Paleogene Penticton Group, Boundary area, Southern British Columbia (Parts of NTS 082E): Geochronology and Implications for Precious Metal Mineralization

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Introduction

Paleogene volcanic and sedimentary rocks of the Penticton Group are exposed in numerous localities throughout southern British Columbia (BC), commonly preserved in north-trending structural basins. Regional mapping in the Boundary area in the eastern half of the Penticton map area (NTS 082E), in conjunction with Ar/Ar and U-Pb zircon dating, has helped to constrain the age of the Penticton Group, its relation to extensional tectonics and its control of precious-metal mineralization. This project is a continuation and enhancement of systematic 1:50 000 geological mapping that has resulted in the publication of six maps (Figure 1): Grand Forks (NTS 082E/01), Greenwood (NTS 082E/02), Almond Mountain (NTS 082E/07), Deer Park (NTS 082E/08), Burrell Creek (NTS 082E/09) and Christian Valley (NTS 082E/10). The Boundary area has had an extensive history of exploration and mining, particularly in the Greenwood, Franklin and Beaverdell mining camps, where intermittent production of base and precious metals continued from the late 1880s to the early 1990s. Exploration continues to be active throughout the area, still largely focused on precious-metal targets.

Geology

The Penticton Group in the Boundary area of the Penticton map area (NTS 082E) includes a basal succession of dominantly conglomerate, sandstone, reworked tuff and minor volcanic flows of the Kettle River Formation that unconformably overlies Paleozoic and Triassic metavolcanic rocks and large suites of intrusive rocks of varying ages (Figure 2). The Kettle River Formation is conformably overlain by a thick sequence of dominantly alkalic volcanic rocks and minor sedimentary units of the Marron Formation. Farther west in the White Lake basin area, the Marron Formation is unconformably overlain by basal conglomerate, felsic lava and tuff of the Marama Formation, and interlayered sedimentary and volcanic rocks of the White Lake and Skaha formations (Church, 1973).

Paleozoic basement rocks in the Boundary area have been studied extensively by Massey (2006). In the Greenwood map area (NTS 082E/02; Figure 1), they include poorly dated metavolcanic and metasedimentary rocks, minor gabbro, serpentinite and locally paragneiss of the Carboniferous to Permian Knob Hill complex (Little, 1983; Church, 1986; Fyles, 1990; Massey, 2007). The Attwood Formation comprises mainly Mississippian to Permian metasedimentary rocks; their relationship to the Knob Hill complex is not known as there are no recognized stratigraphic contacts between the units. Farther north and to the east in the Grand Forks map area (NTS 082E/01; Figure 1), Attwood Formation rocks are correlated with the lithologically similar Wallace group or Mount Roberts Formation.

Middle to late Triassic chert breccia, limestone and volcanic ‘greenstone’ of the Brooklyn Formation unconformably overlie the Attwood Formation or Knob Hill Group in the Greenwood area (Little, 1983; Fyles, 1990). Volcanic rocks correlated with the Jurassic Rossland Group are in thrust contact with serpentinites and gabbro, assumed to be part of the Knob Hill complex, in the southern part of the Grand Forks map area (Höy and Jackaman, 2005).

A large part of the Penticton map area is underlain by granitic and alkalic intrusive rocks that have variously been assigned to granodiorite of the ‘Nelson’ plutonic complex, granite of the Okanagan batholith or Coryell syenite (Tempelman-Kluit, 1989; Höy and Jackaman, 2019; Höy et al., 2020). Locally, the Penticton Group unconformably overlies Triassic to Jurassic Nelson intrusions and in the Almond Mountain map area (NTS 082E/07; Figure 1), a

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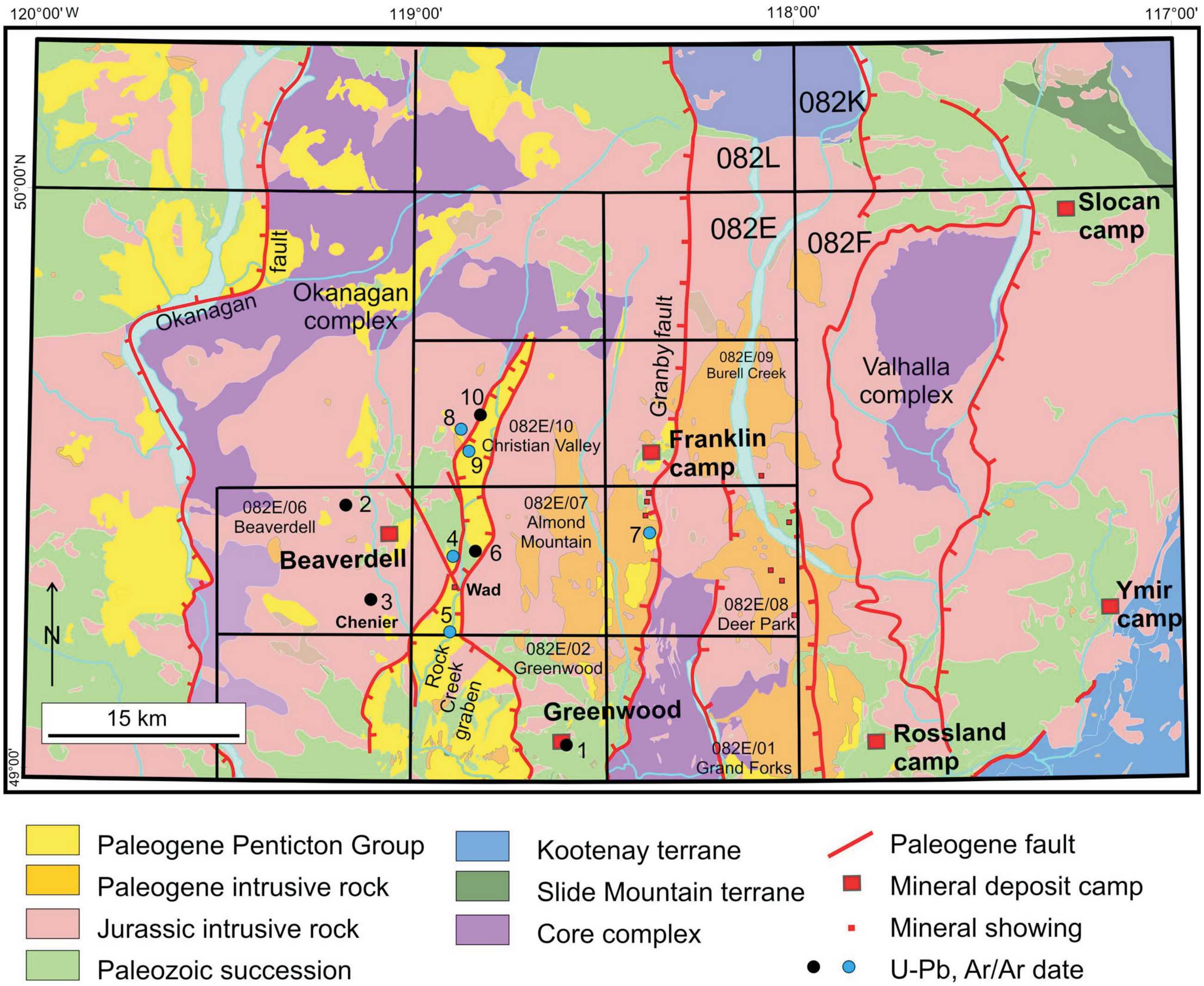

