Boundary Project: Geochronology and Geochemistry of Jurassic and Eocene Intrusions, Southern British Columbia (NTS 082E)

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INTRODUCTION

The Boundary Project was initiated in 2005 with the purpose of better characterizing the lithological and geochemical variations within and between the various Paleozoic sequences in the southern Okanagan region along the United States border (Massey, 2006, 2007a, b; Massey and Duffy, 2008a–c). These sequences occur within Quesnel terrane, which is dominated by Paleozoic mafic volcanic and pelitic rocks that are unconformably overlain by Triassic and Jurassic volcanic and sedimentary rocks, and intruded by various suites of Triassic, Jurassic and Eocene granitic rocks. This paper documents the results of isotopic dating and lithogeochemical studies on several of the granitic intrusions in the project area.

ANALYTICAL METHODOLOGY

U-Pb Zircon Dating

Uranium-lead dating of zircons was carried out at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at The University of British Columbia, using the laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) method. Instrumentation employed at the PCIGR comprises a New Wave UP-213 laser-ablation system and a ThermoFinnigan Element2 single-collector, double-focusing, magnetic-sector ICP-MS. Data acquisition and reduction protocols at the PCIGR have been described by Tafti et al. (2009), and are summarized below. Zircons were hand-picked from the heavy mineral concentrate and mounted in an epoxy puck along with several grains of the Plešovice zircon standard (Sláma et al., 2007), together with an in-house, 197 Ma standard zircon, and brought to a very high polish. High-quality portions of each grain free of alteration, inclusions or possible inherited cores were selected for analysis. The surface of the mount was washed for 10 minutes with dilute nitric acid and rinsed in ultraclean water prior to analysis. Line scans rather than spot analyses were employed in order to minimize elemental fractionation during the analyses. Backgrounds were measured with the laser shutter closed for 10 seconds, followed by data collection with the laser firing for approximately 29 seconds. The time-integrated signals were analyzed using GLITTER software (Van Achterbergh et al., 2001; Griffin et al., 2008), which automatically subtracts background measurements, propagates all analytical errors and calculates isotopic ratios and ages. Corrections for mass and elemental fractionation were made by bracketing analyses of unknown grains with replicate analyses of the Plešovice zircon standard. A typical analytical session at the PCIGR consists of four analyses of the standard zircon, followed by four analyses of unknown zircons, two standard analyses, four unknown analyses, etc., and finally four standard analyses. The 197 Ma in-house zircon standard was analyzed as an unknown in order to monitor the reproducibility of the age determinations on a run-to-run basis. Final interpretation and plotting of the analytical results employ the Isoplot software (version 3.09; Ludwig, 2003). Interpreted ages are based on a weighted average of the individual calculated $^{206}Pb/^{238}U$ ages.

Although zircons typically contain negligible amounts of initial common Pb, it is important to monitor the amount of ^{204}Pb present in order to evaluate the amount of initial common Pb, and/or blank Pb, that is present in the zircons being analyzed. The argon that is used in an ICP-MS plasma commonly contains at least a small amount of Hg, and approximately 7% of natural Hg has a mass of 204. Measured count rates on mass 204 include ^{204}Hg as well as any ^{204}Pb that might be present, and direct measurement of ^{204}Pb in a laser-ablation analysis is therefore not possible. Instead, mass 202 is monitored; this corresponds exclusively to ^{202}Hg. The expected count rate for ^{204}Hg present in the analysis can then be calculated from the known isotopic composition of natural Hg, and any remaining counts at mass 204 can be attributed to ^{204}Pb. Using this method, it is possible to conclude that there was no measurable ^{204}Pb present in any of the analyses in this study.

Ar/Ar Dating

Biotite and hornblende for $^{40}Ar/^{39}Ar$ dating were hand-picked from fine crushed samples. Mineral separates for dating were wrapped in aluminum foil and stacked in an irradiation capsule with samples of similar age and neutron flux monitors (Fish Canyon Tuff sanidine [FCs], 28.02 Ma; Renne et al., 1998). The samples were irradiated at the McMaster Nuclear Reactor in Hamilton, Ontario for 90 MWh, with a flux of approximately 6 x 10^{13} neutrons/cm^2/s. Analyses (n = 45) of 15 neutron-flux monitor positions produced errors of <0.5% in the J value. The samples were analyzed at the Noble Gas Laboratory of the PCIGR. The mineral separates were step-heated at incrementally higher powers in the defocused beam of a 10W CO_2 laser (New Wave Research MIR10) until fused.

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The gas evolved from each step was analyzed by a VG5400 mass spectrometer equipped with an ion-counting electron multiplier. All measurements were corrected for total system blank, mass spectrometer sensitivity, mass discrimination, radioactive decay during and subsequent to irradiation, and interfering Ar from atmospheric contamination and the irradiation of Ca, Cl and K (isotope production ratios: $(^{40}Ar/^{39}Ar)_K$ = 0.0302 ±0.00006; $(^{37}Ar/^{39}Ar)_{Ca}$ = 1416.4 ±0.5; $(^{36}Ar/^{39}Ar)_{Ca}$ = 0.3952 ±0.0004; Ca/K = 1.83 ±0.01$(^{37}Ar_{Ca}/^{39}Ar_K)$. Plateau and correlation ages were calculated using Isoplot (Ludwig, 2003). Errors are quoted at the 2 (95% confidence) level and are propagated from all sources except mass spectrometer sensitivity and age of the flux monitor.

Results of the dating studies are briefly summarized in Table 1. Complete analytical data are presented in Massey et al. (2010). Locations of samples are shown in Figure 1.

JURASSIC AND EOCENE INTRUSIONS

Greenwood Area

GREENWOOD STOCK

Several granodiorite stocks and smaller bodies in the Greenwood area have been ascribed to the Jurassic Nelson suite (Little, 1983; Fyles, 1990). The Greenwood stock (sample 1 on Figure 1 and in Table 1) is one of these bodies, centred on the city of Greenwood. Like the other intrusions, it consists of medium- to coarse-grained, grey biotite-hornblende granodiorite to quartz diorite. It intrudes chert and basalt of the Knob Hill Complex and lies in the footwall of the western extension of the Snowshoe fault, a listric normal fault of Tertiary age (Fyles, 1990).

Results of laser-ablation determinations (Figure 2a) yield a latest Early Jurassic age of 179.9 ±3.8 Ma. This is slightly older than the reported age of 172.5 ±5.0 Ma for the oldest phases of the Nelson batholith (Ghosh, 1995) and suggests earlier plutonic activity in the Boundary district. It is, however, slightly younger than the volcanic rocks of the Sinemurian Elise Formation of the Rossland Group (Höy and Dunne, 1997).

GIDON CREEK PORPHYRY

The Gidon Creek porphyry (sample 5 in Figure 1 and Table 1) is well exposed in roadcuts in the Norwegian Creek and Gidon Creek areas. The porphyry intrudes Triassic Brooklyn Formation metavolcanics in the footwall of the Number 7 fault, although its relationship to the fault was not directly observed.

The sample is a leucocratic quartz-feldspar porphyry. Pink perthitic K-feldspar megacrysts are subhedral to subrounded and about 1 cm in size, ranging up to 2 cm.

