Superimposed Late Cretaceous and earliest Eocene gold mineralization and deformation events along the Llewellyn-Tally Ho deformation corridor in northwest British Columbia and southern Yukon

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ABSTRACT

A revised geological and metallogenic framework for the Llewellyn-Tally Ho deformation corridor in southern Yukon and northwest British Columbia is proposed. The long-lived fault zone generally demarcates the eastern and western limits of the Nisling (Yukon-Tanana) and Stikine terrane, respectively. Epithermal (e.g. Engineer mine), intrusion-related and 'mesothermal' (e.g. Bennett plateau - Middle Ridge areas and part of the Wheaton district and Wann River area) gold deposits and occurrences are spatially associated with the Llewellyn-Tally Ho deformation corridor.

The Llewellyn fault is a southeast-striking, steeply dipping, brittle and dextral strike-slip structure that overprints penetrative fabrics and ductile deformation. The Tally Ho shear zone, Yukon, represents a ductile deformation zone with a penetrative foliation and local mylonite zones. The Tally Ho shear zone is overprinted by late brittle faults, which likely correspond to the northern extension of the Llewellyn fault. Previous work and this study demonstrate that brittle strike-slip deformation along the Llewellyn fault occurred between ca. 56 and 50 Ma.

Two unfoliated ca. 75 Ma granodiorite intrusions crosscut the earlier ductile fabrics, which deform a ca. 98 Ma porphyry dyke in the Tally Ho shear zone and a ca. 98 Ma granodiorite pluton along its western limit, indicating that parts of the early ductile fabrics formed between ca. 98 and 75 Ma. At Bennett plateau, the Skarn Zone represents one of the "early" gold mineralization styles consisting of an amphibole-sulphide skarn with structurally controlled quartz-actinolite-carbonate veins within metasedimentary rocks of the Stuhini Group adjacent to Late (?) Cretaceous intrusions. A massive ca. 76 Ma dyke crosscuts the highly strained and hydrothermally altered host rock and hence provides a minimum age for the mineralization and ductile fabrics. To the south, the Engineer mine is a structurally controlled epithermal vein system related to second-order splays of the Llewellyn fault. A ca. 54 Ma dyke is cut and offset by the main-stage veins and related fractures locally providing a maximum age for mineralization. Vanadian-illite, dated at ca. 50 Ma and intergrown with gold from the Engineer vein constrains the timing of the main-stage veining and mineralization.

The ca. 20 Myr time-gap between the early and late deformation events and their respective gold mineralization not only confirms these occurred at different times and at different structural levels, but also suggest they are related to distinct tectonic events. The intrusion-related and 'mesothermal' gold mineralization along the Llewellyn-Tally Ho deformation corridor is associated with Late Cretaceous deformation and magmatism, and as such, is broadly coeval and analogous with some of the mineral occurrences of Dawson Range polymetallic belt in west-central Yukon. The epithermal mineralization and late brittle event are related to the earliest Eocene magmatism and the Llewellyn fault, and match the timing and tectonic framework of the Juneau gold camp in southeastern Alaska.

INTRODUCTION

Gold deposits of the Cordilleran Orogen range from ca. 180 to 50 Ma, occur at various crustal levels, and frequently result from changing kinematic regimes along major, long-lived fault zones (e.g. Goldfarb et al., 1998). In collaboration with the Yukon Geological

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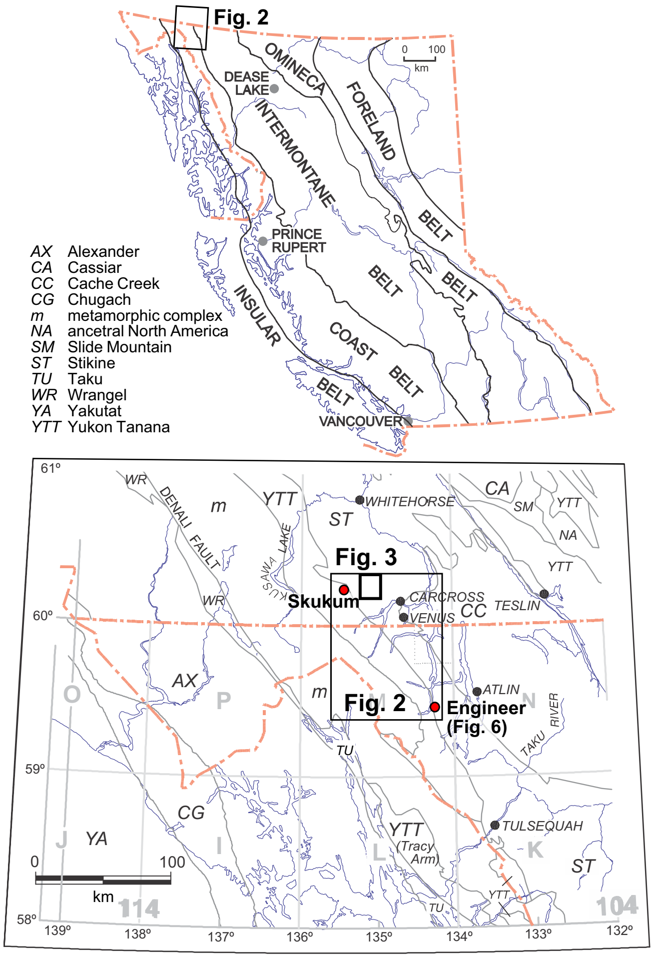

Figure 1. Location map with regional geography and terranes (*modified from* Mihalynuk et al., 1999).

Survey, this joint British Columbia Geological Survey (BCGS)-Geological Survey of Canada (GSC), Targeted Geoscience Initiative (TGI) supported study was designed to document the geological setting and controls on gold mineralization spatially associated with selected major fault zones of the Canadian Cordillera. The chosen field area extends from the Tagish Lake area of northwest British Columbia northward to the Wheaton River area in southern Yukon (Fig. 1, 2). This area is the locus of a series of structurally controlled, vein-hosted gold prospects and deposits, including past-producing mines (e.g. Engineer, Mount Skukum) that are spatially related to the Llewellyn fault and Tally Ho shear zone, which cut multiple lithotectonic suites (Fig. 2; e.g. Hart and Radloff, 1990; Mihalynuk et al., 1999; Tizzard et al., 2009). The Skarn Zone in the Bennett plateau - Middle Ridge area and the epithermal, low-sulphidation Engineer mine provide distinctive field laboratories to illustrate the two main types of gold mineralization along the Llewellyn - Tally Ho deformation corridor. Herein, we build on previous reports (Ootes et al., 2017, 2018, 2019; Castonguay et al., 2018) regarding the relationship between the Llewellyn fault and the Tally Ho shear zone and provide further constraints on the timing of ductile strain and associated gold mineralization that characterizes parts of this long-lived deformation corridor.

GEOLOGICAL SETTING

The Llewellyn fault, in northwest British Columbia, extends directly along strike from the Tally Ho shear zone in southwest Yukon (Fig. 1, 2). Herein both faults are considered as a composite structure and referred to as the Llewellyn-Tally Ho deformation zone or corridor. This northwest-striking deformation zone marks the boundary between the Nisling assemblage of the Yukon-Tanana terrane and the Stikine terrane to the west and east, respectively (Fig. 2; Hart and Radloff, 1990; Mihalynuk et al., 1999). Triassic-Jurassic and Early Cretaceous intrusive rocks, Late Cretaceous to Tertiary plutons (part of the Coast Plutonic Complex; Monger et al., 1982), and minor volcanic complexes occur on both sides of the Llewellyn-Tally Ho deformation zone, although predominantly to the west. Metamorphic grade within the deformation corridor is mostly greenschist facies (Hart and Radloff, 1990; Mihalynuk et al., 1999). A variety of gold prospects and minor past producers are spatially associated with this deformation zone (Fig. 2).

