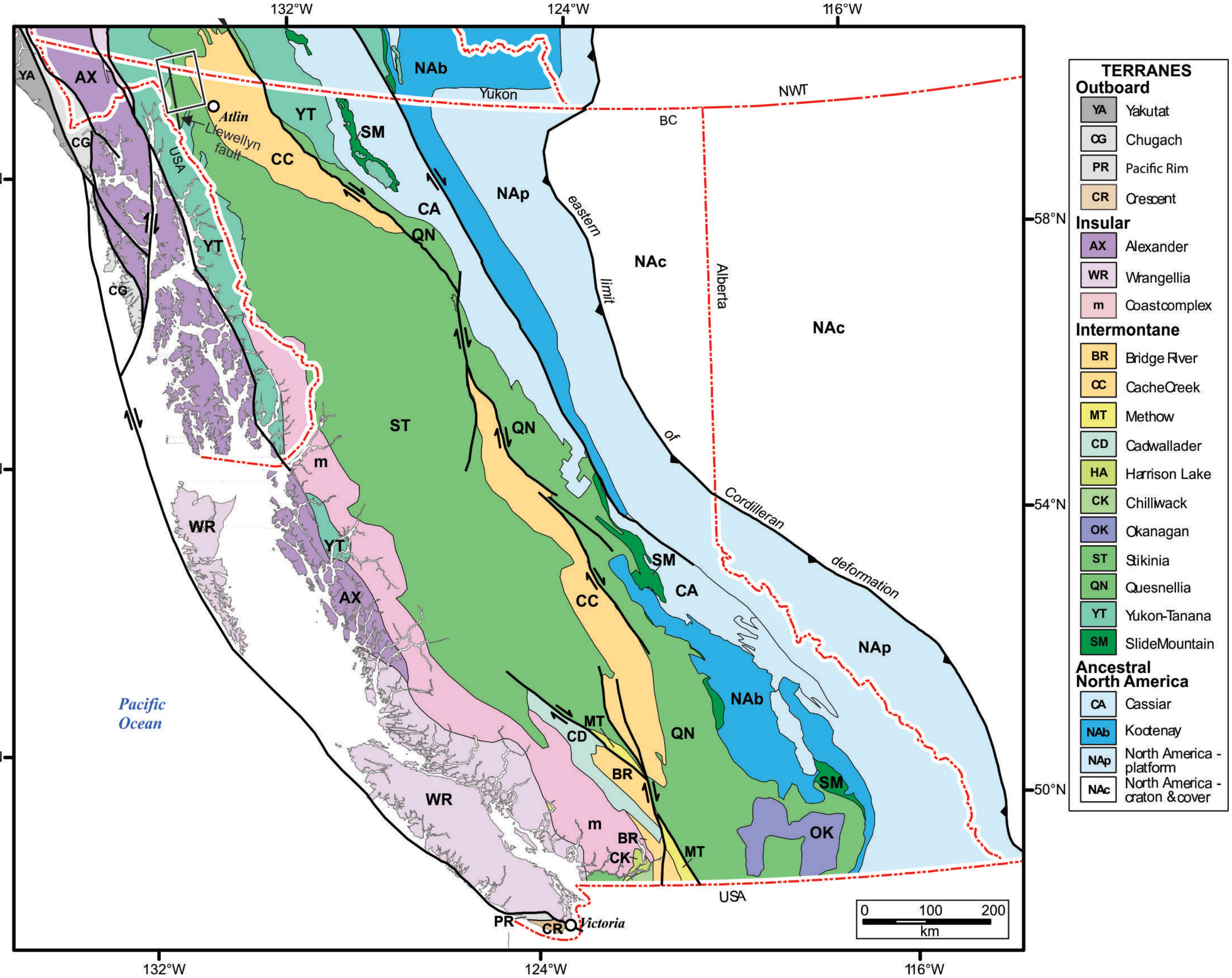

Fig. 1. Geological terrane map of British Columbia and neighbouring jurisdictions. The study area in northwest BC is highlighted by a black outline. Modified after Nelson et al. (2013).

and helicopter in more remote areas.

The part of the study area in British Columbia was previously mapped at 1:50,000 scale and incorporated into a regional geological map at 1:100,000 scale (Mihalynuk et al., 1999). Geological features in the area of Mount Skukum, Yukon, were mapped at 1:50,000 scale by Doherty and Hart (1988); detailed deposit-scale studies were by McDonald (1987), McDonald and Godwin (1986), Pride (1986), and Love (1989; 1990a, b). Roots (1981, 1982) and Hart and Pelletier (1989) described geology of the Montana Mountain area, Yukon, including the past-producing Venus gold-silver and other mines.