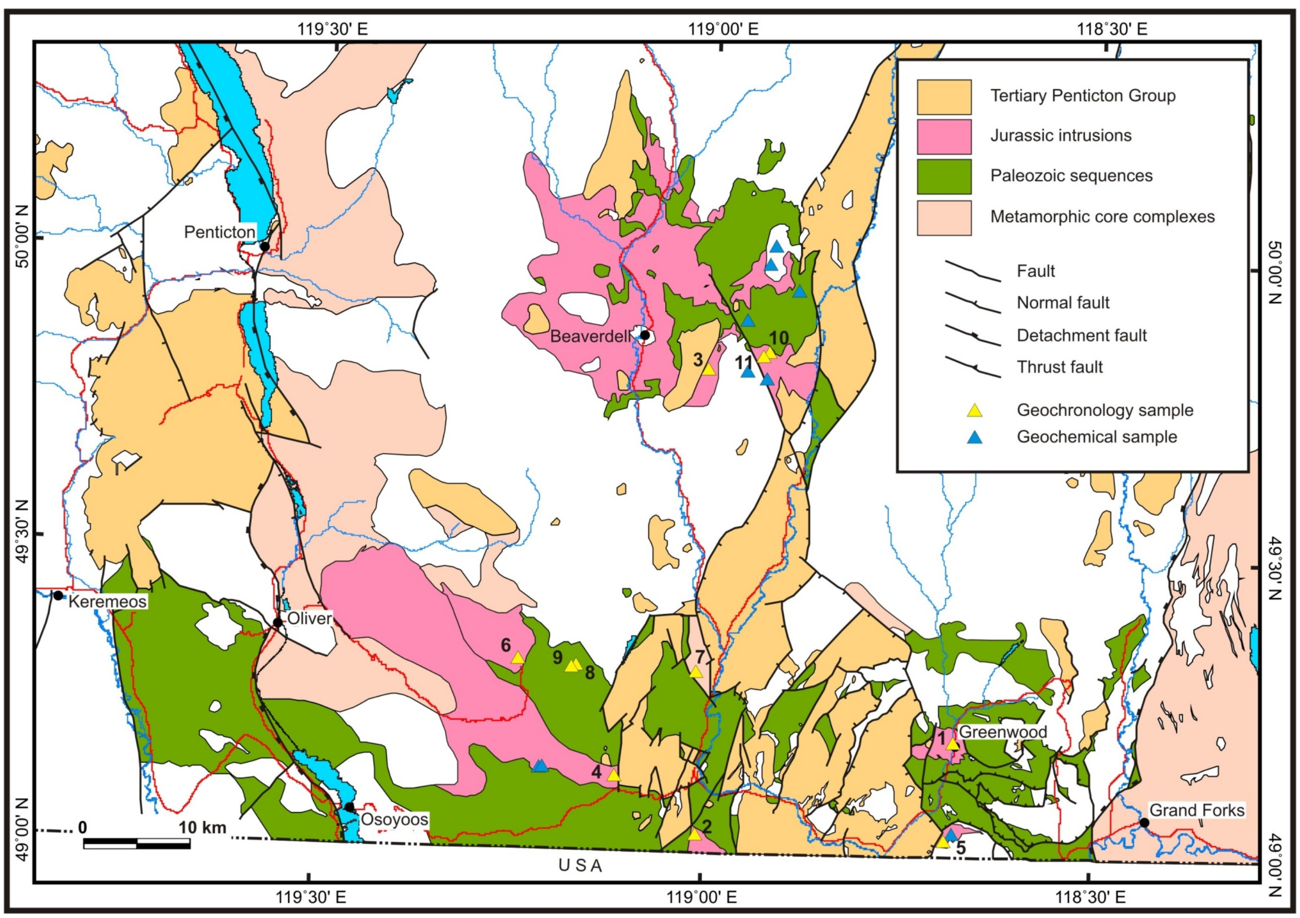


Figure 1. Regional geology of the Boundary Project area (amended from Massey et al., 2005), southern British Columbia, showing the location of samples collected for geochronology and geochemistry. Geochronological samples are numbered as in Table 1. The Paleozoic sequences include the Wallace Formation of the Beaverdell area, which may be Triassic. Only the sampled intrusions are shown on the map; others have been omitted.

Table 1. Summary of U-Pb zircon and $^{40}Ar/^{39}Ar$ ages obtained for intrusive samples collected during the Boundary Project, southern British Columbia. All UTM location data are in Zone 11, NAD83. Errors associated with individual ages are listed at the 2 level (95% confidence interval); see Massey et al. (2010) for complete analytical data.

	Sample number	Map unit	Latitude	Longitude	UTM		Area	Age		Note
			°N	°W	Northing	Easting		Ma	±	
Zircon (laser ablation)										
Jurassic intrusions										
1	06NMAGreenwood1	Greenwood stock (Nelson suite)	49.097050	118.680870	5439604	377298	Greenwood, Trans-Canada Trail	179.9	3.8	Some inherited zircons
2	06NMA05-01-02	Myer's Creek stock (Nelson suite)	49.016554	119.011395	5431245	352934	Old railway, west of Myncaster	157.0	1.2	
3	07NMA45-005	West Kettle batholith (Nelson suite)	49.410378	119.005005	5475009	354563	South Crystal Lake	213.5	0.9	
4	07NMA09-02	McKinney Creek stock (Nelson suite)	49.061520	119.116490	5436452	345390	Roadcut, Jolly Creek campsite	57.1	0.5	Inherited zircons ranging from 80 to ~2500 Ma
5	05NMA25-01B	Gidon Creek porphyry	49.009087	118.695168	5429850	376036	Gidon Creek	171.6	2.3	Inherited zircons ranging from 225 to 1978 Ma
6	07NMA09-01	Mount Baldy granodiorite	49.161480	119.240650	5447824	336650	South slope of ski hill	168.5	1.40	
Unknown age										
7	06NMA22-12A	Ed James orthogneiss	49.151378	119.017097	5446243	352916	Conkle Lake, Ed James Forest Service road	187.7	1.1	
	06NMA22-12B	Unfoliated leucogranite intrudes 06NMA22-12A	49.151378	119.017097	5446243	352916	Conkle Lake, Ed James Forest Service road	--	--	Insufficient zircons recovered
Hornblende ($^{40}Ar/^{39}Ar$)										
8	07NMA05-15-Hb	Diorite, McKinney Creek (Nelson suite?)	49.155757	119.164309	5447025	342198	Powerline, Rock Creek	--	--	No plateau age (extreme excess argon); no sensible isochron
9	07NMA05-16-Hb	Diorite, McKinney Creek (Nelson suite?)	49.154794	119.167530	5446925	341960	Powerline, Rock Creek	--	--	No plateau age; no sensible isochron
	07NMA05-16-Bio	Diorite, McKinney Creek (Nelson suite?)	49.154794	119.167530	5446925	341960	Powerline, Rock Creek	51.00 51.00	0.28 0.31	Plateau age Isochron
10	07NMA41-008-Hb	Crowded feldspar hornblende diorite'	49.420506	118.929211	5475992	360089	GK Property, Crouse Creek	--	--	No plateau age; no sensible isochron
11	07NMA43-010-Hb	Crowded feldspar hornblende diorite'	49.418590	118.937517	5475794	359482	GK Property, Crouse Creek	177.3	1.0	Plateau age

Plagioclase phenocrysts were also observed, although smaller than the K-feldspar. Quartz eyes are rounded and commonly 3–5 mm in size but ranging up to 10 mm. Groundmass is a white to pale pink, finer grained mosaic of quartz, K-feldspar and plagioclase crystals. Mafic minerals are sparse, with colour index often <5%, and are mostly biotite replaced by chlorite.

The margins of the porphyry are sheared, foliation varying from trachytic to mylonitic in appearance. Where preserved, phenocrysts are broken and strung out along the foliation. Quartz shows strained extinction in thin sections. Feldspars are completely altered to sericite, epidote and chlorite.

The Gidon Creek porphyry has been correlated with the nearby Lexington porphyry (Fyles, 1990), subsequently dated at 199 Ma by Church (1992) and Dostal et al. (2001). However, the Gidon Creek quartz-feldspar porphyry is lithologically and chemically distinct from the Lexington porphyry and probably not directly correlatable (Massey, 2007c). Zircons from the Gidon Creek porphyry confirm this, yielding a Middle Jurassic age of 171.6 ±2.3 Ma (Figure 3a). Xenocrystic zircons of several ages, including 225 Ma, 373–363 Ma, 1689 Ma and 1978 Ma, are also present in the sample (Figure 3a; the oldest two analyses are not shown in the figure).

The porphyry may correlate with the Silver King intrusions of the Rossland area, which have similar ages (Höy and Dunne, 1997). These synkinematic intrusions show intensely sheared margins similar to those of the Gidon Creek porphyry but lack the K-feldspar megacrysts (Dunne and Höy, 1992).

Rock Creek–McKinney Creek Area

MCKINNEY CREEK GRANODIORITE

The McKinney Creek granodiorite (sample 4 in Figure 1 and Table 1) forms a linear body just north of Bridesville. It has been correlated with the Nelson intrusions (Little, 1961; Tempelman-Kluit, 1989) and intrudes rocks of the Paleozoic Anarchist schist to the north and south. However, relationships with more gneissic rocks to the west are uncertain. The stock comprises two distinct phases: an early biotite granodiorite and later porphyritic

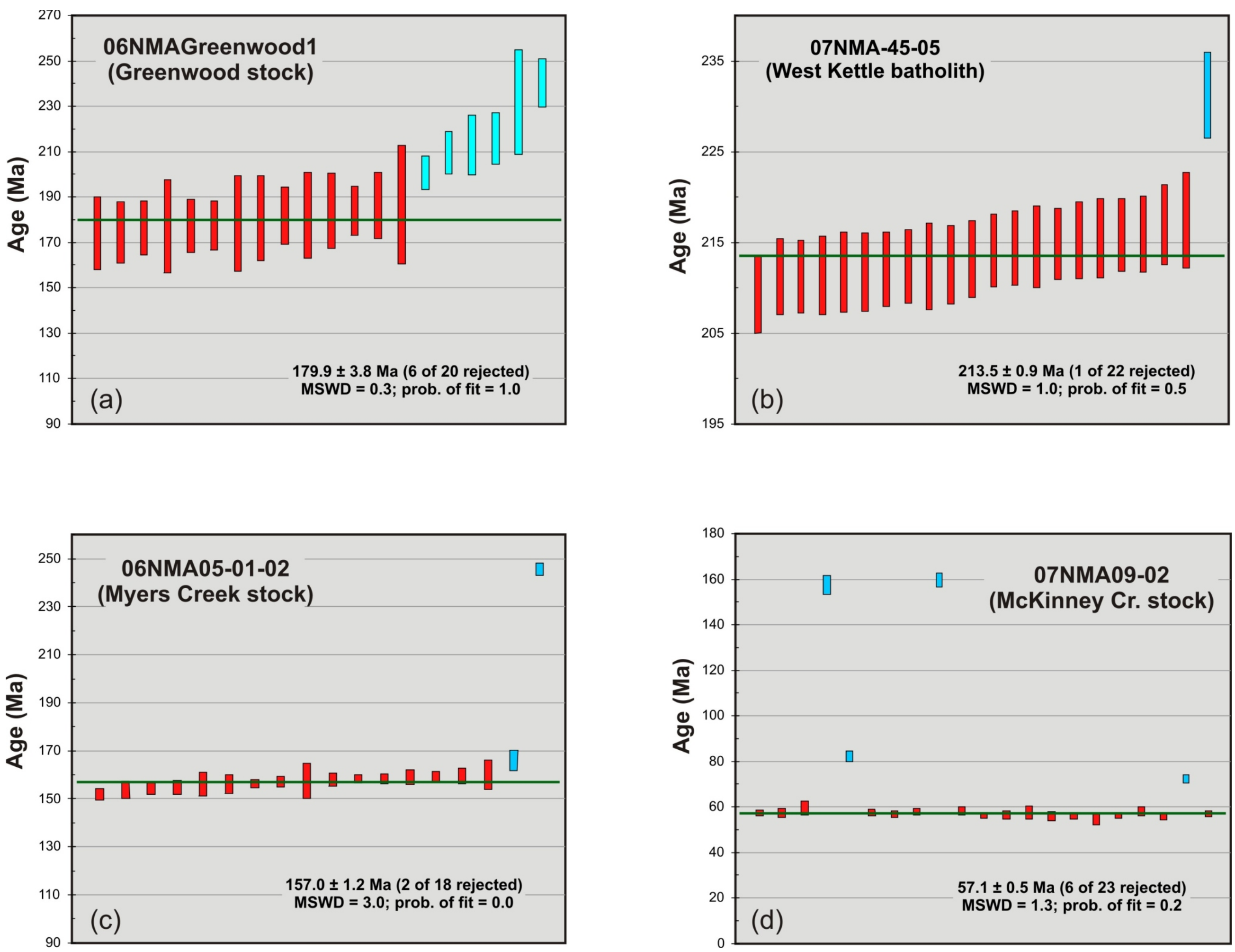
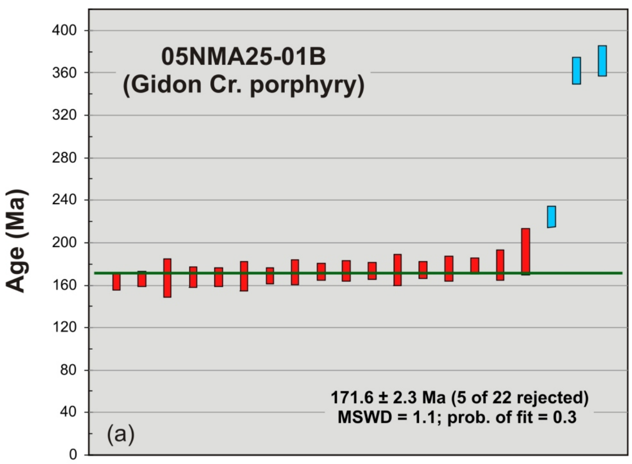


