A new lode gold discovery at Otter Creek: Another source for the Atlin placers

Mitchell G. Mihalynuk[1, a], Alexandre Zagorevski[2], Fionnuala A.M. Devine[3], and Elaine Humphrey[4]

[1] British Columbia Geological Survey, Ministry of Energy and Mines, Victoria, BC, V8W 9N3
[2] Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8
[3] Merlin Geosciences Inc., Atlin, BC, V0W 1A0
[4] Department of Mechanical Engineering, University of Victoria, Victoria, BC, V8P 5C2
[a] corresponding author: Mitch.Mihalynuk@gov.bc.ca

Recommended citation: Mihalynuk, M.G., Zagorevski, A., Devine, F.A.M., and Humphrey, E., 2017. A new lode gold discovery at Otter Creek: Another source for the Atlin placers. In: Geological Fieldwork 2016, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2017-1, pp. 179-193.

Abstract

Primary exploration targets for lode gold near Atlin, northwestern British Columbia have historically been quartz-carbonate-mariposite-altered ('listwanite') ultramafic and mafic bedrocks. These have long been considered the source of nearby placer deposits, and locally do contain fine visible gold. However, despite more than a century of searching, coarse gold such as found in the placer gravels has never been discovered. This has prompted the belief that the 'listwanites' are mere erosional remnants of bedrock sources of the coarse placer gold, and that these sources have been almost entirely lost to erosion. An alternative hypothesis argues that, although gold is found with listwanite, it was not the only bedrock source. Streams with placer deposits are distributed around the evolved Surprise Lake batholith (Sn-U-Th-Mo-W-F rich) and rare gold nuggets contain Sn- and Th-rich mineral intergrowths (cassiterite and thorite), demonstrating that at least some of the placer gold may be related to the batholith. Discovery of coarse lode gold (>5 mm) in graphitic and quartz-rich phyllitic bedrock beneath placer deposits along Otter Creek in 2016 confirms that listwanite-altered mafic and ultramafic rocks are not required for lode gold mineralization. At the discovery site, native gold is intergrown with quartz-albite veins and occurs as open space fillings. Rutile in quartz veins, and perhaps altered titanite in the adjacent phyllite may have grown along with gold deposition. Geochemical analysis of pyrite-rich phyllite adjacent to the gold veins yields no appreciable gold, but is slightly elevated in Cu (11-54 ppm), Pb (~33 ppm) and zinc (60-70 ppm). These results are consistent with petrographic observations that show abundant chalcopyrite inclusions but no gold inclusions in pyrite. Discovery of coarse gold in quartz veins cutting graphitic and quartz-rich phyllitic country rocks significantly expands the lode gold exploration target in the Atlin placer camp.

Keywords: Lode gold, placer gold, Surprise Lake batholith, Fourth of July batholith, Kedahda Formation, listwanite, Cache Creek terrane, Otter Creek, Slonski, Atlin

1. Introduction

Near the turn of the 20th century, the newly discovered placer creeks of the Atlin camp (northwest British Columbia) attracted miners who had abandoned the lode gold mines of California. Placer gold claims in the Atlin camp were first staked on Pine Creek, east of the future Atlin townsite, in 1898 (Robertson, 1898; Debicki, 1984; Figs. 1, 2). Atlin camp placers were spatially associated with quartz-carbonate-mariposite-altered (listwanite) ultramafic rocks (Figs. 2, 3). Prospectors noted similarity to the ultramafic rock associated with the rich ore streaks in the Alleghany district in California where, for example, 35,600 ounces were recovered from one ~4 x 7 m vein section in the Oriental Mine (Ferguson and Gannett, 1932). Aiming to duplicate the lode mining success in California, the ultramafic rocks near Atlin became the prime gold exploration target. Yet, despite intense exploration, only about 3 kg of lode gold was produced in the century following the placer discovery (Imperial Mine, MINFILE 104N 008, BC Geological Survey, 2016; for a summary of lode occurrences see Bloodgood et al., 1989). This lack of lode gold prompted previous workers to conclude that any rich lodes in altered ultramafic and mafic rocks of the Atlin area had been removed by erosion, leaving only gold placers behind (Aitken, 1959; Ash et al., 2001).

Drilling in the listwanite-altered Pine Creek bedrock underlying the historic placers at the Yellowjacket property (Fig. 2) delineated an inferred gold resource of 184,000 tonnes grading 4.4 g/t (781 kg total Au, 0.5 g/t cut-off, Price and Dandy, 2010). Although the gold production and resource are relatively small, they do demonstrate that gold is associated with altered ultramafic rocks. However, this association is lacking in most other places. For example, aerially extensive altered ultramafic rocks southeast of Atlin (Nahlin ultramafic complex; Fig. 1) lack lode and placer gold deposits. Furthermore, coarse gold nuggets in Atlin placers are much coarser than sporadic, barely visible gold in known bedrock-hosted showings (e.g. Spruce Creek holds the provincial record for the largest nugget, weighing 2.6 kilograms (85 ounces) and

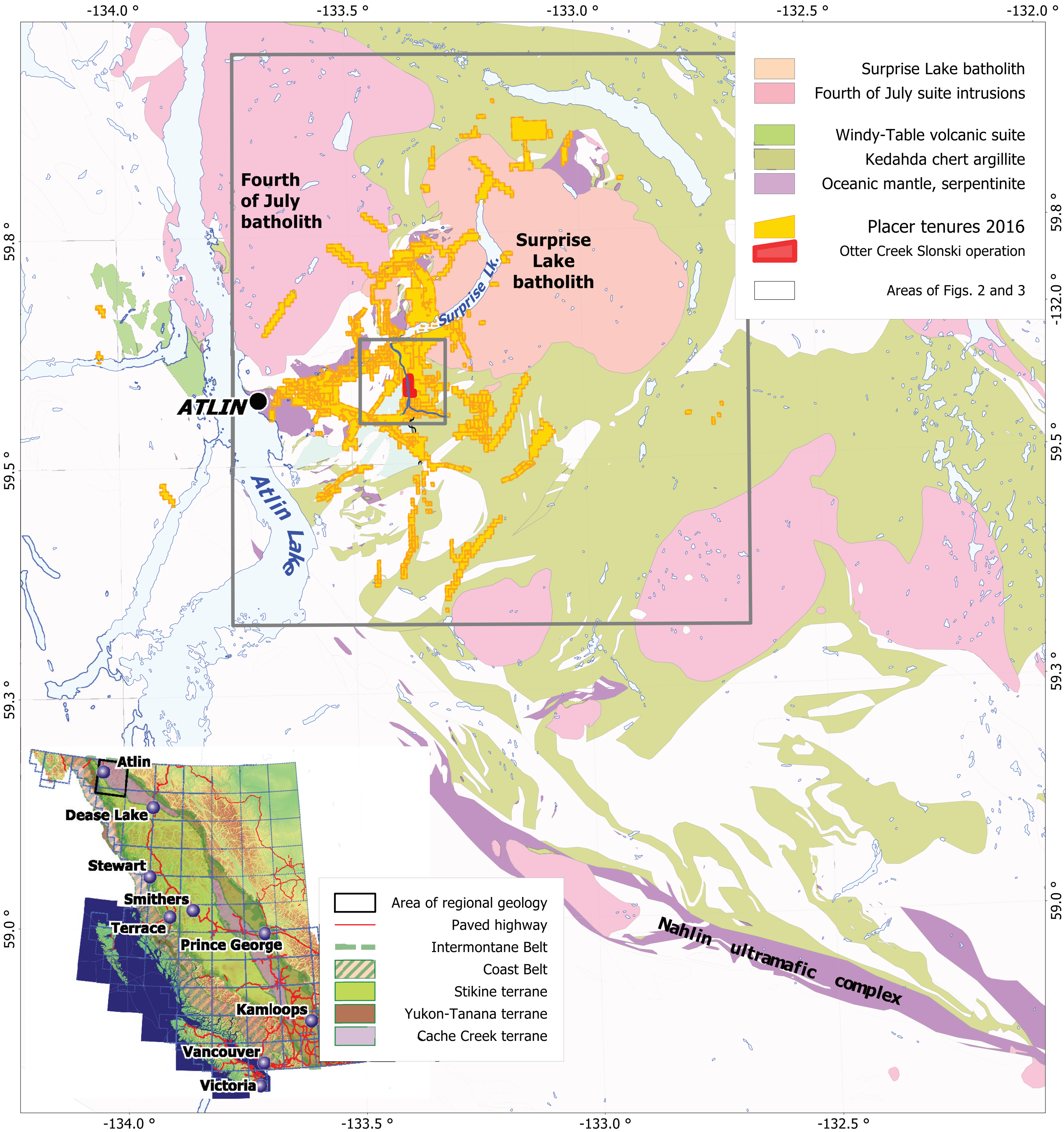

Fig. 1. Distribution of placer claims (yellow and red blocks) around the Surprise Lake batholith. Location of Otter Creek Slonski operation within the Atlin camp (red claim blocks). Geology base modified from Cui et al. (2015). Inset shows location of the study area with respect to major terranes in British Columbia.