Figure 1. Regional terrane map of the Boundary area of southern British Columbia, showing location of major deposit camps, mineral occurrences discussed in this paper, and samples (numbered 1–10) collected for Ar/Ar and U-Pb dating.

Paleocene granite that has been informally named the 'Taurus Creek stock' (Höy and Jackaman, 2016). Dikes and small stocks of the Paleocene to Eocene Okanagan batholith and Eocene Coryell syenite locally intrude the Penticton Group, which helps constrain the age of these rocks.

The Kallis Formation (Figure 2) is preserved in isolated topographic highs throughout the area, unconformably overlying either the Penticton Group or intrusive rocks. It represents the remains of widespread Miocene–Pliocene plateau basalts.

Penticton Group

The Penticton Group is exposed mainly within the north-trending Rock Creek graben, shown on the western part of the Penticton east-half map area, in the northern extension of the Republic graben in the Greenwood area and farther north in the western part of the Deer Park map area (NTS 082E/08; Figure 1; Tempelman-Kluit, 1989; Höy and Jackaman, 2019). The widespread distribution of the Penticton Group rocks and correlations are described by Church (1973), who inferred that they represented the erosional remnants of a continuous belt of dominantly volcanic rocks that extended across southern BC and the northern State of Washington. Alternatively, the distribution of basal Penticton Group rocks, particularly the Marron Formation, may be considerably more limited, largely restricted to the fault-bounded, north-trending grabens.

Kettle River Formation

The Kettle River Formation is the dominantly sedimentary succession that overlies basement rocks, extending upward into a generally conformable contact with alkalic volcanic rocks of the Marron Formation. It has been described in considerable detail by Monger (1968), Little (1983) and

Fyles (1990), and the following description is based largely on these works.

The formation includes pale grey to buff feldspathic sandstone, grey to green-tinged volcanic sandstone and conglomerate, and locally felsic crystal-lithic tuff. The conglomerates occur at several stratigraphic levels but the thickest and coarsest are generally at the base of the formation. Clasts, locally to several tens of centimetres in diameter, are generally composed of local volcanic and chert fragments of the Paleozoic basement, granite and granodiorite of the Nelson plutonic complex and, in the Rock Creek graben, clasts and broken crystals of the immediately underlying Paleocene Taurus Lake granite.

Volcanic rocks are a minor component of the Kettle River formation but include dacitic crystal-lithic tuffs comprising lithic fragments, euhedral feldspar crystals, pyroxene and quartz. Locally, white to pink porphyritic dacite with phenocrysts of plagioclase, orthoclase and rounded quartz in a light green aphanitic matrix also occur, generally near the upper contact with the Marron Formation.

Correlation

The Kettle River Formation correlates with the contiguous O'Brien Formation in the Republic District, Washington (Pearson and Obradovich, 1977), and with the Springbrook Formation in the White Lake basin, 90 km northwest of Greenwood (Church, 1973, 1986).

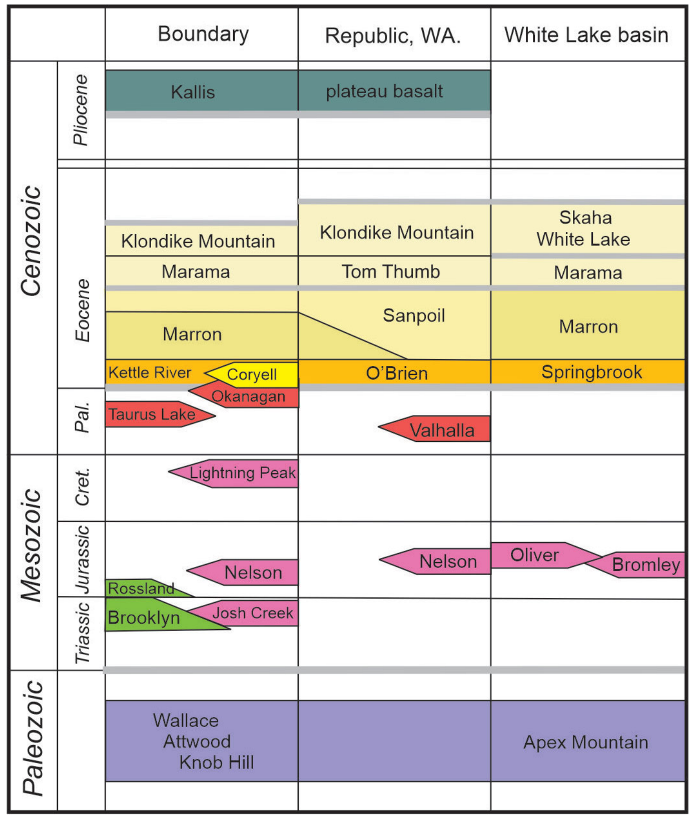

Figure 2. Schematic stratigraphy of the Boundary area, and correlations with the Republic District in the State of Washington (Cheney, 1994, 1998) and the White Lake basin (Church, 1973) area. Abbreviations: Cret., Cretaceous; Pal., Paleocene.

Age

Numerous plant fossils and spores from the Kettle River Formation have been identified as ranging in age from Paleocene to Eocene (e.g., Rouse and Mathews, 1961). Potassium-argon dating of dacite has returned a range of ages, from 53.1 ±1.5 Ma (Pearson and Obradovich, 1977) to 46.2 ±2 Ma (Mathews, 1963).

Three samples of the Kettle River Formation were submitted to the Pacific Centre for Isotopic and Geochemical Research (PCIGR) for U-Pb zircon dating (Figure 1, Table 1). Petrographic descriptions of these samples are not yet completed and, hence, the following descriptions are based on field observations.