LLEWELLYN-TALLY HO DEFORMATION CORRIDOR

‘Early’ Deformation

In southern Yukon, the Tally Ho shear zone is defined by a 40 km long, kilometre-wide corridor of strongly deformed units of the Povoas Formation of the Lewes River Group (Upper Triassic; equivalent to Stuhini Group in British Columbia; Hart and Radloff, 1990). The shear zone comprises marble, mafic schist, and amphibolite that have a steep southwest-dipping penetrative foliation to mylonitic fabric, locally marked by a shallow southeast- or northwest-plunging mineral lineation (Hart and Radloff, 1990). Bedding is locally preserved in strongly deformed marble layers, but is folded and transposed into the foliation. The main foliation is locally folded, especially in less competent lithologies, such as the marble in the Tally Ho mountain area. The shear zone is bounded on either side by foliated Cretaceous intrusions, and by the Early Jurassic Bennett pluton to the southwest (Fig. 2, 3; Doherty and Hart, 1988; Hart and Radloff, 1990; Tizzard et al., 2009; Colpron et al., 2016). Brittle dextral fault zones are parallel to and overprint ductile fabrics, one of which occurs along the east side of the Tally Ho shear zone, and is considered part of the Llewellyn fault (Fig. 2, 3; Hart and Radloff, 1990).

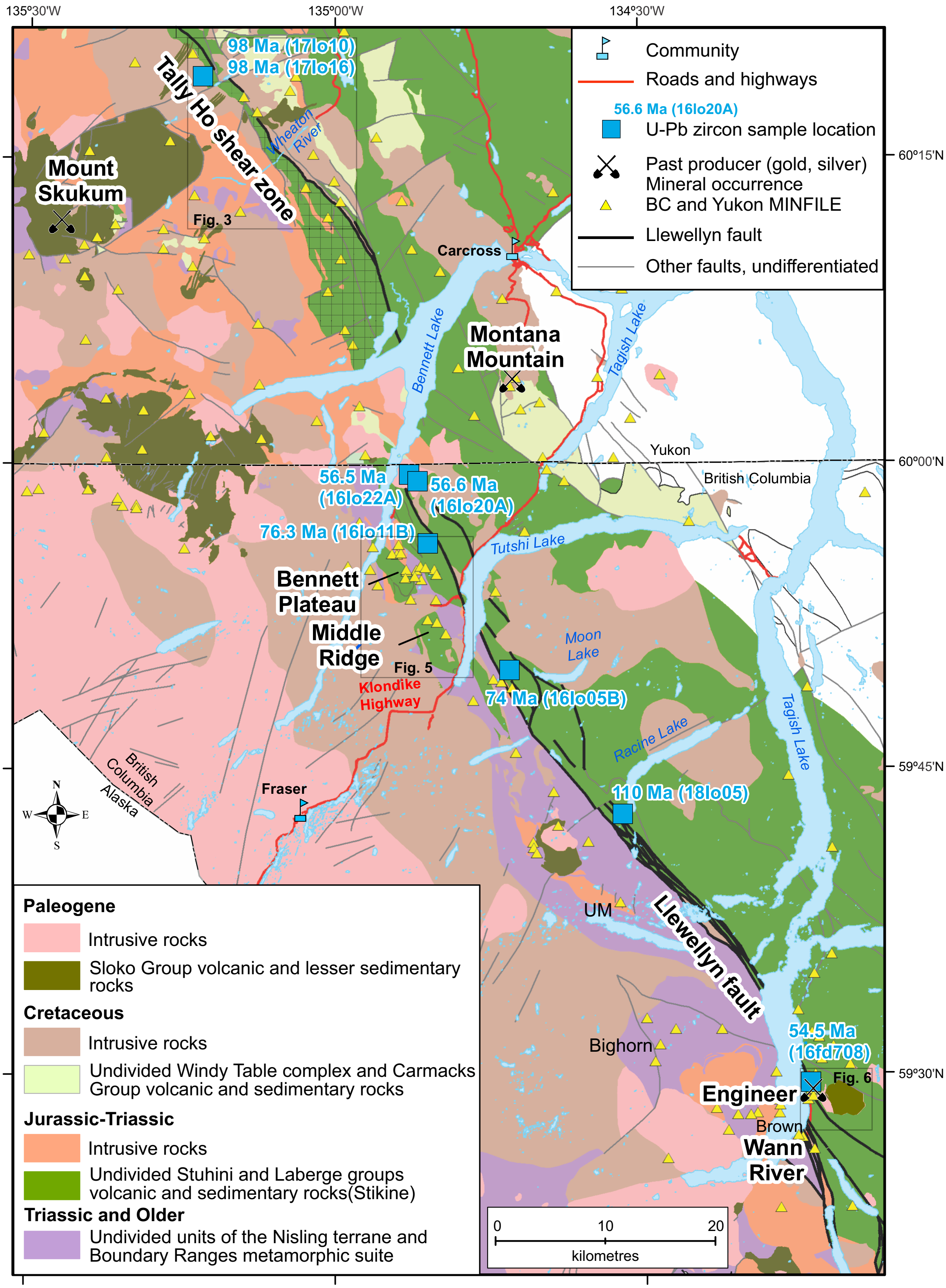

Figure 2. Generalized geology near the Llewellyn fault and Tally Ho shear zone (*modified from* Ootes et al., 2018, 2019). Geology is *after* Doherty and Hart (1988), Hart and Pelletier (1989), Hart and Radloff (1990), and Mihalynuk et al. (1999). Rocks of the Cache Creek assemblage (upper right) are unfilled. The square pattern outlines the Tally Ho shear zone in the Yukon as defined by Hart and Radloff (1990) and revisited by Tizzard et al. (2009). Although it is not formally delineated in British Columbia, Mihalynuk et al. (1999) recognized similar ductile high-strain zones along strike and within the Stuhini Group and Boundary Ranges metamorphic suite units.