The Llewellyn fault is a northwest-striking, steeply-dipping strike-slip deformation zone that displays an early ductile history overprinted by brittle fabrics (Fig. 3). The fault extends from the Tulsequah area in the south (where the fault crosses into Alaska), to Bennett Lake, British Columbia, and likely continues northward into Yukon as the Tally-Ho shear zone (Doherty and Hart, 1988; Hart and Pelletier, 1989; Mihalynuk et al., 1999; Tizzard et al., 2009). South of Atlin Lake, the Llewellyn fault may merge with the southeast striking King Salmon thrust fault (e.g., Mihalynuk et al., 1999). Between Tagish and Bennett lakes (see figure 2-1 in Mihalynuk et al., 1999) the Llewellyn fault marks the eastern extent of the Wann River gneiss, Florence River Metamorphic suite, and the Boundary Ranges metamorphic suite, rocks all considered to be Triassic or older. East of the Llewellyn fault are Triassic-Jurassic rocks of the Stuhini and Laberge groups. Triassic-Jurassic, Early Cretaceous, and Late Cretaceous-Tertiary plutons and minor volcanic complexes are on both sides of the Llewellyn fault, although predominantly to the west (Mihalynuk et al., 1999). Eocene volcano-plutonic centres (Ypresian ca. 55 Ma; Table 1) are preserved adjacent to the trace of Llewellyn fault along its strike length; the volcanic rocks have been assigned to the Sloko Group (Fig. 2; Mihalynuk et al., 1999). In the study area, these magmatic centres generally cap older units, forming steep, high-elevation terrain. Examples of these centres include

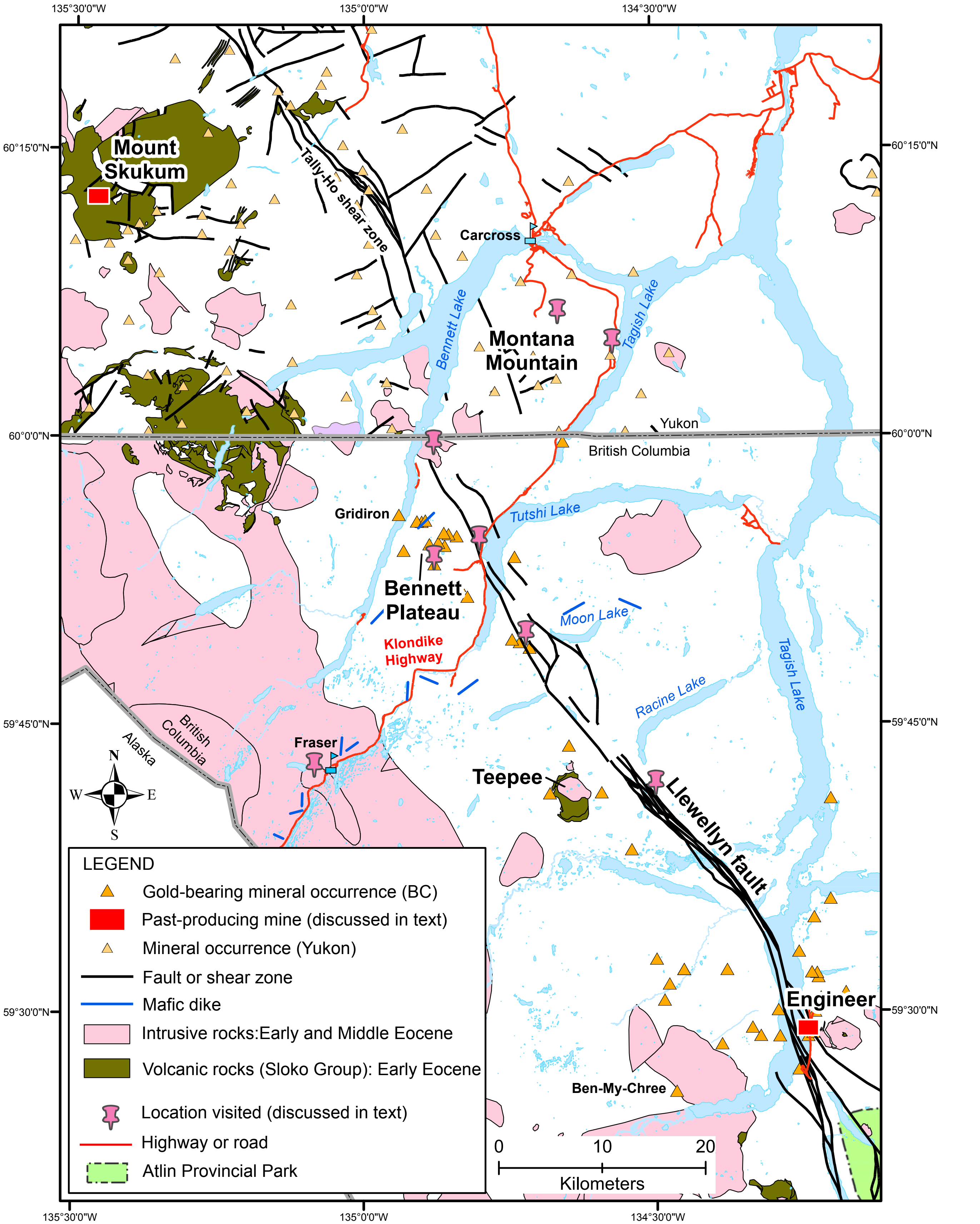

Fig. 2. Simplified geology (Eocene rock units only) near the Llewellyn fault, northwest British Columbia (Doherty and Hart, 1988; Mihalynuk et al., 1999).

Table 1. Temporally relevant magmatism and gold mineralization near the Llewellyn fault, northwest BC and southwest Yukon.

