Synthesis of U-Pb and Fossil Age, Lithogeochemical and Pb-Isotopic Studies of the Paleozoic Basement of the Quesnel Terrane in South-Central British Columbia and Northern Washington State

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Introduction

The Quesnel terrane underlies a large region in south-central and east-central British Columbia (BC), and extends both northward as a narrow fault-bounded sliver into south-central Yukon and southward into northern Washington state (Figure 1; Nelson and Colpron, 2007). The main defining feature of the Quesnel terrane in south-central BC is the Late Triassic Nicola arc assemblage and associated plutons(Figure 1), which have been well studied (e.g., Mortimer, 1987; Mihalynuk et al., 2014), not least because they host several large copper-porphyry deposits.

The basement rocks that unconformably underlie strata of the Nicola arc in this area are much less well understood (Monger, 1977). This basement includes a number of variably deformed and metamorphosed volcanic and sedimentary rock assemblages that include the Harper Ranch, Chapperon, Apex Mountain, Kobau, Knob Hill, Attwood and Anarchist groups. Paleozoic basement rocks of the Quesnel terrane are age equivalent with the Paleozoic Stikine assemblage in Stikinia (Nelson and Colpron, 2007). There has been considerable debate about whether the Quesnel terrane represents an allochthonous terrane that became attached to the edge of North America during Early Jurassic accretion, or comprises continental-margin–arc rocks and underlying Paleozoic basement that formed close to their present position with respect to the North American craton (e.g., Monger et al., 1991; Thompson et al., 2006).

A Geoscience BC-funded project was begun in 2010 aimed at better understanding the nature and origin of the Paleozoic volcanic and sedimentary rocks that make up the basement of the Quesnel terrane in the southern Okanagan area of south-central BC, and contributing new information regarding the mineral potential of the region (Mortensen et al., 2011; Mortensen, 2014). The Paleozoic rocks in this part of the Cordillera were involved in Mesozoic compressional deformation, and early Cenozoic crustal extension has divided them into a series of blocks bounded by large normal faults (Parrish et al., 1988). In addition to the complex deformation, the basement assemblages have been intruded by extensive Late Triassic to Early Jurassic and younger plutonic suites, and are widely overlain by mainly Paleogene volcanic and sedimentary sequences. As a result, the basement rocks are now exposed in a number of scattered outcrop areas (Figure 1), making regional correlations difficult.

In addition, the basement rocks in this region have been the subject of little modern study, especially in the western part (Hedley–Keremeos–Osoyoos area), prior to this work and, although the general distribution of rock units is reasonably well defined by existing mapping, only limited fossil or U-Pb isotopic age information was available and the petrotectonic affiliations of the Paleozoic igneous rocks were not well understood. The general geology of these areas has been documented or compiled at either 1:250 000 (Tempelman-Kluit, 1989) or 1:63 360 scales, although some mapping is quite dated (e.g., Bostock, 1939, 1940, 1941), and parts of the Greenwood and Rock Creek areas have been recently remapped at a 1:50 000 or 1:25 000 scale (e.g., Little, 1983; Church, 1985; Fyles, 1990; Massey, 2006, 2007; Massey and Duffy, 2008). Several small areas have also been the focus of theses or other topical studies over the years (e.g., Okulich, 1969, 1973; Peatfield, 1978; Milford, 1984; Lewis et al., 1989; Ray and Dawson, 1994). Reconnaissance-scale lithogeochemical studies have been carried out on the basement rock units in the Greenwood–Rock Creek area (Dostal et al., 2001; Massey and Dostal, 2013a) and in adjoining portions of northern Washington state (Gaspar,

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2005). However, there has been no comprehensive study of the basement rocks and major questions still remain regarding the nature of rock units in the various areas of exposure, their ages and the tectonic setting(s) in which they formed.

Overview of Paleozoic Basement Rocks in the Southernmost Part of the Quesnel Terrane

Basement rocks in the Hedley–Keremeos–Osoyoos area (Figure 2) have been subdivided into several 'assemblages', based mainly on the relative proportions of volcanic (mainly variably altered basalt or 'greenstone' and associated intrusions) and sedimentary rocks (mainly chert, fine-grained clastic rocks and minor carbonate rocks). Note that the past and current usage of stratigraphic and lithodemic terms such as 'assemblage', 'formation', 'complex', in this region do not follow strict nomenclature guidelines as defined by the Lexicon of Canadian Geologic Units; however, the terms as currently in use have been retained to minimize confusion. In the Keremeos, Oliver and Okanagan Falls areas Bostock (1939, 1940, 1941) identified several lithological assemblages that he called formations,

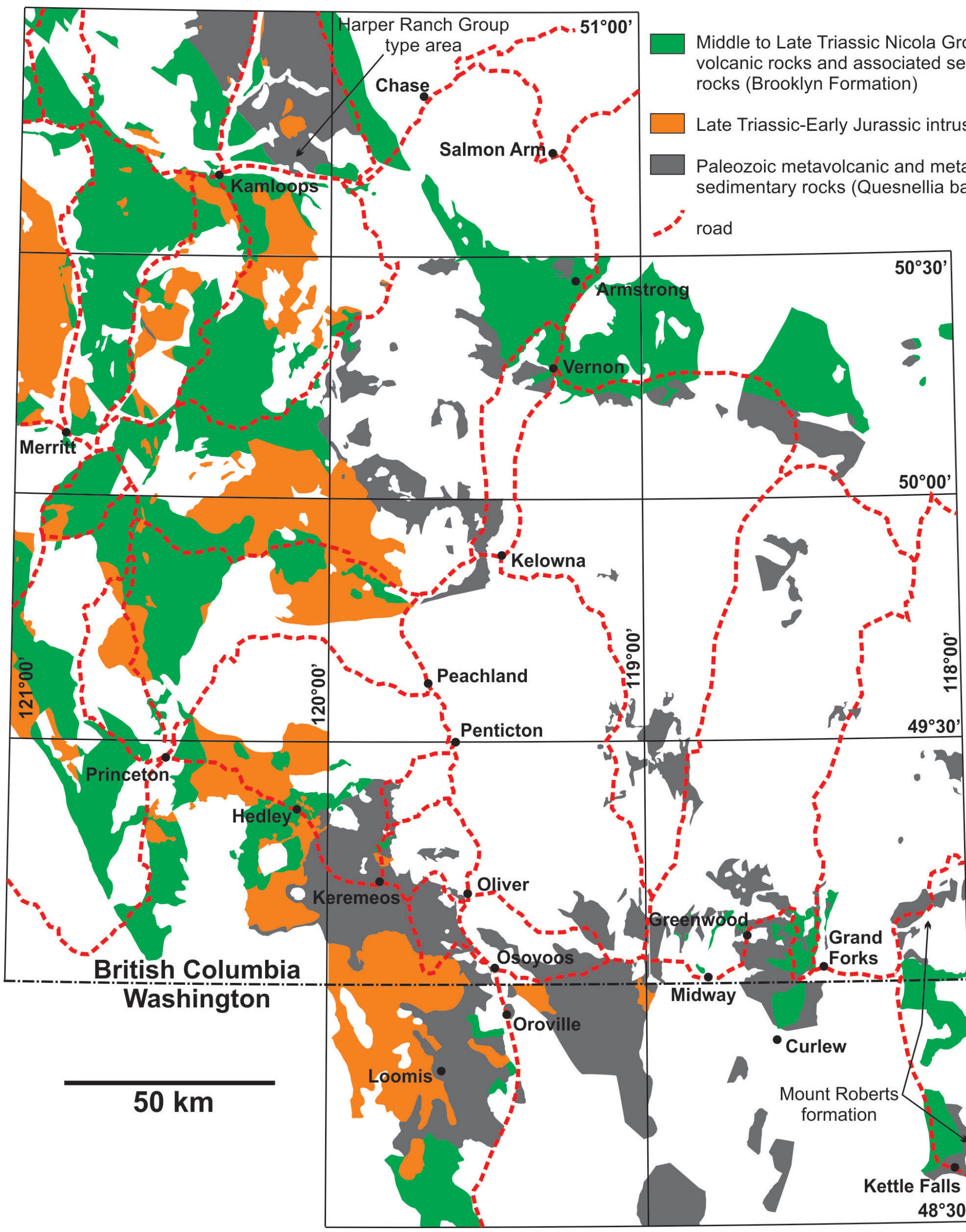

Figure 1. Distribution of Middle and Late Triassic volcanic and sedimentary rocks, Late Triassic and Early Jurassic intrusive rocks, and Paleozoic basement rocks of the Quesnel terrane in south-central British Columbia and northern Washington state.

including the Independence, Bradshaw, Old Tom, Shoemaker and Barslow, based mainly on the relative proportions of mafic volcanic and intrusive rocks, chert and clastic rocks. Rock assemblages that Bostock mapped as Independence and Bradshaw formations (Figure 2) were mainly derived from fine-grained clastic protoliths, locally interlayered with mafic volcanic-flow rocks. In the field, there was little basis on which to distinguish these assemblages one from the other, and they are therefore herein considered together. The Old Tom assemblage (mainly greenstone plus minor mafic intrusive rocks and chert) and Shoemaker assemblage (mainly chert with minor greenstone) underlie much of the Keremeos area. The distinction between Independence–Bradshaw, Old Tom and Shoemaker is not clear in the area southwest of the Similkameen River between Hedley and Keremeos (Figure 2; Bostock, 1939; Monger, 1989; Tempelman-Kluit, 1989). The Barslow assemblage in the Cawston area (Figure 2) comprises fine- to locally coarse-grained clastic strata (including pebble and minor cobble conglomerate) with locally

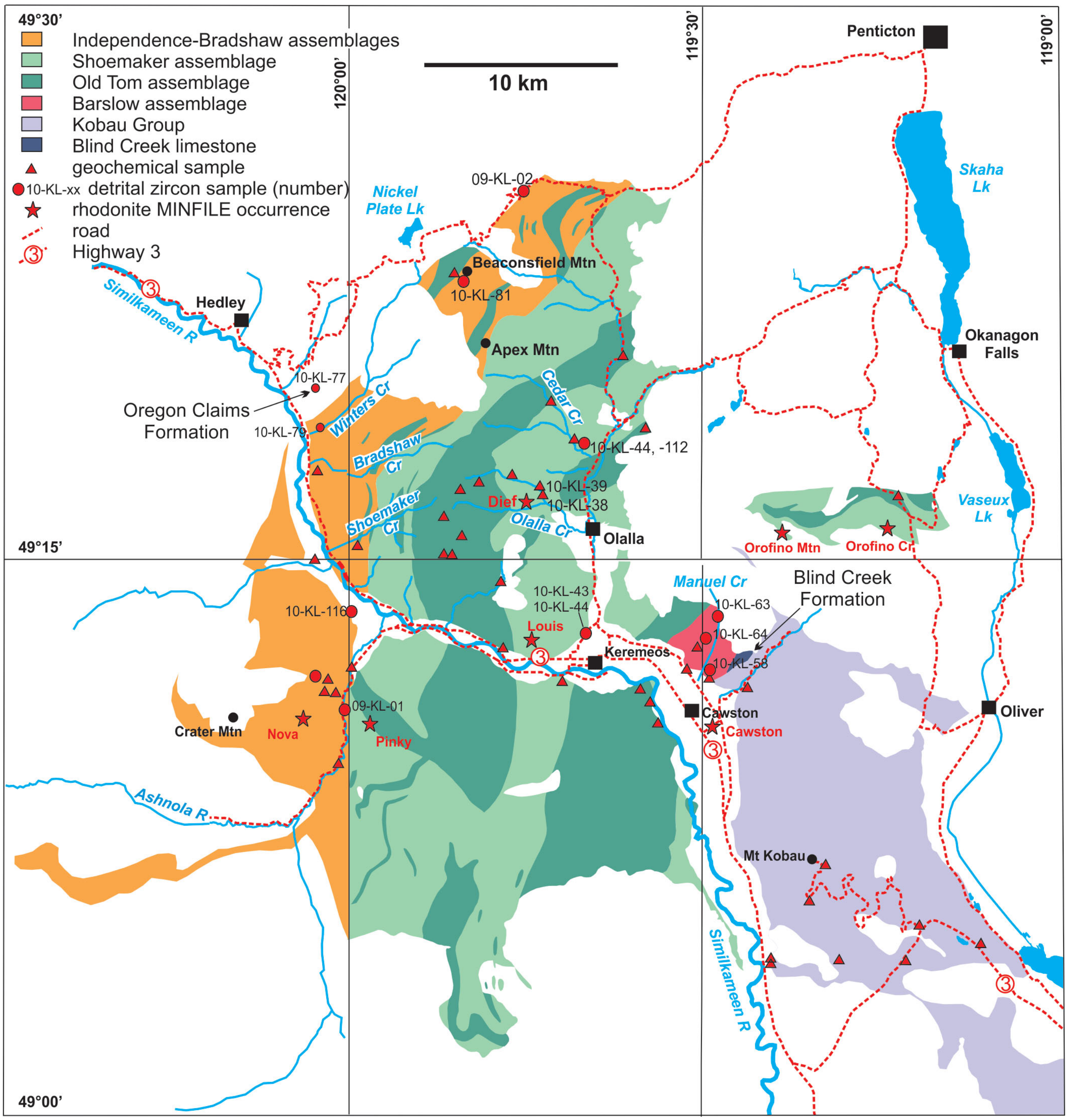

Figure 2. Simplified geology of the Hedley–Keremeos–Osoyoos area in south-central British Columbia. Abbreviations: Cr, Creek; Lk, Lake; Mt, Mount; Mtn, Mountain; R, River.