Figure 2. LA-ICP-MS zircon age determinations for 'Nelson suite' granitic bodies in the Boundary Project area, southern British Columbia: **a)** Greenwood stock, **b)** West Kettle batholith, **c)** Myers Creek stock, and **d)** McKinney Creek stock (two rejected samples >180 Ma have been omitted). See Table 1 for location data. Error bars for individual analyses and for the final weighted average ages on these and subsequent plots are shown at the 2 level. Analyses that were included in the weighted average age are shown as red bars and those that were rejected are shown as blue bars.

granodiorite. Only the biotite granodiorite was sampled for geochronometry. It is coarse grained (up to 4 mm) and white to grey. It is equigranular with typical 'salt-and-pepper' texture made up of white feldspar, translucent quartz and black biotite plates. Biotite also forms clots that can be up to 1 cm. Colour index averages 25. Small rounded amphibolite xenoliths are common and chlorite coats fractures and joints.

Zircons from the McKinney Creek biotite granodiorite yield a Paleocene age of 57.1 ±0.5 Ma (Figure 2d), with some older xenocrystic zircons ranging up to about 2500 Ma (two samples not plotted in Figure 2d). This is in contrast to an age of 160.5 ±2.0 Ma reported by Parkinson (1985), possibly within the same stock, to the northwest of Anarchist Mountain. However, it compares favourably with U-Pb ages of 62–54 Ma obtained from the Ladybird granite and is slightly older than the 52–50 Ma ages reported for the syenitic Coryell suite (Parrish et al., 1988; Ghosh, 1995). Parrish (1992b) also reported an age of 48 ±5 Ma, based on the lower intercept of discordant U-Pb zircon determinations, for biotite granite from the Okanagan batholith in the upper Kettle River area.



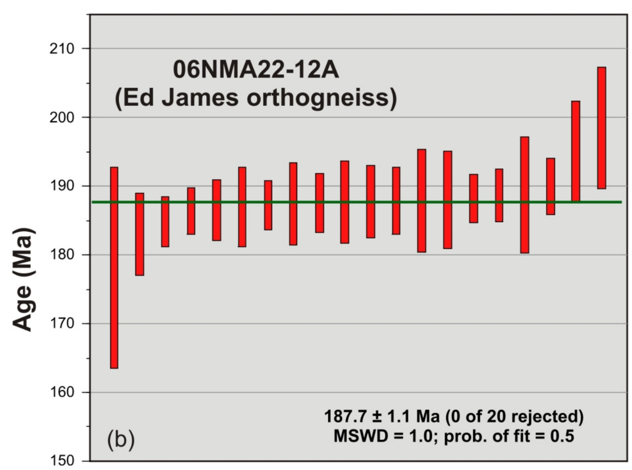


Figure 3. LA-ICP-MS zircon age determinations for felsic bodies of previously unknown age in the Boundary Project area, southern British Columbia: **a)** Gidon Creek porphyry (two rejected samples >100 Ma have been omitted), **b)** Ed James Creek orthogneiss. See Table 1 for sample locations.

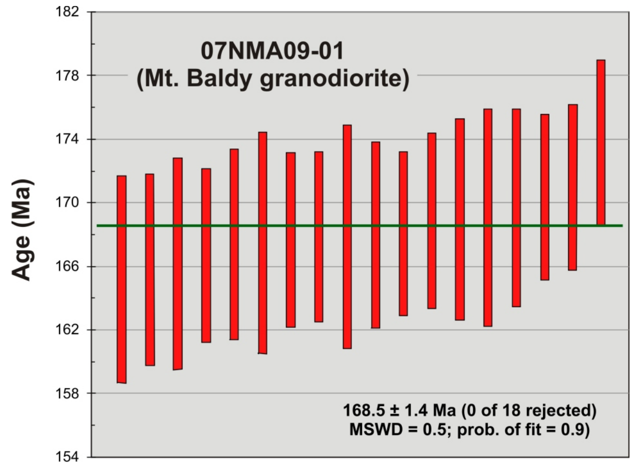


Figure 4. LA-ICP-MS zircon age determinations for the Mount Baldy stock, Boundary Project area, southern British Columbia. See Table 1 for sample locations.

MOUNT BALDY GRANODIORITE

The Mount Baldy granodiorite (sample 6 in Figure 1 and Table 1) is medium to coarse grained, ranging from 2 to 5 mm, and shows an equigranular phaneritic texture. It is light to dark grey and comprises euhedral white feldspar, irregular grey quartz and black tabular biotite. Chlorite alteration is apparent within the rock. The granodiorite is crosscut by feldspar porphyry dikes, assumed to be Tertiary in age. Isotropic, lath-shaped hornblende may be developed in the granodiorite around some porphyry dikes. The stock is part of the Okanagan batholith (Tempelman-Kluit, 1989), a larger body of poorly constrained Jura-Cretaceous age that includes K-feldspar megacrystic granite correlated with the Eocene Coryell suite (Massey and Duffy, 2008c).

Zircons from the Mount Baldy stock yield a Middle Jurassic age of 168.5 ±1.4 Ma (Figure 4), comparable to similar Middle Jurassic ages from the Nelson batholith and Bonnington pluton (Ghosh, 1995). It confirms the presence of Middle Jurassic magmatic products in the Okanagan batholith, although more mapping and geochronological studies are needed to adequately discriminate all its phases.

DIORITE-GABBRO

A belt of diorite occurs along the northeastern edge of the McKinney Creek map area (Massey and Duffy, 2008c), intruding rocks of the Paleozoic Anarchist schist. The unit comprises medium- to coarse-grained, black to grey diorite to gabbro that weathers dark greenish grey. The rock comprises varying quantities of equigranular greenish black hornblende and white feldspar, and occasional quartz. Shear zones are common, accompanied by flattening and stretching of minerals, white veinlets of feldspar and quartz, and chloritization. Pegmatitic diorite veins are also found. The unit is a composite intrusion with fine-grained chills between different diorite phases. These fine-grained chills are difficult to distinguish from basaltic dikes in small outcrops. Several ultramafic intrusions are spatially associated with the belt of diorite, and presumed to be genetically related.

The mafic rocks are intruded by, and included as xenoliths in, Jurassic (?) granodiorite and may be an older phase of the Nelson suite. Diorite and serpentinite are also intruded by the Mount Baldy granodiorite. Alternatively, the diorite and ultramafic rocks may be contemporaneous with older Jurassic ultramafic intrusions in the Greenwood area (e.g., on the Sappho property; Nixon, 2002).

Two samples of hornblende-rich diorite were collected for $^{40}Ar/^{39}Ar$ age determination (samples 8 and 9 in Figure 1 and Table 1). Unfortunately, the separated hornblendes showed excess argon and failed to yield a plateau age. However, one sample of biotite yielded a plateau age of 51.0 ±0.3 Ma (Figure 5), representing a cooling age after the regional heating effects of Eocene magmatism and extensional tectonics. The crystallization age for the diorite remains undetermined.

MYERS CREEK QUARTZ DIORITE

The Myers Creek stock (sample 2 in Figure 1 and Table 1) is a grey to orangey white quartz diorite to diorite. It is medium to coarse grained and equigranular, with a typical salt-and-pepper texture. It comprises white feldspar, colourless quartz, black flakey biotite and minor black hornblende. Mafic minerals locally form up to 30% of the rock. Like the McKinney Creek stock, the Myers Creek stock was correlated with the Nelson suite by Little (1961) and Tempelman-Kluit (1989). It is found in either faulted or intrusive contact with quartzite and metasedimentary rocks of the Anarchist schist (Massey, 2007a).

Zircons from the Myers Creek stock yielded an earliest Late Jurassic age of 157.0 ±1.2 Ma (Figure 2c). This is significantly younger than the other Jurassic intrusions sampled in the area, and the Middle Jurassic Nelson suite with which it was previously correlated. Magmatic activity in the Late Jurassic is poorly documented in southern BC. However, similar late Middle to early Late Jurassic ages have been reported from a biotite granite phase of the Nelson batholith (158.9 ±0.6 Ma; Sevigny and Parrish, 1993), a leucocratic gneiss remnant from the Kinnaid gneiss (156.6 ±6.0 Ma; Ghosh, 1995) and metaporphyry in the Nicola horst (158.3 ±0.6 Ma; Moore et al., 2000; 157.5 ±0.5 Ma; Erdmer et al., 2002), suggesting that this magmatism is more common in southern BC than previously believed.