Location	Interpretation	Age (Ma)	Mineral	Method	Source
Engineer Mountain	rhyolite - SPS	ca. 54	zircon	U-Pb - age only presented	Mihalynuk et al. 1999
Atlin Mountain west	ignimbrite - SG	ca. 54	zircon	U-Pb - age only presented	Mihalynuk et al. 1999
Mount Switzer	rhyolite - SG	ca. 55	zircon	U-Pb - age only presented	Mihalynuk et al. 1999
	quartz monzonite - SPS	ca. 56	zircon	U-Pb - age only presented	Mihalynuk et al. 1999
	diorite - SPS	ca. 56	zircon	U-Pb - age only presented	Mihalynuk et al. 1999
West of Mount Switzer	granite - CPC	ca. 55	biotite	K-Ar - age only presented	Mihalynuk et al. 1999
Teepee Peak	granodiorite-tonalite - SPS	ca. 55	biotite	K-Ar - age only presented	Mihalynuk et al. 1999
	rhyolite flow - SG	ca. 56	zircon	U-Pb - age only presented	Mihalynuk et al. 1999
Skelly Lake	massive rhyolite - SG	58.5 ±1.5	zircon	U-Pb (TIMS) lower intercept	Mihalynuk et al. 1999
middle ridge	rhyolite	124.9 ±1.5	zircon	U-Pb (TIMS) upper intercept	Mihalynuk et al. 2003
Montana Mountain*	Late Cretaceous?	N/A			Roots 1981
	Mid Cretaceous	ca. 95 to 85			Hart 1995
Mount Skukum*	syn-ore intermediate dike - SG	55.7 ±0.3	zircon	U-Pb (TIMS) Concordia	Love et al. 1998
	pre-ore rhyolite dike - SG	56.3 ±0.4	zircon	U-Pb (TIMS) Concordia	Love et al. 1998
Diorite dykes along Klondike Highway	Eocene - CPC	51 ±1	biotite & whole rock	K-Ar	Symons et al. 2000
Mineralization					
Engineer	mineralization	49 ±0.5	V-bearing muscovite	$^{40}Ar/^{39}Ar$ step heating	F. Devine, pers. comm. 2016
Mount Skukum*	ore-related alteration	54.1 ±0.3	adularia	$^{40}Ar/^{39}Ar$ step heating	Love et al. 1999
	pre-ore alteration	55.7 ±0.3	alunite	$^{40}Ar/^{39}Ar$ step heating	Love et al. 1999
Montana Mountain*	post-Cretaceous	N/A			Hart and Pelletier 1989

*Yukon
CPC - Coast Plutonic Complex
SG - Sloko Group
SPS - Sloko plutonic suite
N/A – no radiometric age available. Relative age from field interpretations

Engineer Mountain and Teepee Peak in the study area (Fig. 2; Mihalynuk et al., 1999), and the Bennett Lake and Mount Skukum volcanic complexes in the Yukon (Fig. 2; Doherty and Hart, 1988; Morris and Creaser, 2003).

The Llewellyn fault displays early high-strain fabrics that are overprinted by later brittle features (Mihalynuk et al., 1999; Tizzard et al., 2009). Early ductile deformation is marked by a belt of rocks with a strong northwest striking, steeply dipping penetrative foliation (Fig. 3a), rare lineations, and local minor folds. Similar, possibly correlative fabrics are in the Tally-Ho shear to the north (Doherty and Hart, 1988; Hart and Pelletier, 1989; Mihalynuk et al., 1999; Tizzard et al., 2009). Tizzard et al. (2009) interpreted that ductile movement along the Tally-Ho shear zone took place between ca. 208 and 173 Ma. The timing is based on U-Pb zircon ages of a leucogabbro that transitions into mylonite in the hangingwall of the shear zone, and a post-deformation megacrystic granite that crosscuts the leucogabbro and other mylonites (Tizzard et al., 2009). These ages support timing arguments presented by Mihalynuk et al. (1999). Although the Llewellyn fault and Tally-Ho shear zone are along strike of one another and share early penetrative deformation, they differ. First, the early fabrics in the Llewellyn fault are consistently subvertical (Fig. 3; Mihalynuk et al., 1999), whereas the Tally-Ho shear zone is folded (Tizzard et al., 2009). Second, the Llewelyn fault is a low-grade strike-slip shear zone (Mihalynuk et al., 1999), and the Tally-Ho shear zone is considered a west-over-east thrust fault with mylonite development (Tizzard et al., 2009).

The Llewellyn fault is mainly defined by a corridor of brittle features (Fig. 2), such as fault gouge and vein-filled fractures that overprint the older ductile deformation fabrics (Fig. 4). The brittle fabrics are thought to coincide with up to 2 km of dextral offset along the fault (Mihalynuk et al., 1999). Brittle overprinting of the early ductile fabrics is also documented along the Tally-Ho shear zone (Tizzard et al., 2009). The precise timing of brittle deformation remains uncertain, but components of it are likely Eocene (Table 1; Mihalynuk et al., 1999; Tizzard et al., 2009).

3. Mineralization

More than 50 mineral occurrences spatially related to the Llewellyn fault have been documented in the study area (Fig. 2; for details see Table 14-1 and Figure 14-2 in Mihalynuk et al., 1999). Many of these deposits and prospects have been known for more than 100 years, following discoveries during the Klondike gold rush of the late 1890s. Not surprisingly, these occurrences are in clusters near road and rail routes and water access sites at Bennett and Tutshi lakes in the northwest, and Tagish Lake in the southeast.