interlayered greenstone. Milford (1984), in his study of the Apex Mountain area, lumped all but the Barslow assemblage into a single unit that he termed the Apex Mountain Group (later renamed the Apex Mountain Complex by Monger, 1989), a term that was also subsequently used by Ray and Dawson (1994). Farther to the east, the Kobau Group (Figure 2) of Bostock (1939), Okulich (1969, 1973), Lewis et al. (1989) and Tempelman-Kluit (1989) consists of more strongly metamorphosed and deformed mafic volcanic rocks (now amphibolite) and fine-grained quartzite that probably was derived mainly from a chert protolith. A sequence of mafic tuffs and flows, together with sandstone, siltstone, argillite and minor polymictic conglomerate and carbonate rock, that immediately underlies the Late Triassic volcanic and sedimentary rocks of the Nicola Group in the Hedley area (Figure 2) has been called the 'Oregon Claims formation' (Figure 2) by Ray et al. (1994, 1996). Although the age of this assemblage is unknown at this time, Ray et al. (1996) considered it to be part of the Paleozoic Apex Mountain Complex.

The nature of the contacts between the various lithological assemblages is uncertain. In some cases it appears to be gradational (e.g., the Old Tom assemblage could simply represent a facies of the Shoemaker assemblage). However, there is some evidence for fault imbrication within the Old Tom and Shoemaker assemblages; for example, on Shoemaker Creek just west of Keremeos (Figure 2; see later discussion).

A large composite body of massive to bedded limestone termed the 'Blind Creek limestone' (Figure 2; Bostock, 1939; Barnes and Ross, 1975) that is in fault contact with the Old Tom, Barslow and Kobau assemblages near Cawston (Figure 2) has yielded numerous robust Carboniferous fossil ages and overlaps in age with at least some of the other basement rock units in the area, although the original stratigraphic relationships between this limestone body and adjacent rock packages are uncertain.

Farther to the east, Paleozoic basement rocks between the Okanagan Valley and Grand Forks (Figure 3) occur within a series of north-dipping thrust panels, with the intervening thrust surfaces commonly marked by the presence of thin tectonic slices of serpentinite, all cut and offset by numerous Eocene normal faults (Figure 3; Fyles, 1990; Massey, 2007; Massey and Duffy, 2008; Massey and Dostal, 2013a). Three main lithological assemblages have been distinguished in this area. The Knob Hill Complex in the Greenwood area comprises mafic volcanic flows and locally abundant diabase and gabbro intrusions, together with subordinate amounts of interlayered chert, chert breccia and argillite. The two other assemblages, the sedimentary Attwood Group near Greenwood and the more metamorphosed Anarchist Schist, exposed mainly between Rock Creek and the Okanagan Valley, consist mostly of metasedimentary rocks. The interpreted areal distribution of these two groups has changed considerably over the last two decades. Church (1985) and Fyles (1990) included all of the sediment-dominated basement rocks in the Greenwood area in the Attwood Group, whereas Anarchist Schist was reserved for the more metamorphosed metasedimentary packages. Massey and Duffy (2008) redefined the An-

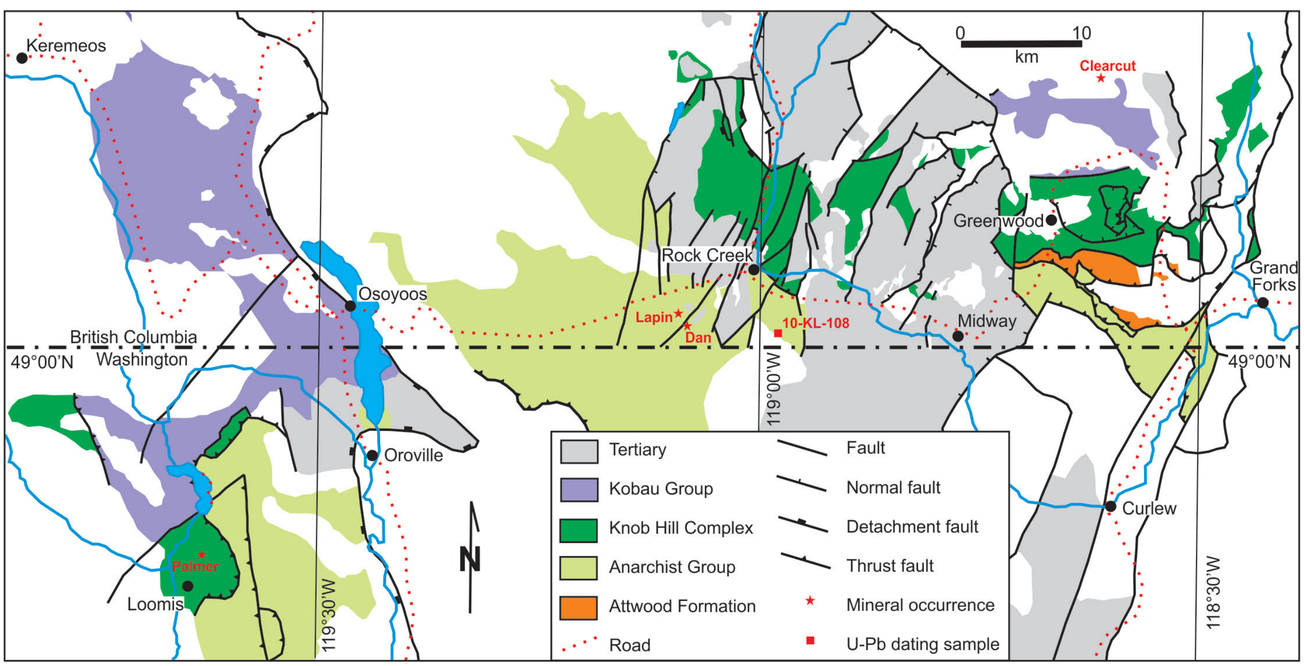

Figure 3. Distribution of, and structural relationships between, Paleozoic assemblages in the southern part of the Quesnel terrane between Keremeos and Grand Forks (modified from Massey and Dostal, 2013a).

archist Schist as the 'Anarchist Group', and included most of the metasedimentary rock units previously mapped as Attwood in this more regionally extensive package (Figure 3). The term 'Attwood Formation' is now restricted by Massey and Dostal (2013a) to a package of argillite, siltstone, greywacke and sandstone, with locally abundant limestone, chert-pebble conglomerate and minor mafic volcanic rocks, in a small area southeast of Greenwood (Figure 3). The Anarchist Group, as now defined, comprises chert, argillaceous chert and argillite, with minor interlayered mafic flows and tuffs, limestone, and rare felsic tuff. The Mount Roberts Formation east of Grand Forks (Figure 1; Roback and Walker, 1995) comprises metaclastic rocks that may be correlative with the Anarchist Group.

A large area in northern Washington state near Loomis and Oroville (Figure 3) is underlain by mafic volcanic and metaclastic rocks that have been variably correlated with the Knob Hill, Anarchist and Kobau groups (e.g., Cheney et al., 1994; Massey and Dostal, 2013a). The 'Palmer Mountain greenstone' north of Loomis (Figure 3) consists of mafic volcanic and volcaniclastic rocks together with gabbro and serpentinite (Rinehart and Fox, 1972) that lithologically closely resemble the Knob Hill Complex (e.g., Massey and Dostal, 2013a) or possibly the Old Tom assemblage.

Biochronology

A limited number of macro- and microfossil ages were available for the Paleozoic basement rocks in the southernmost part of the Quesnel terrane prior to this study. During this study, extensive sampling of chert for radiolarian and/or conodonts was carried out to better constrain the age of the various assemblages present. Although chert in many localities in the study area contains visible radiolarians, in most cases these fossils are too recrystallized to give confident age determinations. A total of eight limestone samples were processed for possible conodonts; however, all proved to be barren. A small number of new localities did produce reliable radiolarian or conodont ages, and resampling of some localities that had previously given preliminary age determinations yielded more confident age assignments. One locality also produced a reliable macrofossil age assignment. All of the new fossil ages produced during this study are listed in Table 1 and these results are summarized below, along with previous fossil information from the region.

The only fossil age constraints available thus far for rock units that are unequivocally part of the Independence–Bradshaw assemblage are from three collections of brachiopods and tentaculitids from a single locality northeast of Highway 3 between Shoemaker and Bradshaw creeks, 10 km southeast of Hedley (Figure 2), that gave Cambrian to Devonian, Devonian, and mid-Early to early Late Devonian (Pragian–Frasnian) ages (Dawson, 1994; Ray and Dawson, 1994). A crinoidal limestone located 3.5 km east of Crater Mountain, north of the Ashnola River (Figure 2), that is interlayered with argillite, sandstone, and minor chert pebble conglomerate and greenstone, is herein tentatively correlated with the Independence–Bradshaw assemblage and gave a Middle Devonian (late Eifelian to early Givetian) conodont age (identified by M.J. Orchard in Nebocat, 1996).

The Old Tom and Shoemaker assemblages have produced a number of fossil ages. A Middle Devonian age (M.J. Orchard, unpublished data, 2006) was obtained for ichthyoliths and conodonts from a limestone interlayered with greenstone and chert of the Old Tom and Shoemaker assemblages 4 km northeast of Olalla (Figure 2; W.R. Danner, unpublished data, 1987). A thinly laminated red radiolarian chert that occurs as a large local talus block on the northern side of Highway 3 about 2 km west of Keremeos (Figure 2) gave a Late Devonian (middle–late Famennian) conodont age (this study; Cordey, 1998; see Table 1). Late Devonian to Mississippian and Pennsylvanian to Permian radiolarian ages were also obtained from grey chert at several localities above the Keremeos garbage dump site, 1 km north of Keremeos, and on the mountain top approximately 3 km northwest of Keremeos (this study; Table 1).

Three localities within the Old Tom and Shoemaker assemblages yielded somewhat puzzling fossil age results. On Shoemaker Creek north of the Similkameen River, 13.5 km northwest of Keremeos (Figure 2), two lenses of limestone that either overlie, or are stratigraphically or structurally interlayered with mainly chert at, or near, the mapped contact between the Independence–Bradshaw and Shoemaker assemblages (Bostock 1939), yielded Middle to Late Triassic (late Ladinian to early Carnian) conodont ages (Read and Okulitch, 1977; Milford, 1984). However, this same limestone also locally contains Silurian corals and Carboniferous foraminifera, both of which are considered to represent reworked fossils incorporated from older, as yet unidentified rock units in the immediate area. Read and Okulitch (1977) interpreted the Triassic rocks on Shoemaker Creek to be small erosional remnants of Triassic clastic rocks that were deposited unconformably on top of the Old Tom or Shoemaker units. An alternative interpretation is that the Triassic rocks are fault-bounded bodies that were imbricated with the Paleozoic rocks during Jurassic folding and thrust faulting. At another locality on the western side of the Similkameen River, approximately 6 km south of Cawston (Figure 2), Tempelman-Kluit (1989) reports a Middle Triassic (Ladinian) conodont age from an argillaceous limestone at a locality that is mapped as being within the Shoemaker assemblage. The presence of these Triassic rock units apparently within the Old Tom and/or

Table 1. New fossil age determinations from the Old Tom, Shoemaker and Barslow assemblages in the Hedley–Keremeos–Cawston area.