ED JAMES CREEK ORTHOGNEISS

Orthogneiss forms an inlier in the Ed James Creek area (sample 7 in Figure 1 and Table 1), lying structurally beneath the Knob Hill Complex, although the bounding fault is not exposed. Schistosity within the gneiss is flat to moderately dipping to the east, matching that in the rocks of the overlying Knob Hill Complex and suggesting an easterly-dipping extensional fault. A subvertical normal fault bounds the gneiss to the east, putting it in contact with Tertiary volcanic and sedimentary rocks. The gneiss is tentatively correlated with gneiss of the Proterozoic Grand Forks Gneiss Complex, which shares a similar structural relationship with the Knob Hill Complex in the Grand Forks area (Höy and Jackaman, 2005) and with the Vaseaux gneiss of the Okanagan Valley (Tempelman-Kluit, 1989).

Several varieties of orthogneiss are observed in the study area. A grey biotite-feldspar-quartz gneiss is most common. It is coarse grained and well foliated, with schistosity defined by the alignment of biotite porphyroblasts. White feldspar porphyroblasts, ranging up to 5 mm in longest dimension, form small augens. Biotite forms large clots, up to 2 cm in diameter, within the foliation plane, giving a spotted appearance to the rock when broken

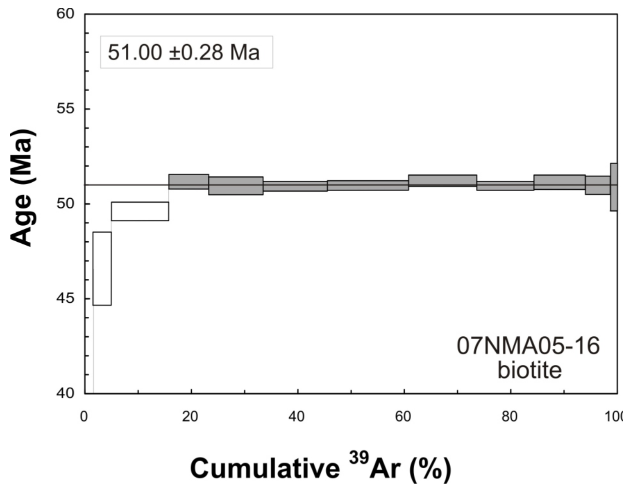


Figure 5. $^{40}Ar/^{39}Ar$ age spectrum for biotite from diorite in the McKinney Creek vicinity of the Boundary Project area, southern British Columbia. See Table 1 for sample locations. Box heights for steps in this plot are shown at the 2 level. Steps that were utilized for that plateau age calculation are filled; rejected steps are open.

appropriately. Variation in mineral proportions results in colour banding and a variation from diorite to granodiorite in composition.

The gneiss is intruded by a medium- to coarse-grained unfoliated leucogranite. The rock is composed predominantly of white feldspar and quartz with minor biotite; colour index is less than 5 and the rock occasionally shows a pinkish hue on fresh surfaces.

Zircons from the biotite-feldspar-quartz gneiss yielded an Early Jurassic age of 187.7 ±1.1 Ma (Figure 3b). This compares to the 197–181 Ma age reported for the Fife diorite of the Christina Lake area (Acton et al., 2002), but is older than the Middle Jurassic ages reported here, and previously (Ghosh, 1995), for the Nelson batholith. Other Early Jurassic diorite and porphyry bodies occur in the Rossland area and have been correlated with volcanic rocks of the Early Jurassic Rossland Group (Fyles, 1984; Brown and Logan, 1989).

No zircons were recovered from the unfoliated leucogranite. Similar post-tectonic granitic intrusions in the Castlegar gneiss yielded early Tertiary ages (Parrish et al., 1988; Parrish, 1992a).

Beaverdell Area

WEST KETTLE BATHOLITH

The West Kettle batholith is composed of granodiorite, quartz diorite and microgranodiorite with minor aplite and pegmatite. The granodiorite is white to light grey and medium to coarse grained equigranular with a typical salt-and-pepper texture. Weathered surfaces are white to grey but can be greenish or slightly pink. The rock comprises white subhedral feldspar, translucent irregular quartz, greenish black tabular hornblende and black biotite flakes. Pink feldspar is minor. Quartz varies from about 5 to 20% or may be absent in dioritic phases. Colour index is about 10–15 but may range up to 25 in diorite and quartz diorite. Chlorite and epidote occur in veins, chlorite and iron oxides on fracture surfaces. Xenoliths of amphibolite and microdiorite are occasionally seen.

Zircons from a sample of granodiorite from the West Kettle batholith (sample 3 in Figure 1 and Table 1) yielded a Late Triassic age of 213.5 ±0.9 Ma (Figure 2b). It compares to the similar Late Triassic age assigned to the Josh Creek diorite in the Christina Lake area by Acton et al. (2002).

Further, the West Kettle batholith has a similar calc-alkaline, volcanic-arc character and normalized rare earth element (REE) patterns that are identical to volcanic rocks of the Wallace Formation, which it intrudes (Massey, 2010). This suggests that the West Kettle batholith may be, at least in part, coeval with the Wallace Formation.

HORNBLENDE CROWDED FELDSPAR DIORITE

Bodies of diorite, quartz diorite, microdiorite and microgranodiorite intrude sedimentary rocks of the Wallace Formation east of Beaverdell (samples 10 and 11 in Figure 1 and Table 1). These are medium- to coarse-grained equigranular rocks comprising white feldspar, green-black hornblende and variable amounts of quartz. One distinctive lithology, termed the 'hornblende crowded feldspar diorite' by Greig and Flasha (2005), underlies much of the GK property. This rock is characterized by abundant subrounded to subhedral lath-shaped, white feldspar crystals set in a finer grained black groundmass of acicular hornblende and feldspar. Tabular hornblende phenocrysts may also be developed. Quartz is rare or absent. The diorite is variably mineralized with up to 5% disseminated pyrrhotite, lesser pyrite and rare arsenopyrite (Greig and Flasha, 2005). The relationship of the dioritic rocks to the West Kettle granodiorite is presently unknown.

One sample yielded a good hornblende $^{40}Ar/^{39}Ar$ plateau age of 177.3 ±1.0 Ma (Figure 6). This is significantly younger than the Late Triassic age obtained for the West Kettle batholith, and compares with that of the Nelson suite Greenwood stock.

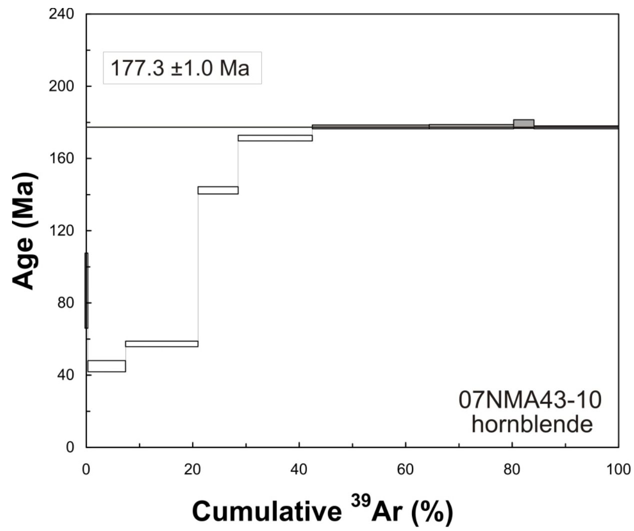


Figure 6. $^{40}Ar/^{39}Ar$ spectrum for hornblende from the 'hornblende crowded feldspar diorite' (Greig and Flasha, 2005), Crouse Creek vicinity, Boundary Project area, southern British Columbia. See Table 1 for sample locations. Box heights for steps in this plot are shown at the 2 level.

GEOCHEMISTRY OF THE GRANITOID INTRUSIONS

Whole-rock geochemical analyses were carried out on all the dated samples, as well as other samples from the Jurassic and Eocene intrusions (Figure 1). Results are summarized in Table 2. Although only a small number of samples was analyzed, the results appear to suggest some differences between the various suites.

All samples are subalkaline, intermediate to felsic (Figure 7), and calcalkaline or high-K calcalkaline (Figures 8, 9) in character, with the exception of