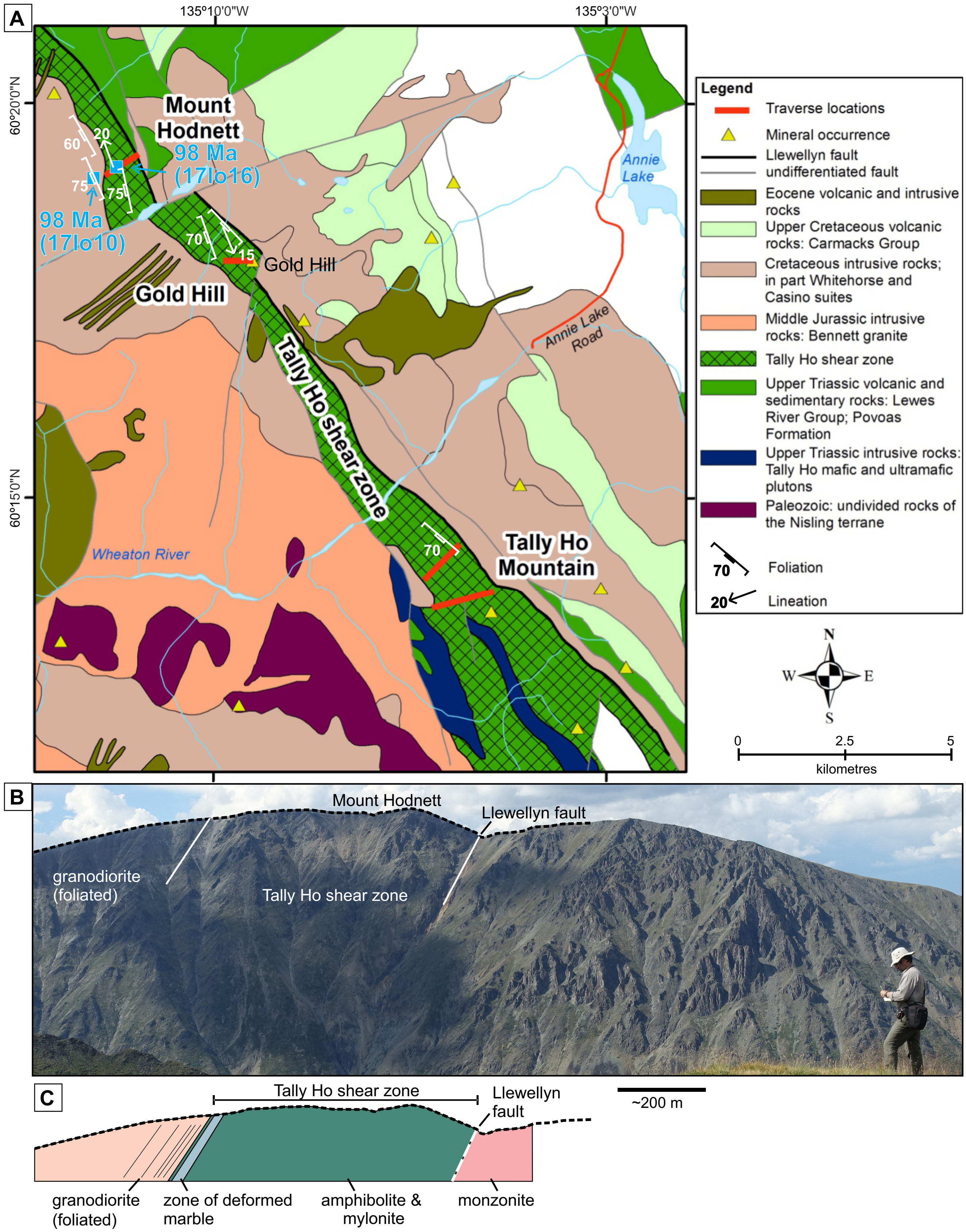

Figure 3. a) Generalized geology of the Tally Ho shear zone, southern Yukon (*modified after* Hart and Radloff, 1990). Foliations (line with pendants) and lineations (arrows) are from this study and Hart and Radloff (1990). **b)** View to the northwest of Mount Hodnett and the Tally Ho shear zone from Gold Hill. The trace of the Llewellyn fault is marked by a gossanous gully. **c)** Geological sketch of Mount Hodnett, in the upper left part of the photo; in part, *modified after* Tizzard et al. (2009).

Hart and Radloff (1990) interpreted the Tally Ho shear zone as a sinistral, terrane-bounding thrust fault that initially formed between 230 and 220 Ma. The lower age limit of deformation is based on a zircon U-Pb regressive intercept age of ca. 220 Ma (Doherty and Hart, 1988) for a sample of massive Bennett pluton collected roughly 3 km west of Tally Ho shear zone. Alternatively, Tizzard et al. (2009) considered that the shear zone represents a top-to-the-east crustal-scale thrust fault that juxtaposed foliated gabbro and pyroxenite (hanging wall) over Povoas Formation (shear zone and footwall). Faulted rocks were subsequently folded during the Nisling-Stikine collision. Tizzard et al. (2009) provided U-Pb zircon ages of ca. 208 Ma for a foliated leucogabbro in the hanging wall and ca. 173 Ma for a massive megacrystic granite sample (part of the Bennett granite; Fig. 3) west of the shear zone, which they interpreted as bracketing the timing of thrusting and subsequent folding. However, although the Bennett granite is not pervasively deformed, it contains xenoliths of foliated and unstrained Povoas Formation and is locally weakly foliated at its eastern margin and affected by the Tally Ho shear zone deformation, such as sinistral shear bands (Hart and Radloff, 1990). Consequently, there is evidence of a post-Early Jurassic ductile fabric, and the Tally Ho shear zone must have been active after ca. 173 Ma.

Traverses across the Tally Ho shear zone were conducted in the Tally Ho Mountain, Gold Hill, and Mount Hodnett areas of Yukon (Fig. 2, 3; Castonguay et al., 2018; Ootes et al., 2018, 2019). The best exposed section is at Mount Hodnett (Fig. 3) where units include (from west to east): weakly to moderately foliated granodiorite in sheared intrusive contact with steeply west-dipping amphibolite and marble; strongly sheared mafic volcaniclastic rocks (mylonite); and foliated metabasalt, locally intruded by massive to weakly foliated (at contacts) intermediate feldspar porphyry dykes. The steep southwest-dipping main foliation (S_{main}) occurs in most rocks but is best developed in mylonitic volcaniclastic beds. To the east, the shear zone mostly comprises strongly foliated amphibolite and metabasalt. Rare kinematic indicators include shear bands, sigmoidal clasts, and quartz vein boudins, which indicate apparent northeast-directed motion (Ootes et al., 2018). However, the shallowly southeast- or locally northwest-plunging stretching and/or mineral lineation on the S_{main} foliation and frequent L-S tectonites indicate a strike-slip component. Along the eastern side of the shear zone, the foliated amphibolite/metabasalt is structurally interlayered with moderately foliated monzonite of the Wheaton River pluton (part of the Late Cretaceous Casino suite; Colpron et al., 2016; Fig. 3). This juxtaposition is the result of a less than 10 m wide subvertical brittle high-strain zone, the Llewellyn fault (*see below*), which is marked by cataclasite and carbonate alteration that overprints the foliation in the metabasalt. All units are intruded by late, massive, intermediate to felsic feldspar-porphyritic dykes.

The granodiorite west of the shear zone (Fig. 3) is assigned to the Whitehorse plutonic suite (ca. 112–98 Ma; Hart and Radloff, 1990; Colpron et al., 2016). This granodiorite contains a steep southwest-dipping heterogeneously developed foliation (Fig. 4a), defined by chlorite-altered biotite and hornblende, which occurs in southeast-trending, high-strain corridors, and increases in intensity northeast toward the fault contact with the mylonitic metabasalt. This foliation in the granodiorite strikes south-southeast, dips west, and is subparallel to the S_{main} foliation in the shear zone (Ootes et al., 2018). In the contact zone, the foliated intrusion becomes progressively finer grained, more felsic, and interfingered with the mylonitic metabasalt. Basalt xenoliths also occur in strongly foliated granodiorite. The contact is overprinted by brittle fault and breccia zones and intruded by a late, massive, intermediate dyke. Based on these relationships, including the eastward-increasing heterogeneous strain gradient observed in the granodiorite and the occurrence of only one subparallel penetrative foliation across both units, the zone is interpreted as a sheared intrusive contact (Ootes et al., 2018, 2019). Ductile strain along this faulted contact was strongly partitioned in the metabasalt during the development of the Tally Ho shear zone. Two samples were analyzed for U-Pb zircon geochronology (Table 1; Ootes et al., 2018). The first sample comes from a moderately foliated granodiorite (sample 17lo10; Fig. 3) collected roughly 110 m west of the Tally Ho shear zone, which yielded a $^{206}Pb/^{238}U$ weighted mean zircon age of ca. 98.6 Ma (4 of 5 analyzed zircon grains), which is interpreted as the crystallization age of the granodiorite. The second sample (17lo16) is from the central part of an approximately 8 m thick feldspar porphyritic monzonite dyke intruding the metabasalt within the shear zone. The dyke is massive to locally weakly foliated (marked by the alignment of amphibole and biotite grains; Fig. 4b) and is probably folded. Five analyzed grains yielded ages between 98 and 99 Ma, and all are concordant. An older grouping of three results, at ca. 98.6 Ma, are interpreted as xenocrysts or possibly antecrysts, with two overlapping results at ca. 98.3 Ma, which is taken as the best age estimate for crystallization of the dyke. Ootes et al. (2019) previously incorrectly reported preliminary analytical results of this sample as having a maximum age of ca. 95 Ma.