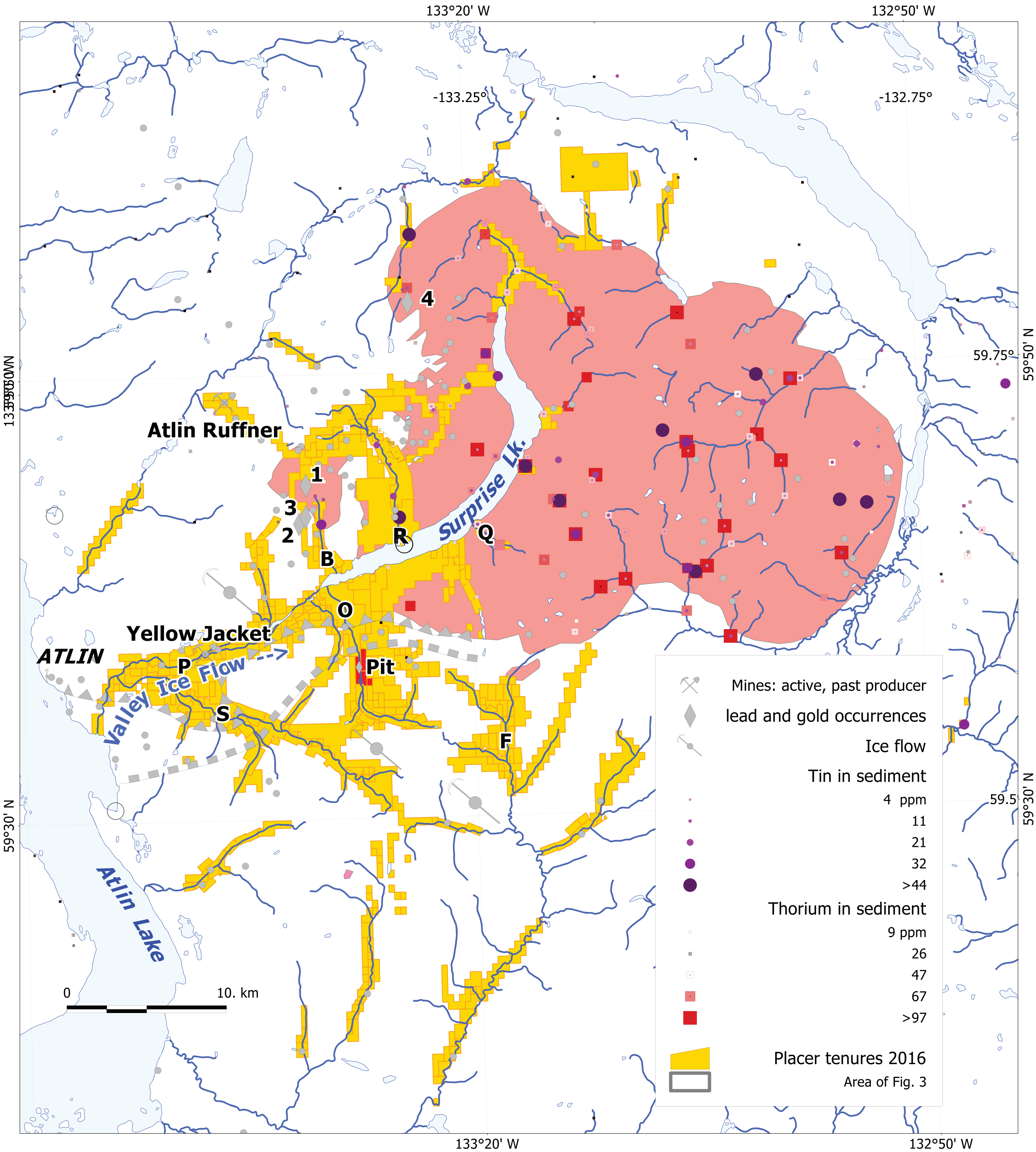

Fig. 2. Map of the Atlin placer camp showing placer tenures as of November, 2016. Almost all of the placer streams or their headwaters are underlain by the Surprise Lake batholith (pink) or its thermal metamorphic halo. There is a direct spatial relationship of regional stream sediment geochemical survey results for thorium (squares in shades of red) and tin (circles in shades of purple) with the areas underlain by the Surprise Lake batholith, showing that these elements are derived from the batholith. Creeks discussed in the text are denoted by the letters: B = Boulder, F = Feather, O = Otter, P = Pine, Q = Quartz, R = Ruby, S = Spruce.

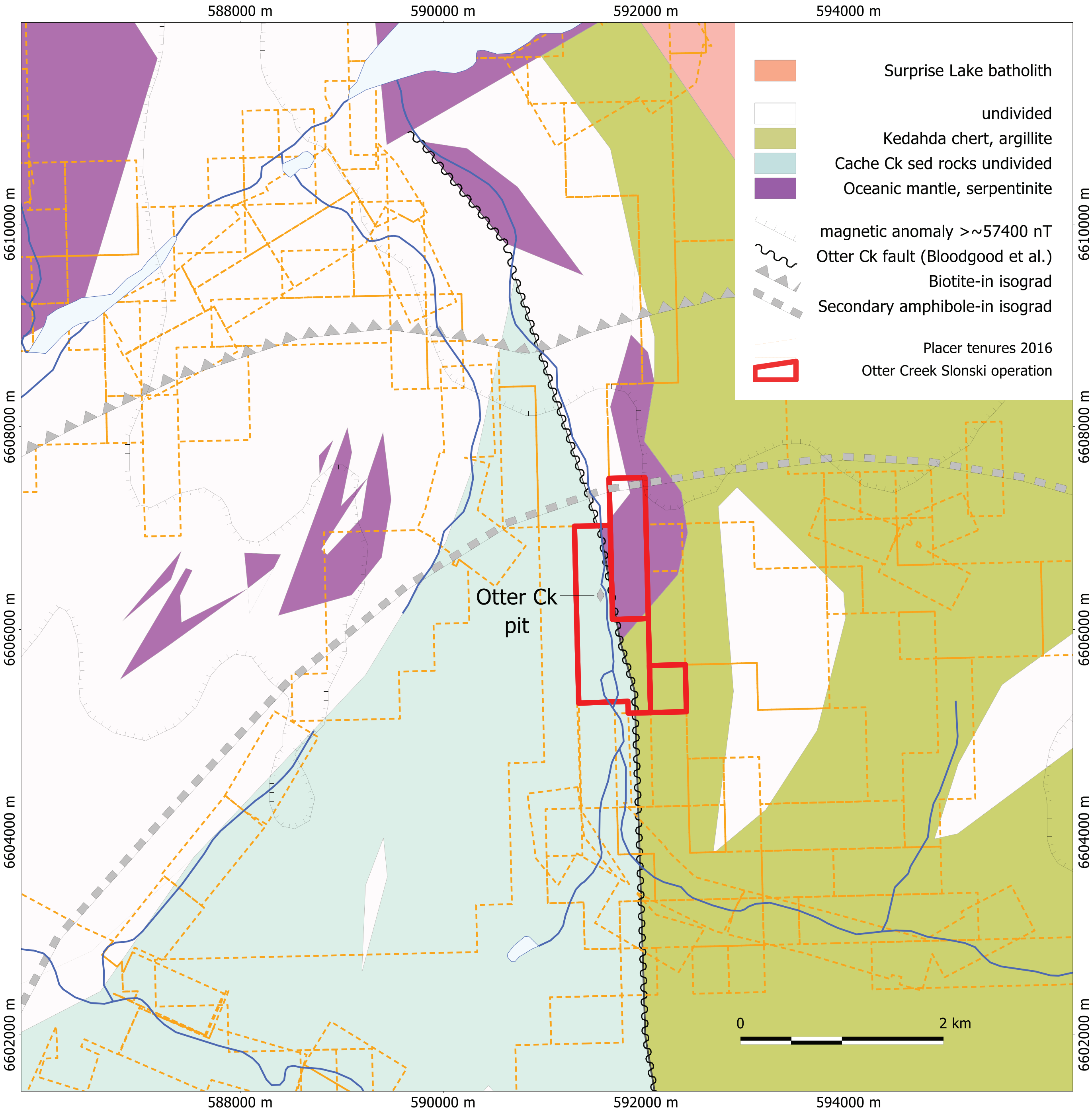

Fig. 3. Geology of the Otter Creek area, from Cui et al. (2015). Map shows Otter Creek fault following lower Otter Creek valley. Ultramafic bodies are broadly outlined by the >~57400 nT contour (ticks on high side of contour). Also shown are locations of the biotite-in and amphibole-in isograds (after Aitken, 1959). Sparse outcrops west of Otter Creek on the Slonski operation placer claims are metachert-argillite, like the Kedahda unit east of the fault. Universal Transverse Mercator grid designations, zone 8, NAD83.

for placer gold production; Levson, 1992), indicating that the source of the coarse placer gold is yet to be discovered. One possible alternative source is suggested by the distribution of placer streams. Their headwaters are underlain by the Surprise Lake batholith (Cretaceous), or country rock in its thermal metamorphic halo (cf. Aitken, 1959; Figs. 1, 2), suggesting a first-order relation between the batholith and placer gold.

In 2016, gold-quartz-albite-muscovite veins were discovered in graphitic phyllite bedrock in the Atlin placer camp. This discovery, on the middle section of Otter Creek amidst active placer operations (Figs. 2, 3), confirms a local source for the placer gold. The lode gold - graphitic phyllite association in Otter Creek valley is significant because it demonstrates that listwanite or mafic-ultramafic rock associations are not necessary for lode gold deposition in the Atlin camp. This expands the prospects for lode gold exploration adjacent to the Surprise Lake batholith, and perhaps beyond.

2. Atlin geology and previous work

Gwillim (1901) and Cairnes (1913) conducted the initial systematic regional geological surveys of the Atlin region. Subsequent mapping by Aitken (1959; 1:250,000 scale) established the regional framework for modern geological studies that is still in use today. More detailed studies of the area around Otter Creek were conducted by Bloodgood et al. (1989, Fig. 3) at 1:50,000 scale and in the area west of Otter Creek, by Ash (2004) at 1:25,000 scale.