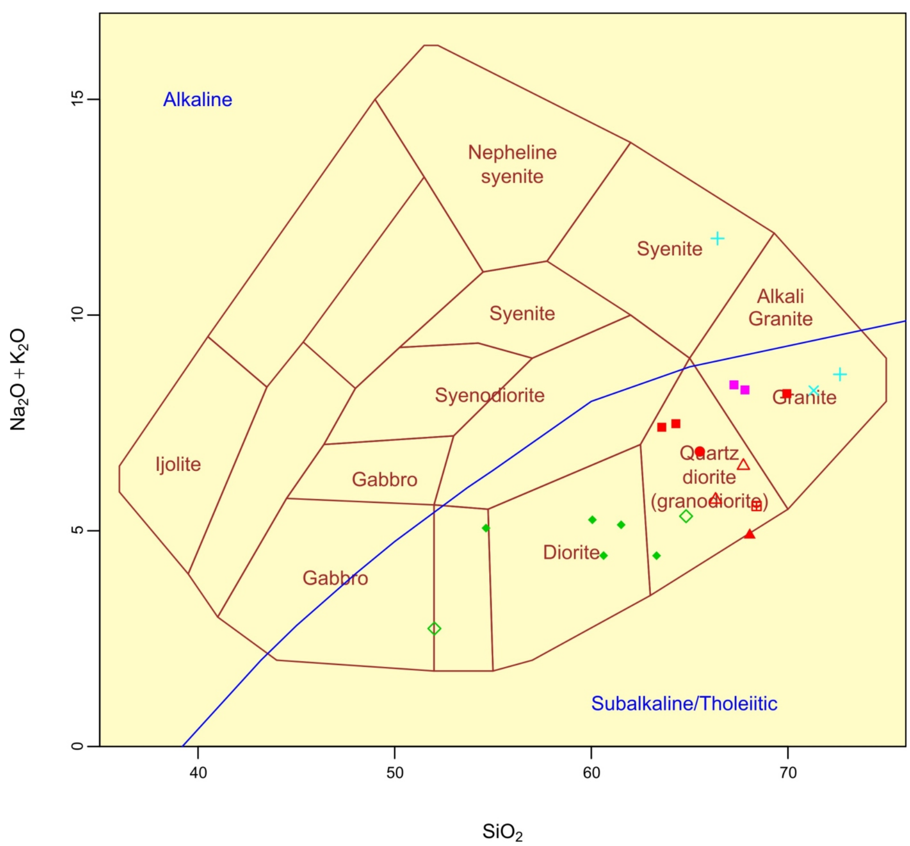


Figure 7. Total alkali versus SiO_2 plot for granitic intrusions in the Boundary Project area, southern British Columbia. Classification fields and nomenclature from Wilson (1989) after Cox et al. (1979). The alkaline-subalkaline dividing line is from Irvine and Baragar (1971). Symbols: open green diamonds, McKinney diorite; solid green diamonds, Beaverdell diorite; open red triangles, Triassic West Kettle batholith; solid red triangle, Middle Jurassic Greenwood stock; red X, Middle Jurassic Mount Baldy stock; solid purple squares, Middle Jurassic Gidon Creek porphyry; red crossed square, Middle Jurassic Ed James orthogneiss; solid red circle, Late Jurassic Myers Creek stock; solid blue squares, Eocene McKinney Creek stock; blue crosses, Eocene Beaverdell intrusion; blue crossed square, Eocene Ed James leucogranite.

Table 2. Whole-rock geochemical analyses for granitic intrusions in the Boundary Project area, southern British Columbia. Major elements and Rb, Sr, Ba, Y, Zr, Nb, V, Ni and Cr were determined by x-ray fluorescence (major elements on fused disc, trace elements on pressed-powder pellet) by Teck (Global Discovery) Labs. Rare earth elements, Th, Ta and Hf were determined by peroxide-fusion inductively coupled plasma–mass spectrometry at Memorial University of Newfoundland. Dashes indicate element determination below detection limit; blank values indicate elements not analyzed.

	McKinney diorite'		McKinney Creek stock			Mount Baldy stock	Myers Creek stock	Ed James Lake orthogneiss		Gidon Creek porphyry	
Analytical parameter	07NMA05-15	07NMA05-16	07NMA09-02	07NMA14-16	07NMA14-17	07NMA09-01	06NMA05-01-02	06NMA22-12A	06NMA22-12B	05NMA25-01B	05NMA25-03A
SiO_2	51.38	64.36	60.92	69.09	63.42	70.61	64.30	67.50	75.96	66.62	66.03
TiO_2	0.45	0.47	0.63	0.22	0.53	0.27	0.49	0.29	0.05	0.34	0.32
Al_2O_3	15.15	16.06	16.57	15.75	16.31	15.63	15.68	16.80	13.74	16.28	16.60
Fe_2O_3							1.40			1.62	1.81
FeO							2.65			1.00	0.72
Fe_2O_3t	7.74	5.17	5.58	2.38	5.03	1.60		2.86	0.50		
MnO	0.17	0.09	0.06	0.04	0.09	0.02	0.08	0.08	0.01	0.07	0.07
MgO	9.15	2.33	1.89	0.84	1.89	0.46	1.83	0.94	0.02	0.77	0.68
CaO	11.98	5.33	2.84	2.29	3.79	2.18	4.53	4.59	0.66	3.19	3.46
Na_2O	2.47	3.47	2.78	3.48	3.59	4.95	3.23	3.95	4.42	4.74	4.50
K_2O	0.23	1.83	4.31	4.60	3.79	3.22	3.48	1.55	4.07	3.38	3.73
P_2O_5	0.05	0.18	0.23	0.09	0.19	0.08	0.18	0.12	0.01	0.12	0.18
BaO	0.01	0.09	0.09	0.11	0.09	0.16	0.09	0.09	0.01	0.07	0.08
LOI	1.20	0.60	3.42	0.49	0.67	0.31	1.81	0.58	0.15	1.03	1.12
Total	99.98	99.98	99.32	99.38	99.39	99.49	99.75	99.35	99.60	99.23	99.30
Rb	-	66	185	175	198	60	98	51	137	80	106
Sr	181	512	386	378	467	1084	703	560	175	1062	1087
Ba	122	870	868	1128	865	1575	869	894	99	751	836
Y	17	8	15	10	21	-	15	11	4	21	10
Zr	27	86	183	101	188	134	150	69	54	144	146
Nb	7	10	18	14	21	8	11	3	9	16	23
V	169	115	127	47	103	33	76	77	18	63	61
Ni	99	-	6	-	3	-		-	-		
Cr	353	10	27	22	30	15		60	-		
La	1.243	15.346	36.980	30.329	49.986	36.935	29.817	7.829	3.672	19.798	18.209
Ce	3.661	25.062	68.400	54.991	91.380	67.791	54.659	14.829	8.150	35.702	34.140
Pr	0.676	2.621	7.695	5.829	9.998	7.754	6.174	1.819	0.666	4.225	4.037
Nd	4.315	9.784	28.578	19.776	35.663	28.428	22.857	7.353	1.899	16.687	16.161
Sm	1.833	1.799	5.276	3.486	6.350	4.237	4.145	1.538	0.272	3.124	3.043
Eu	0.659	0.504	1.098	0.694	1.092	0.922	1.056	0.494	0.094	0.850	0.818
Gd	2.749	1.715	4.204	2.602	5.140	2.287	3.495	1.397	0.134	2.825	2.716
Tb	0.489	0.257	0.590	0.361	0.737	0.245	0.499	0.203	0.020	0.400	0.398
Dy	3.409	1.569	3.239	1.915	4.072	1.022	2.777	1.244	0.098	2.437	2.362
Ho	0.744	0.330	0.634	0.363	0.759	0.177	0.505	0.232	0.024	0.540	0.524
Er	2.186	0.970	1.796	1.037	2.131	0.476	1.441	0.692	0.078	1.584	1.514
Tm	0.318	0.147	0.264	0.152	0.305	0.073	0.209	0.106	0.015	0.240	0.232
Yb	2.007	1.034	1.696	1.061	1.968	0.436	1.451	0.705	0.124	1.565	1.558
Lu	0.294	0.160	0.254	0.161	0.280	0.069	0.217	0.111	0.028	0.240	0.232
Hf	0.848	2.415	3.670	2.854	4.704	3.982	4.187	2.162	2.799	3.428	3.068
Ta	0.077	0.279	1.581	1.463	2.053	0.396	0.886	0.280	0.283	1.014	1.142
Th	0.212	4.182	24.408	23.439	38.029	6.195	10.043	1.492	17.562	4.405	4.701
Latitude	49.155757	49.155757	49.061520	49.069317	49.069552	49.161480	49.016554	49.151378	49.151378	49.009087	49.021726
Longitude	-119.164309	-119.164309	-119.116490	-119.206104	-119.204795	-119.240650	-119.011395	-119.017097	-119.017097	-118.695168	-118.677616
UTM Zone	11	11	11	11	11	11	11	11	11	11	11
Northing	5447025	5447025	5436452	5437505	5437528	5447824	5431245	5446243	5446243	5429850	5431227
Easting	342198	342198	345390	338871	338967	336650	352934	352916	352916	376036	377351

Table 2. (continued)

Greenwood stock	Westkettle batholith		"Crick Creek diorite"	Crowded feldspar diorite				Collier Lake stock	Unnamed stock west of Crouse Creek
06NMAGreenwood1	07NMA28-20	07NMA45-05	07NMA27-17	07NMA33-07B	07NMA34-15	07NMA41-08	07NMA43-10	07NMA28-17	07NMA38-01
66.53	65.39	66.84	53.11	62.42	59.02	58.86	59.74	65.71	71.50
0.27	0.40	0.38	0.87	0.45	0.47	0.49	0.48	0.40	0.28
16.81	16.02	15.33	18.72	17.15	17.31	17.53	17.42	16.67	14.67
3.05	4.39	4.06	8.43	5.49	5.81	6.56	6.80	2.89	1.49
0.07	0.09	0.07	0.15	0.10	0.15	0.14	0.13	0.10	0.01
1.02	1.95	1.58	3.23	1.85	1.86	2.52	2.29	0.40	0.45
5.06	4.61	3.88	7.49	6.57	6.20	6.56	7.12	1.04	1.46
3.42	3.64	3.35	3.71	3.40	3.94	3.79	3.12	5.14	4.15
1.37	2.00	3.07	1.21	0.96	0.99	1.36	1.24	6.51	4.34
0.15	0.11	0.12	0.27	0.19	0.19	0.20	0.20	0.07	0.07
0.12	0.14	0.14	0.07	0.09	0.09	0.14	0.09	0.02	0.16
1.73	0.87	1.05	2.22	0.81	3.45	1.43	0.98	0.31	0.55
99.60	99.60	99.87	99.48	99.48	99.48	99.58	99.61	99.26	99.13
34	58	69	20	20	24	28	33	270	140
602	332	452	538	537	567	511	537	100	1050
1166	1439	1377	687	860	880	1402	853	170	1553
9	10	11	22	11	9	10	13	22	6
86	83	94	98	82	75	74	76	631	186
6	8	8	7	7	8	7	8	71	14
64	92	84	201	101	123	139	136	19	35
-	-	-	3	-	-	-	-	-	-
35	35	22	30	17	36	23	20	45	35
5.549	9.347	16.004	15.154	11.285	10.264	10.639	10.398	92.146	60.742
11.063	17.973	28.881	30.919	22.574	20.992	21.416	20.891	165.029	114.865
1.430	2.253	3.365	4.160	2.952	2.750	2.766	2.745	17.515	13.067
6.216	9.414	13.192	18.401	12.699	11.875	12.089	11.958	58.594	47.994
1.494	2.126	2.695	4.348	2.928	2.765	2.864	2.816	8.727	7.115
0.464	0.553	0.603	1.230	0.893	0.848	0.765	0.851	0.789	1.168
1.471	2.145	2.531	4.358	2.955	2.685	2.866	2.788	5.817	3.635
0.229	0.335	0.391	0.683	0.458	0.431	0.443	0.436	0.826	0.366
1.386	2.053	2.366	4.120	2.813	2.579	2.744	2.625	4.582	1.792
0.278	0.424	0.490	0.821	0.561	0.518	0.560	0.522	0.873	0.272
0.841	1.254	1.482	2.424	1.684	1.516	1.679	1.528	2.618	0.739
0.130	0.197	0.236	0.350	0.258	0.235	0.247	0.228	0.401	0.101
0.878	1.319	1.603	2.397	1.713	1.614	1.685	1.556	2.686	0.664
0.142	0.205	0.260	0.355	0.263	0.242	0.257	0.247	0.413	0.093
2.193	2.534	4.183	3.067	2.489	1.994	2.277	2.256	14.829	3.978
0.358	0.414	0.522	0.351	0.286	0.348	0.248	0.252	4.610	0.674
1.109	3.099	8.861	2.591	2.483	2.078	2.164	2.010	32.916	19.217
49.097050	49.495475	49.410378	49.473268	49.448155	49.399108	49.420506	49.418590	49.510924	49.405806
-119.680870	-118.927312	-119.005005	-118.888715	-118.955065	-118.932716	-118.929211	-118.937517	-118.920253	-118.953738
11	11	11	11	11	11	11	11	11	11
5439562	5484322	5475009	5481783	5479114	5473620	5475992	5475794	5486026	5474403
377348	360440	354563	363173	358294	359774	360089	359482	360995	358268