Field number	Collector	UTM			Location	Rock unit	Description	Fossil type	Age
		Zone	Northing	Easting					
K10-01[1]	Cordey, F	11	287494	5460776	Olalla Creek, float	Old Tom-Shoemaker	Red chert	Conodonts	Latest Devonian to Mississippian
K10-02[1]	Cordey, F	11	286955	5459885	Olalla Creek, float	Old Tom-Shoemaker	Red chert	Radiolarians	Late Paleozoic
K10-03[1]	Cordey, F	11	286557	5459966	Olalla Creek, float	Old Tom-Shoemaker	Red chert	Radiolarians	Late Paleozoic
K10-05[1]	Cordey, F	11	289210	5460384	Olalla Creek, in situ	Old Tom-Shoemaker	Grey ribbon chert	Radiolarians	Probably Mississippian
K10-09[1]	Cordey, F	11	291316	5454405	Float block in talus sheet ~2 km west of Keremeos	Old Tom-Shoemaker	Red chert	Conodonts	Late Devonian to middle-late Famennian
K07-05[1]	Cordey, F	11	293338	5455818	Above Keremeos dump site, in situ	Old Tom-Shoemaker	Grey chert	Radiolarians	Pennsylvanian to Permian
K07-07[1]	Cordey, F	11	293517	5455870	Above Keremeos dump site, in situ	Old Tom-Shoemaker	Grey chert	Radiolarians	Late Devonian to Mississippian
K07-23[1]	Cordey, F	11	291200	5456040	Top of mountain 3 km northwest of Keremeos, in situ	Old Tom-Shoemaker	Grey chert	Radiolarians	Possibly Mississippian
K10-12[1]	Cordey, F	11	293244	5455470	Above Keremeos dump site, in situ	Old Tom-Shoemaker	Grey chert	Conodonts, radiolarians	P'robably Late Devonian or Mississippian (conodonts); Mississippian (radiolarians)
K10-15-8[1]	Cordey, F	11	298683	5454383	Float block in talus sheet north of Cawston	Barslow	Green chert	Conodonts	Likely Late Mississippian or Pennsylvanian
10-KL-60[2]	Monger, JWH	11	298738	5454102	3.5 km due north of Cawston; float at bottom of talus cone	Barslow	Fossiliferous argillite, crinoid-bearing limestone	Brachiopods	Early Carboniferous, probably Tournaisian

[1]Sample processing and fossil identification by F. Cordey, Laboratoire de Géologie de Lyon, Université Claude Bernard, Lyon, France
[2]Fossil identification by W. Bamber, Geological Survey of Canada-Calgary, Calgary, Alberta

Shoemaker assemblages led Tempelman-Kluit (1989) to assign a probable Triassic age to all of these units. More detailed examination of both localities is needed to resolve these problems.

On Cedar Creek approximately 3 km north of Olalla (Figure 2), a large block of limestone within an area mapped as Shoemaker assemblage yielded Middle to Late Ordovician conodont ages (Pohler et al., 1989). Red radiolarian chert on Olalla Creek approximately 3 km southwest of the Cedar Creek locality gave latest Devonian to Mississippian conodonts and probably Mississippian radiolarians (this study; Table 1). Tempelman-Kluit (1989) and Orchard (1993) also reported a Mississippian conodont age from a nearby locality on Olalla Creek. It thus appears that the Shoemaker assemblage in this area is mostly of Late Devonian to Mississippian age, and the Ordovician limestone body is interpreted to be either a large olistolith contained within argillite and sandstone of the Shoemaker assemblage, or alternatively it could be a thrust-fault–bounded body that was structurally imbricated with the Shoemaker rock units. Either of these interpretations is complicated by the fact that there are no known limestone of Ordovician age anywhere west of the Rocky Mountains in BC, from which the limestone block could have been sourced.

The Blind Creek limestone unit (Figure 2) has given consistent Middle Mississippian to Early Pennsylvanian conodont ages from numerous samples (Barnes and Ross, 1975; Tempelman-Kluit, 1989; Orchard, 1993). The Barslow assemblage in the Cawston area (Figure 2) contains a heterogeneous clastic package, including pebbles and cobbles of crinoidal limestone, brachiopod-bearing argillite and chert, as well as greywacke with well-preserved plant fossils. A chert clast gave a probably Late Mississippian or Pennsylvanian conodont age (this study; Table 1) and brachiopods from an argillite layer that included abundant brachiopod fragments and wood debris gave an Early Carboniferous, probably Tournaisian, age (this study; Table 1).

The high degree of strain and strong metamorphic recrystallization that has affected the Kobau Group precludes any possibility of preservation of fossils. Middle to Late Devonian conodont ages have been obtained from the lower part of the Knob Hill Complex (Orchard, 1993; note that this same limestone bed had previously been interpreted as "Carboniferous or Permian" by Little, 1983, based on corals and bryozoans), and chert in the upper part of the Group has given a Late Pennsylvanian or earliest Permian radiolarian age (identified by F. Cordey in Massey, 2007). The Anarchist Group has not yet yielded any fossil ages; however, a number of collections of brachiopods, crinoids, corals and bryozoans from the Attwood Group have given "Carboniferous or Permian" ages (Little, 1983). Limited fossil age constraints for the Paleozoic volcanic and sedimentary packages in adjacent parts of northern Washington state include fusilinids of possible Early Permian age in the southeastern part of the Curlew quadrangle, approximately 30 km south of Grand Forks (Figure 3; Parker and Calkins, 1964), and fusilinids, corals, bryozoans, gastropods and crinoid of Early Permian age in the Marcus and Kettle Falls quadrangles, approximately 55 km south-southeast of Grand Forks (Figure 1; Mills and Davis, 1962; Mills, 1985). The latter locality has been included in the Mount Roberts Formation by Roback and Walker (1995).

U-Pb Geochronology

Rock Ages

Nearly all of the igneous rocks present within the Paleozoic basement of the Quesnel terrane in south-central BC are mafic in composition and only rarely contain igneous zircon; hence, there are very few rock units that can be dated using the U-Pb method. Massey et al. (2013) reported U-Pb zircon ages, ranging from 389 to 380 Ma (late Middle Devonian), for four separate samples of gabbro of the Knob Hill Complex in the Greenwood area. A quartz-muscovite schist unit sampled from the Anarchist Group south of Rock Creek (sample 10-KL-108; Figure 3) is interpreted to be a felsic metavolcanic rock, likely a metatuff. The sample yielded abundant clear, colourless, euhedral zircons. The analytical results are given in Table 2 and shown graphically in Figure 4. Nineteen zircon grains were analyzed using the laser ablation inductively coupled plasma–mass spectrometry method, as described in Massey et al. (2013). One grain gave a Paleoproterozoic age (2.33 Ga) and is clearly a detrital zircon that was incorporated into the sample. The remaining grains form one loose cluster between ~390 and 375 Ma, and a second, tight cluster at ~365 Ma. This younger cluster of seven analyses gives a weighted average $^{206}Pb/^{238}U$ age of 365.2 ±1.0 Ma (MSWD = 0.02; probability of fit = 1.0), which is interpreted to be the crystallization age of the volcanic protolith for the sample. The older cluster represents somewhat older detrital (late Middle to early Late Devonian) zircons. One zircon grain gave a younger $^{206}Pb/^{238}U$ age (359 Ma), which is interpreted to be the result of post-crystallization Pb loss. The latest Devonian U-Pb zircon age reported here is the first depositional age that has ever been produced for rocks of the Anarchist Group.

Detrital Zircon Ages

A major goal of the present study was to use the ages of detrital zircons from clastic rock units within the various Paleozoic assemblages to constrain their depositional age, which cannot be older than the youngest significant detrital zircon age population present. In addition, the detrital zircon ages were used to evaluate linkages between the assemblages, and between them and the North American craton. This approach is particularly useful when there is no possibility of using fossil information to test such linkages. De-

Table 2. Results of U-Pb zircon analysis for a felsic metavolcanic rock of the Anarchist Group (sample 10-KL-108) in the Rock Creek area.

Fraction	Isotopic ratios							Isotopic ages (Ma)						Background corrected mean counts per second at specified mass							
	$^{207}Pb/^{235}U$	1σ(%)	$^{206}Pb/^{238}U$	1σ(%)	$^{207}Pb/^{206}Pb$	1σ(%)	ρ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	202	204	206	207	208	232	235	238
Sample 10-KL-108 (UTM 355293E, 5430667N, Zone 11, NAD 83):																					
1		0.00066	0.44787	0.00694	0.06028	0.0003	0.32	337.3	27.86	375.8	4.87	377.3	1.81	15	10	50404	2732	11986	119868	3182	396780
2	0.05367	0.00069	0.45656	0.00728	0.0609	0.00031	0.32	357	28.66	381.9	5.07	381.1	1.85	0	0	26954	1473	5446	54746	1683	209992
3	0.05501	0.00078	0.46334	0.00829	0.06222	0.00036	0.32	412.8	31.3	386.6	5.75	389.1	2.16	22	26	28080	1572	7018	64770	1771	214051
4	0.05348	0.0004	0.44854	0.00412	0.06092	0.00018	0.32	349	16.87	376.3	2.89	381.2	1.12	8	27	86035	4682	27048	264512	5450	669784
5	0.05378	0.00053	0.45243	0.00558	0.06048	0.00024	0.32	361.9	22.3	379	3.9	378.5	1.46	19	20	60803	3326	16158	168476	3840	476715
6	0.0533	0.00057	0.43242	0.00567	0.05832	0.00025	0.33	341.5	23.89	364.9	4.02	365.4	1.5	32	0	45104	2443	10389	110069	2953	366561
7	0.05227	0.00075	0.44467	0.00791	0.06096	0.00034	0.31	297.4	32.2	373.5	5.56	381.5	2.07	29	24	38454	2042	7674	78686	2401	298934
8	0.0529	0.00063	0.43017	0.00623	0.06078	0.00028	0.32	324.3	26.69	363.3	4.43	380.4	1.68	41	12	22465	1206	4553	50812	1467	175096
9	0.05287	0.00087	0.41306	0.00837	0.05733	0.00037	0.32	323.4	37.05	351.1	6.01	359.4	2.25	0	16	24857	1333	4418	47917	1690	205362
10	0.05354	0.00059	0.44696	0.00612	0.06094	0.00027	0.32	351.5	24.73	375.1	4.29	381.3	1.62	19	9	40512	2197	7693	79359	2577	314708
11	0.14829	0.00086	8.5601	0.12674	0.42837	0.00153	0.24	2326.3	9.93	2292.3	13.46	2298.3	6.89	12	0	124908	18758	18267	31733	1149	138007
12	0.05466	0.00066	0.44687	0.00663	0.06157	0.00029	0.32	398.5	26.59	375.1	4.65	385.2	1.79	5	14	41550	2299	10026	104103	2699	319322
13	0.05262	0.00061	0.43249	0.00623	0.05827	0.00027	0.32	312.2	26.33	364.9	4.42	365.1	1.63	40	0	59484	3166	12051	121533	3843	482946
14	0.04897	0.00052	0.17361	0.00201	0.02466	0.0001	0.35	146.5	24.94	162.5	1.74	157	0.61	0	20	28796	1426	4123	109104	4313	552387
15	0.05345	0.00057	0.4268	0.00556	0.05827	0.00024	0.32	347.7	23.93	360.9	3.95	365.1	1.48	27	7	29268	1580	5306	57924	1946	237503
16	0.0536	0.00053	0.43205	0.00519	0.05833	0.00023	0.33	354.1	21.95	364.6	3.68	365.5	1.38	0	0	58811	3183	9115	95193	3873	476638
17	0.05363	0.00051	0.43552	0.00504	0.05831	0.00022	0.33	355.5	21.27	367.1	3.57	365.3	1.32	0	22	40670	2202	8473	91072	2659	329686
18	0.05401	0.00052	0.43892	0.00518	0.05825	0.00022	0.32	371.4	21.72	369.5	3.66	365	1.35	55	0	56010	3052	14132	161129	3659	454451
19	0.0535	0.00051	0.43355	0.00498	0.0583	0.00022	0.33	350	21.16	365.7	3.53	365.3	1.31	103	13	37468	2022	8641	87292	2454	303650