Bedrocks of the Atlin area are predominantly Carboniferous to Early Jurassic oceanic crustal and sedimentary strata that were structurally imbricated and then cut by Mesozoic magmatic rocks of the Fourth of July batholith (Middle Jurassic) and Surprise Lake batholith (Late Cretaceous). Oceanic rock units of Cache Creek terrane originally formed at mantle to shallow-marine levels and have been fault juxtaposed such that lenses of ultramafic and mafic rocks are commonly interleaved with limestone, chert, and wacke at all scales. Early juxtaposition of contrasting rock packages probably originally occurred in multiple episodes at an accretionary margin (Monger, 1975; Monger et al., 1982). This has produced confounding geological relationships between rock types, hindering geological understanding and challenging standard practices of stratigraphic nomenclature in the Atlin area (see Monger, 1975; Mihalynuk et al., 1999).

Regionally, the youngest folded rocks are fossiliferous Aalenian to Bajocian strata (Mihalynuk et al., 1995; Shirmohammad et al., 2011). Following deformation, these early Middle Jurassic strata (~174 - ~169 Ma, time scale of Cohen et al., 2013) were intruded by the Fourth of July batholith at ~172 Ma, which is part of the Three Sisters suite. Plutonic members of this suite cut structures affecting correlative strata from Atlin to Dease Lake (Mihalynuk et al., 2004) and cooled within about 10 m.y. based on K/Ar cooling ages from the Fourth of July Batholith (Dawson, 1988, in Breitsprecher and Mortensen, 2004) and mariposite (Cr-mica) in listwanite-associated lode gold occurrences elsewhere in the Atlin camp (Ash et al., 2001). Fourth of July and Cache Creek rocks were subsequently intruded by the highly evolved and geochemically distinct Surprise Lake batholith (Late Cretaceous; Zagorevski et al., 2017).

Sack and Mihalynuk (2003) evaluated the spatial association of gold and the geochemically anomalous Surprise Lake batholith (e.g., elevated Sn, Th, Fig. 2) by conducting a provenance study on non-quartz mineral intergrowths in placer gold nuggets. Their study focused on the placer deposits of Feather Creek (Fig. 2), known to contain abundant crystalline nuggets that are not rounded, presumably indicating nearby derivation. Nuggets collected from Feather Creek contain diagnostic mineral intergrowths of thorite ($ThSiO_4$) and cassiterite (SnO_2), providing an unambiguous genetic link to the Surprise Lake batholith, which is known to be enriched in U, Th, Sn, Mo, W, and F (Fig. 2), rather than to ultramafic rocks, which lack these elements. In a follow-up study, Mihalynuk et al. (2011) attempted to find similar intergrowths in nuggets from other creeks in the Atlin camp. Although this attempt was unsuccessful, Mihalynuk et al. (2011) found that rare gold nuggets from Otter Creek placers (Fig. 4a) are intergrown with phyllite similar to phyllitic metasedimentary rocks of the regionally extensive 'Kedahda Formation' (Watson and Mathews, 1944) that underlies the local Otter Creek drainage. Unfortunately, this type of country rock is common regionally, providing little help in pinpointing a lode gold source. Conceivably, these nuggets could have been transported by glaciers, either early valley ice that flowed up the Pine Creek drainage, or from continental ice sheets that flowed to the northwest (Fig. 2). However, most of the productive placer gravels in the Atlin camp are located stratigraphically below tills, proglacial outwash, postglacial debris flows, and Holocene channel gravels (Levson, 1992; Levson et al., 2003; Fig. 4b), suggesting that these phyllite-gold nuggets are locally derived.

Understanding the geology of the Otter Creek drainage, and other placer-bearing drainages, is hindered by lack of outcrop. For example, geology of the middle section of Otter Creek drainage was extrapolated by Bloodgood et al. (1989) from adjacent hillsides, which are underlain predominantly by chert and siliciclastic metasedimentary rocks, generally having uncertain contact relations with domains up to 2 km across of massive grey limestone, mafic volcanic, and ultramafic rocks. Bloodgood et al. (1989) also inferred that a south-trending, high-angle fault (Otter Creek fault) extends 9 km from the lower stretches of the drainage to beyond the main fork on the upper creek, where it is presumably beneath colluvial cover. It is extended farther south on the geological compilation of Figure 3.

3. Geology of the Otter Creek pit

Excavation during placer mining creates ephemeral bedrock exposures in the creek valleys (Fig. 4b). At active placer operations, these exposures can only be examined for brief periods when mining ceases. Active mining limited our investigation of bedrock at the Slonski operation pit in the

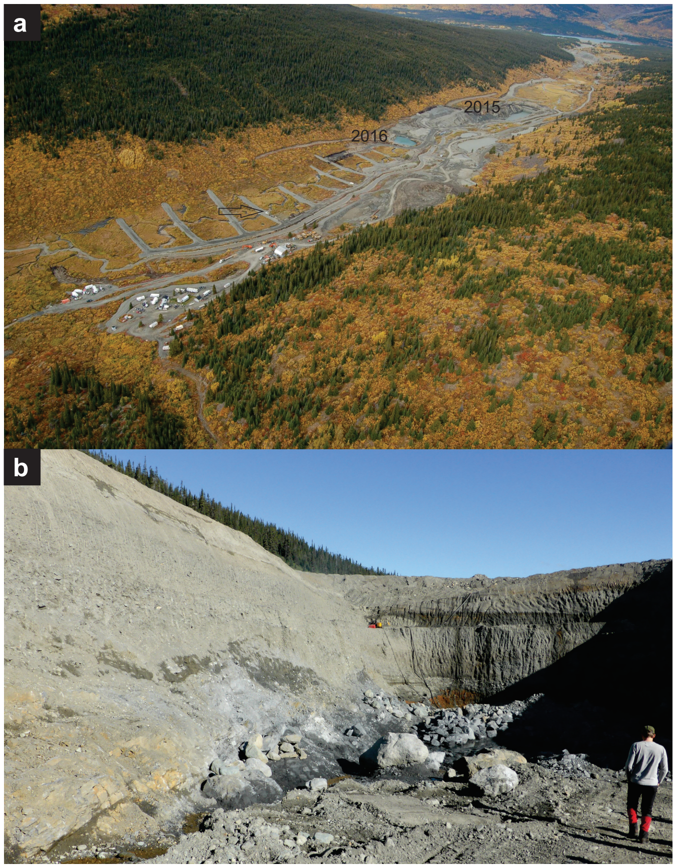

Fig. 4. a) View of Otter Creek Slonski operation pit on the central stretch of the creek as it appeared in autumn, 2015. Location of the 2015 pit is indicated, as is the future location of the 2016 (near pond) pit seen in b). Farther up the valley, a series of exploration roads are established for placer exploration drilling (drill rig is at the arrow head). **b)** View to the north of the pit bottom as it appeared in early August, 2016. Rusty pay gravels at the far end of the pit are overlain by tan to grey gravel and then dense, jointed basal till (immediately beneath yellow and red pump equipment). Dark grey-brown and tan layers above the till are channel gravels of probable Holocene age (cf. Levson, 1992). Yellow and grey bedrock at the left foreground are phyllites, dipping moderately to the west, an orientation that is common elsewhere in the pit.

middle part of the Otter Creek valley (henceforth referred to as "Otter Creek pit"). Immediately before our visit, gold-bearing veins were discovered in the pit by Doug (Gold Nuggie Dougie) Finlayson during a routine metal detector sweep of bedrock following stripping of pay gravels (Figs. 4, 5). Recovery of another 5-cm angular block of gold-phyllite during placer cleanup (Figs. 5e, f) suggests that gold in bedrock along this section of Otter Creek is not limited to the discovery site.

3.1. Graphitic phyllite

Bedrock in the Otter Creek pit is mostly graphitic and siliceous phyllite that typically contains less than 2%, but up to 5% euhedral pyrite cubes (Fig. 6a). Graphite content varies from strongly graphitic to almost graphite-free. Chlorite and muscovite are locally important foliation-defining constituents. However, where individual muscovite flakes are visible (up to ~1 mm across where coarsest), they tend to be oblique to the foliation. Carbonate and silica contents also vary, probably reflecting differences in protolith compositions. This is consistent with relict interbedded (?) ribbon chert and cherty limestone that are exposed at adjacent mountainsides east and west of the pit (Bloodgood et al., 1989; Fig. 3). Outcrops southwest of the pit are sugary, silica-rich phyllite that is interpreted to be thermally altered interbedded chert and fine-grained siliciclastic strata.

Phyllite foliation orientation generally dips moderately to the west (~175°/50°; Fig. 4b), but does vary to east-southeast-dipping on an outcrop scale. The phyllitic foliation in the pit commonly preserves millimetre-scale intrafolial isoclinal folds indicating that it is a transposition fabric. Carbonate-rich layers commonly display an anastomosing foliation (Fig. 6b).

3.2. Dikes

Dikes cut phyllite in the pit (Figs. 7a, b, c) and form angular broken outcrop in the bank of a skid trail northwest of the pit that is coarser (medium grained) and less altered. The dike northwest of the pit is equigranular and light tan-weathering with medium grey fresh surfaces (Fig. 7d). A felted texture is well developed by intergrowth of elongate feldspar and hornblende and is overprinted by carbonate-chlorite alteration such that plagioclase is turbid and hornblende almost completely pseudomorphed by chlorite and epidote (Figs. 7e, f).

In the pit, dikes are cream coloured and form a steeply dipping, northeast-southwest striking set (225°-235°/80°-90°; 052°/79°). They range from a few centimeters to nearly a metre wide (Fig. 7a). Where least altered, they display a fine-grained felted texture. The dikes are strongly altered; the original minerals are replaced by chlorite and calcite (Figs. 7b, c) and only relicts remain. Secondary muscovite forms local booklets lacking a preferred orientation (Figs. 7b, c).