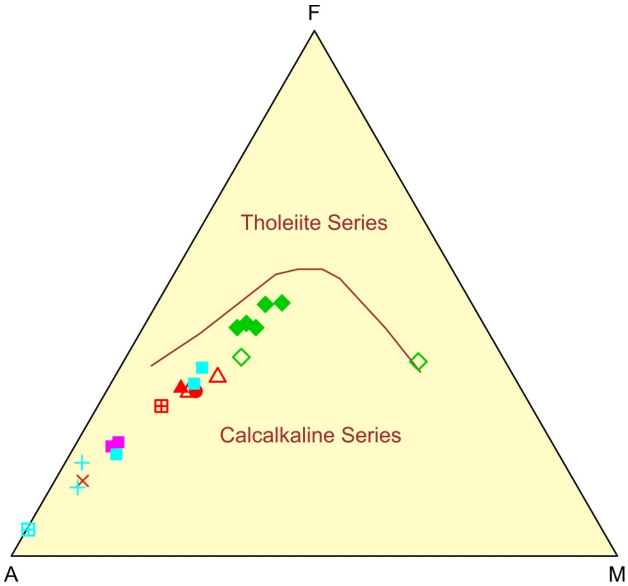


Figure 8. AFM diagram for granitic intrusions in the Boundary Project area, southern British Columbia (after Irvine and Baragar, 1971). A = $Na_2O + K_2O$; F = FeO_{total}; M = MgO, all as weight percent. Symbols as in Figure 7.

one McKinney Creek diorite sample (07NMA05-15), which is more mafic and tholeiitic, and the Eocene Collier Lake stock, which is alkalic. Major and trace elements, however, do show distinctions between the various suites. Triassic and Jurassic intrusions, including both the diorites and the granodiorites, show a typical volcanic-arc character (Figures 10, 11), although the Gidon Creek and Mount Baldy stocks have a late-orogenic signature.

Eocene intrusions, including the post-foliation leucogranite from the Ed James Creek area, are also distinct on geochemical plots. However, their extensional tectonic environment (Parrish et al., 1988) is poorly discriminated in Figures 10 and 11, although the alkalic Collier Creek stock does show a within-plate anorogenic character. Other samples have a character transitional between syn- and post- collisional.

Chondrite-normalized REE diagrams further demonstrate the geochemical distinction of the various suites. Diorites from both the McKinney and Beaverdell areas show typical light rare earth element (LREE)–enriched calcalkaline patterns, except for the tholeiitic sample from McKinney (07NMA-15, Figure 12a), which shows a LREE-depleted pattern. This sample also shows other trace-element characteristics that are comparable to island-arc tholeiite, a magma type that has not been recognized previously in the Mesozoic rocks of the study area but that is present in the Paleozoic in both the Knob Hill Complex and the Anarchist schist. Further mapping and sampling are needed to adequately discriminate the components of this composite diorite body, to determine if it includes Paleozoic material.

All Jurassic intrusive suites show typical LREE-enriched calcalkaline patterns (Figures 13, 14), although they differ in absolute abundances and steepness of the REE pattern. In particular, the Middle Jurassic Mount Baldy stock is more LREE enriched than the other Jurassic samples (Figure 13b). Tertiary intrusions have higher REE contents and are more LREE enriched than the main Triassic and Middle Jurassic suites (Figure 14a). Sample 07NMA38-01, from the unnamed stock west of Crouse Creek, is from a K-feldspar megacrystic granite that was correlated with the Coryell suite (Massey and Duffy, 2008b). However, it has a normalized REE pattern similar to that of the Mount Baldy stock (Figure 13b). This intrusion has not been directly dated and may have been incorrectly designated as Eocene instead of Middle Jurassic. Further geochronological and geochemical studies are warranted.

The Ed James Creek leucogranite has the lowest REE contents of any sample and a distinct concave-upward REE pattern (Figure 14b), perhaps reflecting end-product fractionation with the removal of hornblende and the minor phases that normally host the REEs and other high-field-strength elements.

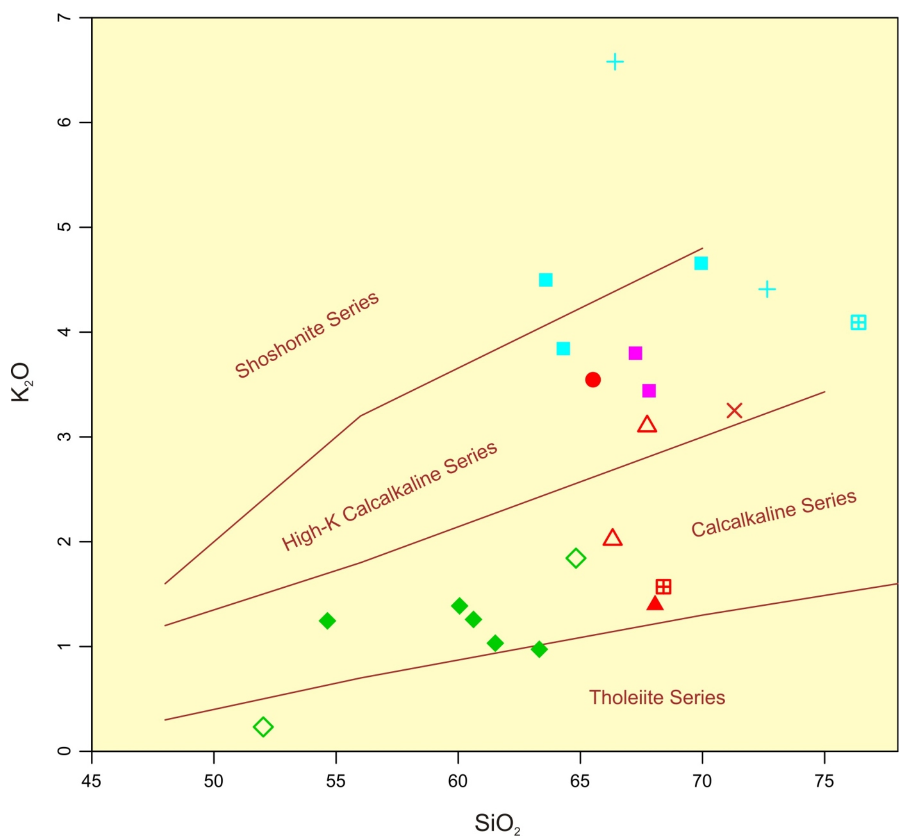


Figure 9. K_2O-SiO_2 plot for granitic intrusions in the Boundary Project area, southern British Columbia, showing fields from Peccerillo and Taylor (1976). Symbols as in Figure 7.

CONCLUSIONS

The data presented here illustrate that the magmatic history of the Boundary Project area is more complex than previously thought. Granitic intrusions in the area were previously ascribed to the Middle Jurassic Nelson suite, a poorly defined Jura-Cretaceous suite, or to the Eocene Coryell suite. New isotopic age data suggest that at least four pre-Eocene suites are present: Late Triassic (213 Ma), Early Jurassic (188 Ma), Early to Middle Jurassic (179–168 Ma) and earliest Late Jurassic (157 Ma). Although these are generally all of a similar continental arc–like geochemistry, the Mount Baldy intrusion is significantly distinct.

Eocene intrusions are present and, although they are enriched in lithophile elements, they are not all alkaline like the classic Coryell suite intrusions. More detailed mapping, coupled with systematic sampling for geochemistry and isotopic dating, is needed to confirm these results, and possibly reveal even more complications, throughout the region.