Three past-producing vein-hosted precious and base-metal deposits are in the British Columbia part of the study area. The Engineer Mine was the most productive gold deposit;

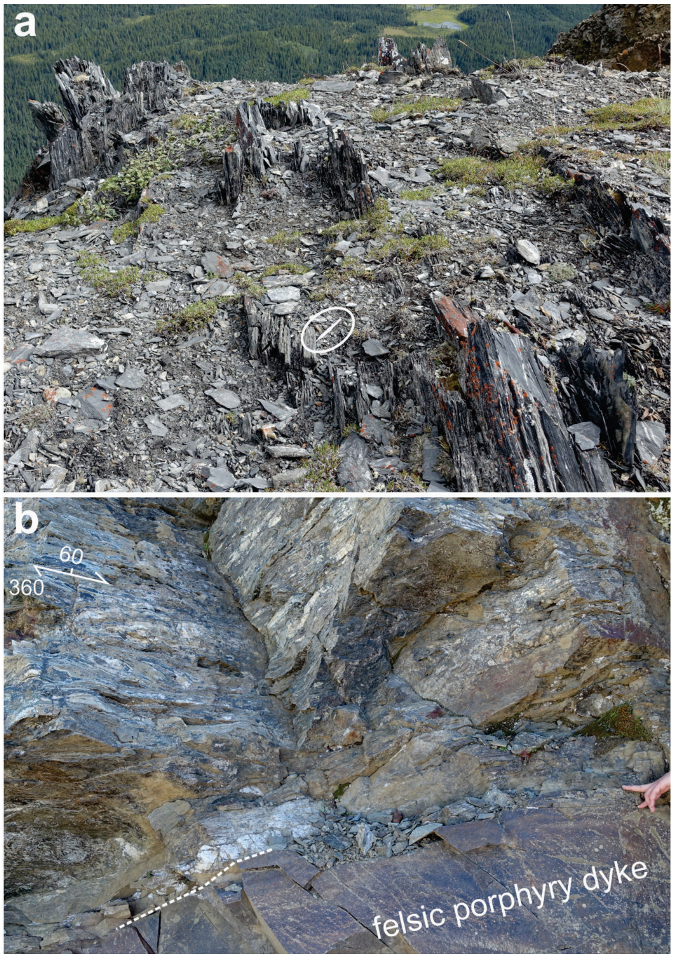

Fig. 3. Early ductile features near the Llewellyn fault trace. **a)** Well-developed cleavage in shale of the Stuhini Group (Triassic; Mihalynuk et al., 1999). View is southeast, scribe for scale (circled). **b)** Ductile deformation fabrics in well-foliated amphibolite gneiss of the Stuhini Formation or Laberge Group (Mihalynuk, et al., 1999). Amphibole+quartz veins are flattened, folded and boudinaged. In the foreground is a felsic hornblende-plagioclase porphyry dike that was injected along foliation in the host rocks. We collected a sample for U-Pb geochronology. From the Skarn Zone mineral prospect on Bennett Plateau, east of Bennett Lake; view is to the east.

production at Gridiron and Ben-My-Chree was relatively minor (Fig. 2). Gold has been mined intermittently at the Engineer Mine for more than 90 years. BCGold Corp. reported a NI 43-101-compliant Inferred Mineral Resource of about 41,000 tonnes grading 19.0 g/t of total contained gold (5 g/t cut-off grade; Dominy and Platten, 2011). Surficial and underground maps of the Engineer deposit are presented by Millonig et al. (2015).

The Engineer mine consists of several gold-bearing quartz-carbonate veins. Because of historical mining, very little of the original surface exposures remain (Fig. 5a) and veins and mineralization are generally only visible in sample dumps (underground workings are currently inaccessible). The mine workings have collapsed and these provide the orientation of past ore-hosting veins (Fig. 5a). The structures hosting ore at the Engineer mine are related to splays of the Llewellyn fault, 10 km south of a 20° bend (Fig. 2; Mihalynuk et al., 1999; Millonig et al., 2015). Ore-related alteration includes a mica that is colloquially referred to as roscoellite, but is a different vanadium-bearing muscovite (L. Millonig et al., 2015; pers. comm. 2016). A sample of this mineral has yielded an $^{40}Ar/^{39}Ar$ step-heating age of ca. 49 Ma (F. Devine, pers. comm. 2016). This age supports a temporal relationship between structure, gold mineralization, and possibly Sloko Group magmatism at Engineer, although Sloko Group volcanic rocks are slightly older (ca. 55 Ma; Table 1).

In addition to the past-producers, many vein-hosted precious and base-metal mineralized prospects and skarn-like precious metal prospects appear spatially related to the Llewellyn fault. Collectively referred to as the Golden Eagle project, many of these prospects are currently held by Troymet Exploration Corp. One example is the the Skarn Zone gold prospect at Bennett Plateau (Fig. 2), that is in a zone of deformed quartz and amphibolite veins and intruded by granitic porphyry dikes (Fig. 3b).

Similar to British Columbia, many mineral occurrences are adjacent to the Llewellyn fault in the Yukon. We visited three past-producing vein-hosted precious and base-metal mines in the Yukon including Mount Skukum (e.g., Love, 1989), and two on Montana Mountain (Venus and Arctic Caribou mines; e.g., Roots, 1981). At Mount Skukum, only minor parts of the mineralized structures are preserved at the surface, but the collapsed underground workings provide a visual aid to the historic location and orientation of the ore-hosting veins (Fig. 5b; Love, 1989, 1990b; Love et al., 1998). The Venus mine is the most significant past-producer at Montana Mountain, but mineralization is rarely exposed on surface and therefore sample dumps provide the best material to study (Fig. 5c). At Arctic Caribou, bedrock is not exposed and only scattered waste-rock is available along a dilapidated rail-track leading from an abandoned mine portal.