Table 1. Summary of U-Pb zircon and Ar^{40}/Ar^{39} mineral ages obtained for selected samples of intrusive and Penticton Group rocks collected during mapping in the Boundary area; more complete sets of the data have also been studied (Höy et al., 2019; T. Höy, J. Gabites and R. Friedman, work in progress). Abbreviations: Bi, biotite; Ksp, K-feldspar; WR, whole rock; Zr, zircon.

No.	Sample	Easting	Northing	NTS map area	Unit	Rock type	Method	Age	Error
1	H20-60	383577	5438992	082E/02 Greenwood	Kettle River	crystal-lithic tuff	U-Pb Zr	50.80	0.49
2	H19-149	344974	5482539	082E/06 Beaverdell	Marama	trachyte	U-Pb Zr	48.88	0.44
3	H20-09	344093	5464081	082E/06 Beaverdell	Kettle River	crystal-lithic tuff	U-Pb Zr	51.45	0.47
4	AM-470	361491	5471677	082E/07 Almond Mountain	Marron	basalt	Ar/Ar Ksp	57.80	2.10
5	AM-557	361478	5457103	082E/07 Almond Mountain	Marron	andesite	Ar/Ar Ksp	59.22	0.83
6	H20-59	366290	5471486	082E/07 Almond Mountain	Kettle River	tuffaceous sandstone	U-Pb Zr	51.50	0.44
7	H19-26	399631	5475801	082E/08 Deer Park	Marron	alkali basalt	Ar/Ar Ksp	53.22	0.79
8	CV-41	364772	5497380	082E/10 Christian Valley	Marron	lava or possible dike	Ar/Ar WR	50.60	0.90
9	CV-159	365992	5491657	082E/10 Christian Valley	Marron	mafic lava	Ar/Ar Bi	52.77	0.38
10	CV-294	368478	5498093	082E/10 Christian Valley	dike(?)	andesite dike	U-Pb Zr	49.40	0.77

Sample H20-60: Greenwood

Sample H20-60 (no. 1 on Figure 1) is a vaguely layered, medium to fine-grained, light grey volcanic sandstone or reworked tuff from the Phoenix deposit pit near Greenwood (Figures 3, 4). It contains dominantly feldspar and quartz crystals and small, generally dark, lithic fragments. It is within a succession of massive to layered siltstone, sandstone, grit, conglomerate and dacitic tuff, approximately 80 m in thickness, that is bracketed by unconformably underlying Paleozoic basement and overlying Marron Formation volcanic rocks. Plant fossils are common in the succession. The sample was collected from a pit wall, several tens of metres above the base of the formation.

The weighted $^{207}Pb/^{206}Pb$ average of 12 zircon grains yielded a date of 50.80 ±0.49 Ma (Table 1) and is assumed to record the age of extrusion of the dacitic tuff. Other dates obtained from individual zircons range from ca. 87 to 65 Ma and may record inclusion of detrital grains from underlying granitic rocks.

Sample H20-59: Lost Horse Creek

Sample H20-59 (no. 6 on Figure 1) is from a thick succession of bedded to massive conglomerate, quartzite, siltstone, minor shale and minor tuff that unconformably overlies late Paleozoic Wallace group volcanics and is overlain by Marron Formation. The sample is a massive to vaguely bedded light grey, green-tinged crystal-lithic tuff or tuffaceous sandstone, comprising mainly light grey and pink-tinged feldspar, quartz and dark (volcanic) lithic fragments.

The weighted $^{206}Pb/^{238}U$ average of 15 zircons gave a date of 51.50 ±0.44 Ma (Table 1) and is assumed to record the depositional age of dacitic tuff within the Kettle River Formation. Other probable detrital zircon dates may reflect the ages of underlying lower Jurassic, Cretaceous and Paleogene granitic rocks.

Sample H20-09: Chenier Creek

Sample H20-09 (no. 3 on Figure 1) is from a succession of conglomerate, breccia, volcanic flows and tuff that unconformably overlies Middle Jurassic granite, probable Paleocene granite and minor Paleozoic metasedimentary rocks in the Kelly River area, approximately 30 km north of Rock Creek. Mineral exploration in the immediate vicinity has been directed toward a porphyry copper-gold prospect, the Chenier or CuAu property (Höy, 2007; Thompson et al., 2018), and the following description of the Kettle River Formation is largely taken from the cited reports. Crystal-lithic tuff, in part interlayered with polymictic breccia and conglomerate, occurs at the base of the succession immediately overlying Jurassic granodiorite. The conglomerate comprises numerous angular to rounded fragments of dominantly granite or granodiorite and dark fragments of either mafic volcanic rocks or dikes. The crystal-lithic units comprise mainly broken feldspar crystals, quartz and lithic granite fragments. Feldspar (±pyroxene) flows, interlayered with tuff and breccia, locally overlie the basal succession. Massive conglomerate, consisting mainly of granitic clasts and occasional dark fragments, interlayered with volcanic sandstone, may represent a lateral facies change of

Figure 3. Phoenix deposit pit near Greenwood, British Columbia; sample H20-60 was taken from the pit wall at the far end of the lower bench.

Figure 4. Well-bedded, reworked Kettle River Formation felsic tuff and tuffaceous sandstone from the Phoenix deposit pit near Greenwood, British Columbia.

the crystal-lithic tuffs and breccia units (Thompson et al., 2018, p 56). The dated sample (H20-09) is from a poorly bedded, medium-grained crystal-lithic tuff that contains mainly white feldspar, quartz and minor biotite (Figure 5). It is lithologically similar to the other dated samples of the Kettle River Formation.

The weighted ^{206}Pb/^{238}U average of 18 zircons returned a date of 51.45 ±0.47 Ma (Table 1) and is assumed to record the depositional age of dacitic tuff on the Chenier property. Numerous other zircon grains range in age up to ca. 70 Ma and reflect the age of underlying Paleogene granitic rocks. However, the only dated intrusion in the immediate vicinity, 1.2 km east of the Kettle River contact, is Middle Jurassic in age.

Marron Formation

The Marron Formation was first defined by Bostock (1941) as an early Tertiary[1] volcanic succession in the Okanagan area, southwest of the town of Penticton. Church (1973) defined a type section in that area, and Monger (1968) and Little (1983) subsequently applied the terminology to correlative rocks in the southern part of the Penticton map area (NTS 082E), a succession previously referred to as the 'Midway Volcanic Group' (Daly, 1912) or the 'Phoenix Volcanic Group' (Little, 1957). The Marron Formation in the Greenwood map area (NTS 082E/02) has been mapped and subdivided by Monger (1968) and Little (1983) but little work other than regional (1:50 000 scale) mapping has been done farther north in the Penticton map area.