‘Late’ Deformation

The Llewellyn fault is an over 100 km long, northwest-striking, steeply dipping, brittle dextral strike-slip

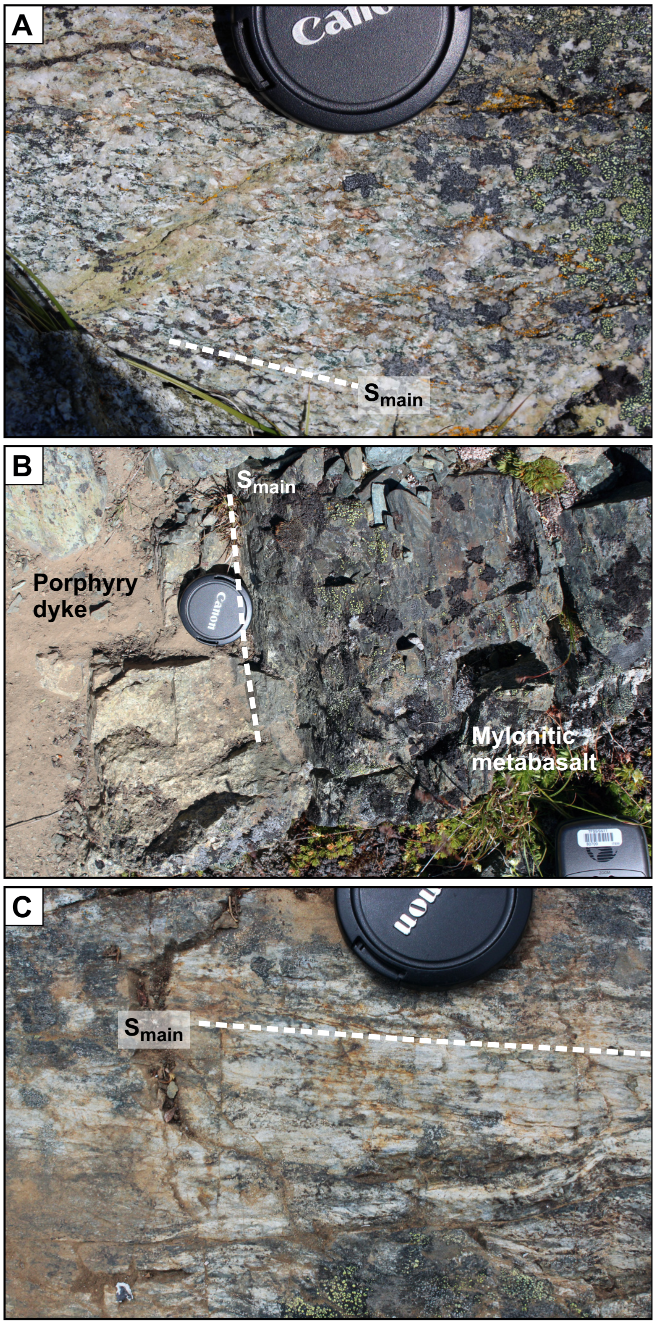

Figure 4. a) A foliated granodiorite near sample locality 17lo10, roughly 110 m west of the Tally Ho shear zone at Mount Hodnett, Yukon. **b)** A sheared intrusive contact, subparallel to the S_{main} schistosity, between a weakly foliated dyke and a mylonitic metabasalt within the Tally Ho shear zone at Mount Hodnett. **c)** A moderately foliated rhyolitic rock at sample locality 18lo05, along the Llewellyn fault zone, west of Racine Lake, British Columbia. For scale, the lens cap is 6 cm in diameter. *See* Figures 2 and 3 for location.

structure that extends from the Tulsequah region in the south to past the Mount Hodnett area in the Yukon (Fig. 1; Hart and Radloff, 1990; Mihalynuk et al., 1994, 1999). In northernmost British Columbia, it juxtaposes the Boundary Ranges metamorphic suite to the west (pre-Triassic; part of Nisling/Yukon Tanana terrane) against the volcano-sedimentary rocks of the Stuhini and Laberge groups to the east (Triassic-Jurassic; part of the Stikine Terrane; Fig. 2; Mihalynuk et al., 1999). The Llewellyn fault mostly consists of several anastomosed splays representing duplexes, marked by recessive zones of gouge comprising shear bands and slickensided surfaces, and locally developed L-S tectonites. As mentioned above, the Llewellyn fault overprints rocks affected by earlier south-southeast-trending penetrative fabrics, correlative with those of the Tally Ho shear zone (i.e. S_{main}). The S_{main} ductile fabric post-dates deposition of the Jurassic Laberge Group and is much better developed in the Boundary Ranges metamorphic suite (S_2 of Mihalynuk et al., 1999), where it is folded by northeast-verging folds, similar to those occurring at Tally Ho Mountain. Latest Cretaceous and Eocene plutons crosscut the ductile fabrics, providing a minimum age for the ductile deformation (Mihalynuk et al., 1999).

U-Pb geochronological data from key localities along the Llewellyn fault, south of the British Columbia-Yukon border, including the Bennett plateau area and a few others southeastward toward Tagish Lake, British Columbia (Fig. 2; Table 1; Ootes et al., 2017, 2018), provide constraints on the timing of structural and gold mineralization events. Two different granitic intrusions from east of Bennett Lake were dated (Fig. 2). A medium-grained unfoliated granite with K-feldspar phenocrysts (sample 16lo20A), mapped as middle Cretaceous to Tertiary (Mihalynuk et al., 1999), and intruding foliated Laberge Group metasedimentary rocks, yielded a weighted average $^{206}Pb/^{238}U$ concordant zircon age of 56.58 ± 0.07 Ma (2σ), which is interpreted as the crystallization age of the granite (Ootes et al., 2018). The second biotite-hornblende granite, mapped as the middle Cretaceous to Tertiary Pennington pluton (Hart and Radloff, 1990; Mihalynuk et al., 1999), crosscuts ductile fabrics but contains closely spaced (<30 cm), moderately east-dipping, brittle fractures that are subparallel and probably related to the Llewellyn fault (sample 16lo22A; Fig. 2). A $^{206}Pb/^{238}U$ weighted mean of four of the five concordant zircon analyses yields a crystallization age of 56.46 ± 0.06 Ma (Ootes et al., 2018).

A fine- to medium-grained, weakly porphyritic granodiorite pluton occurs within the trace of the Llewellyn fault, west of Moon Lake (Fig. 2), where it cuts the contact between the Stuhini Group and the Boundary Ranges metamorphic suite. The granodiorite is not foliated, but it contains moderate carbonate alteration and partially chloritized biotite and hornblende. The granodiorite post-dates the ductile deformation preserved in the host argillite, but is cut by a southeast-striking two metre wide gouge zone that is part of the Llewellyn fault (Ootes et al., 2017). A sample of the

Table 1. Geochronological data for the Llewellyn-Tally Ho deformation corridor area.

Sample	Location	Rock type	Field relationship	Method	Age (Ma)	Reference
	Engineer mine	quartz-vanadian mica vein	mineralized vein	$^{40}Ar/^{39}Ar$ V-illite	49.9 ± 0.25	Millonig et al. (2017)
16fd708	Engineer mine	monzodiorite dyke	cut by mineralized vein	U-Pb zircon	ca. 54.5	This report; preliminary
	Mt Skukum deposit	Au-quartz-calcite-adularia vein	mineralized vein	$^{40}Ar/^{39}Ar$ adularia	54.05 ± 0.31	Love et al. (1998)
16lo22A	Bennett Lake	biotite-hornblende granite	unfoliated	U-Pb zircon	56.46 ± 0.06	Ootes et al. (2018)
16lo20A	Bennett Lake	K-feldspar granite	unstrained	U-Pb zircon	56.58 ± 0.07	Ootes et al. (2018)
16lo05B	west of Moon Lake	biotite-hornblende granodiorite	unfoliated	U-Pb zircon	ca. 74	Ootes et al. (2018)
16lo11B	Bennett plateau	granodiorite porphyry	unfoliated	U-Pb zircon	76.30 ± 0.05	Ootes et al. (2018)
17lo16	Mount Hodnett	monzonite dyke	weakly foliated/folded	U-Pb zircon	ca. 98.3	This report; preliminary
17lo10	Mount Hodnett	biotite-hornblende granodiorite	foliated	U-Pb zircon	ca. 98.6	This report; preliminary
18lo05	SW of Racine Lake	rhyolitic unit	foliated	U-Pb zircon	ca. 110.2	This report; preliminary
	Middle Ridge	volcanic unit	openly folded	U-Pb zircon	124.9 ± 0.5	Mihalynuk et al. (2003)
	Tally Ho Mountain	megacrystic granite	massive	U-Pb zircon	172.9 ± 0.2	Tizzard et al. (2009)
	Tally Ho Mountain	Tally Ho leuco-gabbro	foliated	U-Pb zircon	208.4 ± 4.3	Tizzard et al. (2009)

least altered part of the granodiorite (sample 16lo05B) was collected near the contact with the host argillite, and yielded concordant to slightly discordant zircon analyses with a range of $^{206}Pb/^{238}U$ ages from ca. 92 to 74 Ma (Ootes et al., 2018), the youngest of which (i.e. 73.9 ± 0.3 Ma) gives the best estimate for the timing of crystallization.