Dikes and local bedrock were analyzed by Inductively Coupled Plasma (ICP) / Mass Spectroscopy (MS) using the analytical package WRA + trace 4Lithoresearch at Activation Laboratories, Ancaster, Ontario. Samples were dissolved following lithium metaborate/tetraborate fusion and major elements were determined by fusion ICP and trace elements by fusion ICP/MS. Geochemical analyses show that, despite their light colour, these altered dikes have basaltic compositions (Fig. 8a). Although alteration resulted in almost complete replacement of igneous mineralogy, it does not appear to have resulted in extensive mobility of major or minor elements, with the exception of Rb. All samples plot in the basalt field with a trend toward trachybasalt on an immobile trace element rock classification plot (Fig. 8a; and basalt to trachybasalt field on major oxide rock classification plot SiO_2 versus Na_2O+K_2O of Le Bas et al., 1986, not shown). Dikes within and outside of the pit are chemically similar, especially their immobile trace element compositions (Figs. 8a-d).

Otter Creek dikes are geochemically similar to the mafic to intermediate phases of the Fourth of July batholith (Middle Jurassic) and to andesitic rocks at Atlin Mountain (west of

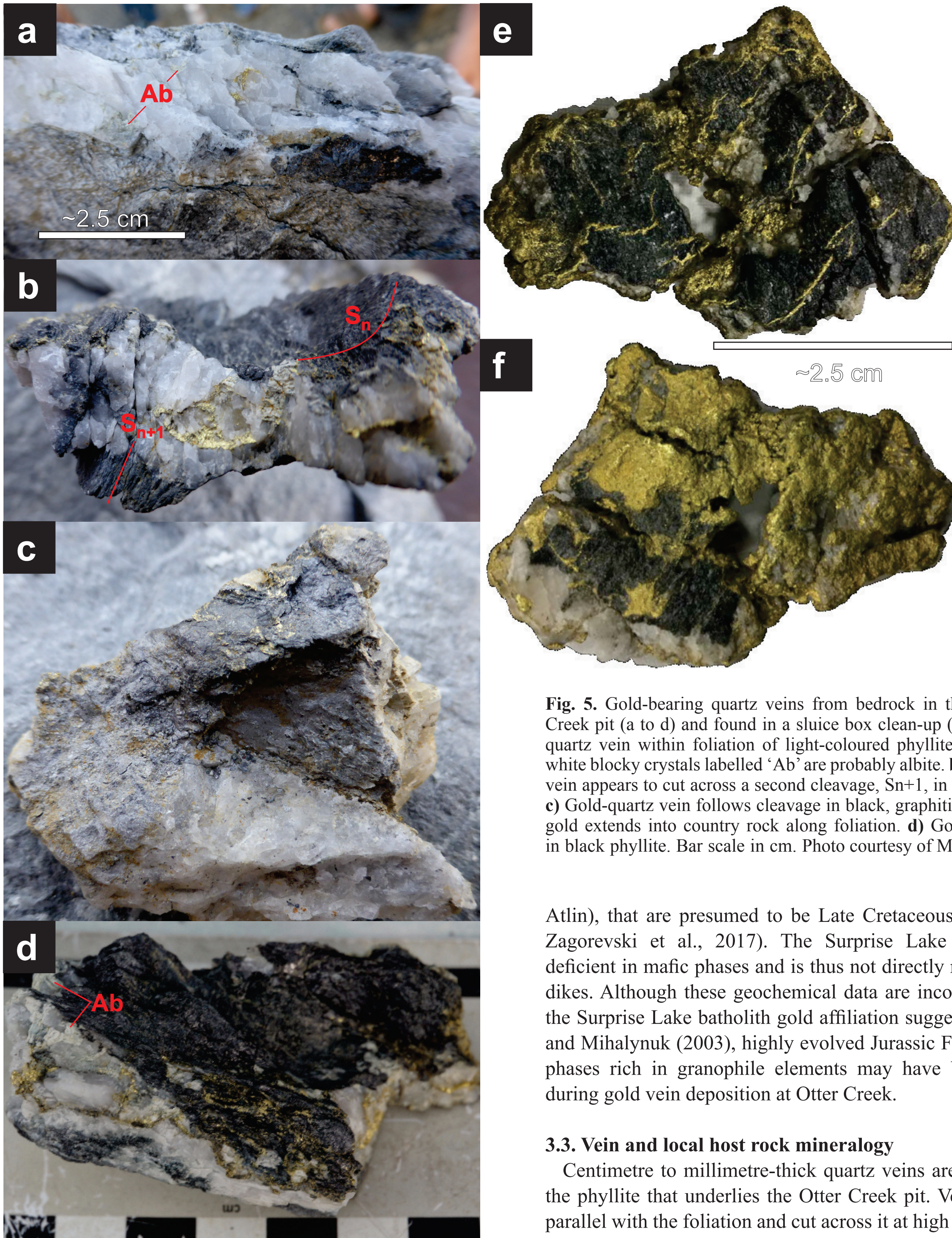

Fig. 5. Gold-bearing quartz veins from bedrock in the 2016 Otter Creek pit (a to d) and found in a sluice box clean-up (e, f). **a)** Gold-quartz vein within foliation of light-coloured phyllite. Green-tinted white blocky crystals labelled 'Ab' are probably albite. **b)** Gold-quartz vein appears to cut across a second cleavage, Sn+1, in black phyllite. **c)** Gold-quartz vein follows cleavage in black, graphitic phyllite, and gold extends into country rock along foliation. **d)** Gold-quartz vein in black phyllite. Bar scale in cm. Photo courtesy of Matt Fraser.

Atlin), that are presumed to be Late Cretaceous (Fig. 8, see Zagorevski et al., 2017). The Surprise Lake batholith is deficient in mafic phases and is thus not directly related to the dikes. Although these geochemical data are inconsistent with the Surprise Lake batholith gold affiliation suggested by Sack and Mihalynuk (2003), highly evolved Jurassic Fourth of July phases rich in granophile elements may have been present during gold vein deposition at Otter Creek.

3.3. Vein and local host rock mineralogy

Centimetre to millimetre-thick quartz veins are common in the phyllite that underlies the Otter Creek pit. Veins are both parallel with the foliation and cut across it at high angles (Figs. 5, 9a). Vein mineralogy is quartz–albite–pyrite–graphite ±rutile

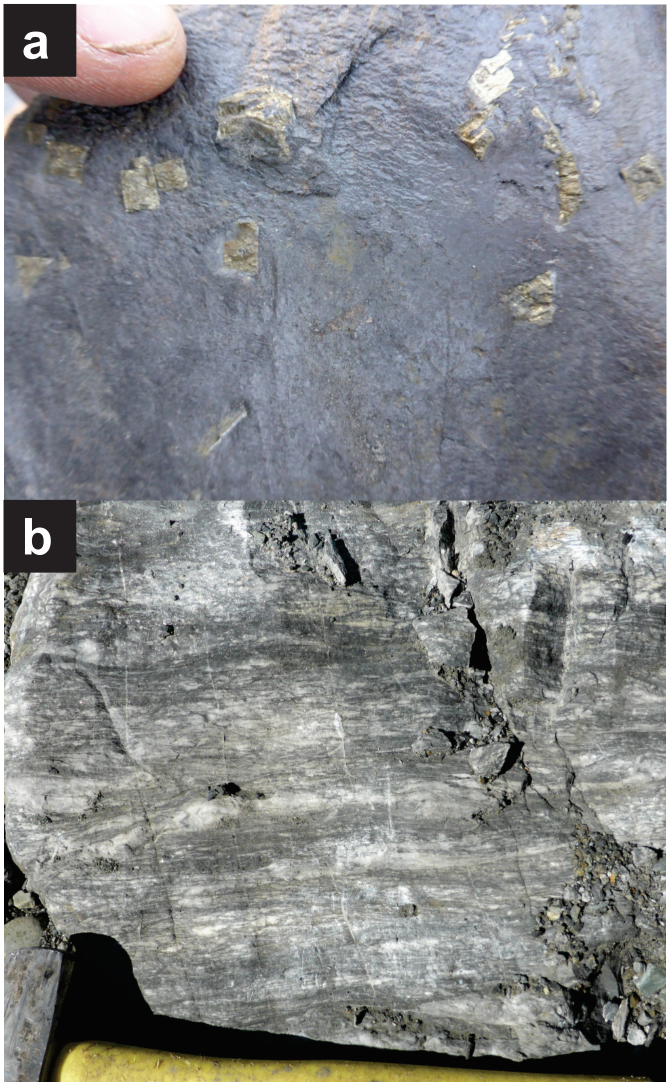

Fig. 6. a) Black graphitic phyllite displays zones where coarse euhedral pyrite cubes and aggregates are common. Pyrite grains show fracturing, embayments and deformation to varying degrees. **b)** Anastomosing fabric in carbonate-rich zone.

and possibly titanite. Both veins and the adjacent enclosing host rocks display this mineralogy. Gold was present in the only gold-bearing vein sample that could be obtained for destructive analyses. Like other veins, this gold-bearing vein contains a conspicuous medium- to coarse-grained, blocky white albite (confirmed by X-Ray Diffraction analysis; see below) that comprises ~5% of the vein volume (Figs. 5a, d, 9b). Albite cleavage planes are invaded by fine pyrite veins (<0.05 mm thick, Fig. 9b).