The Marron Formation unconformably overlies the Kettle River Formation and is locally overlain by Miocene plateau basalts of the Kallis Formation. In the Greenwood area, it has been subdivided into three informal divisions: a lower division comprising dominantly rhomb-porphyry soda trachyte and phonolite; a middle division comprising pyroxene andesite and trachyandesite; and an upper division comprising mainly andesite (Monger, 1968; Little, 1983). These subdivisions are not readily apparent farther north, perhaps due to lack of detailed mapping. The thickness of the exposed Marron Formation varies considerably, from locally less than 100 m in the Greenwood area in the south to 900–1800 m farther west in the Rock Creek graben. The original thicknesses of the formation are not known, as the upper limit is often either an erosional surface or, as in the Greenwood area, a faulted contact.

[1] *'Tertiary' is a historical term. The International Commission on Stratigraphy recommends using 'Paleogene' (comprising the Paleocene to Oligocene epochs) and 'Neogene' (comprising the Miocene and Pliocene epochs). The author used the term 'Tertiary' because it was used in the source material for this paper.*

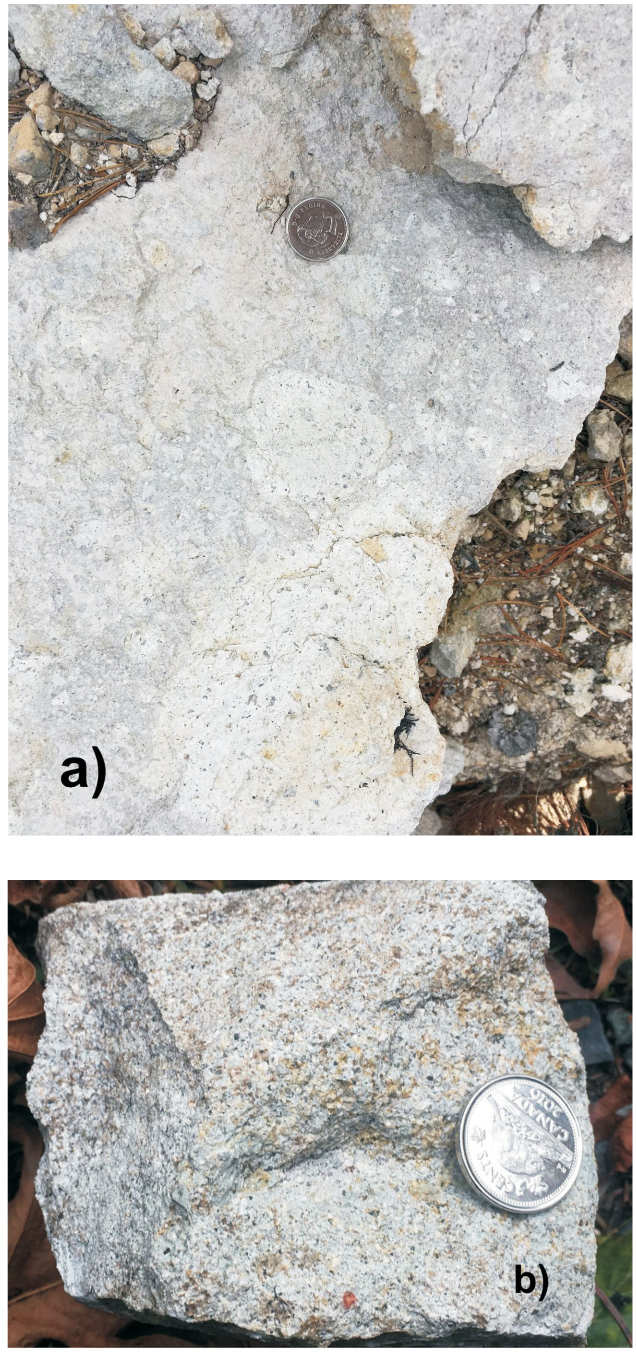

Figure 5. Kettle River Formation lapilli tuff **(a)** and sampled quartz-crystal lapilli tuff **(b)** from the Chenier property, south of Beaverdell.

Correlation

Based on gross lithological similarities, Church (1973, 1986) correlated the Marron Formation in the White Lake basin area with the exposed sections of Marron Formation in the Greenwood map area. Although it is difficult to correlate individual members of the type White Lake basin section with those in the Penticton area, both Church (1973) and Little (1983) suggested that the basal Yellow Lake member correlated with the lower division in the

Greenwood area; the Kitley Lake, Kearns Creek and Nimpit Lake members correlated with the middle division; and the Park Rill member, with the upper division in the Greenwood area. Direct correlations with sections immediately south in the Republic District, Washington, are also difficult. Pearson and Obradovich (1977) and Cheney (1994, 1998) suggested that the Sanpoil volcanics correlated with the lithologically similar Park Rill member in the White Lake basin and the upper division of the Marron Formation in the Penticton map area (Figure 2).

Age

The Marron Formation, and correlative rocks, are generally poorly dated. In the Penticton map area, the formation is underlain by the middle Eocene (ca. 52–51 Ma) Kettle River Formation and locally overlain by the Miocene–Pliocene (ca. 6–4 Ma) Kallis Formation. Several K-Ar mineral dates of volcanic rocks in the Marron Formation range from ca. 49–48 Ma in the Greenwood area (Mathews, 1964) to 51.6 ±1.8 Ma in the White Lake basin (Church, 1973). Pearson and Obradovich (1977) obtained 13 K-Ar mineral dates from samples of Sanpoil volcanics that range from 53.4 ±2.0 Ma to 48.4 ±3.0.