U-Pb analyses done at the Pacific Centre for Isotopic and geochemical Research, University of British Columbia, Vancouver

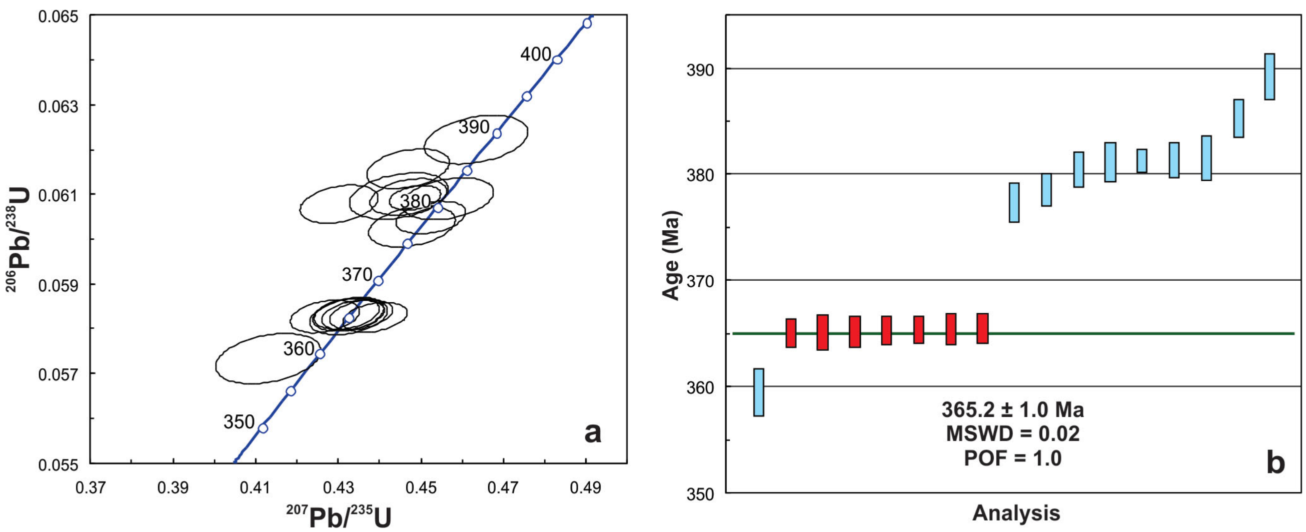

Figure 4. Conventional concordia diagrams and plots of **a)** U-Pb analyses by laser ablation inductively coupled plasma–mass spectrometry of zircon from a felsic metatuff of the Anarchist Group (sample 10-KL-108; Figure 3). Analytical errors are shown at the 2ó uncertainty level; **b)** analyses shown as blue error boxes were excluded from the calculated weighted-average age for the sample. Abbreviations: MSWD, mean square of weighted deviates; POF, probability of fit.

trital zircons had previously been dated from a sample (n= 44) of Barslow assemblage (J.E. Wright, unpublished data, 2007). Although it was not expected there would be any difficulty finding suitable clastic rock units from which to recover detrital zircons from the more sediment-dominated lithological assemblages in the southern part of the Quesnel terrane (e.g., Independence–Bradshaw, Barslow, Anarchist and Attwood) , there was some concern at the beginning of the study about whether any clastic rocks were actually present within some of the greenstone/chert-dominated assemblages such as Old Tom and Shoemaker, which appeared to represent deposition in deep oceanic settings., However, a large number of localities, where the presence of greywacke, lithic sandstone and, in some cases, quartz sandstone was noted as thin clastic units interlayered with the greenstone and chert within most of the various assemblages, were located and sampled during the course of the study.

A total of 1410 individual zircon grains were dated in the study, from a total of 21 samples from the Independence–Bradshaw, Old Tom, Shoemaker, Barslow, Anarchist and Attwood assemblages. No samples for detrital zircon dating were collected in this study from either the Blind Creek or Knob Hill assemblages. Several samples of highly metamorphosed quartzite from the Kobau Group were processed but did not yield zircons; these units are now thought to have likely been derived from chert protoliths. Detrital zircons were also separated and dated from the Oregon Claims formation in the Hedley area to test possible correlations with the other Paleozoic assemblages in the area (see earlier discussion). The complete results of the work will be presented in detail in a separate paper. In this contribution, summary probability plots for zircon ages from each sample are shown; these are stacked for each assemblage or group of assemblages so that the detrital zircon signature can be compared between samples.

Independence–Bradshaw Assemblage and Oregon Claims Formation

Zircons recovered from the Independence–Bradshaw assemblage metasandstone on Winters Creek (sample 10-KL-79; Figure 2) are all euhedral to subhedral. The youngest grain recovered gave an age of 301 Ma, and a total of 15 grains gave ages in the 315–300 Ma range (early Middle to latest Pennsylvanian; Figure 5a). The remaining 50 grains gave ages ranging from 372 to 316 Ma (mid-Late Devonian to Middle Pennsylvanian). Zircons recovered from the Oregon Claims formation (sample 10-KL-77; Figure 2) are all euhedral to subhedral, and are mainly very young (Figure 5b). A single grain gave an age of 296 Ma (Early Permian), 33 grains gave ages of 315–300 Ma (Middle and Late Pennsylvanian), most of the rest of the grains ranged from 332 to 315 Ma (Middle Mississippian to Middle Pennsylvanian); and a single grain gave an age of 363 Ma (latest Devonian). Taken together the detrital zircon age signature is very similar between the two samples. This could either indicate that the Oregon Claims formation is equivalent to the Independence–Bradshaw assemblage (as previously suggested by Ray and Dawson, 1994), or alternatively, that the Oregon Claims formation is younger but all the zircons within it were reworked from the underlying Independence–Bradshaw units. In any case, neither of the two samples can be older than Early Permian.

Two samples (10-KL-30, -34) were collected from quartz-rich sandstone from within a sequence of grey argillite, sandstone, grit and minor chert pebble conglomerate and dark grey chert 5 km east of Crater Mountain (Figure 2), which is tentatively correlated on lithological grounds with

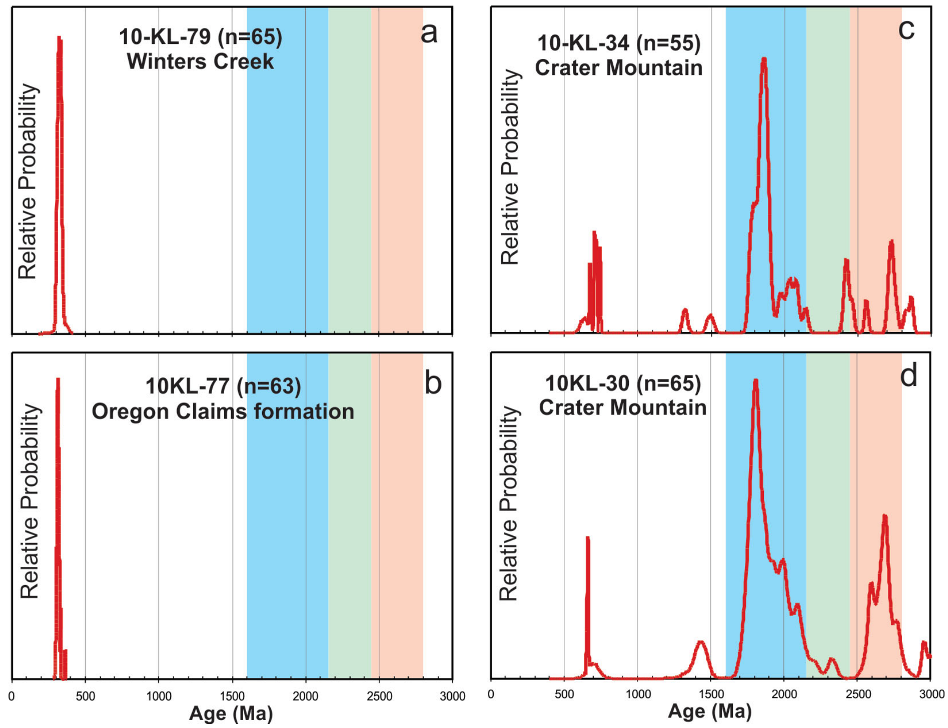

Figure 5. Probability density plots for detrital zircon ages from samples of **a)** the Independence–Bradshaw assemblage; **b)** the Oregon Claims formation; **c)** and **d)** the Crater Mountain area. Colour bands are: pink, 2450–2800 Ma; green, 2150–2450 Ma; blue, 1600–2150 Ma. These age ranges are typical for detrital zircons shed from the northwestern part of the North American craton (Gehrels et al., 1995; Gehrels and Ross, 1998; Leslie, 2009; Lemieux et al., 2011; Kraft, 2013).

the Independence–Bradshaw assemblage. Each yielded abundant detrital zircon, most of which was subrounded. Zircons from both samples gave predominantly Mesoproterozoic and older ages (Figures 5c–d). The youngest grains from the two samples were late Proterozoic (743–662 Ma; Figure 5c, d).

The mid-Early to early Late Devonian brachiopod/tentaculitid age reported by Ray and Dawson (1994) from metasandstone in the Independence–Bradshaw metasedimentary units was from a locality approximately 4 km to the southeast of the Winters Creek sample locality that gave an Early Permian maximum depositional age. The combined data suggest that as much as 80 million years of sedimentation may be represented by the Independence–Bradshaw assemblage. In view of the fine-grained nature of most of the sedimentary rocks of this package, and the lack of any obvious marker horizons within it, such a long period of sedimentation is entirely possible.

Detrital zircon age spectra from the two Crater Mountain area samples show prominent peaks in the 2800–2450 Ma and 2150–1600 Ma ranges (pink and blue bands, respectively, in Figure 5c, d). These age ranges are typical of zircon in early and middle Paleozoic sedimentary units that were shed off the western part of the North American craton and deposited in the continental margin (e.g., Gehrels et al., 1995; Gehrels and Ross, 1998; Leslie, 2009; Lemieux et al., 2011; Kraft, 2013). The data therefore suggest that the Independence–Bradshaw assemblage was likely deposited along the western edge of the North American craton. Zircons in the range of 2450–2150 Ma (green band in Figures 5c, d), which are present in minor amounts in both Crater Mountain samples, are generally thought to indicate a provenance from a specific part of the northwestern portion of the craton, namely from the Buffalo Head and Hottah terranes of northern Alberta and southwestern Northwest Territories (e.g., Gehrels and Ross, 1998; Kraft, 2013).