4. Ongoing and future work

In addition to regional structural analysis, we are conducting geochronologic studies along the length of the Llewellyn fault. The purpose of the geochronology is to address the timing of fault movement and to assess the significance of mafic dikes (ca. 51 Ma; Symons et al., 2000), some of which may be lamprophyres.

4.1. Structural analysis

Key questions arising from our reconnaissance are: what is the structural and/or genetic relationship between the Llewellyn fault and gold mineralization, and how do the structural relations compare between deposits?

The Engineer and Mount Skukum mines are well mapped (Love, 1989) and, although the apparent timing of gold mineralization is similar (Eocene; Table 1), these deposits have never been directly compared. Love (1990b) used the vein distribution at Mount Skukum to present a kinematic solution

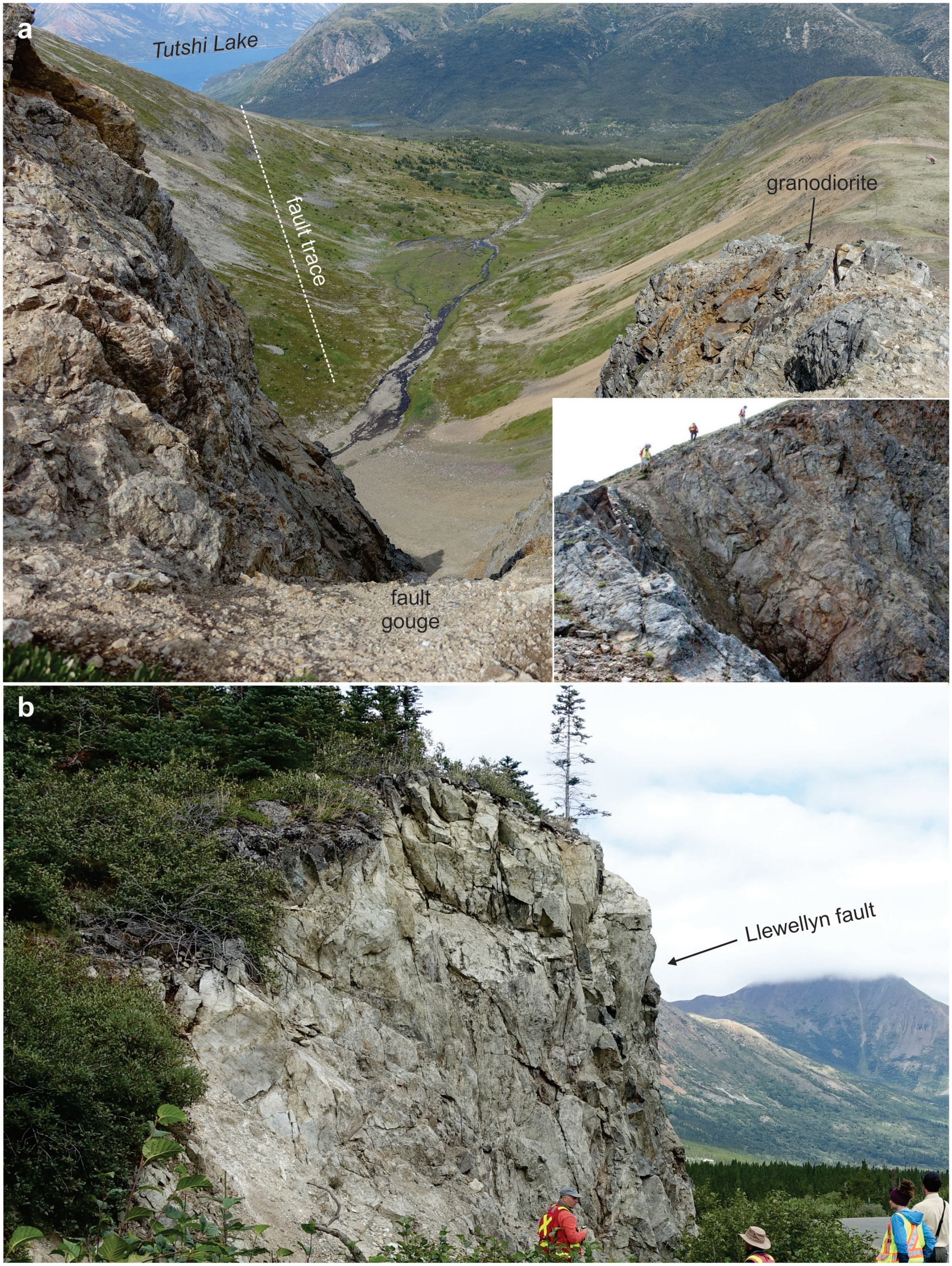

Fig. 4. Late brittle features along the Llewellyn fault. **a)** Fault gouge with brittle deformation features (e.g., fractures) preserved in granodiorite wall-rock (Mesozoic?). Location is west of Moon Lake and view is to the northwest. Inset is a view of the wall of the fault. **b)** Road-cut exposure of the Llewellyn fault preserving brittle deformation features, including cracks and quartz vein-filled fractures in granodiorite (Mesozoic?). Outcrop is adjacent to the Klondike Highway west of Tutshi Lake.