Four samples of the Marron Formation have been analyzed at the PCIGR:

- Sample AM-470 (no. 4 on Figure 1), a medium grey, amygdaloidal alkali andesite with minor disseminated biotite and hornblende and small euhedral plagioclase grains, was collected near the base of the formation, on a paleotectonic high within the north-trending Rock Creek graben (Höy and Jackaman, 2016); an Ar/Ar plateau age of 57.8 ±2.1 Ma was determined on K-feldspar (Table 1).
- Sample AM-557 (no. 5 on Figure 1), a sample of light grey plagioclase-phyric porphyritic andesite with minor disseminated biotite in a fine-grained matrix, was collected from a roadcut near the base of the Marron Formation in the Rock Creek graben along the Christian Valley road, 10 km north of Westbridge; an Ar/Ar plateau age of 59.22 ±0.83 Ma was determined on K-feldspar (Table 1).
- Sample CV-41 (no. 8 on Figure 1) was sampled from a small exposure of altered, pale grey crowded feldspar porphyry located 1 km northwest of Little Sandrift Lake (Höy and Jackaman, 2017) and is associated with either a Marron dike or an outcrop of Marron Formation that overlies Paleocene granite; an Ar/Ar plateau age of 53.8 ±1.8 Ma was determined on feldspar and the whole rock produced a plateau age of 50.6 ±0.9 Ma (Table 1).
- Sample CV-159 (no. 9 on Figure 1), a black, fine-grained amygdaloidal basalt flow unit located in the upper member of the Marron Formation near the centre of the Rock Creek graben, was petrographically analyzed and the results indicate it is a biotite-clinopyroxene trachyte lava, with approximately 5% disseminated biotite and 3–5% plagioclase phenocrysts (Höy et al., 2019); an Ar/Ar plateau age of 52.77 ±0.38 Ma was determined on biotite (Table 1).

Discussion on the Radiometric Dating

The plateau Ar/Ar dates determined for three of the known Marron Formation flows cannot be reconciled with the younger U-Pb zircon ages of the underlying Kettle River Formation. There is no petrographic evidence to suggest that the biotites or feldspars used for the radiometric dating are xenocrystic or detrital grains. However, analyses of the oldest feldspars revealed they contained extremely low volumes of ^{39}Ar (K) which could lead to spurious older ages. The age of the Marron is therefore assumed to be bracketed by the ca. 51.5 Ma age of the underlying Kettle River formation and the age of overlying Marama Formation, ca. 48.9 Ma (see below).

Marama Formation

The Marama Formation is defined as a succession of dominantly rhyolitic and rhyodacitic rocks that unconformably overlie the Marron Formation in the White Lake basin (Church, 1973). The formation comprises basal "conglomerate, minor sandstone and shale with seams of pyroclastic rocks throughout" (Church, 1973, p. 40). These are overlain by rhyolite breccia and pyroclastic deposits, and capped by thick rhyodacite lavas. The Marama Formation is unconformably overlain by stream and lake deposits interlayered with trachyte and trachyandesites of the White Lake Formation, and dominantly slide breccias, conglomerate and lava flows of the Skaha formation, which are the youngest Paleogene deposits in the White Lake basin (Church, 1973).

The Marama Formation has been correlated with the upper part of the Sanpoil Formation in the Toroda Creek graben in Washington, south of Greenwood (Church, 1973; Pearson and Obradovich, 1977). However, it is lithologically similar to rhyolitic and rhyodacitic rocks of the Tom Thumb member, which forms the basal part of the Klondike Mountain Formation that overlies the Sanpoil in northern Washington. Both units unconformably overlie correlative Marron and Sanpoil formations, contain distinctive interbedded rhyolitic and dacitic tuffs and shales, and locally contain abundant plant fossil remains. Hence, a correlation of the Marama Formation with the Tom Thumb member is preferred (Figure 2), with the overlying White Lake and Skaha formations correlating with middle and upper divisions of the Klondike Mountain Formation (Cheney, 1994, 1998).

The Marama Formation has not been recognized previously in the Boundary area. However, Little (1983) described an epiclastic breccia-tuff succession south of Greenwood that he correlated with the Klondike Mountain

Formation; subsequently, Fyles (1990) included this unit in the Marron Formation. Reconnaissance geological mapping west of Beaverdell has recognized a distinctive tuff succession that unconformably overlies Paleocene granite and Paleozoic metavolcanics; based in part on similar rock types and a U-Pb zircon date, this unit has been tentatively correlated with the Marama Formation, or possibly the overlying White Lake Formation.

Age

The Marama Formation is clearly younger than the underlying Kettle River (ca. 51.5 Ma) and Marron formations. Klondike Mountain Formation rock samples have yielded several K-Ar mineral dates that range from 49.1 to 41.3 Ma, with a mean age of ca. 46 Ma, which is assumed to be the age of the middle member of the formation (Pearson and Obradovich, 1977). However, due to possible inherent Ar loss, older K-Ar dates are considered more reliable and hence the ca. 49.1 Ma date may more closely reflect the age of the Klondike Mountain Formation.

Sample H19-149: Beaverdell

A poorly exposed succession of dacitic to trachytic tuff, unconformably overlying Paleocene granite and Paleozoic metavolcanics was recognized west of Beaverdell during reconnaissance mapping in 2019 (no. 2 on Figure 1). It is lithologically similar to some phases of the Klondike Mountain Formation and to the Marama Formation, although the latter is typically more felsic.

A sample of the bedded trachytic tuff (Figure 6), taken from a large angular block directly downslope from surface exposures, was dated at The University of British Columbia. The weighted $^{206}Pb/^{238}U$ average of 19 zircons gave a date of 48.8 ±0.44 Ma (Table 1), with a fairly wide scatter of older dates to ca. 53 Ma. The date is close to the average K-Ar mineral date of the Klondike Mountain Formation, in contrast to the older dates of the basal Kettle River Formation. Hence, this exposure is considered the first evidence of post-Marron volcanism in the Boundary area.

Figure 6. Sample of poorly bedded to massive trachytic tuff (no. 2 on Figure 1, Table 1), taken immediately downslope from similar tuff of the Marama(?) Formation northeast of Beaverdell.

Eocene Dike

Regional mapping throughout the Boundary area has recognized numerous suites of dominantly alkalic dikes. Many of these are assumed to be comagmatic with, and similar to, the Marron Formation, and commonly intrude lower stratigraphic levels of the formation.