Old Tom and Shoemaker Assemblages

Detrital zircons were separated and dated from a total of nine samples of clastic rock from the Old Tom and Shoemaker assemblages, from localities throughout much of the outcrop area of these units. The data from each of the samples are shown in Figure 6 a–i. Many (but not all) of the samples have prominent age peaks from zircon grains that show rounded and frosted morphologies (and therefore are probably multiply reworked) in the ranges of 2150–1600 Ma and 2800–2450 Ma, and most samples also contained a substantial number of grains in the 2450–2150 Ma range, which is interpreted to indicate derivation from the northwestern part of the North American craton. This suggests that, although the abundance of chert, scarcity of clastic sedimentary rocks and absence of carbonate rocks

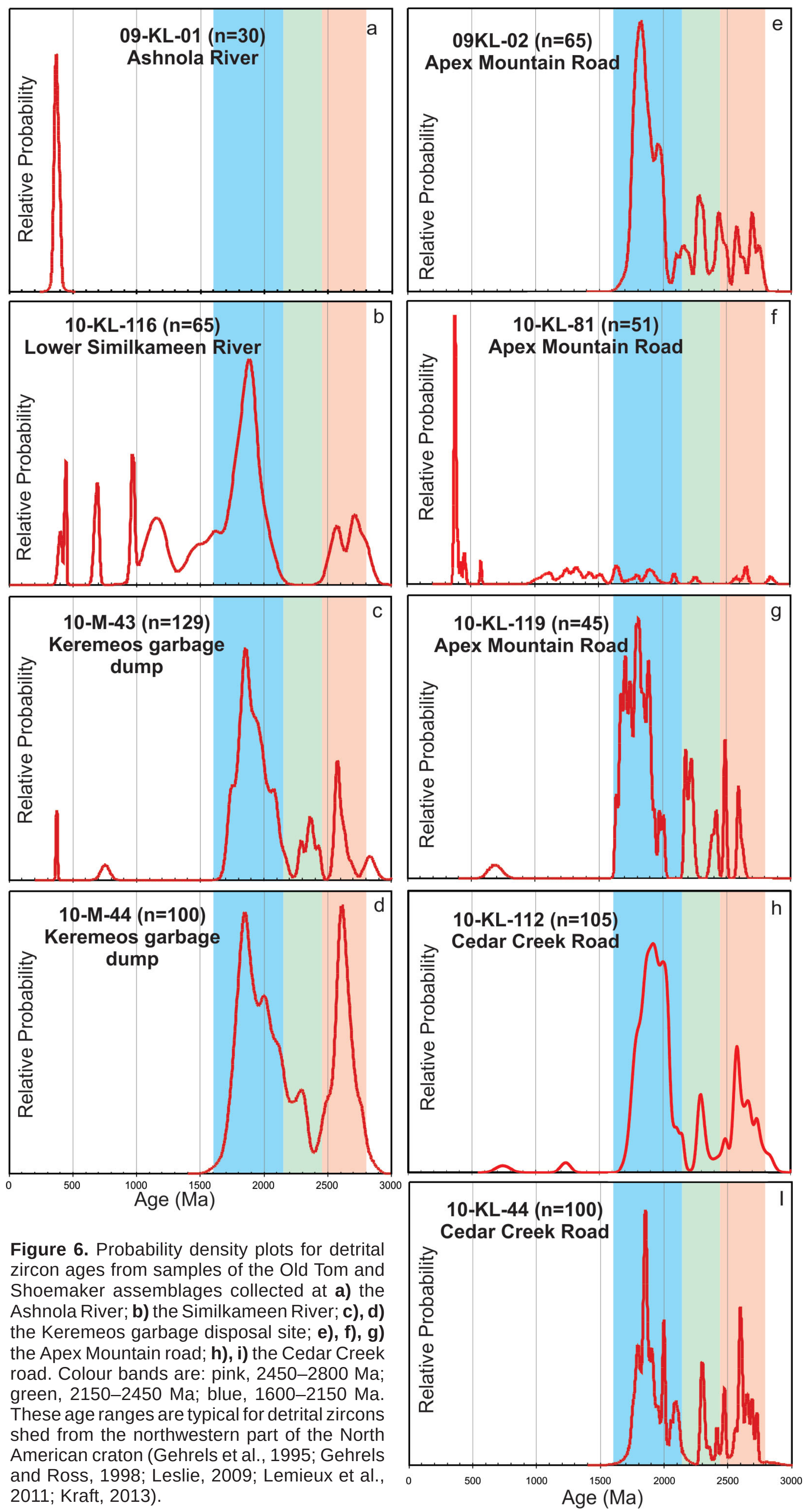

Figure 6. Probability density plots for detrital zircon ages from samples of the Old Tom and Shoemaker assemblages collected at **a)** the Ashnola River; **b)** the Similkameen River; **c), d)** the Keremeos garbage disposal site; **e), f), g)** the Apex Mountain road; **h), i)** the Cedar Creek road. Colour bands are: pink, 2450–2800 Ma; green, 2150–2450 Ma; blue, 1600–2150 Ma. These age ranges are typical for detrital zircons shed from the northwestern part of the North American craton (Gehrels et al., 1995; Gehrels and Ross, 1998; Leslie, 2009; Lemieux et al., 2011; Kraft, 2013).

indicate deposition in deep water at some distance from a continental margin, the Old Tom and Shoemaker assemblages were likely deposited offshore of the northwestern part of the North American craton. Several of the samples contain small populations of zircons that yielded late Meso- and early Neoproterozoic (~1500–1000 Ma) ages, and a few samples also contain a small number of early Paleozoic zircons. Again, this is consistent with detrital-zircon age spectra that have been reported for sedimentary units in the miogeocline of the northwestern North American craton (e.g., Gehrels et al., 1995; Leslie, 2009; Lemieux et al., 2011; Hadlari et al., 2012).

In addition, a small number of samples also contain prominent Devonian to Early Mississippian age populations. A greywacke unit (sample 09-KL-01; see Figure 2) interlayered with greenstone on the Ashnola River contained only euhedral zircon grains, which yielded consistently mid- to late Paleozoic ages. Thirty grains were dated (Figure 6a); of these, ten gave ages of 360–350 Ma, and the remainder ranged from 404 to 360 Ma. Three samples were processed from localities along the Apex Mountain resort road (Figure 2). A modest proportion of the zircons recovered from one sample (10-KL-81; Figure 6f) were euhedral in outline. One grain gave an age of 360 Ma, and fifteen additional grains gave ages ranging from 393 to 367 Ma (Middle to Late Devonian). All the rest of the zircons in this sample, and all zircons from both of the other Apex Mountain road samples (09-KL-02 and 10-KL-119; Figures 6g, i), are subrounded to rounded, and yielded older ages (mostly in the 1600–2150 Ma and 2450–2800 Ma brackets; Figure 5).

The range of rock units present, especially the local abundance of radiolarian chert, together with detrital zircon information for the Old Tom and Shoemaker assemblages, suggests that these rocks were deposited in a relatively deep ocean setting somewhat distant from the continental margin of the northwestern North American craton, but also received sporadic input of first-cycle igneous zircon grains ranging from 404 to as young as 350 Ma (Early Devonian to Early Mississippian). The fact that one sample (Ashnola River; Figure 2, 6a) contains only Late Devonian–Early Mississippian zircons and that, of three samples from relatively closely spaced samples in the Apex Mountain road area, only one contains any young zircons, suggests that the source(s) of these younger grains could probably have been volcanoes that were located within the depositional basin (i.e., relatively proximal to the sample site), rather than on the continental margin.

The constraints on possible depositional ages for the Old Tom and Shoemaker assemblages provided by the youngest detrital zircons present in each sample are generally consistent with the fossil-age constraints for the units (Middle Devonian to Pennsylvanian or possibly Permian; see discussion above). Unfortunately the fossil and detrital zircon age constraints are too sparse to provide the basis for firm conclusions regarding the relative stratigraphic position of the various exposure areas of Old Tom and Shoemaker units. It was hoped that detrital zircon age data from rocks associated with the blocks of Ordovician limestone on Cedar Creek would shed some light on the nature and origin of these units. The youngest detrital zircons dated from two samples of sandstone, one of which forms the immediate host for the Ordovician limestone block, and one of which occurs along stratigraphic strike from it (samples 10-KL-44 and 10-KL-112), are 1727 and 743 Ma (Figure 6 h, i), respectively; therefore, the detrital zircon ages unfortunately do not provide any useful constraints on the actual depositional age of the sedimentary rocks that host the Ordovician limestone body.

Barslow Assemblage

Three samples of clastic rocks from the Barslow assemblage were collected in the Manuel Creek area, north of Cawston (Figure 2); these were a coarse-grained sandstone (10-KL-61), a fine-grained sandstone (10-KM-63) and a pebble conglomerate (10-KL-64). The conglomerate consisted mainly of chert pebbles; however, rare pebbles of quartz-feldspar porphyry clasts, along with some aphanitic felsic volcanic material, were also present. The two sandstone samples yielded abundant zircon, most of which comprised euhedral, first-cycle grains. One grain from sample 10-KL-61 gave an age of 312 Ma (Middle Pennsylvanian); 53 grains gave ages ranging from 360 to 333 Ma (Early to Middle Mississippian), and nine additional grains gave ages of 383–360 Ma (Late Devonian; Figure 7a). A single grain gave a Neoarchean age of 2684 Ma. In sample 10-KL-63, forty-three grains gave ages of 360–342 Ma (Early Mississippian), fifteen grains gave ages ranging from 392 to 360 Ma (Middle to Late Devonian), and the seven remaining grains gave Neoproterozoic to Neoarchean ages (Figure 7b). Zircons recovered from the conglomerate sample (10-KL-64) were mainly subrounded to rounded, and the youngest ages that were obtained were 631 and 506 Ma (Figure 7c). Six grains gave ‘Grenvillian’ ages (1160–936 Ma) and the remaining grains gave Mesoproterozoic to Mesoarchean zircons, whose ages suggest derivation from the northwestern North American craton. The age ranges for detrital zircons from this latter sample are very similar to those obtained from a nearby sample (n=44; J.E. Wright, unpublished data, 2007).

The detrital zircon age data for the Barslow assemblage samples are consistent with the Early Mississippian to Pennsylvanian depositional age that was inferred from fossil-age information (see discussion above).

Attwood and Anarchist Groups and Mount Roberts Formation

One sample of pebble conglomerate from the Attwood Group in the Greenwood area (Figure 3), together with four samples of sandstone and conglomerate from the Greenwood and Rock Creek areas, all yielded very similar detrital zircon age signatures, with abundant Devonian to Pennsylvanian ages (Figure 8a–e). The Attwood conglomerate sample (09-KL-11) yielded one grain at 327 Ma and five more in the range of 355–344 Ma (Early to Middle Mississippian). Two samples of coarse- and fine-grained sandstone from a single locality in the Anarchist assemblage (10-KL-91,-92) each contain one or more zircons at 300–299 Ma (earliest Permian), significant populations of zircons at 310–300 Ma (Late Pennsylvanian) and abundant grains that are only slightly older. A calcarenite sample from the Anarchist group (10-KL-94) yields a similar age signature, with the three youngest grains giving ages of 310–308 Ma (Middle Pennsylvanian). The final Anarchist sandstone sample (10-KL-107) yielded a significant number of 800 Ma and older grains (Figure 8e); however, it also contains a large proportion of euhedral zircon grains with one grain at 340 Ma and five in the range of 365–350 Ma (Late Devonian to Early Mississippian). This sample was collected less than 1 km from the felsic tuff sample that yielded a latest Devonian U-Pb zircon depositional age of 365.2 ±1.0 Ma (see discussion above). Collectively the detrital zircon age information from the Greenwood–Rock Creek area shows that much of the Attwood and Anarchist groups are Middle or Late Pennsylvanian in age, and part(?) may be younger than earliest Permian but that the Anarchist, at least locally, also includes felsic metatuff that is latest Devonian in age.

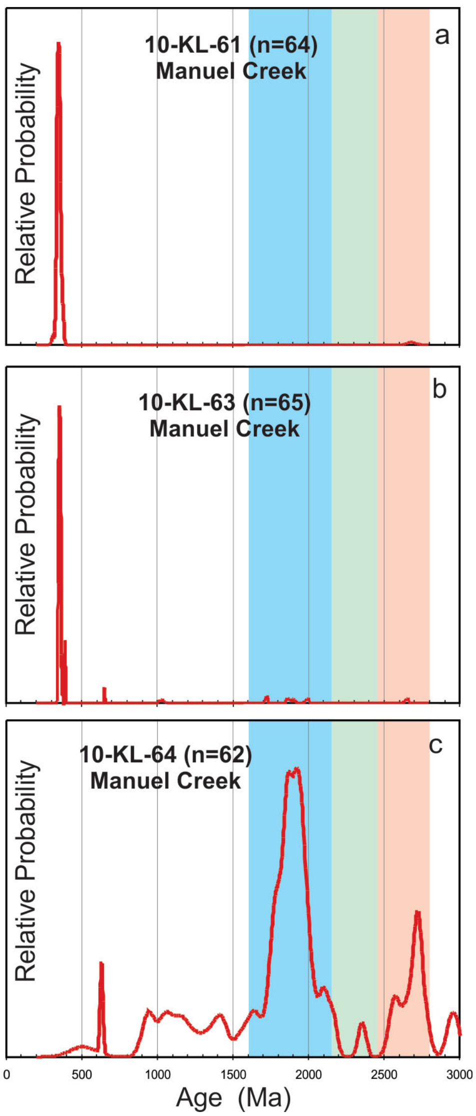

Figure 7. Probability density plots for detrital zircon ages from samples of the Barslow assemblage collected from **a)** a coarse-grained sandstone; **b)** a fine-grained sandstone; **c)** a pebble conglomerate at Manuel Creek. Colour bands are: pink, 2450–2800 Ma; green, 2150–2450 Ma; blue, 1600–2150 Ma. These age ranges are typical for detrital zircons shed from the northwestern part of the North American craton (Gehrels et al., 1995; Gehrels and Ross, 1998; Leslie, 2009; Lemieux et al., 2011; Kraft, 2013).