Phyllite hosting the gold veins commonly contains pyrite, most conspicuously as coarse euhedral cubes in graphitic country rocks. In samples containing gold, pyrite can form framboid-like aggregates (Fig. 9c) or corroded cubes, commonly with abundant irregular inclusions of chalcopyrite (Fig. 9d) and sparse, minute pyrrhotite inclusions. Pyrite is also intergrown with slender prismatic white crystals that are interpreted as altered titanite (Figs. 9e, f). Graphite is a constituent of many, but not all, rock types that are cut by quartz veins near the lode gold occurrence in the Otter Creek pit. Although graphite can be easily identified in sooty hand samples, in none of our sectioned samples is graphite sufficiently well crystallized to permit it to be unequivocally identified petrographically. Instead, it occurs as a finely dispersed black discolouration of the rock (Fig. 9a). In places, similar dark discolouration seems to be introduced to a quartz-rich host along fractures (Fig. 9f).

Phyllite cut by quartz veins locally contains millimeter-size white mica booklets with no strongly-preferred orientation. They are confirmed by XRD analysis to be muscovite or phengite. Muscovite/phengite probably also defines the phyllitic fabric in some outcrops. XRD analysis of gold-bearing vein material also identified kaolinite, although this mineral has not been observed petrographically, so the relationship to gold-quartz veins is not yet known.

4. Texture and composition of a gold nugget

In 2015, the Slonski placer operations at Otter Creek pit recovered a nugget with a 4 mm to 7 mm gold plate core enveloped by bladed carbonate and quartz. This sample was of particular interest because bladed calcite textures can be produced in hydrothermal veins, during boiling of CO_2-supersaturated fluid in environments forming epithermal Au-Ag mineralization (Browne and Ellis, 1970; Simmons and Christenson, 1994; Simmons et al., 2005). Approximately two thirds of the surfaces of the gold plate are free of mineral intergrowths and shiny (Figs. 10a, b). Coarse bladed carbonate in the gold nugget is light tan to brown on the weathered surface and tan to white on fresh surfaces. Lesser amounts of milky anhedral quartz are also intergrown with the gold. Subordinate gold plates that grew perpendicular to the vein, between carbonate blades that have been eroded or dissolved, have been subjected to only minor alluvial rounding (Figs. 10a, b).

4.1. SEM-EDS methods

Gold and carbonate of the gold nugget were investigated using Scanning Electron Microscope (SEM) – Energy Dispersive X-ray Spectroscopy (EDS). SEM-EDS analyses were conducted at the University of Victoria (British Columbia) Advanced Microscopy Facility using a Hitachi S-4800 scanning SEM fitted with a Bruker Quantax EDS system. Distilled water and acetone were used to clean the gold nugget sample, which was then dried in a vacuum chamber. Electrical conductivity of most parts of the sample surface are excellent, so conductive coating of the sample was not necessary. Elemental analyses reported here are semi-quantitative, calculated using (ρz) matrix corrections without using a standard. They were obtained using operating conditions optimized for EDS analysis of both points and fields on the grains. Working distance was set to ~15 mm with a beam voltage of 20kV.

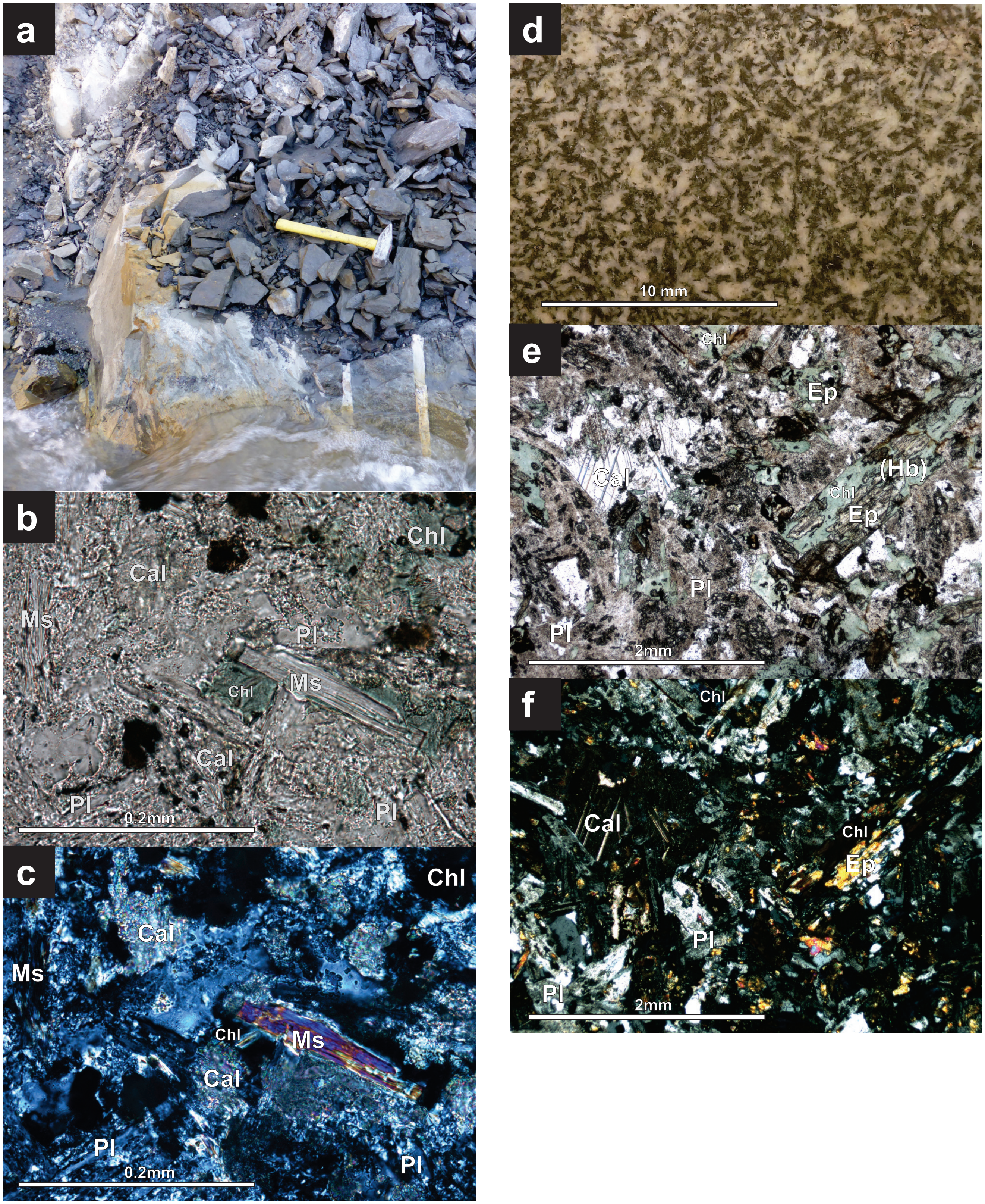

Fig. 7. a) View towards the northeast of a prominent set of white dikes (below and left of hammer) ranging from a few centimetres to ~0.75 m thick. Angular slabs of broken graphitic phyllite blanket the outcrop beneath hammer. **b)** Secondary muscovite booklets (Ms) have no preferred orientation. **c)** Same field of view as b) under cross-polarized light. **d)** Felted texture of blocky dike nearcrop from outside of the pit. **e)** Photomicrograph under transmitted, plane-polarized light, of altered dike in d) shows carbonate (Cal), chlorite (Chl), and epidote (Ep) alteration. Plagioclase (Pl) is turbid from alteration to fine secondary minerals. Hornblende (Hb) is completely replaced by chlorite and epidote. **f)** Same field of view as e) under cross-polarized light.