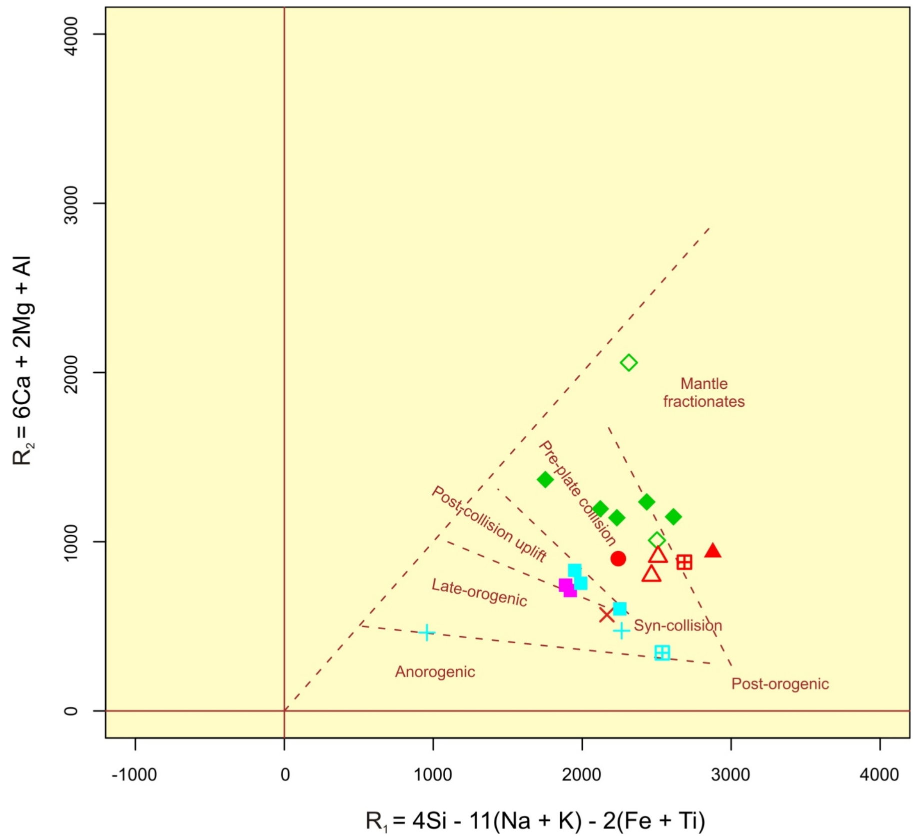


Figure 10. Major-element multi-cation plot for granitic intrusions in the Boundary Project area, southern British Columbia, with fields from Batchelor and Bowden (1985). Symbols as in Figure 7.

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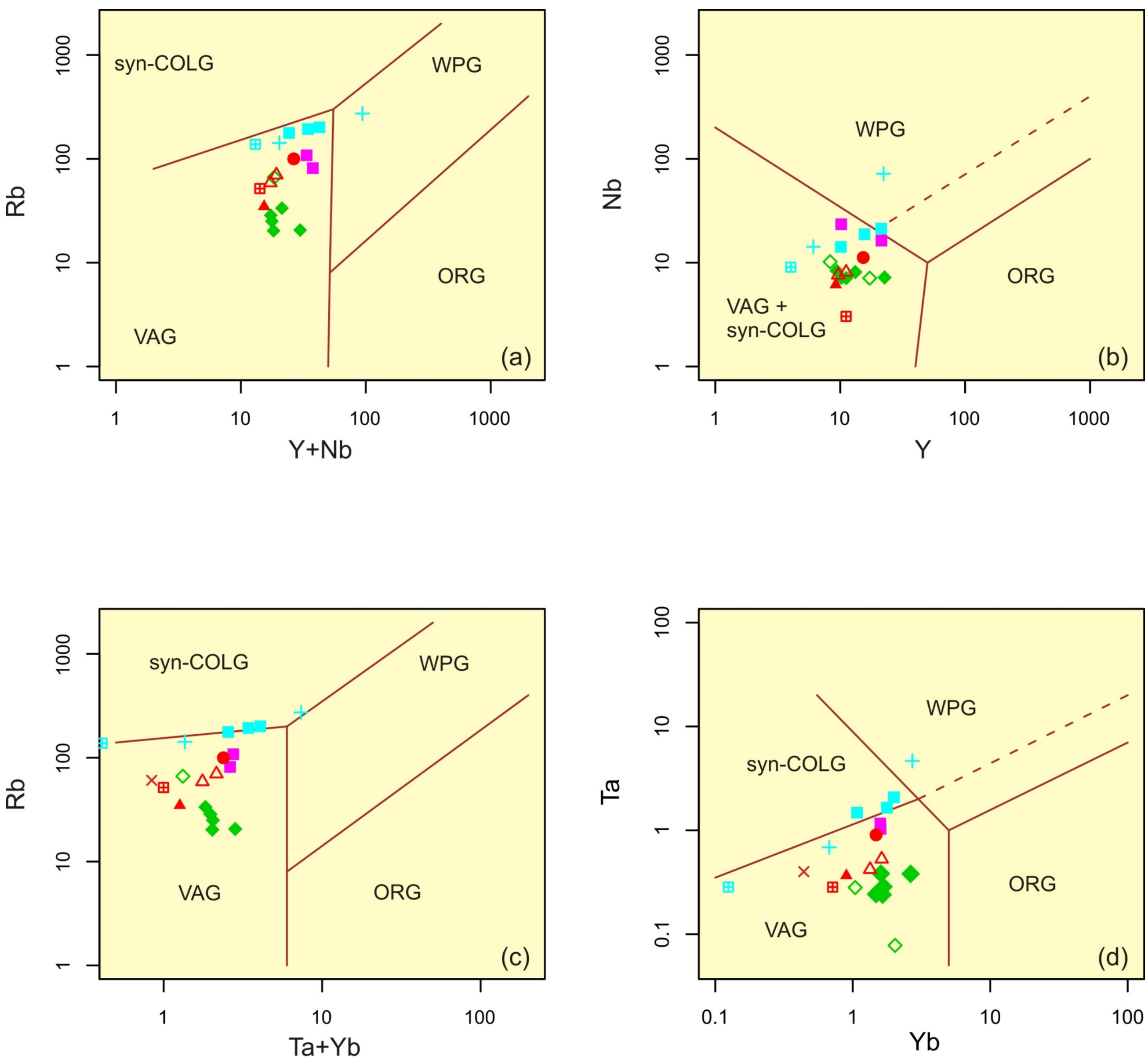

Figure 11. Trace-element discrimination diagrams for granitic intrusions in the Boundary Project area, southern British Columbia, with fields from Pearce et al. (1984). Abbreviations: VAG, volcanic-arc granites; syn-COLG, syn-collisional granites; WPG, within-plate granites; ORG, ocean-ridge granites. Symbols as in Figure 7.

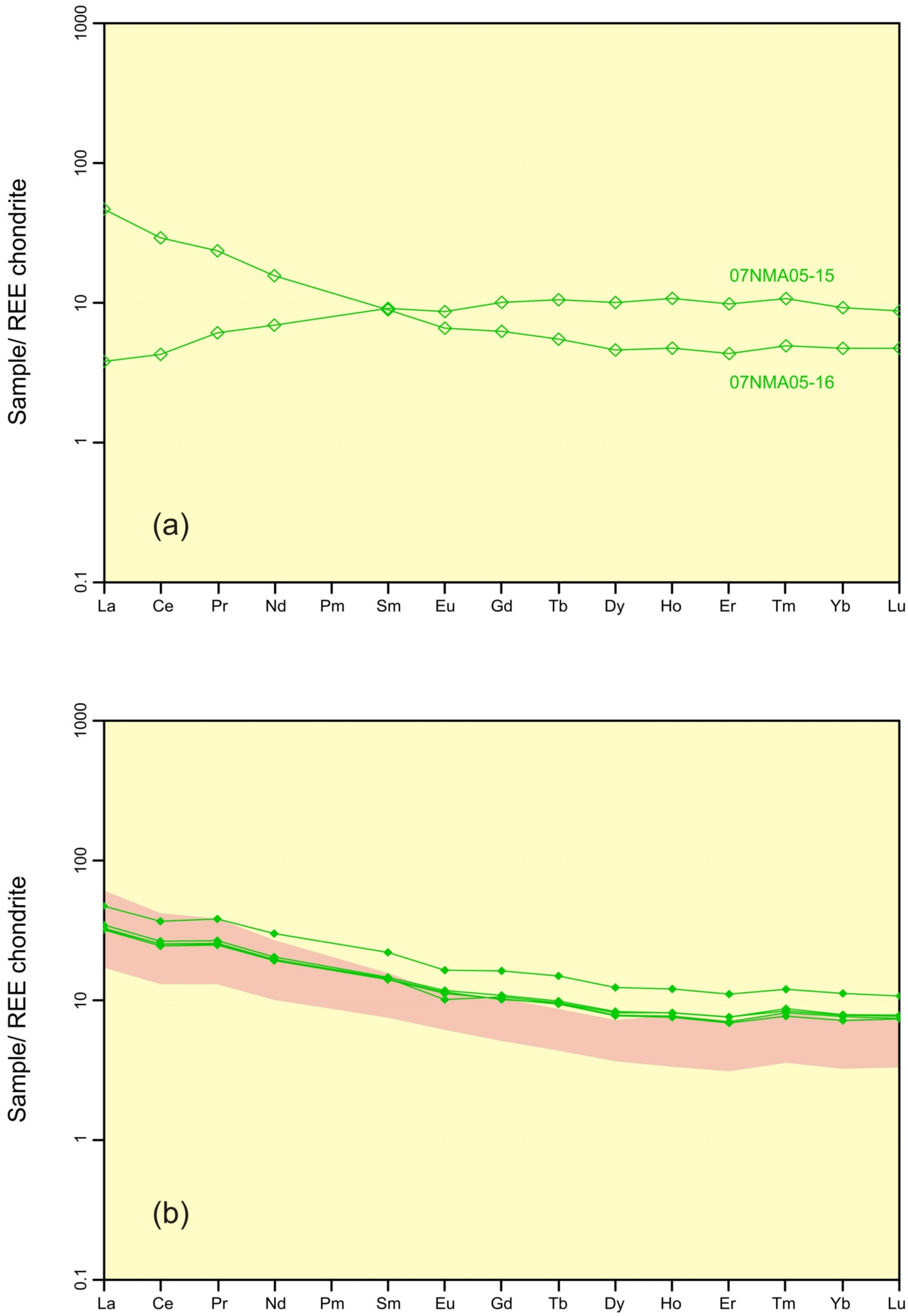

Figure 12. Chondrite-normalized rare earth element plots for diorites from the Boundary Project area, southern British Columbia (normalizing values after Nakamura, 1974): **a)** diorites from the McKinney Creek area; 07NMA05-15 is tholeiitic in composition, 07NMA05-16 is calcalkaline; **b)** diorites from the Beaverdell area; pink-shaded field is for all Triassic to Middle Jurassic granodiorites, except for the Mount Baldy stock (Figure 13).