Detrital zircons from a sample of Mount Roberts Formation in the Kettle Falls area in northern Washington state were analyzed by Roback and Walker (1995) using the isotope dilution–thermal ionization mass spectrometry method. The Mount Roberts assemblage is generally thought to be correlative with the Anarchist Group. Only 23 single zircon grains were analyzed; however, the age signature (Figure 8f) shows a substantial population of grains with ages ranging from 2719 to 1001 Ma, but four grains with ages of 378–375 Ma (early Late Devonian), which is generally consistent with the ages obtained from some of the Anarchist samples in this study.

Most of the samples contained minor Mesoproterozoic and Archean populations, whose ages suggest derivation from the northwestern part of the North American craton.

Lithogeochemical Studies

A total of 61 samples of greenstone (and some mafic intrusive rocks) was collected during this study, with the goal of geochemically characterizing the igneous components of each of the Paleozoic assemblages, and to use these results in an attempt to establish the tectonic setting in which the rocks were erupted. The new data has been compiled along with extensive datasets from the Greenwood and Rock Creek areas (Dostal et al., 2001; Massey and Dostal, 2013a), and from potentially correlative successions in northern Washington state (Gaspar, 2005). The data generated by this study will be presented in detail in a separate publication, but the main characteristics of the various assemblages are described briefly herein, along with the overall tectonic significance of these results.

Hedley–Keremeos–Osoyoos Area

Geochemical data from greenstone contained within the Independence–Bradshaw, Old Tom, Shoemaker, Barslow and Kobau assemblages are plotted on a variety of geochemical and tectonic discrimination diagrams in Figure 9. Analyses for two samples from a thick gabbro sill within the Old Tom greenstone on the southwestern side of the Silmilkameen River near Cawston are also included, along with two analyses of mafic tuff in the Oregon Claims formation near Hedley (from Ray et al., 1996). There is a large degree of scatter on the total alkalis versus silica diagram (Figure 9a) of Le Bas et al. (1986), and at least some of this is likely due to mobility of alkalis and other elements during alteration that these rock units experienced after they were erupted on the seafloor, or during greenschist– to locally lower-amphibolite–facies regional metamorphism and later surface weathering. However, on a plot of immobile-element ratios (Figure 9b), the data also shows a significant amount of scatter, suggesting that a substantial range of protolith compositions is represented within this suite of samples. Most of the samples yielded basalt to alkaline-basalt compositions. One sample of greenstone from the Independence–Bradshaw assemblage yielded an anomalously high Zr/TiO_2 ratio (Figure 9b). This may reflect contamination by mixing of a trace amount of detrital zircon into a mafic volcaniclastic rock unit. On a Shervais-type discrimination diagram of V versus Ti (Shervais, 1982; Figure 9c) samples fall in both arc and non-arc fields; however, some consistent trends are observed. All of the Barslow samples plot as arc rocks, whereas all but one of the Kobau samples yield non-arc (mid-ocean ridge basalt [MORB] and within-plate) compositions. Old Tom and Shoemaker greenstone samples are equally split between arc and non-arc signa-

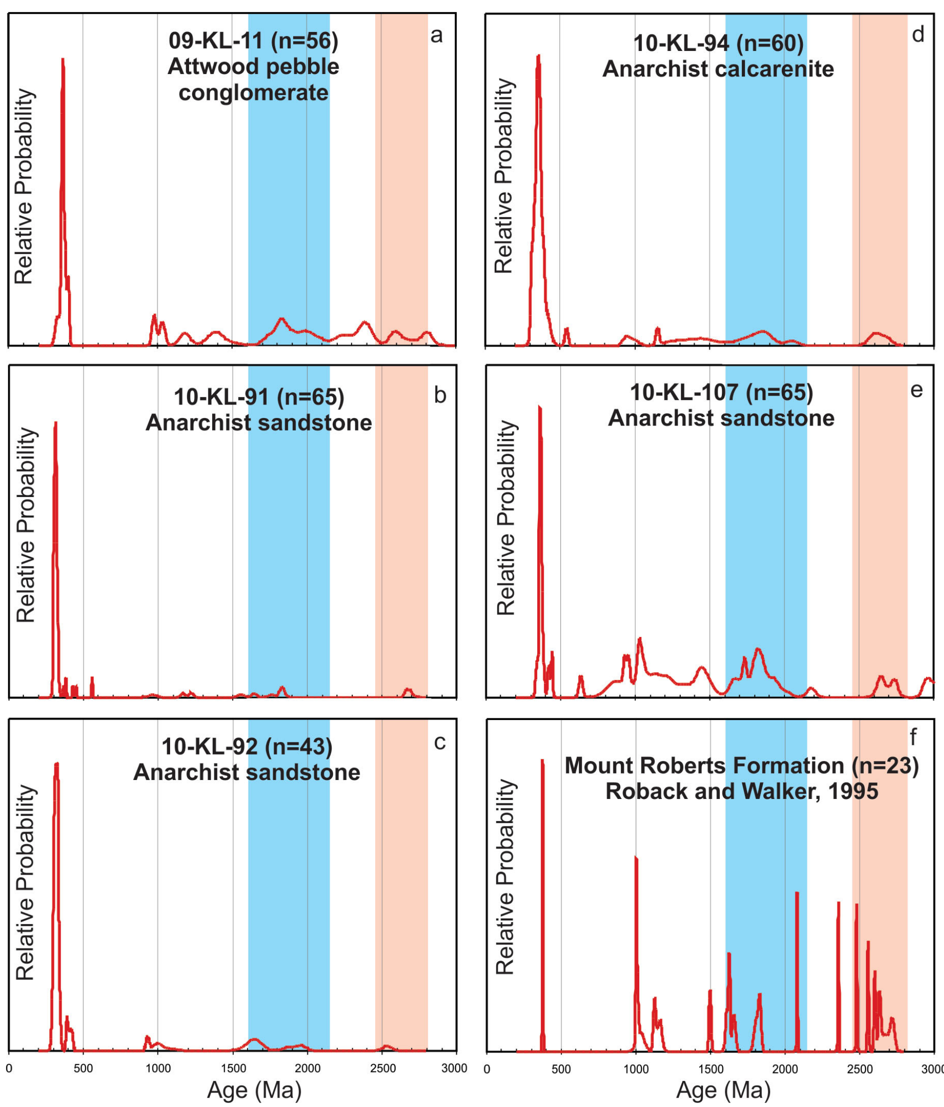

Figure 8. Probability density plots for detrital zircon ages from samples of **a)** Attwood pebble conglomerate; **b), c)** Anarchist sandstone: **d)** Anarchist calcarenite; **e)** another Anarchist sandstone; **f)** the Mount Roberts assemblage. Colour bands are: pink, 2450–2800 Ma; green, 2150–2450 Ma; blue, 1600–2150 Ma. These age ranges are typical for detrital zircons shed from the northwestern part of the North American craton (Gehrels et al., 1995; Gehrels and Ross, 1998; Leslie, 2009; Lemieux et al., 2011; Kraft, 2013).

tures in Figure 9c. Two samples from a thick gabbro sill that intrudes Old Tom greenstone on the southwestern side of the Similkameen River across from Cawston (Figure 2) plot as alkaline basalt on the Nb/Y versus Zr/TiO_2 plot (Winchester and Floyd, 1977; Figure 9b) and in the alkaline field on the Shervais plot (Figure 9c); these samples also fall in the enriched mid-ocean ridge basalt (E-MORB) and ocean-island basalt fields on a Wood (1980) ternary plot (Figure 9d). The Barslow greenstone, as well as a few greenstone samples from the Old Tom and Shoemaker assemblages, one sample from the Independence–Bradshaw assemblage and interestingly, both samples from the Ore-

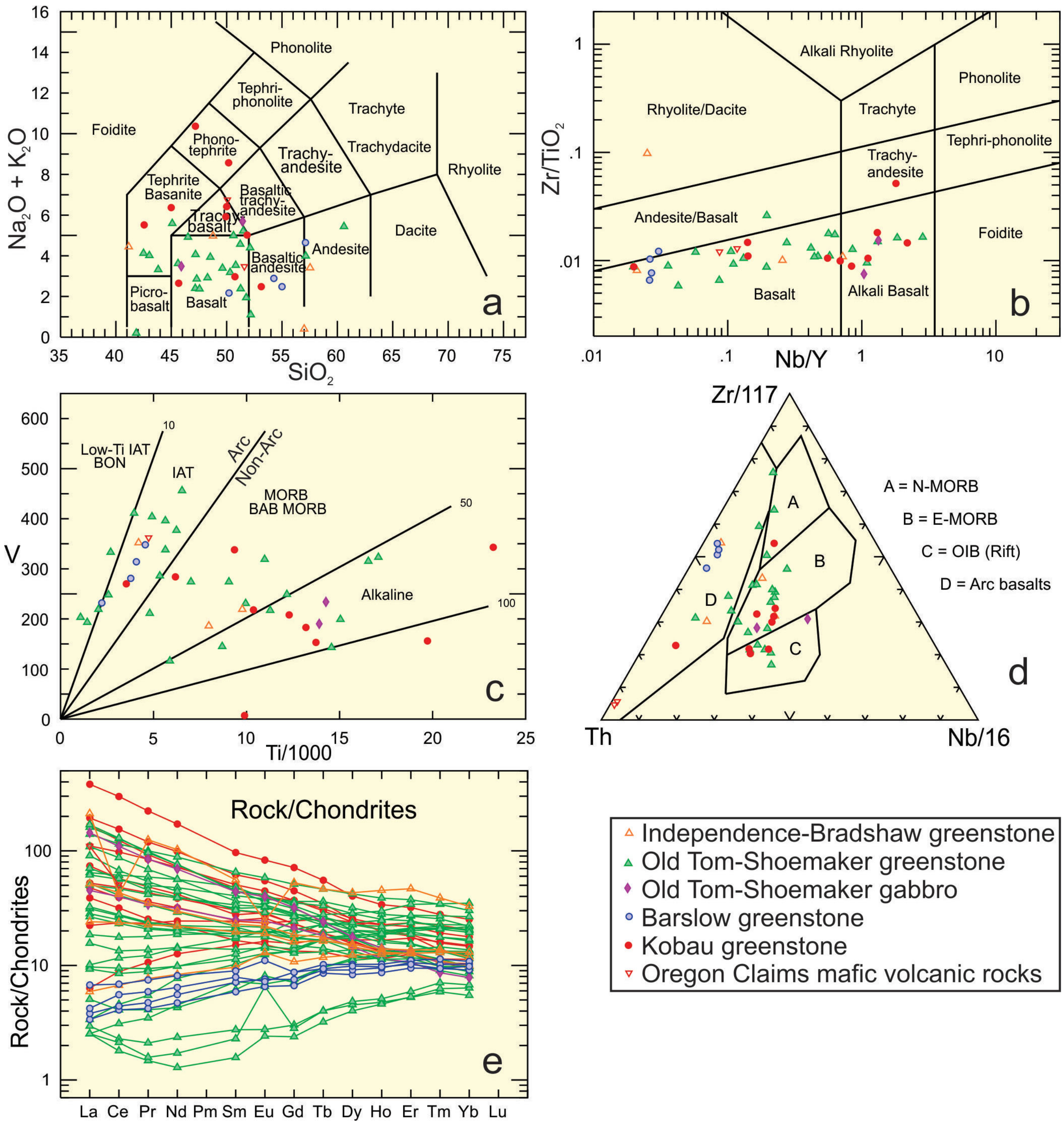

Figure 9. Lithogeochemical discrimination diagrams for samples from the Independence–Bradshaw, Old Tom, Shoemaker, Barslow and Kobau assemblages. Data are from this study, except two analyses of samples from the Oregon Claims formation that are from Ray et al. (1996). References for the various discrimination diagrams are **a)** Le Bas et al. (1986); **b)** Winchester and Floyd (1977) as revised by Pearce (1996); **c)** Shervais (1982); **d)** Wood (1980); **e)** Sun and McDonough (1989). Abbreviations: BAB MORB, back-arc basin mid-ocean ridge basalt; BON, boninite; E-MORB, enriched mid-ocean ridge basalt; IAT, island-arc tholeiite; MORB, mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt; OIB, ocean-island basalt.

gon Claims formation (data from Ray et al., 1996), also plot as arc rocks on the Wood (1980) discrimination diagram (Figure 9d). On a plot of rare earth elements (REE), normalized to chondritic values (Sun and McDonough, 1989; Figure 9e), the Barslow samples show consistent minor light-REE depletion, as do several samples from the Old Tom and Shoemaker and one from the Independence–Bradshaw assemblage. Most other samples show slight to strong light-REE enrichment.