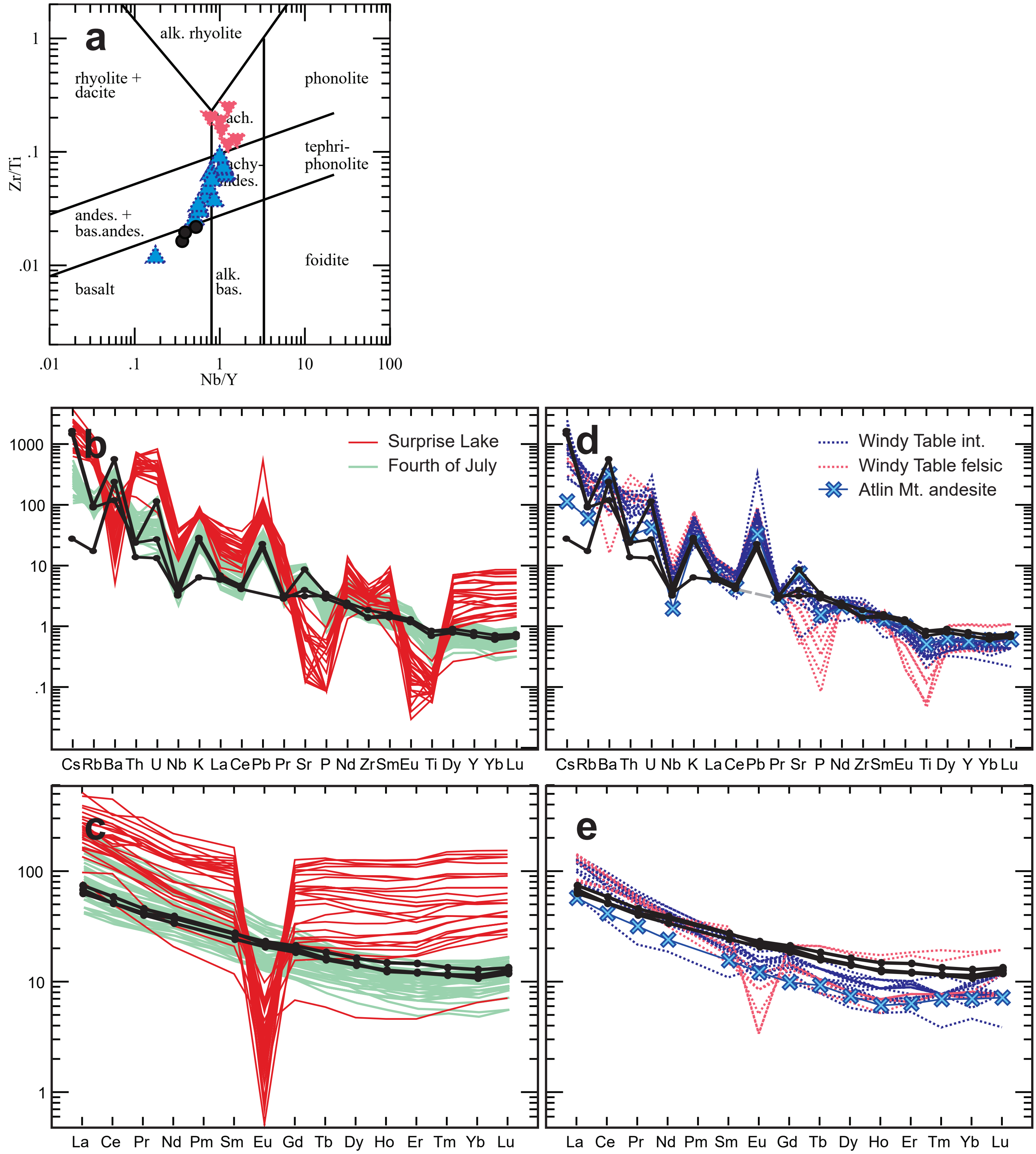

Fig. 8. Geochemistry of dikes inside and adjacent to the Otter Creek pit location (as of August, 2016). **a)** Dike compositions (black points) are plotted with respect to the compositional fields of Windy-Table felsic (red inverted triangles) and intermediate volcanic rocks (blue triangles). **b)** Otter Creek dikes (black) plotted on Primitive Mantle-normalized extended element plot with Surprise Lake (red) and Fourth of July (green) compositions. **c)** Like b), but for rare earth elements only. **d)** Like b), but showing Windy Table intrusive (blue dotted) and felsic volcanic (red dotted) compositions for comparison. **e)** Like c), but for rocks in legend of d). Data from all rocks other than Otter Creek dikes are from Zagorevski et al. (2017).

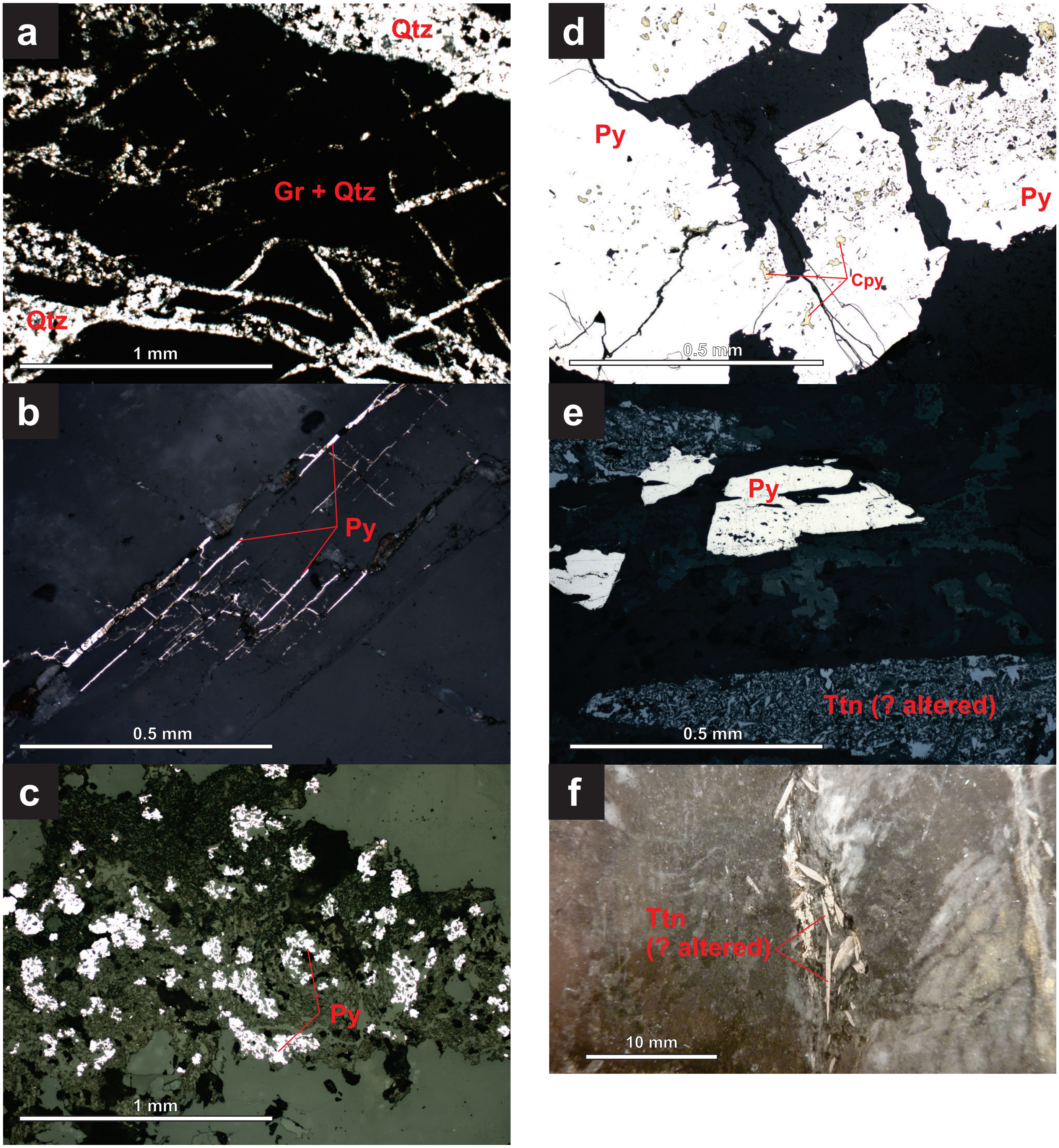

Fig. 9. Veins and vein mineralogy from bedrock in the Otter Creek pit. **a)** Plane polarized, transmitted light view of graphitic quartz-rich rock (black, Gr + Qtz) is cut by fine-grained quartz (Qtz). **b)** Reflected light view of albite with veinlets of pyrite (white, Py) along cleavage planes. **c)** Highly reflective (white, Py) framboid-like texture of pyrite in host rock adjacent to, and as patches in, gold-bearing veins. **d)** Reflected light view of corroded pyrite crystals (white, Py) containing abundant inclusions of yellow chalcopyrite (Cpy). Rare pyrrhotite inclusions are too small to see at this magnification. **e)** Corroded pyrite grains (cream, Py) in quartz-rich rock is intergrown with mineral tentatively identified as altered titanite (Ttn (?altered), polycrystalline grey and black, upper left and lower). **f)** The slab of rock from which the polished section in e) was made. Irregular quartz veins along the right side and with slender, euhedral "Ttn? altered" cut the black (graphitic) and white quartz-rich rock.

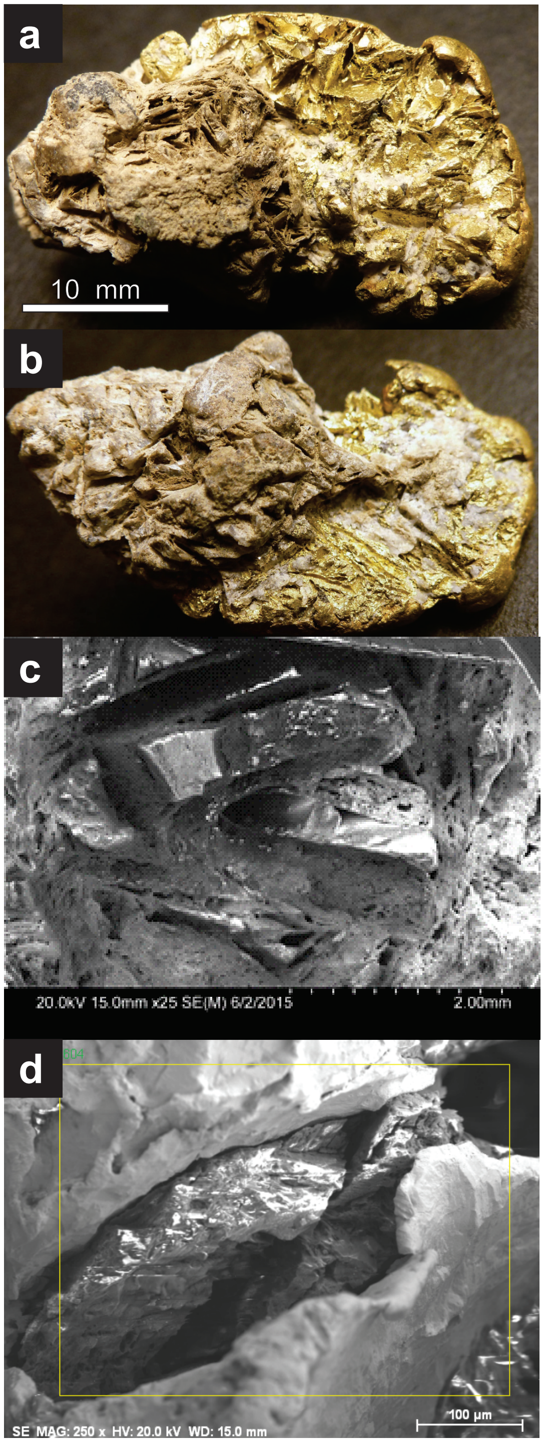

Fig. 10. a) Gold nugget with attached siliceous material shows evidence of bladed mineral moulds formed by gold and the siliceous rock material. Bladed calcite in hydrothermal deposits can take this form when crystallized rapidly from boiling fluids which leads to saturation and precipitation of metals carried in the fluid, including gold (thickness of the gold seam forming the nugget is 4 mm to 7 mm). **b)** Opposite side of nugget in a). **c)** Scanning Electron Microscope backscattered electron image showing a detailed view of the euhedral rhombic corner of the bladed mineral and moulds. **d)** Dissolution interface between carbonate displaying rhombic cleavage (dark grey with brightly highlighted crystal faces) and enclosing gold (light grey and amorphous).