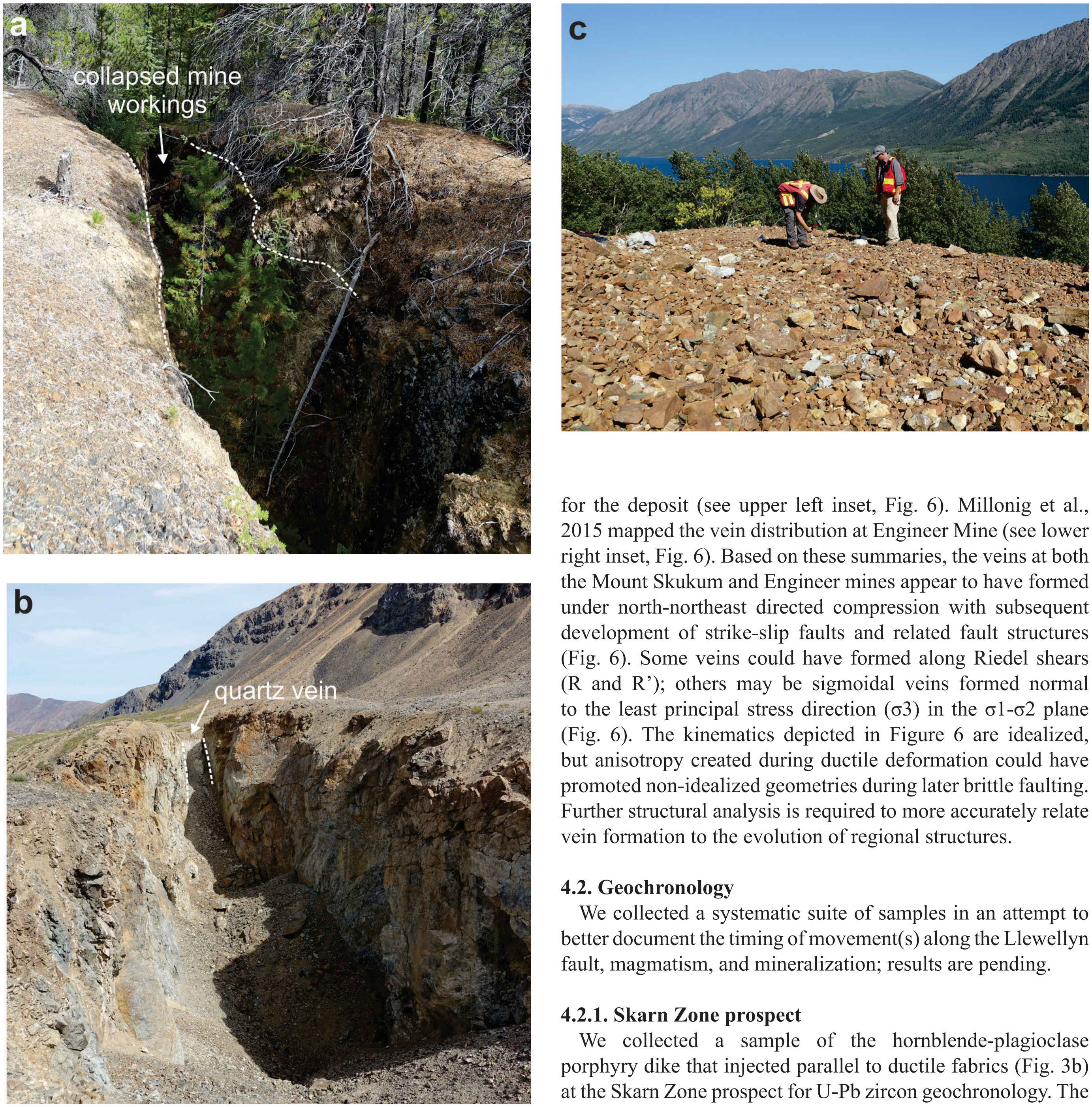

Fig. 5. Surface remains of past-producing gold mines. **a)** Collapsed and overgrown mine workings at Engineer Mine. The 1.5 metre-wide, 030°-striking crevasse (collapsed workings, not a trench) represents the width and strike of mined out hydrothermal veins. **b)** Mostly mined out, 3-metre-wide, 040°-striking quartz vein, Cirque Zone, Mount Skukum. The pit in the foreground is above collapsed underground workings. All bedrock exposures hosting the hydrothermal veins are volcanic rocks of the Sloko Group (ca. 55 Ma). **c)** Waste-rock-pile at the past-producing Venus Mine, Yukon, adjacent to the Klondike Highway.

for the deposit (see upper left inset, Fig. 6). Millonig et al., 2015 mapped the vein distribution at Engineer Mine (see lower right inset, Fig. 6). Based on these summaries, the veins at both the Mount Skukum and Engineer mines appear to have formed under north-northeast directed compression with subsequent development of strike-slip faults and related fault structures (Fig. 6). Some veins could have formed along Riedel shears (R and R'); others may be sigmoidal veins formed normal to the least principal stress direction (σ3) in the σ1-σ2 plane (Fig. 6). The kinematics depicted in Figure 6 are idealized, but anisotropy created during ductile deformation could have promoted non-idealized geometries during later brittle faulting. Further structural analysis is required to more accurately relate vein formation to the evolution of regional structures.