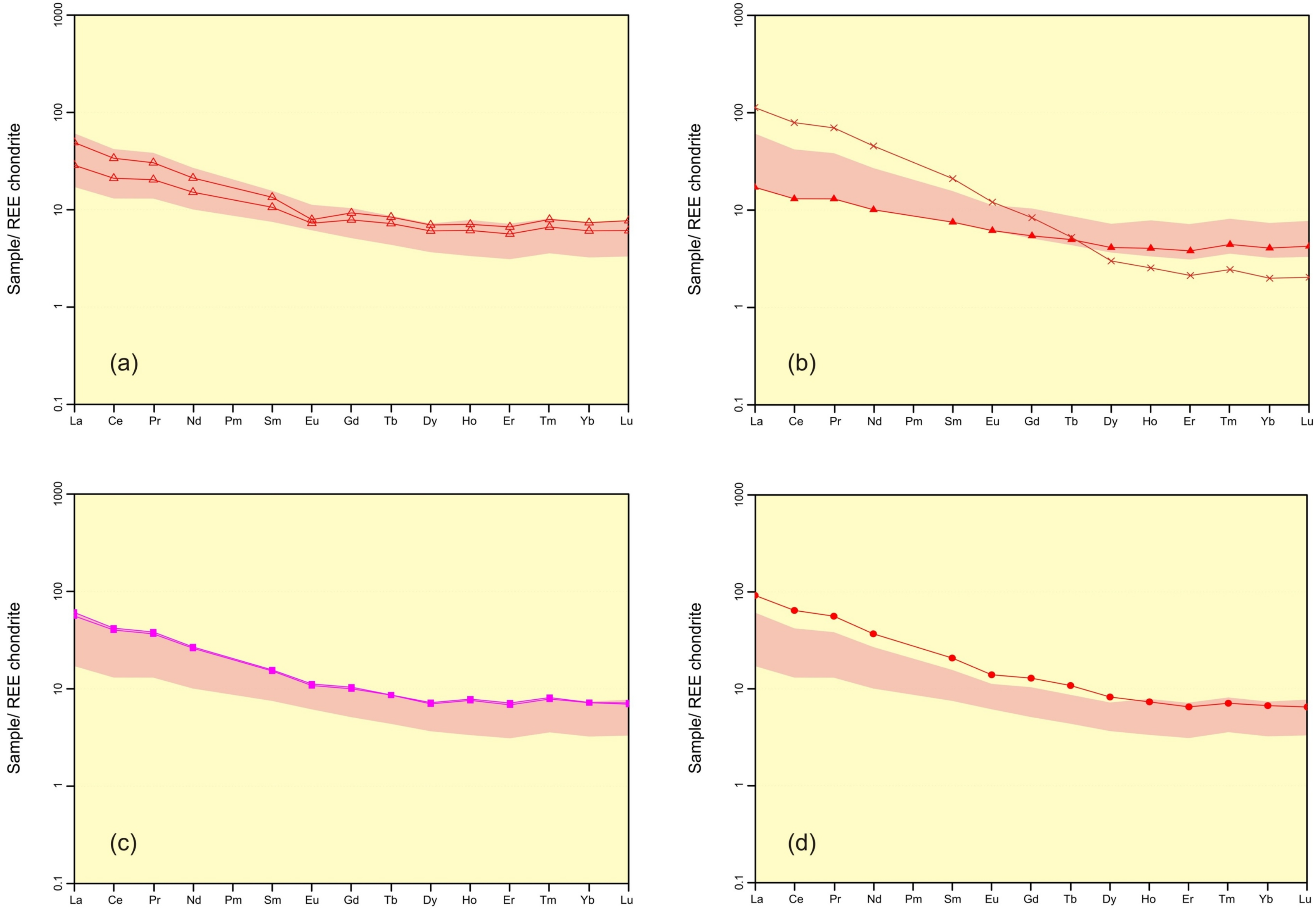

Figure 13. Chondrite-normalized rare earth element plots for Triassic and Jurassic granitic rocks in the Boundary Project area, southern British Columbia (normalizing values from Nakamura, 1974): **a)** Triassic West Kettle batholith; **b)** Middle Jurassic Greenwood stock (closed red triangles) and Mount Baldy stock (red Xs); **c)** Middle Jurassic Gidon Creek stock; **d)** Late Jurassic Myers Creek stock. For comparison, the pink-shaded field in all diagrams includes all Triassic to Middle Jurassic intrusions except the Mount Baldy stock.

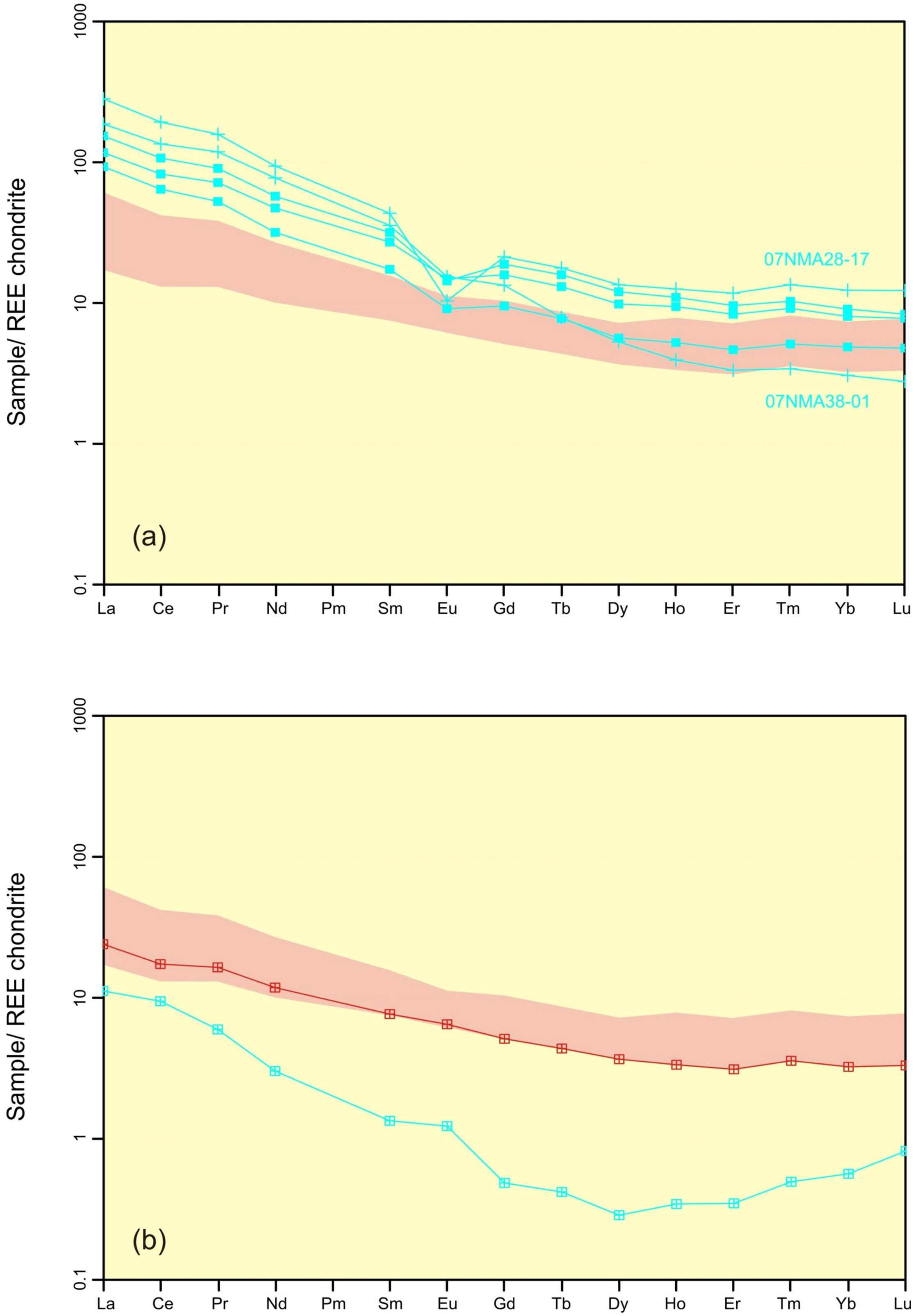

Figure 14. Chondrite-normalized rare earth element plot for rocks in the Boundary Project area, southern British Columbia: **a)** Tertiary granitic McKinney Creek stock (solid blue squares) and Beaverdell suite stocks (blue crosses; normalizing values after Nakamura, 1974); 07NMA28-17 is the alkalic Collier Creek stock and 07NMA38-01 an unnamed stock west of Crouse Creek. **b)** Early Jurassic Ed James Creek biotite-feldspar-quartz orthogneiss (red crossed squares) and undated, unfoliated leucogranite (blue crossed squares). For comparison, the pink-shaded field is for the Triassic to Middle Jurassic granodiorite, except the Mount Baldy stock (Figure 13).

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