The paucity of depositional ages for igneous rock units analyzed in this study from each of the assemblages makes it difficult to establish whether rock units of similar age throughout the whole area show comparable compositions, possibly reflecting a similar evolution of tectonic setting over time (see later discussion).

Greenwood–Rock Creek and Loomis (Washington State) Areas

Dostal et al. (2001) and Massey and Dostal (2013a, b) have produced an extensive set of lithogeochemical data for mafic volcanic rocks and gabbro from the Greenwood and Rock Creek areas. A limited number of additional samples from the area were analyzed for this study, and the entire dataset is presented in a series of geochemical and tectonic discrimination diagrams in Figure 10a–e. A substantial number of lithogeochemical analyses were also reported for samples from the 'Palmer Mountain greenstone' unit in the Loomis area of northern Washington state by Gaspar (2005; see earlier discussion). Massey and Dostal (2013a) demonstrate that the Knob Hill greenstone and gabbro show a mainly island-arc tholeiite (IAT) affinity, with minor MORB and E-MORB units present as well. They suggest that greenstone from the Anarchist Group mainly shows within-plate E-MORB compositions, along with some units that give IAT and MORB signatures. Most Knob Hill greenstone and all Knob Hill gabbro, as well as the Palmer Mountain greenstone analyses, show a very limited range of lithogeochemical compositions, with almost all plotting as arc rocks on the Shervais (1982)- and Wood (1980)-type plots (Figure 10c, d).

As with the sample suite discussed previously from the Hedley–Keremeos–Osoyoos area, the data from the Greenwood–Rock Creek–Loomis areas show a considerable range of compositions and inferred paleotectonic settings. The limited age constraints from this area indicate that depositional ages of the various rock units range from Middle Devonian to Middle or Late Pennsylvanian, but there is insufficient age information to identify any significant geochemical trends over time.

Pb-Isotopic Studies of VMS and Related Mineralization the Southern part of the Quesnel Terrane

Numerous stratabound, apparently stratiform rhodonite occurrences, commonly associated with abundant hematitic jasperoid, have been recognized within the volcanic rock- and chert-dominated Paleozoic assemblages in the Quesnel terrane in south-central BC (Figures 2, 3). The presence of these occurrences, together with a single occurrence of massive iron formation interpreted to be >100 m thick and associated with widespread Cu and minor Zn anomalies in soil samples (Nova occurrence; MINFILE 092HSE249, BC Geological Survey, 2016; Nebocat, 1993, 1996; Figure 2), suggest that there could be potential for volcanogenic massive sulphide (VMS) mineralization in the region. Although no stratiform sulphide occurrences have been identified thus far in south-central BC, a significant stratiform Cu-Zn massive sulphide deposit (the Copper World Extension mine) is present in the Palmer Mountain area near Loomis, approximately 20 km south of the BC–Washington state border (Figure 3). This deposit was mined on a small scale in the early 1900s, and produced approximately 3500 tonnes of ore grading 3.1% Cu (Caron, 2008). Recent diamond drilling is reported to have intersected massive sulphide lenses up to 8 m thick, and up to 40 m of stratigraphically underlying footwall stringer-type mineralization (Caron, 2008). The deposit is hosted in the Palmer Mountain greenstone, which has been variably correlated with the Old Tom, Kobau, Knob Hill and/or Anarchist assemblages in the past by various workers. Although no reliable depositional ages are available for the Palmer Mountain greenstone, the lithogeochemical signature of the greenstone indicates that it formed in a magmatic arc environment, and this signature, together with the overall lithological character of the rocks, suggests that the Palmer Mountain greenstone most likely correlates with the Knob Hill Complex in the Greenwood area (as suggested by Massey and Dostal, 2013a; see discussion above).

A Pb-isotopic study of several samples of massive sulphides from drillcore from the Palmer Mountain deposit was undertaken to determine whether the massive sulphide mineralization is indeed syngenetic. Analytical data is given in Table 3, together with a Pb-isotopic analysis of mineralization from the deposit that was reported by Church (2010). The analytical results are shown on a ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb diagram in Figure 11. Fields of Pb-isotopic compositions for Paleozoic VMS deposits and occurrences in other terranes in the northern Cordillera that occupy a similar 'pericratonic' position as the Quesnel terrane area are also shown for comparison.

The Pb-isotopic analyses from the Palmer Mountain deposit are well clustered and relatively nonradiogenic (Figure 11). The data are entirely consistent with a VMS origin for the deposit, and suggest an association with very juvenile igneous source rocks. As shown in Figure 11, the deposit has some of the least radiogenic (most 'primitive') isotopic signatures of any Paleozoic VMS mineralization in the northern Cordillera. This would be consistent with the hostrocks (Palmer Mountain greenstone) representing a juvenile arc and/or ophiolitic complex. It is not possible at this time to correlate the Palmer Mountain greenstone with the assemblages north of the border. However, it was suggested above that these rocks are lithologically and geochemically very similar to the mainly Middle Devonian Knob Hill Complex. Greenstone and chert of Middle Devo-

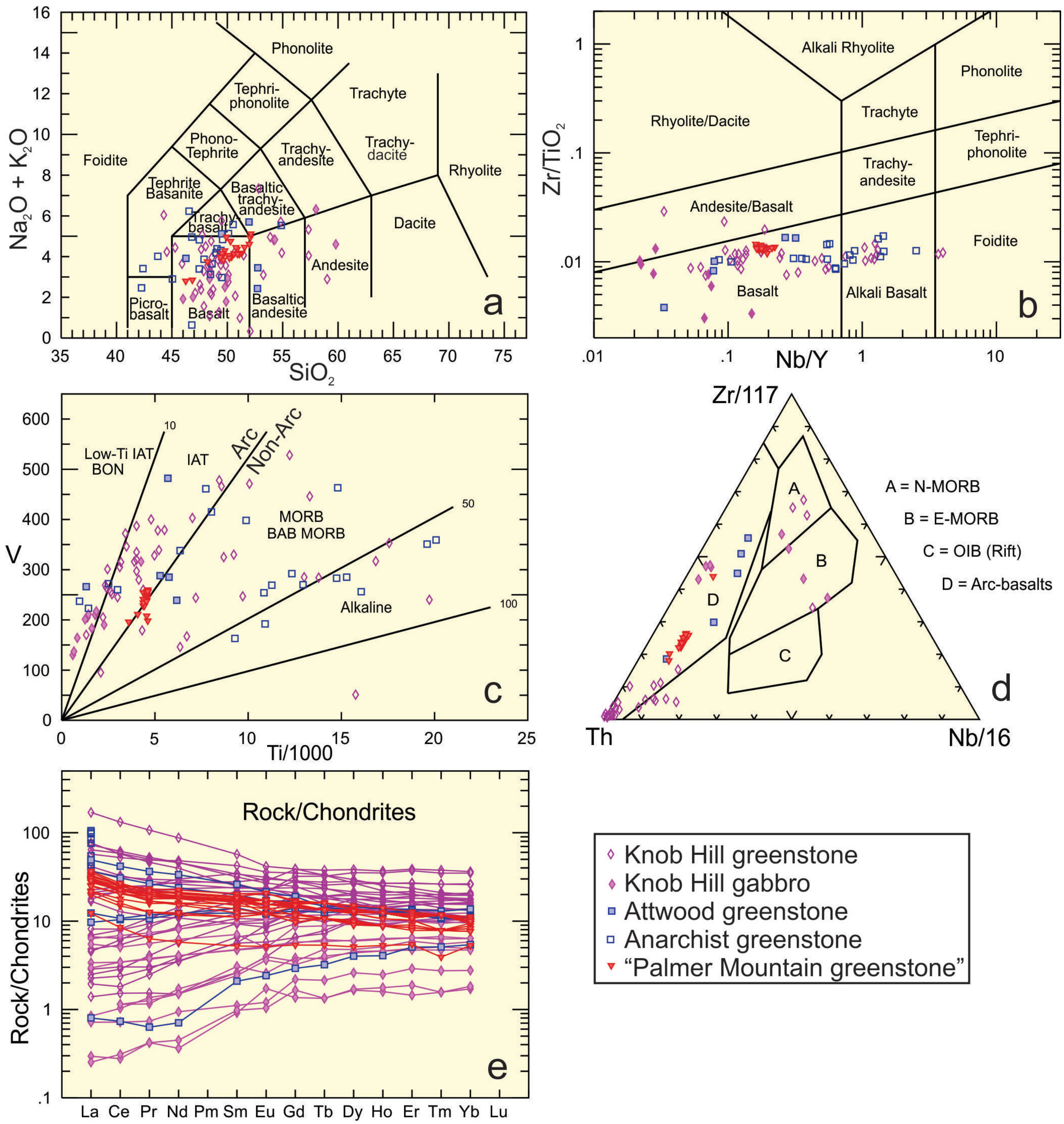

Figure 10. Lithogeochemical discrimination diagrams for samples from Knob Hill greenstone and gabbro, and Attwood and Anarchist greenstone (data from Dostal et al., 2001; Massey and Dostal, 2013a; this study), and the 'Palmer Mountain greenstone' in the Loomis area of northern Washington state (from Gaspar, 2005). References for the various discrimination diagrams are **a)** Le Bas et al. (1986); **b)** Winchester and Floyd (1977) as revised by Pearce (1996); **c)** Shervais (1982); **d)** Wood (1980); **e)** Sun and McDonough (1989). Abbreviations: BAB MORB, back-arc basin mid-ocean ridge basalt; BON, boninite ; E-MORB, enriched mid-ocean ridge basalt; IAT, island-arc tholeiite; MORB, mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt; OIB, ocean-island basalt.

Table 3. Lead-isotopic compositions of volcanogenic massive sulphide mineralization on the Palmer Mountain property near Loomis, Washington state.

Sample no.	Mineralogy	$^{206}Pb/^{204}Pb$	1σ error	$^{207}Pb/^{204}Pb$	1σ error	$^{208}Pb/^{204}Pb$	1σ error	$^{207}Pb/^{206}Pb$	1σ error	$^{208}Pb/^{206}Pb$	1σ error
PM-7-150.5-a[1]	py + sl	18.124	0.11	15.503	0.05	37.798	0.15	0.8554	0.09	2.0855	0.11
PM-7-150.5-b[1]	py + sl	18.198	0.03	15.502	0.02	37.633	0.03	0.8518	0.02	2.068	0.01
PM-5-186-a[1]	py+cp+sl	18.16	0.03	15.517	0.03	37.725	0.03	0.8545	0	2.0774	0.01
PM-5-186-b[1]	py+cp+sl	18.15	0.01	15.507	0.01	37.692	0.01	0.8544	0	2.0767	0.01
PM-5-186-b[1]	py+cp+sl	18.139	0.03	15.47	0.02	37.572	0.03	0.8529	0.02	2.0713	0.02
PM-5-186-b[1]	py+cp+sl	18.194	0.02	15.523	0.02	37.746	0.03	0.8532	0.01	2.0746	0.01
PM-5-145-a[1]	py	18.141	0.02	15.469	0.02	37.57	0.02	0.8527	0.01	2.071	0.01
PM-5-145-b[1]	py	18.111	1	15.404	1	37.51	1.02	0.8505	0.12	2.0711	0.18
86WACWE 3[2]	py+cp+po	18.16		15.54		37.793					

[1]Source of data: this study
[2]Source of data: Church (2010)
All analyses done at the Pacific Centre for Isotopic and Geochemical Research, University of British Columbia, Vancouver

nian age are also recognized in the Old Tom, Shoemaker and Independence–Bradshaw assemblages in the Hedley–Keremeos–Osoyoos area, and it is interesting to note that many of the known rhodonite occurrences in the Paleozoic rocks in southern BC occur within the Old Tom and Shoemaker assemblages (Figure 2). None of these rhodonite occurrences, or the Nova iron formation in the Crater Mountain area (Nebocat, 1996; Figure 2), contain significant amounts of sulphides, with the exception of trace amounts of pyrite, pyrrhotite and chalcopyrite in the Clearcut rhodonite occurrence (MINFILE 082ESE241), 13 km northeast of Greenwood (Caron, 1996; Simandl and Church, 1996; Figure 3). It is therefore not possible to compare the Pb-isotopic signature of these occurrences with that of the Copper World Extension mineralization. Caron (1996) briefly describes small zones of massive pyrite, pyrrhotite and chalcopyrite in the vicinity of the Clearcut occurrence that contain up to 0.4% Cu and anomalous levels of Pb and Zn. However, the relationship, if any, between these sulphide occurrences and the rhodonite exhalite is uncertain. The area has experienced strong contact metamorphism and it is possible that the massive sulphides result from later skarn development (Caron, 1996).