4.2. SEM-EDS results

Back Scatter Electron imaging (BSE) of the gold-carbonate intergrowths confirm the macroscopic relationships (Fig. 10c), but also shows that there was dissolution along the gold-carbonate interface (Figs. 10d, 11). EDS analysis shows that gold contains significant Ag, and traces of Hg (Figs. 11b, c). Silver contents are consistent with findings of Hora et al. (2012) from samples collected on Ruby and Wright creeks in the Altin placer camp (Fig. 2), where silver-in-gold values range up to 30 wt.%. Both copper and platinum may be present at concentrations of up to ~1 wt.%.

5. Gold vein genesis

Chronology of the regional deformation fabrics cut by veins and dikes in the Otter Creek pit is bracketed by the age of the youngest deformed unit (Bajocian, south of the Otter Creek area) and the age of the oldest intrusions that cut the fabrics (~172 Ma). Chronology of the gold-bearing quartz vein emplacement is more difficult to constrain. These veins clearly cut the foliation in the phyllite in the Otter Creek pit and, if formed during regional deformation, this foliation pre-dates the Fourth of July batholith (~172 Ma; Mihalynuk et al., 2004; Harris et al., 2003). However, veining in the Otter Creek pit appears to be cut by the altered dikes that are geochemically similar to the Fourth of July batholith (Fig. 8).

Altered dikes, and country rocks contain muscovite lacking a preferred orientation and gold-quartz veins are intergrown with muscovite of similar character. A sample of course muscovite-pyrite-quartz vein (Fig. 12) derived from bedrock during mining was salvaged from the wash plant. A muscovite separate from this vein yielded a preliminary $^{40}Ar/^{39}Ar$ age of ~160 Ma (A. Camacho, pers. comm., 2016) and efforts to refine this determination are ongoing. Muscovite from the sample of the gold-quartz vein collected from the Otter creek pit for destructive analyses will be evaluated for suitability of dating by the in-situ laser $^{40}Ar/^{39}Ar$ technique.

It seems most likely that gold-quartz veins in the Otter Creek area immediately post-date ~174 Ma deformation and immediately predate, or are broadly synchronous with, cooling of the Fourth of July batholith. The batholith crystallized at ~172 Ma, was cut by comagmatic mafic and then possible lamprophyre dikes with $^{40}Ar/^{39}Ar$ mineral closure ages between ~165 and ~162 Ma (Harris et al., 2003), and cooled through the K-Ar closure temperature of sericite by ~160 Ma (Dawson, 1988 in Breitsprecher and Mortensen, 2004). Establishing the exact relationship of gold-quartz veins with the dikes in Otter Creek and establishing the age of both will be necessary to fully understand lode gold deposition in the Otter Creek valley.

6. Summary and implications for regional exploration

So far, only a single set of quartz veins containing coarse gold has been recorded in bedrock of the Otter Creek valley. From the existing evidence, it seems likely that the phyllite-hosted gold-bearing quartz veins in Otter Creek were emplaced following Jurassic regional deformation, and synchronous to,

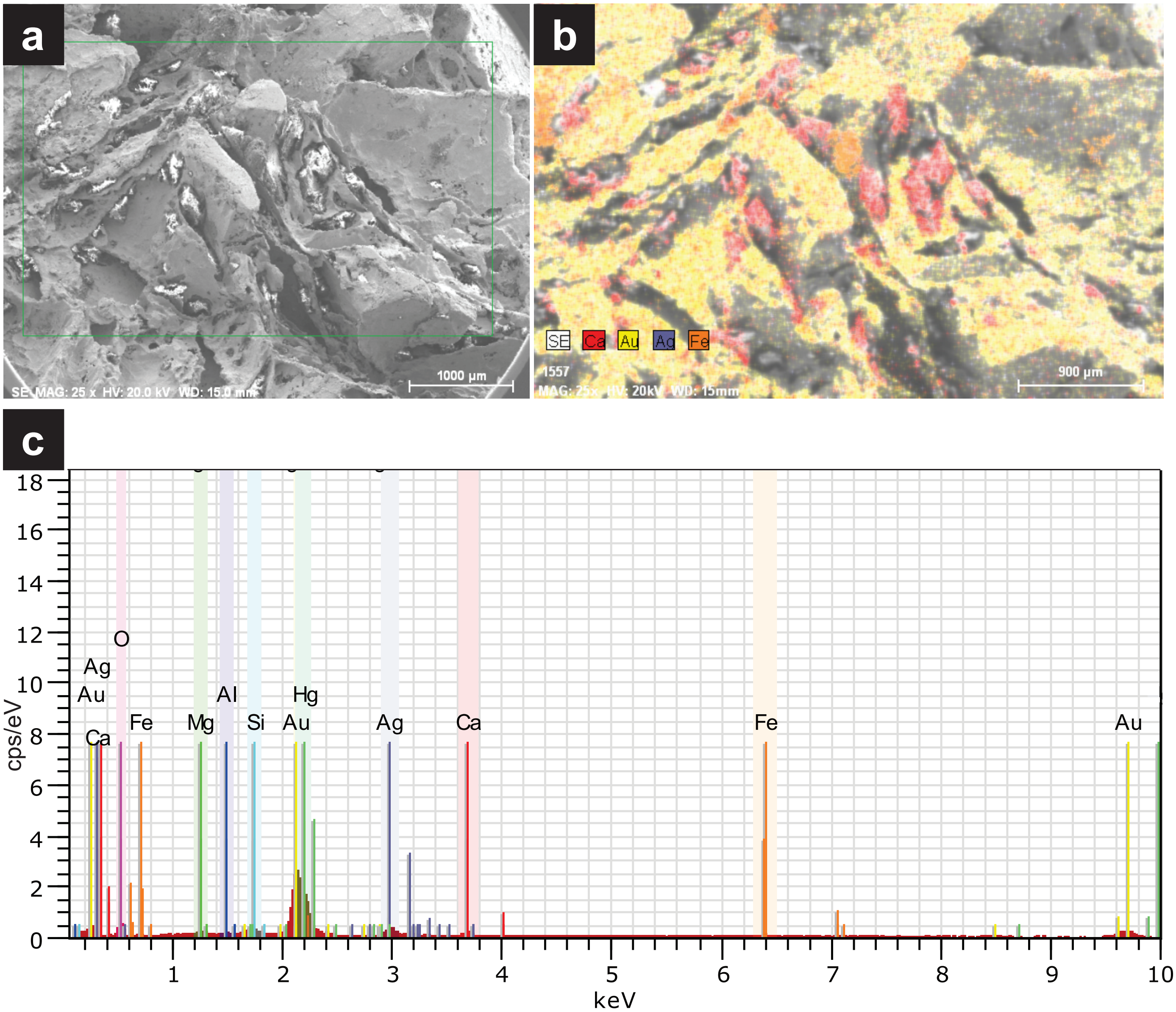

Fig.11. a) Scanning Electron Microscope backscattered electron image of corroded relicts of carbonate grains within gold. **b)** Elemental map of the same surface as shown in a). **c)** Induced X-ray energy spectrum of the area outlined in A, showing calcium, Ca-Kα (characteristic X-rays emitted during transitions from K, L, and M shell induced vacancies are shown), gold, Au-MAB, silver, Ag-Lα, silicon, Si-Kα, aluminum, Al-K, O-K, iron, Fe-Kα, magnesium, Mg-K, and mercury, Hg-Mα counts. All peaks are accounted for. Notable are silver and mercury (Ag, Hg) as impurities in the gold. Accelerating voltage for this analysis was 20.0 kV.

or immediately preceding emplacement of crosscutting dikes that share geochemical characteristics with the Fourth of July batholith and other bodies of the Three Sisters suite (Fig. 8; see Zagorevski et al., 2017). Secondary muscovite in the dikes, gold veins, and unmineralized quartz veins lacks a strongly-preferred orientation. Preliminary $^{40}Ar/^{39}Ar$ data indicate growth of this static muscovite at ca. 160 Ma, which is broadly coeval with cooling age determinations from the Fourth of July Batholith. In terms of phyllitic sedimentary host rocks, the Otter Creek lode occurrence is similar to well-known gold deposits like Maruntau (Uzbekistan) where nearby magmatic rocks may be important (Kempe et al., 2016) or Macraes (New Zealand) where modern noble gas analytical techniques point to metamorphic fluid transport of gold (Goodwin et al., 2016).

Lode gold discovered along Otter Creek is in weakly metamorphosed sedimentary rocks of the Kedahda Formation, one of the most widespread units in the northern Cache Creek terrane. The Otter Creek discovery unequivocally demonstrates that lode gold mineralization is not restricted to zones in, or immediately adjacent to, listwanite-altered ultramafic or mafic rocks, significantly expanding areas near Atlin that are prospective for lode gold exploration.