4.2. Geochronology

We collected a systematic suite of samples in an attempt to better document the timing of movement(s) along the Llewellyn fault, magmatism, and mineralization; results are pending.

4.2.1. Skarn Zone prospect

We collected a sample of the hornblende-plagioclase porphyry dike that injected parallel to ductile fabrics (Fig. 3b) at the Skarn Zone prospect for U-Pb zircon geochronology. The Skarn Zone contains low-grade gold mineralization in veins of amphibole and quartz that are now strongly deformed. The dike is undeformed and strikes parallel to the main wallrock foliation. The crystallization age of this dike will provide both a minimum age for the ductile deformation in this area and this style of gold mineralization.

4.2.2. Granite pluton east of Bennett Lake

A granitic pluton east of Bennett Lake at the British Columbia-Yukon border appears to crosscut the Llewellyn fault (Fig. 6),

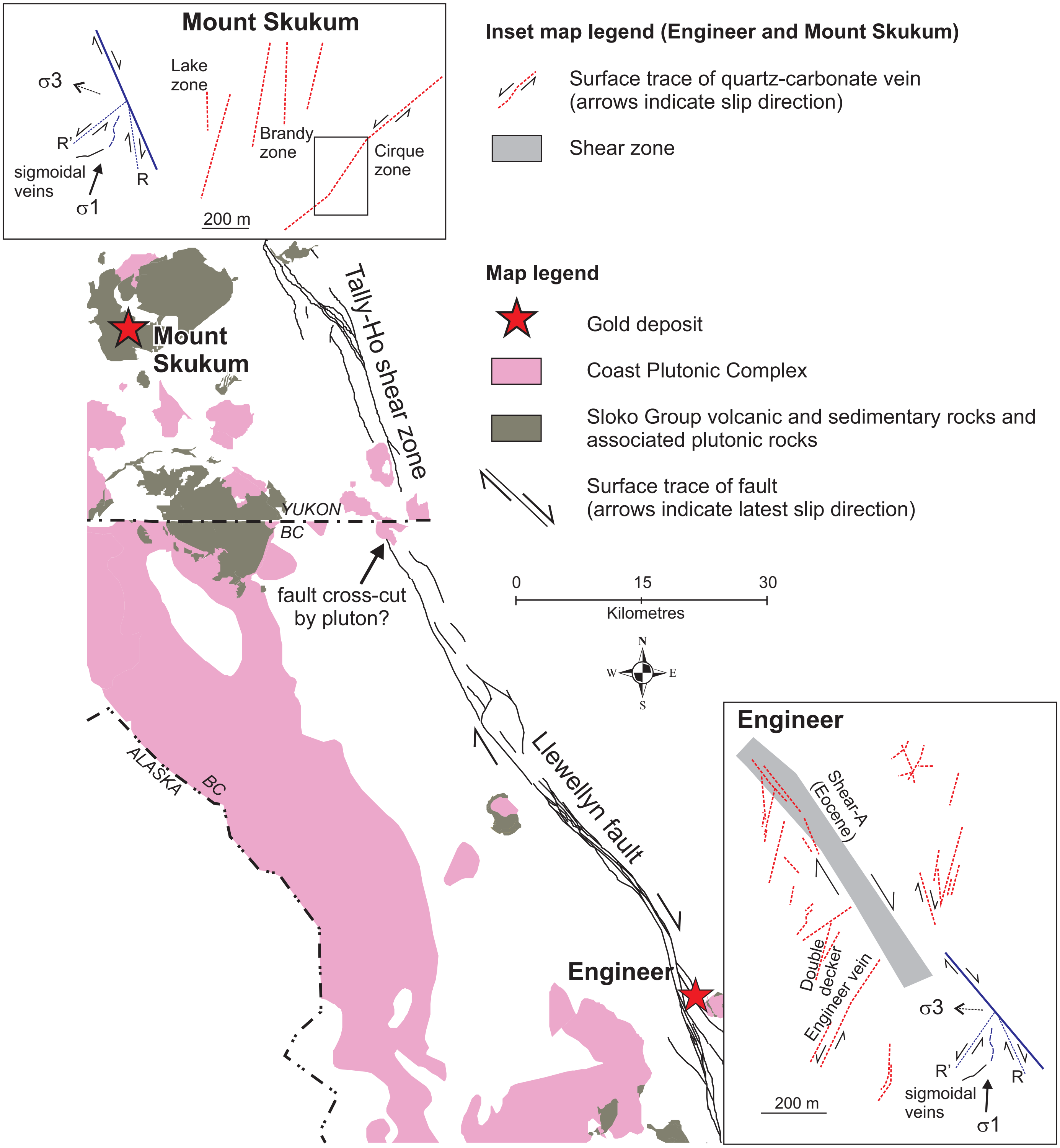

Fig. 6. Map of Llewellyn fault - Tally-Ho shear zone, Coast Plutonic Complex and Sloko Group volcano-plutonic complexes (Eocene), and locations of past-producing Mount Skukum and Engineer vein-hosted gold mines. The location where a granitic pluton has been mapped crosscutting the Llewellyn fault is also located. Geology is simpified after Doherty and Hart (1988) and Mihalynuk et al. (1999). Inset maps show surface traces of gold-bearing quartz-carbonate veins at Engineer and Mount Skukum. Principal stress directions are based on major faults and demonstrate veins are likely related to associated fracture sets (R and R' and sigmoidal veins). Engineer is simplified after Millonig et al. (2015) and Mount Skukum is modified after Love (1990b). Both demonstrate veining at each of the deposits is related to north-northeast directed compression.

as mapped by Mihalynuk et al. (1999). The granite post-dates the early ductile deformation but is cut by a fracture set parallel to the strike of the fault indicating it may be older than the late brittle deformation. A U-Pb zircon crystallization age of this granite will help provide a limit to the timing of both ductile and brittle strain.