Southwest of Racine Lake, along splays of the Llewellyn fault, is a zone of imbricated Stuhini and Laberge group rocks juxtaposed against the Boundary Ranges metamorphic suite (Mihalynuk et al., 1999). There, a penetrative moderate to strong foliation, potentially related to the regional S_{main} foliation, affects fault-bounded slices of carbonate-altered 'rhyolite' (Fig. 4c). The rhyolitic unit was sampled twice (samples 16lo18B and 18lo05) for geochronology. The first yielded two overlapping and concordant zircon results at ca. 121 Ma (reported in Ootes et al., 2018) and reinterpreted herein as xenocrysts or grains with older inheritance. The second gives a weighted $^{206}Pb/^{238}U$ crystallization age of ca. 110.2 Ma, based on the two youngest concordant and overlapping results.

GOLD MINERALIZATION

The Llewellyn-Tally Ho deformation corridor is spatially related to structurally controlled gold mineralization that has characteristics ranging from (1) 'mesothermal' (as per historically entrenched in the regional literature and assessments reports), such as the auriferous quartz veins (e.g. Bighorn, UM showings: Mihalynuk et al., 1999) and the polymetallic veins of the Wheaton district (e.g. Gold Hill: Hart and Radloff, 1990), the Wann River area south of the Engineer mine (e.g. Wann River project: Blind Creek Resources Limited, 2012; Engineer Gold Mines Limited, 2018), and part of the Montana Mountain mines (e.g. Venus vein; Fig. 2; Roots, 1981; Walton, 1986; Hart and Pelletier, 1989; Hart and Radloff, 1990); to (2) intrusion-related, such as the Bennett plateau and Middle Ridge prospects (Golden Eagle project: Mihalynuk et al., 2003; Wark, 2012); to (3) epithermal, such as the Engineer and Mount Skukum mines (Love, 1990, Love et al., 1998; Millonig et al., 2017; O'Brien et al., 2018).

Except for Montana Mountain mines, which are closer and probably related to reactivation of the Nahlin fault (Hart and Pelletier, 1989), the intrusion-related and 'mesothermal' gold mineralization is hosted in metamorphosed and moderately to strongly foliated units of Stuhini/Lewes River groups and Boundary Range metamorphic suite and predominantly occurs in the central part of the deformation corridor that is west of the Llewellyn fault (*sensu stricto*). The epithermal gold mineralization occurs on both sides of this deformation corridor and coincides both spatially and temporally with Eocene volcanic complexes and brittle faults (Love et al., 1998; Millonig et al., 2017; Ootes et al., 2018, 2019), suggesting a possible genetic relationship between large-scale deformation zones, gold mineralization, and Eocene magmatism in southwest Yukon and northwest British Columbia.

'Early' Intrusion-Related and 'Mesothermal' Gold

Some of the gold and base metal mineralization along the Llewellyn-Tally Ho deformation corridor predates, or is synchronous to late versus ductile deformation fabrics, and termed herein as 'early' mineralization. As mentioned above, some of this mineralization has been historically described in assessment or governmental reports as 'mesothermal' (as per Nesbitt et al., 1986). Although not studied in detail herein, these occurrences are likely analogs to deep epizonal to shallow mesozonal mineralization (as per Groves et al., 1998) to best match the depicted vein types and the deformation style of the host rocks.

A good and better documented example of 'early' mineralization are prospects named the Skarn Zone and Tannis (also known as Middle Ridge), which are part of a series of amalgamated mineral claims referred to as the Golden Eagle property (e.g. Rowins, 1997; Wark,

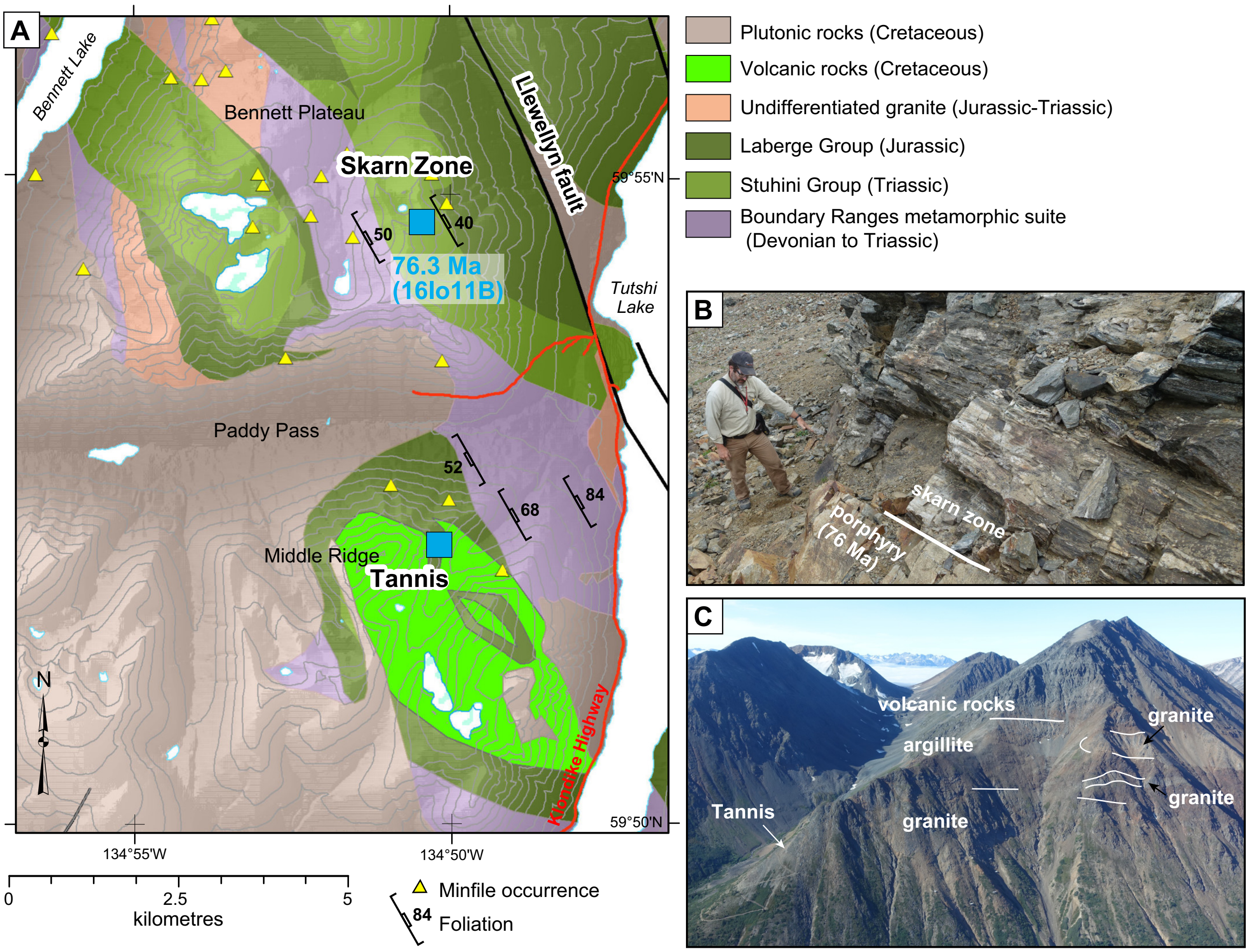

Figure 5. a) Generalized geology of the Bennett plateau - Middle Ridge area. Geology is *after* Mihalynuk et al. (1999). **b)** Typical exposure of the Skarn Zone near Bennett plateau, where an unfoliated porphyry intruded previously strongly deformed metasedimentary rocks of the Stuhini Group that host hydrothermal quartz-actinolite veins. The view is northeast. **c)** Aerial view of Middle ridge looking south-southwest.