In the eastern part of the Christian Valley map area (NTS 082E/10; Höy and DeFields, 2017) the western margin of the Rock Creek graben is characterized locally by several fault splays marked by shearing, brecciation and alteration (Figure 7). In one of these exposures (Figure 8), highly broken and sheared Eocene(?) granite containing

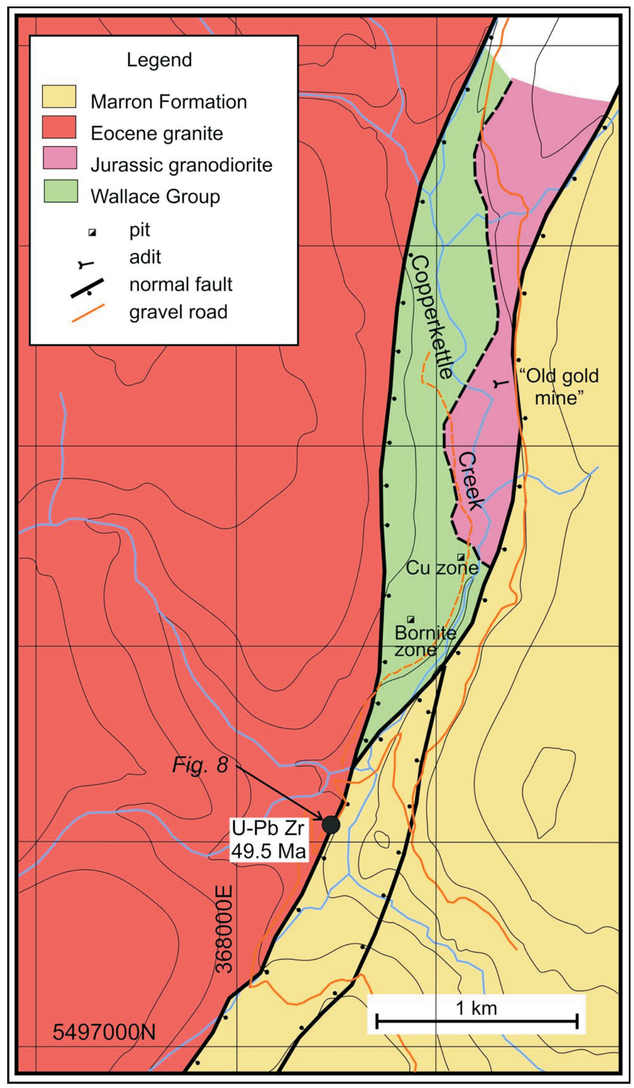

Figure 7. Geology of the western margin of the Rock Creek graben in the Boundary area, showing fault splays and location of chalcopyrite-galena-gold vein and skarn mineralization of the Copket property (location of the Eocene(?) dike, sample CV-294 and Figure 8 are also shown). Map modified from Whiting (1991) and Höy and DeFields (2017).

blocks of crushed Wallace group, is cut by a fresh, unaltered north-trending hornblende-porphyry dike. A U-Pb zircon date on the dike constrains the timing of movement along this fault splay to predate 49.4 ±0.77 Ma (sample CV-294; no. 10 on Table 1).

Penticton Group: Depositional Controls

The Penticton Group in the Boundary area is mainly exposed in the northern extension of the Republic graben north of Greenwood and in the Rock Creek graben, which is the northern extension of the Toroda Creek graben. Several studies have either stated or implied that the Penticton Group extended over a large part of southern BC and northern Washington, and its present distribution is due largely to its preservation in postdepositional downdropped fault blocks.

However, considerable evidence exists for syndeposition of the Kettle River and Marron formations during extension, and within, the grabens. The basal Kettle River Formation is considerably coarser and thicker in exposures within the graben than it is in the few exposures both to the west, at the Chenier deposit area (Figure 1), and in a crosscutting northwest-trending paleotectonic high, in the Rock Creek graben. Furthermore, the total thickness of the Marron Formation exceeds 1800 m in the Rock Creek graben (Little, 1983) in contrast to a few tens of metres at the Chenier and Wad deposit areas (see below). Northwest of Beaverdell, the Kettle River and Marron formations are missing, and 'basement' granite is unconformably overlain by tuff and tuffaceous sands of the Marama or Klondike Mountain formations. It is possible, but unlikely, that these older formations were eroded away prior to deposition of the Marama Formation, though this in itself would be evidence of considerable vertical movements during Penticton Group deposition.

The Marron Formation is geochemically similar in all downdropped blocks throughout the Okanagan and Boundary areas and northern Washington. This evidence further supports a model according to which "these deposits occur as scattered erosional remnants of what was probably a once continuous belt composed mainly of volcanic rocks extending from at least central Washington through the Interior to central British Columbia" (Church, 1973, p. 17). However, individual members within the well-recognized succession in the White Lake basin (Church, 1973) do not match those in the Marron Formation in the Rock Creek graben, nor those in the Sanpoil Formation of Washington.

Growth faulting along the western margin of the Rock Creek graben is constrained by the age of the basal Kettle River Formation at ca. 51.5 Ma. As the graben faults cut both the Marron and Kettle River formations, movement must also clearly postdate deposition of these rocks. The age of the post-fault, crosscutting dike at ca. 49.4 Ma constrains the timing of fault movement along the western margin of the graben, thereby limiting deposition of the Kettle River and Marron formations to a few million years (Figure 9). This supports the contention of Bardoux and Irving (1989) that all but the lower beds of the Marron Formation were deposited in a limited period of normal geomagnetic polarity between 51.5 and 50.5 Ma. There is little record of Penticton Group rocks on the upthrown blocks, though thinned successions may have been largely eroded during continued movement along these extensional faults. Therefore, the Marama Formation or younger Penticton Group rocks may have formed a more extensive, regional cover over both the graben fill and the marginal highlands.

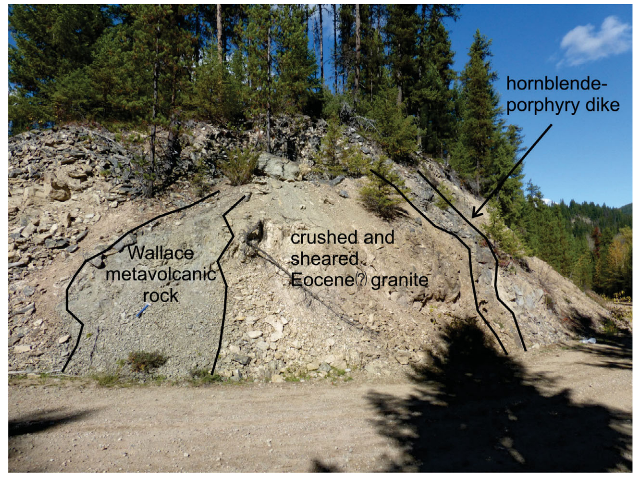

Figure 8. Crushed and altered Eocene(?) granite in the fault along the western margin of the Rock Creek graben in the Boundary area, containing blocks of altered and sheared Paleozoic Wallace group and cut by a fresh, unaltered hornblende dike. The age of the dike (ca. 49.4 Ma) constrains the timing of the latest movement along this splay of the fault (location shown on Figures 1 and 7).