4.2.3. Engineer Mine

A sample of monzodiorite was collected from drill core at the Engineer Mine. This granodiorite is part of a suite that cuts the early ductile fabrics at Engineer, but is offset by discrete brittle faults and veins. A U-Pb zircon crystallization age for this monzodiorite would yield a minimum age for the ductile deformation and a maximum age for the gold-related hydrothermal system.

4.2.4. Granodiorites near Llewellyn fault, west of Moon Lake

We collected samples of undeformed granodiorite adjacent to the Llewellyn fault and granodiorite that underwent brittle deformation in Llewellyn fault (Fig. 4a). These samples will be used for lower temperature thermochronology including $^{40}Ar/^{39}Ar$ (hornblende, biotite, and muscovite) U- Pb (monazite and titanite) and U/Th-He (zircon and apatite). Results of such analyses will help provide a thermal history of movement along the Llewellyn fault.

4.2.5. Venus and Arctic Caribou mines, Yukon

Specimens collected from sample dumps at the Venus and Arctic Caribou mines at Montana Mountain contain arsenopyrite that may be amenable to Re-Os isochron geochronology (e.g., Morelli et al., 2007). These ages could accurately date the time of mineralization. Previous constraints indicate the timing of mineralization at Montana Mountain is younger than Paleocene (Table 1; Hart and Pelletier, 1989).

4.3. Establishing the significance of 51 Ma (?) mafic dikes flanking the Llewellyn fault

A series of mafic (gabbro/diabase) dikes cut Cretaceous and younger plutons of the Coast Plutonic Complex (Figs. 2, 7; Mihalynuk et al., 1999; Symons et al., 2000). At least some of which were emplaced at ca. 51 Ma, as determined by K-Ar whole rock and biotite dating (Table 1; Symons et al., 2000). We recognized similar, but previously undocumented mafic dikes, flanking the Llewellyn fault. Possibly lamprophyres, these dikes might be related to early Eocene gold mineralization along the fault (Table 1). The dikes all have near-vertical dips but have three distinct strikes (Fig. 2), north (010°, n=3), northeast (040° to 055°, n=6), and east-southeast (110°, n=3).

The indirect relationship between mafic magmatism, particularly lamprophyric magmatism, and gold mineralization throughout geologic time has been recognized globally (e.g., Rock and Groves, 1988; Wyman and Kerrich, 1988). Testing this relationship in northwest British Columbia, in conjunction with the relationship between Eocene volcano-plutonism and the deep structure of the Llewellyn fault, could increase its attractiveness for mineral exploration.

Fig. 7. Vertically dipping, 010°-striking mafic dike (ca. 51 Ma) that crosscuts Cretaceous-Paleogene granite of the Coast Plutonic Complex (beige). Adjacent the Klondike Highway near Fraser, BC.

5. Discussion

The Llewellyn fault represents a long-lived, structure of significant strike length along which numerous gold occurrences are distributed. Similar structures in other parts of the North American Cordillera (e.g., Bohlke and Kistler, 1986; Nesbitt et al., 1989) are much better mineralized, as are the structural 'breaks' in the Archean Abitibi greenstone belt of the Superior Province in central Canada (e.g., Dubé and Gosselin, 2007). The apparent difference in degrees of gold mineralization between superficially similar structures raises the important question of whether the Llewellyn fault is actually well mineralized but underexplored, or whether it has simply failed to produce and preserve large gold deposits; did late motion along the faults lead to exposure and erosion? Dating gold mineralization and associated igneous rocks, further structural analysis of the deposits and their host rocks, and fluid inclusion and isotopic studies of ore fluids will help characterize the physicochemical conditions of ore formation and identify the key parameters controlling the location of gold deposits along the Llewellyn fault.

Whether or not there are more economic deposits to be discovered remains to be demonstrated. Unfortunately, much of the Llewellyn fault in the study area lacks regional geophysical coverage and remains a blank-spot on Canadian geophysical maps. Historically such geophysical mapping has generated new exploration interest in remote areas of Canada. The area also lacks significant publicly available high-resolution digital imagery. The 50+ mineral prospects and past-producing gold deposits in a relatively infrastructure-poor region indicates potential for future mineral exploration. Geophysical and remote sensing mapping may help attract mineral exploration and investment to the region.

The timing of gold mineralization and the relationship to Eocene magmatism adjacent to the Llewellyn fault is replicated by some gold occurrences in central British Columbia (e.g., Blackdome mine; Bordet et al., 2011; 2014). Further definition of the structural and temporal relationship between the Llewellyn fault, gold mineralization, and Eocene magmatism (Fig. 6) will permit comparison between these districts and will help establish if, collectively, these areas represent an Eocene orogenic gold belt.

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