Stratabound, apparently syngenetic, lenses of recrystallized barite are interlayered with clastic rocks of the Anarchist Group at the Lapin and Dan occurrences (BC MINFILE 082ESW256 and 082ESW168, respectively), approximately 8 km southwest of Rock Creek (Figure 3). These occurrences are not obviously associated with geochemical anomalies that would suggest a relationship with base-metal–rich sedimentary exhalative- or volcanogenic massive sulphide-type deposits. However, the presence of stratiform barite within the Anarchist Group, does suggest that there may be potential for other syngenetic deposits in this assemblage, especially in light of the 365 Ma felsic tuff unit that was dated approximately 9 km east of the barite mineralization (this study; see earlier discussion).

Tectonic Synthesis and VMS Potential of the Paleozoic Basement of the South-Central Part of the Quesnel Terrane

Limited fossil-age constraints indicate that the Paleozoic volcanic and sedimentary assemblages of the southern part of the Quesnel terrane get as old as late Middle and Late Devonian, but most are Mississippian to Pennsylvanian, and some are as young as Early Permian in age (this study). Several gabbro bodies that are part of the Knob Hill Complex in the Greenwood area have yielded consistent Middle Devonian U-Pb zircon ages (Massey et al., 2013). A thin felsic metavolcanic (probably metatuff) unit within the Anarchist Group yields a 365 Ma (latest Devonian) U-Pb zircon age (this study). However, detrital zircon ages of euhedral grains from several clastic rock units, especially in the Greenwood area but also in the Independence–Bradshaw assemblage near Hedley, are as young as 315–300 Ma (Middle Pennsylvanian to earliest Permian), indicating that depositional ages for some of the assemblages get at least as young as Early Permian (this study). Collectively therefore, the ages of the Quesnel terrane basement rocks in south-central BC are now known to span at least 90 million years.

Detrital zircon age signatures for the various Paleozoic assemblages that were investigated during this study are all very similar in terms of specific age populations that are present in each assemblage (although there are wide variations in the relative size of each age population between assemblages, and between individual samples within each assemblage). This is taken as strong evidence for a close primary stratigraphic linkage between all of the various assemblages that make up the Paleozoic basement of the southern part of the Quesnel terrane. Furthermore, the specific Mesoproterozoic to Neoarchean detrital zircon age populations indicate that all of the assemblages likely formed in a near-offshore position adjacent to the northwestern margin of the North American craton.

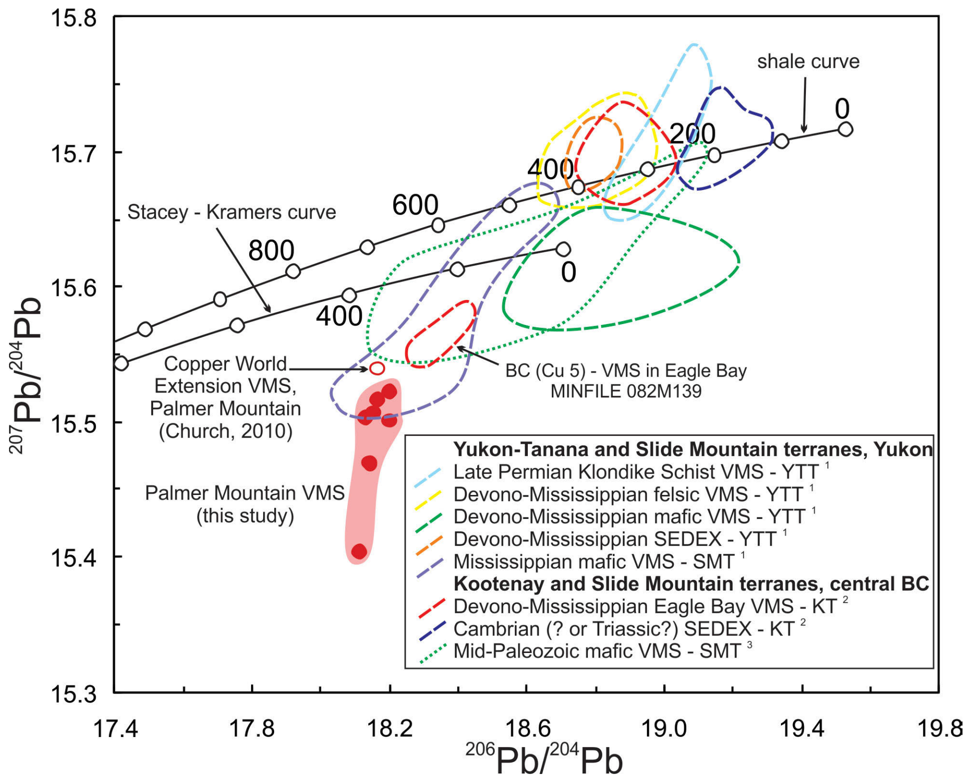

Figure 11. Plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ for sulphides from volcanogenic massive sulphide (VMS) mineralization in the Palmer Mountain greenstone near Loomis, Washington state (solid and open red circles, and dark pink field), together with data from VMS deposits and occurrences in a variety of other VMS deposits elsewhere in the northern Cordillera. The 'shale curve' of Godwin and Sinclair (1982), which is an approximation of the evolution of upper crustal Pb isotopes in the miogeocline of western North America and adjacent pericratonic terranes (Mortensen et al., 2006), and the global average upper crustal Pb-isotopic growth curve of Stacey and Kramers (1975) are shown for reference, as is a MINFILE occurrence in Eagle Bay (BC Geological Survey, 2016). Sources of data for outlined fields are: (1) Mortensen et al. (2006); (2) Goutier (1987); (3) Aggarwal and Nesbitt (1984). Abbreviations: KT, Kootenay terrane; SEDEX, sedimentary exhalative sulphides; SMT, Slide Mountain terrane; VMS, volcanogenic massive sulphides; YTT, Yukon–Tanana terrane.

A considerable range of tectonic affinities is indicated by the lithogeochemical studies of the metavolcanic rocks in the southern part of the Quesnel terrane (Gaspar, 2005; Massey and Dostal, 2013a; this study). Some packages (especially the Barslow, parts of Knob Hill and parts of Old Tom assemblages) show definitive magmatic arc chemistry; however, most assemblages yield mainly non-arc chemistry (normal mid-ocean ridge basalt, enriched mid-ocean ridge basalt and ocean-island basalt). Existing age constraints are not sufficient to establish whether consistent correlations exist between age and indicated paleotectonic affinity. Detailed lithogeochemical and U-Pb studies of the Knob Hill Complex by Massey and Dostal (2013a) and Massey et al. (2013), respectively, suggest that magmas typical of both arc and possibly fore-arc settings were erupting more or less simultaneously in that part of the Quesnel terrane in Middle and Late Devonian time. The presence of nearly coeval igneous suites with markedly different petrotectonic affinities is well recognized in many of the pericratonic terranes that make up the easternmost part of the North American Cordillera (e.g., Piercey et al., 2006). Recent detailed lithogeochemical and isotopic studies of the middle Paleozoic Sicker Group on Vancouver Island by Ruks (2015) has shown that such a 'mixed' petrotectonic signature also appears to be relatively common in some more juvenile arc settings. The Harper Ranch assemblage, which is mainly exposed farther to the north within the Quesnel terrane, was not investigated in the present study; however, limited lithogeochemical work on that package suggests a more clearly magmatic arc/back-arc affinity than is observed in most of the Paleozoic assemblages of south-central BC (e.g., Monger et al., 1991; Beatty, 2003).

Extensive U-Pb–dating studies of detrital zircons extracted from thin clastic units (greywacke to fine-grained quartz sandstone) that are interlayered with the mafic volcanic and chert-dominated assemblages (Old Tom and Shoemaker, Independence, Bradshaw) indicate variable mixtures of well-rounded, probably extensively recycled Neoarchean to Mesoproterozoic zircons, whose age ranges are consistent with having been derived mainly from the northwestern part of the North American craton, and subhedral to euhedral grains that are much less travelled and yield Late Devonian and younger ages. Assemblages that are dominantly clastic in nature (Attwood and parts of the Barslow and Anarchist assemblages) show a similar mix of detrital zircon ages; however, these samples typically contain a much higher proportion of the middle and late Paleozoic grains, and locally also contain felsic porphyry and rhyolite clasts. Preliminary detrital zircon dating of euhedral grains (n=25) from a single sample from the oldest known, Late Devonian, part of the Harper Ranch assemblage near Kamloops (J.E. Wright, unpublished data, 2007) shows a nearly unimodal age range of Late Devonian to Early Mississippian. The detrital zircon dating results of this study are therefore interpreted as indicating that the Attwood Formation and probably much of the Anarchist Group are likely correlative with the Harper Ranch Group to the north, as has been suggested by some previous workers (e.g., Nelson et al., 1995). The complete overlap between the detrital zircon age signatures of the various Paleozoic assemblages that make up the Quesnel terrane in south-central BC strongly suggests that these assemblages probably formed in close proximity to one another, in an original position off the northwestern margin of the North American craton.

The different assemblages that make up the Paleozoic basement of the southern part of the Quesnel terrane comprise varying proportions of 1) rocks that were deposited in a mainly oceanic setting (mafic volcanic rocks and chert) and 2) clastic rocks that include a large proportion of material that was likely shed off of a magmatic arc (as first recognized by Peatfield, 1978). The latter component is correlated with the Harper Ranch Group as defined in the Kamloops area (Beatty et al., 2006), on the basis of both rock units and detrital zircon age signature. Although the mafic volcanic rock and chert component reflects deposition in a submarine basin, a minor component of clastic rocks with close similarities to the Harper Ranch equivalents is present throughout the package, indicating that this basin was not far removed from the site of eruption and deposition of the Harper Ranch Group and its equivalents.

Lithogeochemical studies indicate a diversity of paleotectonic settings for Paleozoic magmatism in the Quesnel terrane in south-central BC. There is insufficient information as yet to determine whether there was any consistent change in paleotectonic setting with time; however, in at least some of the assemblages (e.g., Knob Hill) both arc and non-arc magmatism was occurring simultaneously.

Lead-isotopic studies of stratabound Zn-Cu massive sulphide mineralization in the Palmer Mountain area immediately south of the BC–Washington state border, which is hosted in mafic volcanic rocks that are coextensive with the Paleozoic mafic rocks of the southern part of the Quesnel terrane, confirm that this mineralization is indeed volcanogenic in nature. This emphasizes the potential for similar VMS mineralization within the volcanic-rock–dominated Paleozoic assemblages north of the border, especially because of the known occurrence of stratiform rhodonite in several localities. In addition, two occurrences of apparently stratiform barite are known within clastic rocks of the Anarchist Group southwest of Rock Creek, which suggests that there may be potential for SEDEX- or (distal) Kuroko-type VMS mineralization in that assemblage as well.

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