In the northern extension of the Republic graben, the basal Kettle River Formation in the Phoenix deposit pit near Greenwood may be slightly younger at 50.8 ±0.49 Ma. Farther north, within the projected northern extension of the graben, large exposures of undifferentiated Penticton Group appear to unconformably overlie Coryell syenite (Tempelman-Kluit, 1989), dated at 51.1 Ma (Carr and Parkinson, 1989). This contrasts with small, higher level Coryell dikes in the Rock Creek graben that intrude Marron Formation rocks (Höy and Jackaman, 2016) and support a model of essentially contemporaneous intrusion of Coryell syenite with extrusion of Marron Formation volcanic rocks and graben development (Figure 9).

Grabens formed in a zone of regional extension in the hangingwall of the Granby fault, a relatively low-angle crustal structure that separates high-grade Proterozoic metamorphic rocks of the Grand Forks complex in the east (Preto, 1970) from lower grade Paleozoic to Eocene rocks in its hangingwall to the west (Tempelman-Kluit and Par-

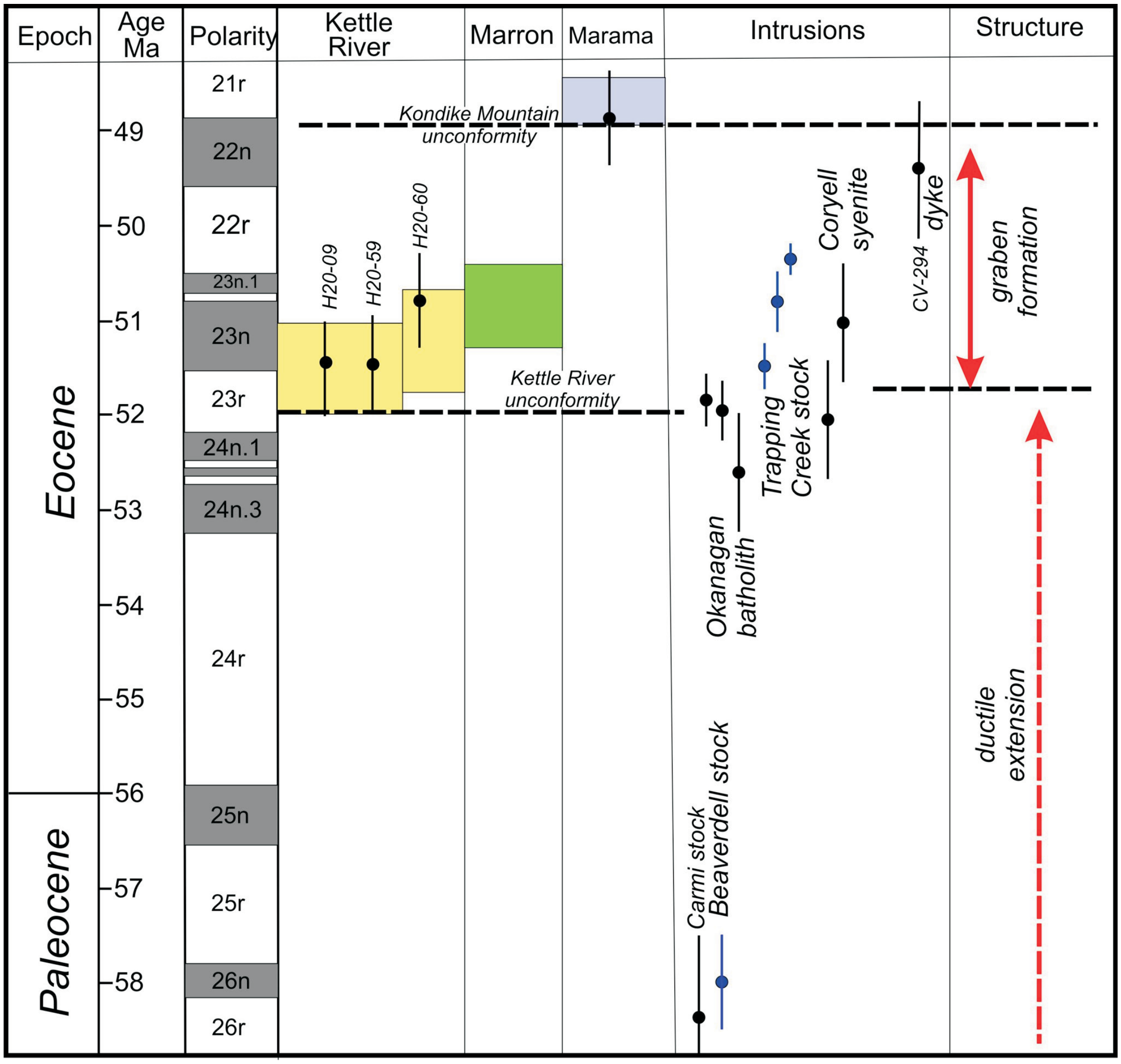

Figure 9. Geochronological chart of the Paleocene and Eocene Penticton Group and intrusions in the Boundary area, showing geochronology discussed in the text and geomagnetic polarities (after Wingate and Irvine, 1994). Note that the entire Kettle River and Marron formations were deposited in the developing grabens between ca. 51.5 and 49.5 Ma (intrusion ages from Höy et al., 2019).

kinson, 1986; Tempelman-Kluit, 1989). The Granby fault cuts Coryell syenite, dated at ca. 51.1 Ma (Carr and Parkinson, 1989), but is locally cut by Coryell dikes (Laberge and Pattison, 2007), which lends support to movement in the area continuing up to ca. 50 Ma (Parrish et al., 1988). Based on evidence from paleomagnetic data, Wingate and Irving (1994) argued that motion along the Granby fault began at or after 50.6 Ma and that motion along this and other extensional faults was limited to 'short intervals' of 1 to 2 million years. However, a number of regional studies indicate that extension and exhumation occurred over approximately 12 million years, from ca. 61 to 49 Ma (Kruckenberg et al., 2008) with early ductile movements and associated formation of migmatite and granite melts, followed by late, more brittle extensional faulting at higher structural levels. Based on Ar^{40}/Ar^{39} analyses of biotite and titanite in the Okanogan dome, Washington, Kruckenberg et al. (2008) determined that rapid cooling of leucosome pegmatites from ca. 51 to 47 Ma was related to rapid exhumation during graben formation.