2012). Both occurrences are west of Tutshi Lake and east of Bennett Lake on different mountains, separated by Paddy Pass (Fig. 2). In general, mineralization in this area was originally explored in the late 1800s and early 1900s, but, except for a few exploration adits and drillholes, there has been no development. Recent exploration drilling took place in the late 1980s to mid-2000s and in 2011, with varying results (e.g. Rowins, 1997).

The Skarn Zone (Fig. 5a,b) is a structurally controlled, amphibole-sulphide skarn that is thought to be related to felsic dykes and the sheared contact between the Stuhini Group and Boundary Range metamorphic suites (locally termed the "Paddy fault"; e.g. Rowins, 1997; Wark, 2012). Gold and base metal mineralization (disseminated pyrrhotite, chalcopyrite, and minor pyrite) is hosted within amphibole-albite-calcite-sulphide skarn and deformed (boudinaged and folded) quartz-actinolite-carbonate veins. Most of these veins cut metasedimentary rocks of the Stuhini Group and are adjacent (underlying) to Cretaceous intrusions (Rowins, 1997). The mineralization is erratic, with one historical sample reported to contain >185 g/t Au, with the vast majority of results indicating 1 g/t Au over 1 to 9 m and locally 100 g/t Au over narrow widths (Rowins, 1997 and references therein). More recent drilling on the Skarn Zone intersected 36.5 m grading 1.3 g/t Au, including a 4.1 g/t Ag over 15.5 m interval, in altered felsic volcanic units (Troymet Exploration Corporation, 2014). A two metre thick unfoliated granodiorite porphyry, which intruded the Skarn Zone subparallel to the host-rock fabrics (Fig. 5b), postdates the ductile deformation. Uranium-Pb zircon dating of this granodiorite porphyry (sample 16lo11B; Fig. 2) yielded a weighted mean age (four concordant zircon analyses) of 76.30 ± 0.05 Ma, which is interpreted as the crystallization age of the intrusion (Ootes et al., 2018). The age of the mineralization is unresolved, but the spatial relationship with Cretaceous intrusions (undated) suggests that it occurred between ca. 98 and 76 Ma.

South of Bennett plateau, at Middle Ridge (Fig. 5a,c), a series of auriferous quartz-arsenopyrite veins are hosted in fine-grained granite and quartz porphyry, and along the contacts between the Laberge Group and Boundary Range metamorphic suite (Tannis prospect; Mihalynuk et al., 2003; Wark, 2012). Multiple sets of veins are present in the pervasively fractured host rock. The main mineralized vein set is discordant (N070/85) to the main regional fabric (north-northwest), but lesser north-northwest-striking veins are subparallel to the regional foliation. The highest gold values near the Tannis zone from surface sampling yielded between 1.0 and 13.8 g/t Au. Drill core assays range between 0.2 g/t Au over 13 m to 66 g/t Au over 0.6 m, and are typically around 1–3 g/t Au over 1.0 to 1.5 m (Wark, 2012). The intrusions crosscut ca. 124 Ma volcanic rocks (Mihalynuk et al., 2003), providing a local maximum age for mineralization. Mihalynuk et al. (2003) suggested that this mineralization was genetically related to underlying Late Cretaceous intrusions.

'Late' Epithermal Gold

The vein system at the Engineer mine is an important example of Eocene epithermal gold mineralization along the Llewellyn fault (Fig. 2; e.g. Mihalynuk et al., 1999; Millonig, et al., 2017; O'Brien et al., 2018). It is spatially associated to a roughly 20º-clockwise variation in the orientation of the Llewellyn fault at Tagish Lake. The vein system is related to a dextral fault zone referred to as 'Shear A', which is a southeastward splay of the Llewellyn fault where the main fault trends under the south end of Tagish Lake (Fig. 6a). The mine occurs adjacent to the Engineer Mountain volcanic complex (part of the Eocene Sloko Group; Mihalynuk et al., 1999), approximately 600 m vertically below the basal unconformity where Eocene volcanic rocks rest on Laberge Group sedimentary rocks.

Gold-bearing veins were discovered on the shore of Tagish Lake in 1899 by prospectors (e.g. O'Brien et al., 2018). This initial discovery led to significant mine development and continues to spur exploration interest in the region to this day. Over three kilometres of underground workings over eight levels (180 m vertical extent) were excavated from 1912 to 1927 during two main phases of mine development. The high-grade sections of the veins were targeted, with the Engineer and Double Decker veins being the highest producing (Fig. 6b). Reported production for 1925–1926 was over 10,000 ounces at an average grade of 26.4 g/t Au (O'Brien et al., 2018). Mining used stoping methods, creating a series of interconnected workings primarily following the main producing veins. The well exposed underground geology was mapped as part of an exploration program in 2008 (Fig. 6b; Devine, unpub. rep.). Recent drilling across the Double Decker vein revealed an interval of 22.3 g/t Au over 0.96 m (0.8 m true width; BCGE10-01; O'Brien et al., 2018).

The Engineer vein system includes a series of veins hosted in argillite and wacke of the Laberge Group and occurring on both sides of the Shear A fault (Fig. 6b). Veins include multistage vuggy and drusy quartz and carbonate (Fig. 6c) with gold-sulphide mineralization in multiple forms, namely as free gold in quartz, gold intergrown with vanadian illite, and gold associated with arsenopyrite (Millonig et al., 2017). On the southern side of the fault, the gold-rich Engineer and Double Decker vein systems are 5 cm to 2 m, locally up to 5 m thick, forming anastomosing sets of moderately to steeply southeast-dipping veins that pinch and swell along strike. Along with a series of more minor veins, these extensional veins outline a pattern correlative with dextral brittle deformation along the northeastern side of Shear A. Evidence of brittle shearing with identical relationships to the macro scale are mimicked in core (Fig. 6d). Sulphide (mainly pyrite)-cemented hydrothermal breccia along the northeastern side of the Shear A deformation zone was emplaced contemporaneous with this latest movement (Fig. 6e). Vanadian-illite intergrown with gold from the Engineer vein returns an age of 49.9 ± 0.25 Ma (^{40}Ar/^{39}Ar: Millonig et al., 2017). This age is interpreted to constrain the main-stage veining and mineralization and the most recent movement on Shear A.

The main-stage veining and youngest deformation events along the Shear A fault overprint several older features in the Engineer area. The foliation in the host Laberge Group sedimentary rocks progressively increases in intensity towards the south side of Shear A. This early, fault-parallel foliation is cut by a series of feldspar-porphyritic monzodiorite dykes (Fig. 6b). Many dykes are laterally and vertically continuous over 100s of metres, following fractures in orientations that suggest control by dextral brittle movement related to this earlier deformation along Shear A. A dyke sample from 63 m down drillhole BCGE08-05 (Fig. 6b) was dated as part of this study and returned a U-Pb zircon ^{206}Pb/^{238}U weighted mean age of ca. 54.5 Ma, based on five concordant and overlapping results. This concurs with field relationships, which demonstrate that the main-stage veins cut and occur along fractures that offset these dykes and suggests that the earliest movement along the Shear A fault occurred at least 4 Myr prior to the main veining event.