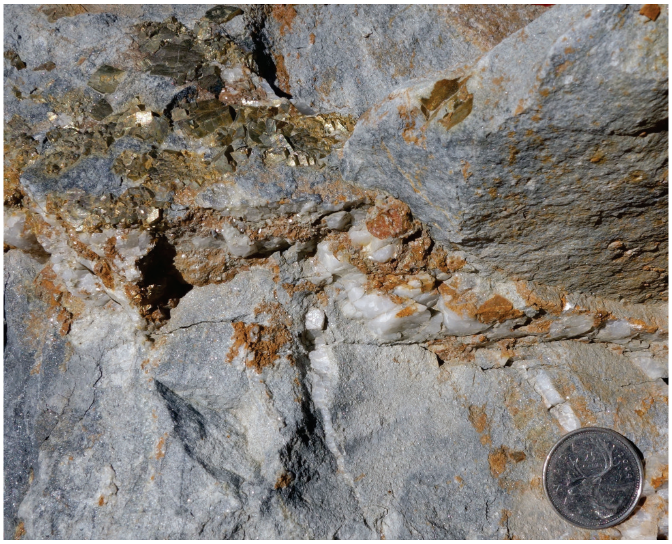

Fig. 12. Sample of quartz and coarse pyrite-muscovite veining in semi-schist from Otter Creek valley bedrock. This bedrock sample was collected from the placer washing plant and a sample of the coarse muscovite was submitted for $^{40}Ar/^{39}Ar$ age determination, yielding a preliminary age of ~160 Ma (see text).

Acknowledgments

Peter Shorts has been a generous supporter of our work, and together with Glen Slonski provided access to the Otter Creek Mining pits in 2015 and 2016, and donated gold-bearing quartz vein materials for destructive analyses. Peter Shorts, Glen Slonski and John Buckle provided editorial comments and clarifications on an earlier draft. Jean Pautler shared a collection of samples from the 2016 Otter Creek Mines pit. Discussions and correspondence with Jeff Kyba were illuminating and appreciated. We thank Atlin placer operators and supporters for their enduring encouragement, tolerance and willingness to share information in the furtherance of lode gold exploration in the region.

References cited

Aitken, J.D., 1959. Atlin map-area, British Columbia. Geological Survey of Canada, Memoir 307, 89p.

Ash, C.H., 1994. Origin and tectonic setting of ophiolitic ultramafic and related rocks in the Atlin area, Northwestern British Columbia. BC Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, Bulletin 94, 140p.

Ash, C.H., 2004. Geology of the Atlin area, northwestern British Columbia. British Columbia Ministry of Energy and Mines, BC Geological Survey, Geoscience Map 2004-4, scale 1:25,000.

Ash, C.H., MacDonald, R.W., and Reynolds, P.R., 2001. Relationship between ophiolites and gold-quartz veins in the North American Cordillera. BC Ministry of Energy and Mines, British Columbia Geological Survey, Bulletin 108, 140p.

BC Geological Survey, 2016. MINFILE Mineral Inventory database. URL < http://minfile.ca/> November, 2016.

Bloodgood, A., Rees, C.J., and Lefebure, D.V., 1989. Geology of the Atlin area (NTS 104N/11W, 12E). BC Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, Open File 1989-15, scale: 1:50,000.

Breitsprecher, K., and Mortensen, J.K., 2004. BCAge 2004A-1- a database of isotopic age determinations for rock units from British Columbia. BC Ministry of Energy and Mines, British Columbia Geological Survey, Open File 2004-03 (Release 2.0), 7766 records, 9.3 Mb.

Browne, P.R.L., and Ellis, A.J., 1970. The Ohaki-Broadlands hydrothermal area, New Zealand; mineralogy and related geochemistry. American Journal of Science, 269, 97-131.

Cairnes, D.D., 1913. Portions of Atlin District, British Columbia: with Special Reference to Lode Mining. Geological Survey of Canada, Memoir 37, 129p.

Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.X., 2013. The ICS International Chronostratigraphic Chart. Episodes, 36, 199-204.

Cui, Y., Miller, D., Nixon, G., and Nelson, J., 2015. British Columbia digital geology. BC Ministry of Energy and Mines, British Columbia Geological Survey, Open File 2015-2.

Debicki, R.L., 1984. An Overview of the Placer Mining Industry in Atlin Mining Division, 1978 to 1982. British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Branch, Paper 1984-2, 21p.

Ferguson, H.G., and Gannett, R.W., 1932. Gold quartz veins of the Alleghany district, California. US Department of the Interior, Geological Survey Professional Paper 172, 139p.

Goodwin, N.R., Burgess, R., Craw, D., Teagle, D.A., and Ballentine, C.J., 2016. Noble gases fingerprint a metasedimentary fluid source in the Macraes orogenic gold deposit, New Zealand. Mineralium Deposita, 1-13. doi:10.1007/s00126-016-0648-x.

Gwillim, J.C., 1901. Atlin mining district. Annual Report 1899, Geological Survey of Canada, Volume 12, 48p. doi:10.4095/294883.

Harris, M.J., Symons, D.T., Blackburn, W.H., Hart, C.J., and Villeneuve, M., 2003. Travels of the Cache Creek Terrane: a paleomagnetic, geobarometric and 40 Ar/39 Ar study of the Jurassic Fourth of July Batholith, Canadian Cordillera. Tectonophysics, 362, 137-159.

Hora, Z.D., Pivec, E., and Langrova, A., 2012. Irarsite (IrAsS), Osarsite (OsAsS) and Gold from Placer Black Sands, Ruby Creek and Wright Creek, Atlin, British Columbia. In: Geological Fieldwork 2011, BC Ministry of Energy, Mines and Petroleum Resources, Paper 2012-1, pp. 11-15.

Kempe, U., Graupner, T., Seltmann, R., de Boorder, H., Dolgopolova, A., and van Emmichoven, M.Z., 2016. The Muruntau gold deposit (Uzbekistan)–A unique ancient hydrothermal system in the southern Tien Shan. Geoscience Frontiers, 7, 495-528.

Le Bas, M.J.L., Maitre, R.W.L., Streckeisen, A., and Zanettin, B., 1986. A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram. Journal of Petrology, 27, 745-750, doi: 10.1093/petrology/27.3.745.

Levson, V.M., Kerr, D.E., Lowe, C., and Blyth, H., 2003. Quaternary geology of the Atlin area, British Columbia; BC Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Branch, Geoscience Map 2003-1 and Geological Survey of Canada, Open File 1562. Scale 1:50,000.

Levson, V.M., 1992. Quaternary Geology of the Atlin area; (104N/11W, 104N/12E). In: Geological Fieldwork 1991, BC Ministry of Energy and Mines, British Columbia Geological Survey Branch, Paper 1992-1, pp. 375-390.

Mihalynuk, M.G., Ambrose, T.K., Devine, F.A.M., and Johnston, S.T., 2011. Atlin placer gold nuggets containing mineral and rock matter: implications for lode gold exploration. In: Geological Fieldwork 2010, BC Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Branch, Paper 2010-1, pp. 56-72.

Mihalynuk, M.G., Erdmer, P., Ghent, E.D., Cordey, F., Archibald, D.A., Friedman, R.M., and Johannson, G.G., 2004. Coherent French Range blueschist: Subduction to exhumation in < 2.5 m.y.? Geological Society of America Bulletin, 116, 910–922, 7-8. doi: 10.1130/b25393.

Mihalynuk, M.G., Mountjoy, K.J., Smith, M.T., Currie, L.D., Gabites, J.E., Tipper, H.W., Orchard, M.J., Poulton, T.P., and Cordey, F., 1999. Geology and mineral resources of the Tagish Lake area (NTS 104M/ 8,9,10E, 15 and 104N/ 12W), Northwestern British Columbia. BC Ministry of Energy and Mines, British Columbia Geological Survey Branch, Bulletin 105, 202p.

Mihalynuk, M.G., Meldrum, D., Sears, S., and Johannson, G., 1995. Geology and mineralization of the Stuhini Creek area (104K/ 11). In: Geological Fieldwork 1994, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1995-1, pp. 321-342.

Monger, J., 1975. Upper Paleozoic rocks of the Atlin Terrane, northwestern British Columbia and south-central Yukon. Paper 74-47, Geological Survey of Canada, Paper 74-47, 73p.

Monger, J.W.H., Price, R.A., and Tempelman-Kluit, D.J., 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera. Geology, 10, 70-75.

Price, B.J., and Dandy, L., 2010. Yellowjacket gold project. 43-101 Technical report prepared for Eagle Plains Resources Ltd. and Prize Mining Corporation, January 27, 2010, 92p.

Robertson, W.F., 1898. Cassiar district. In: Annual report of the Minister of Mines, Province of British Columbia, pp. 985-991.

Sack, P.J., and Mihalynuk, M.G., 2003. Proximal gold cassiterite nuggets and composition of the Feather Creek placer gravels: clues to a lode source near Atlin, BC. In: Geological Fieldwork 2003, BC Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Branch, Paper 2004-1 pp. 147-162.

Shirmohammad, F., Smith, P., Anderson, R., and McNicoll, V., 2011. The Jurassic succession at Lisadele Lake (Tulsequah map area, British Columbia, Canada) and its bearing on the tectonic evolution of the Stikine terrane. Volumina Jurassica, 9, 43-60.

Simmons, S.F., White, N.C., and John, D.A., 2005. Geological characteristics of epithermal precious and base metal deposits. In: Economic Geology 100th Anniversary Volume, Jeffrey W. Hedenquist, John F. H. Thompson, Richard J. Goldfarb, and Jeremy P. Richards (Editors), pp. 485-522.

Simmons, S.F., and Christenson, B.W., 1994. Origins of calcite in a boiling geothermal system. American Journal of Science, 294, 361-400.

Watson, K.D., and Mathews, W.H., 1944. The Tuya-Teslin area, northern British Columbia. British Columbia Department of Mines, Bulletin 19, 52p.

Zagorerevski, A., Mihalynuk, M.G., Joyce, N., and Anderson, R.G., 2017. Late Cretaceous magmatism in the Atlin-Tagish area, northern British Columbia (104M, 104N). In: Geological Fieldwork 2016, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2017-1, this volume.