Eocene Epithermal Mineralization

More than 2.5 million ounces of gold have been produced from Eocene low-sulphidation epithermal veins in the Republic and Curlew areas of Washington, less than 20 km south of Greenwood (Lasmanis, 1966; Muessig, 1967). The Greenwood area has seen an extended period of exploration and mining dating back to the 1880s, and much of this work is described by Peatfield (1978), Church (1986) and Fyles (1990). Recent exploration in the camp is described in numerous industry assessment reports, including summaries by Dufresne (2015) and Caron (2016). This paper is intended to highlight the potential for discovery of epithermal deposits in Eocene volcanic rocks in the Boundary area north of Greenwood.

Most of the production from epithermal deposits in the Republic and Curlew areas are from a paleohorizon in the basal part of the Klondike Mountain Formation. However, as noted by Caron (2016), this paleosurface can cut down into and bevel any underlying stratigraphic horizon and, hence, epithermal mineralization can form in any host, including the Sanpoil, Marron or Kettle River formations, or in the underlying granitic rocks. Furthermore, examples of epithermal mineralization in Kettle River rocks that are overlain by Marron Formation imply mineralization is also related to the Kettle River paleosurface (L. Caron, pers. comm., 2020).

Two factors enhance the potential for discovery of epithermal mineralization in the Boundary area north of the Greenwood mining camp:

- recognition that the Marama or Klondike Mountain stratigraphy is locally present
- recognition that the basal Kettle River formation may also control epithermal mineralization

Klondike Mountain Formation Target Areas

There is little evidence of Klondike Mountain stratigraphy in the Boundary area north of the United States border. Little (1983) mapped some heterogeneous nonvolcanic epiclastic breccia south of Greenwood as Klondike Mountain but, subsequently, Fyles (1990) included these in the Marron Formation. Caron (2016) also suggested that some exposures with epithermal-style mineralization in the Marsh Creek area west of Midway, may be Klondike Mountain Formation. Farther north, northwest of Beaverdell, a succession of dacitic to trachytic tuff, similar to some exposures of either Marama, Klondike Mountain or Kettle River formations, unconformably overlies Eocene granite and Paleozoic metavolcanic rocks. There is no immediately underlying or overlying volcanic stratigraphy to constrain the age of the horizon. However, the U-Pb zircon age of 48.9 Ma (sample H19-149; no. 2 on Figure 1) defines this succession as part of the Marama Formation (or Klondike Mountain Formation), and possibly correlative with the Tom Thumb tuff member.

The age, or correlation, of other similar horizons throughout the Boundary area, characterized by basal conglomerate and felsic tuff or rhyolite, is generally not known. At the recently discovered Wad epithermal gold showing (Murton, 2020), tuffaceous sandstone and felsic tuff that unconformably overlie Eocene megacrystic granite may be equivalent in age to either the Kettle River or Marama formations (see below). Farther north, several other Eocene basins contain felsic tuff and rhyolite, and generally their age or stratigraphic position is not well established (e.g., Tempelman-Kluit, 1983; Okulitch, 2013). These and other horizons have been variously and successfully explored for epithermal mineralization (e.g., Lenard, 1996; Caron, 2015).

Kettle River Host

Several occurrences of epithermal precious-metal deposits are documented in the Greenwood camp (e.g., Dufresne, 2015; Caron, 2016) and farther north in the Franklin camp (Caron, 2005). Recently, a low-sulphidation epithermal-gold occurrence, the Wad property, was discovered in rocks correlated with the Kettle River Formation in the central part of the Rock Creek graben, approximately 30 km north of Rock Creek (Murton, 2020).

Hostrocks on the Wad property are mainly highly altered tuffaceous sandstone, felsic tuff, trachyte and trachyte breccia that have been mapped as Kettle River Formation (Höy and Jackaman, 2016) but which could possibly be correlated with the younger Tom Thumb member of the Klondike Mountain Formation, as suggested by Murton (2020). These rocks unconformably overlie Taurus Lake megacrystic granite dated at ca. 67–63 Ma (Höy et al., 2019) and are unconformably overlain by basalt of the Miocene Kallis Formation. The deposit is within a northwest-trending, fault-bounded paleohigh that crosses the western margin of the Rock Creek graben (Höy and Jackaman, 2016).

At the Wad property, a zone of intense alteration, with carbonate (calcite), drusy quartz and chalcedony, adularia and possibly alunite, occurs within breccias over a strike length of approximately 1 km, with anomalous values of gold ranging up to 2.4 g/t (Murton, 2020).

Summary

The basal part of the Eocene Penticton Group, the Kettle River and Marron formations, was deposited mainly in the north-trending Rock Creek graben and along the northern inferred extension of the Republic graben over a relatively short time period, from ca. 51.5 to 49.5 Ma. Graben development initiated in the hangingwall of the Granby fault, along with deposition of basal Kettle River conglomerate, sandstone and locally felsic tuff, after an extended period of regional ductile extension and magma generation lasting 10 to 12 million years.

Marama Formation conglomerate, sandstone and felsic to alkalic tuff unconformably overlie Marron formation rocks in several locations north and west of the Boundary area. Exposures of Marama trachytic tuff northwest of Beaverdell and west of the Rock Creek graben are similar in age (48.9 Ma) and are correlated with the basal part of the Klondike Mountain Formation in Washington. Northwest of Beaverdell, the Marron and Kettle River formations are missing, and the Marama unconformably overlies Eocene granite and Paleozoic 'basement' on a tectonic high along the margins of the graben. It is probable that other similar exposures record Marama or basal Klondike Mountain stratigraphy rather than the lithologically similar basal Kettle River Formation.

Most epithermal mineralization in the highly productive Republic and Curlew camps in northern Washington is related to the basal Klondike Mountain Formation unconformity, within or directly overlying Sanpoil volcanic rocks. The recognition of correlative Marama Formation rocks in the Boundary area enhances the potential for discovery of epithermal mineralization here as well.

A recently discovered, low-sulphidation epithermal-gold prospect, the Wad occurrence, in a structural paleohigh in the Rock Creek graben may be evidence of mineralization in the basal Kettle River horizon, which is similarly host to some epithermal deposits in the Greenwood camp to the south.

In summary, geological mapping and geochronological dating in the Boundary area have more clearly defined the relationship between the deposition of the early Penticton Group volcanic rocks, brittle extensional faulting and intrusion of high-level Eocene plutonic rocks (Höy et al., 2020). The early Eocene, specifically ca. 51.5 to 49.5 Ma, was a period of extensive volcanism, graben formation, rapid uplift and intrusive activity, conditions that were conducive to the formation of mineral deposits, including epithermal precious-metal mineralization.

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