DISCUSSION

Timing of Deformation

Herein we define two spatially superimposed structural events along the Llewellyn-Tally Ho deformation cor-

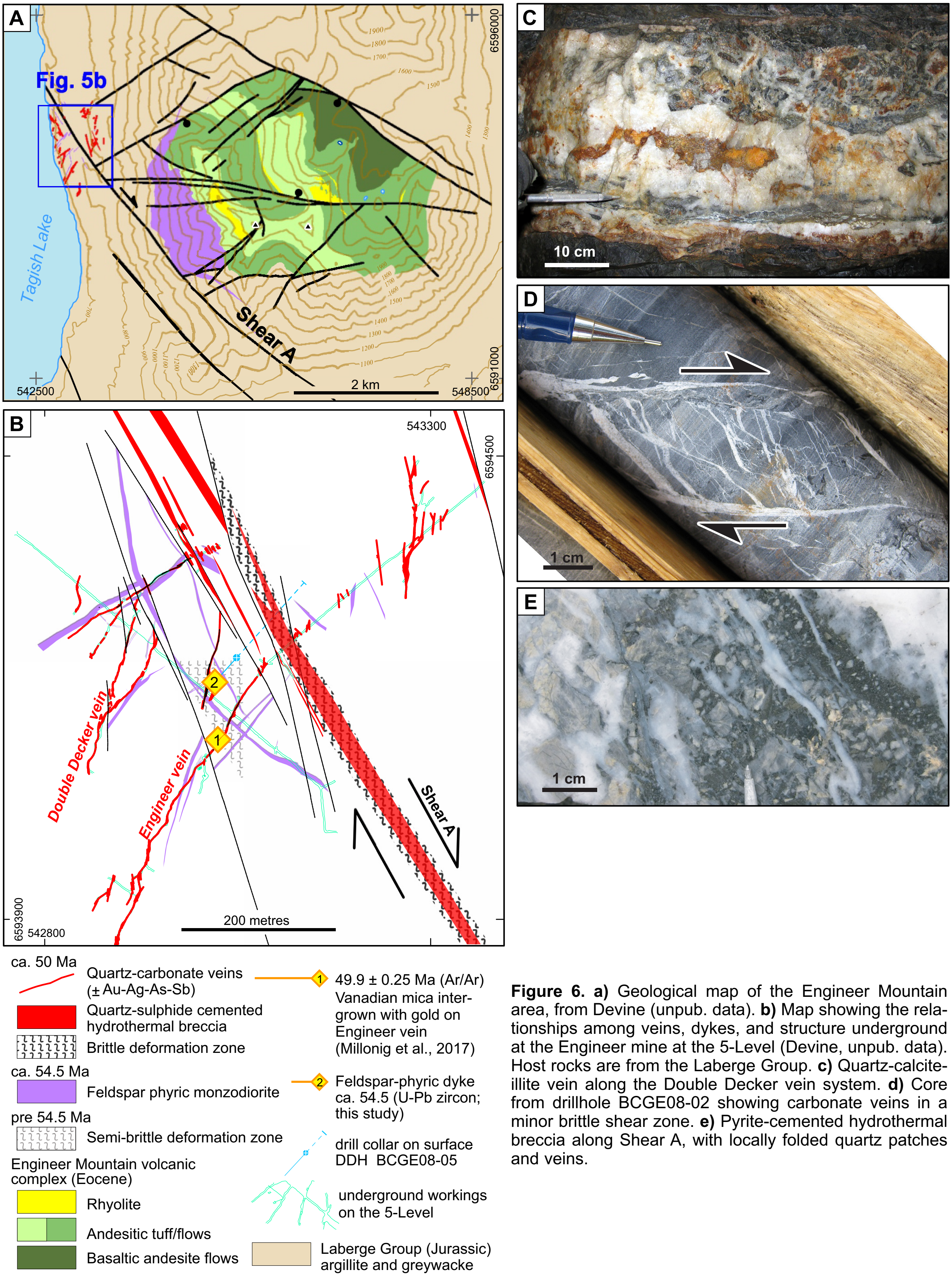

Figure 6. a) Geological map of the Engineer Mountain area, from Devine (unpub. data). **b)** Map showing the relationships among veins, dykes, and structure underground at the Engineer mine at the 5-Level (Devine, unpub. data). Host rocks are from the Laberge Group. **c)** Quartz-calcite-illite vein along the Double Decker vein system. **d)** Core from drillhole BCGE08-02 showing carbonate veins in a minor brittle shear zone. **e)** Pyrite-cemented hydrothermal breccia along Shear A, with locally folded quartz patches and veins.

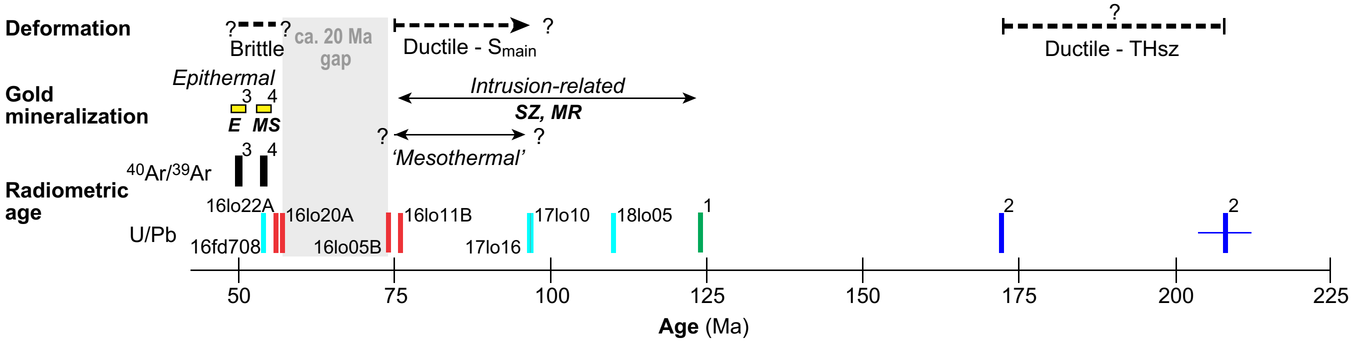

Figure 7. Timeline summary of the deformation and gold mineralization events in the Llewellyn-Tally Ho deformation corridor. The U-Pb zircon age data (labelled by sample number) from Ootes et al. (2018) are shown by a red bar, and preliminary data from this report are shown by a light blue bar. Label 1 data are from Mihalynuk et al. (2003; green bar) and label 2 are from Tizzard et al. (2009; blue bar). The $^{40}Ar/^{39}Ar$ mica results, labelled 3, are from Millonig et al. (2017) and those labelled 4 are from Love et al. (1998); these constrain the timing of epithermal gold mineralization at the Engineer mine (E) and Mount Skukum (MS), respectively. The suggested timing of intrusion-related mineralization at the Skarn Zone (SZ) is from this study and for Middle Ridge (MR), the suggested timing is from Mihalynuk et al. (2003). The tentative timing of 'mesothermal' mineralization is based on the relative relationship between S_{main} and auriferous quartz or polymetallic veins. Abbreviations: ? = uncertainty; S_{main} = main foliation along the Llewellyn-Tally Ho deformation corridor; THsz = Tally Ho shear zone timing of Tizzard et al. (2009). *See* the text for discussion.

ridor. An early ductile deformation phase exemplified by the Tally Ho shear zone in the Yukon, and its correlative, albeit lesser documented, ductile deformation zones in the Boundary Ranges metamorphic suite and Stuhini Group in British Columbia. Brittle fault zones related to the Llewellyn fault overprint these early ductile deformation zones. U-Pb geochronological data (Ootes et al., 2018, 2019, this study) provide new constraints on the timing of deformation of these superimposed structural events and associated gold mineralization (Fig. 7, Table 1).

Early ductile event

Although there is regional evidence for long-lived polyphase deformation and metamorphism (e.g. pre-Middle Jurassic; Hart and Radloff, 1990; Mihalynuk et al., 1999), only one penetrative ductile foliation (S_{main}) has been observed along the entire Llewellyn fault and Tally Ho shear zone corridor. In British Columbia, foliated and faulted rhyolite along the Llewellyn fault southwest of Racine Lake has a crystallization age of ca. 110 Ma, thus constraining the maximum age of ductile and brittle deformation. To further bracket the maximum age of the main foliation (S_{main}), we investigated the Tally Ho shear zone at Mount Hodnett, Yukon. There, the main foliation and related mylonitic fabric are parallel and probably formed at the same time as the locally penetrative foliation in the neighbouring granodiorite pluton to the west (part of the Whitehorse plutonic suite; Hart and Radloff, 1990). Tizzard et al. (2009) suggested that the foliation in the granodiorite is temporally distinct and related to a fault that juxtaposes the granodiorite and Tally Ho shear zone. Based on field relationships and geochronology at Tally Ho Mountain (Fig. 2), they interpreted that the S_{main} foliation and the development of the Tally Ho shear zone as coeval during the latest Triassic to Early Jurassic (i.e. 208–173 Ma). Instead, our field observations and U-Pb zircon data from the granodiorite at Mount Hodnett (ca. 98 Ma; sample 17lo10) suggest that the penetrative foliation (in the granodiorite pluton), the S_{main} foliation, and the consanguineous mylonitic fabric (in the shear zone) must have developed after ca. 98 Ma. Within the shear zone, the ca. 98 Ma dyke (sample 17lo16) contains a foliation in its margins that we interpret as equivalent to the S_{main} foliation, further constraining the maximum age of ductile deformation. In British Columbia, the ca. 74 Ma granodiorite pluton west of Moon Lake (sample 16lo05B) and the ca. 76 Ma granodiorite porphyry on Bennett plateau (sample 16lo11B) postdate ductile deformation in the Stuhini and Laberge groups and Boundary Ranges metamorphic suite. Therefore, ductile deformation fabrics along the Llewellyn-Tally Ho corridor developed between ca. 98 and 75 Ma.

Late brittle event

In British Columbia, the granodiorite west of Moon Lake (sample 16lo05B) is crosscut by the Llewellyn fault, constraining the brittle deformation to younger than ca. 74 Ma. The two granitic plutons sampled near the British Columbia-Yukon border along the Llewellyn fault (samples 16lo20A, 16lo22A; Fig. 2) both yield an indistinguishable age of ca. 56 Ma. Both intrusive phases postdate ductile deformation. However, the slightly younger equigranular granite pluton (sample 16lo20A) contains fractures that are along strike, and parallel to the Llewellyn fault, and is interpreted to have acted as a rigid body during brittle faulting (Ootes et al., 2018). The earliest phase of brittle deformation may have started prior to ca. 56 Ma. However, new data from the Engineer mine (about 70 km to the southeast, Fig. 2, 5) suggest that brittle deformation and associated epithermal veining along the fault occurred between 54 and 50 Ma (Millonig et al., 2017; and sample 16fd708). This timing is coeval with epithermal mineralization at Mount Skukum (Love et al., 1998) and Cordilleran-scale brittle dextral strike-slip faulting (e.g. Gabrielse et al., 2006).

Gold Mineralization and Deformation

An important objective of this study was to test the apparent relationship between the various styles of gold mineralization and the structural and magmatic events along the Llewellyn-Tally Ho deformation corridor. One of the initial hypotheses was that the various gold mineralization styles were part of the same system in which gold mineralization occurs synchronously at various depths in the crust ("crustal continuum" model; e.g. Groves, 1993; Goldfarb et al., 2005). However, the field relationships and U-Pb zircon geochronology presented herein demonstrate a time gap of ca. 20 Myr between the mineralization associated with intrusions and "early" ductile fabrics and that related with the brittle deformation (Fig. 7). The ductile deformation is older than ca. 75 Ma and is defined by a regional foliation (S_{main}) in the Stikine terrane rocks (Stuhini, Lewes River, and Laberge groups) and possibly the Boundary Ranges metamorphic suite. Intrusion-related gold mineralization in the Skarn Zone at Bennett plateau is pre- to syn-(ductile) deformation and likely occurred between ca. 98 and 75 Ma. The polymetallic veins, such as at the Brown showing (Wann river area; Blind Creek Resources Limited, 2012), Tannis (Middle Ridge), Gold Hill (Hart and Radloff, 1990) and auriferous quartz vein occurrences hosted in metamorphic and intrusive rocks along the Llewellyn-Tally Ho corridor (e.g. Bighorn, UM; Mihalynuk et al., 1999), are locally strained and oriented subparallel to the S_{main} foliation, but most are discordant and thus are probably late relative to the associated ductile deformation. To the northeast, gold mineralization at Montana Mountain is related to late reactivation of the Nahlin fault, roughly constrained between ca. 88 and 59 Ma (Hart and Pelletier, 1989; Hart and Radloff, 1990). The epithermal gold mineralization, such as at Engineer mine and Mount Skukum, has been dated at ca. 55 to 50 Ma and is clearly related to brittle deformation and Eocene volcanism (Fig. 7; Love, 1990; Love et al., 1998; Millonig et al., 2017; Ootes et al., 2018). This epithermal mineralization is associated with Eocene dextral fault zones and is hosted in proximal second-order synthetic faults such as at Engineer (Fig. 6) or along distal antithetic faults, like at Mount Skukum (Love, 1990).

First-Order Comparison with an Archean Setting

The evolution of distinct structural and mineralization events related to the Llewellyn-Tally Ho deformation corridor is analogous to the Neoarchean southern Abitibi belt, where major deformation zones, such as the prolific Destor-Porcupine and Larder Lake-Cadillac deformation zones or "breaks" are spatially associated with numerous gold mineralization deposits of various styles (e.g. orogenic quartz-carbonate and intrusion-associated gold deposits; Monecke et al., 2017). These two Archean deformation zones have undergone a polyphase structural evolution, including early extension, syn-orogenic sedimentation and magmatism, inversion to ductile reverse faulting associated with metamorphism and gold mineralization (e.g. Bleeker, 2015). Late, brittle-ductile transpressional deformation subsequently reactivated parts of those deformation zones as strike-slip faults. However, neither the premetamorphic extensional faulting nor the late brittle-ductile structural event are associated with preserved epithermal gold deposits in the southern Abitibi, even for fault zones that demarcate conglomerate-filled syn-orogenic basin remnants with minor subsequent exhumation and erosion. Such first-order comparisons highlight similarities, but also differences in the tectonometamorphic and metallogenic evolution of these major structural corridors. Project results also highlight key differences between Phanerozoic versus Archean gold metallogenesis.

IMPLICATIONS FOR EXPLORATION

The Llewellyn fault and second-order brittle splays overprint early ductile fabrics in British Columbia and the Tally Ho shear zone in Yukon. Earliest Eocene epithermal gold mineralization is spatially associated with penecontemporaneous volcanic complexes, such as the past-producing Mount Skukum and Engineer mines, and occurs on both sides of the Llewellyn fault. This timeframe of late brittle deformation corresponds to that of major strike-slip Cordilleran faults (e.g. Gabrielse et al., 2006) and matches the timing and structural framework of orogenic gold in the Juneau camp in Alaska (e.g. Miller et al., 1994), suggesting a similar first-order tectonic or genetic process led to gold mineralization in both environments.

Previous work proposed that the Tally Ho shear zone developed between 208 and 173 Ma (Tizzard et al., 2009). Observations and U-Pb zircon data from this study indicate that some of the ductile deformation related to the Tally Ho shear zone and regional foliation occurred during the Late Cretaceous, between ca. 98 and 75 Ma. Structurally controlled intrusion-related and 'mesothermal' gold mineralization, for example at the Skarn Zone, is older than ca. 75 Ma and occurs in foliated, metamorphosed units of the Stikine and Nisling assemblages, principally in the central part of the Llewellyn-Tally Ho deformation corridor. If this gold mineralization event developed between ca. 98 Ma and 75 Ma, then it is broadly coeval and analogous with some of the gold deposits and occurrences, plutonic suites, and regional structural controls (e.g. Big Creek fault zone) of the Dawson Range polymetallic belt in west-central Yukon (e.g. Allan et al., 2013).

The ca. 20 Myr time-gap between early and late deformation (Fig. 7) shows that intrusion-related/ 'mesothermal' and epithermal gold mineralization, respectively, associated with ductile and brittle fabrics and structures, not only formed at different times and tectonometamorphic levels, but are also related to distinct tectonic events. Disparate gold mineralization styles are thus the product of overprinting events, rather than a so-called 'crustal continuum' of mineralization (e.g. Groves, 1993) along the Llewellyn-Tally Ho deformation corridor.

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