

The Riddle Creek prospect, an unusual example of Sr-Ba-REE-F mineralization outside the Alkaline Province, British Columbia, Canada

Trofanenko, J.^{1,a}, Williams-Jones, A.E.¹, Simandl, G.J.^{2,3} and Reid, H.M.²

¹ McGill University, Department of Earth and Planetary Sciences, Montreal, QC, H3A 0G4

² British Columbia Geological Survey, Ministry of Energy, Mines and Natural Gas, Victoria, BC, V8W 9N3

³ University of Victoria, School of Earth and Ocean Sciences, Victoria, BC, V8P 5C2

^a corresponding author: joel.trofanenko@gmail.com

Recommended citation: Trofanenko, J., Williams-Jones, A.E., Simandl, G.J., and Reid, H.M., 2013. The Riddle Creek prospect, an unusual example of Sr-Ba-REE-F mineralization outside the Alkaline Province, British Columbia, Canada. In: Geological Fieldwork 2012, British Columbia Ministry of Energy, Mines and Natural Gas, British Columbia Geological Survey Paper 2013-1, pp. 139-148.

Abstract

The Riddle Creek prospect is an unusual occurrence of Sr-Ba-REE-F mineralization in the Okanagan Valley of British Columbia. It is hosted by alkaline volcanoclastic and sedimentary rocks of the Tertiary Penticton outlier, which are interpreted to have formed adjacent to a "Kula-Farallon" slab window, and lies west of the Alkaline Province, hosting the bulk of the known REE mineralization in the province. Macroscopically, the REE-mineralized rocks are fine grained, brown to purple and are contained in a narrow, steeply dipping zone, interpreted to be a shear zone. The surrounding rocks are fine-grained greyish green porphyries comprising anorthoclase and pyroxene in a largely devitrified matrix (Yellow Lake rhomb porphyry). Contacts between the fresh and mineralized rocks are sharp and are most evident by a change in colour from green through yellow and gray, to pale purple (weak mineralization), and dark purple (strong mineralization). This colour change provides an excellent vector to the mineralization. Rocks hosting the REE have been intensely altered, and consist mainly of small fragments of sericitized anorthoclase set in a matrix of purple fluorite, subordinate barite-celestite, and minor dolomite, quartz, and hematite. Alteration was accompanied by major losses of silica, alumina and alkalis (Na+K) and large additions of calcium, fluorine, barium, strontium, and sulphur (sulphate). Unlike most REE deposits, the rare earth elements are not concentrated in a REE-rich phase such as, bastnäsite-(Ce) or monazite-(Ce). Instead, the REE occur mainly as a minor component in barite-celestite and, to a much lesser extent, in fluorite. The prospect is light-REE enriched with a La/Lu ratio of 359 compared to 153 in the unaltered porphyry. The TREO concentration of seven mineralized samples averages 0.7 wt.% and ranges between 0.6 and 0.8 wt.%. Cerium and lanthanum concentrations reach 0.4 wt.% and 0.3 wt.%, respectively. A preliminary model is proposed in which the REE (preferentially the light-REE) were mobilized as chloride complexes by a fluorine-sulphate-bearing hydrothermal fluid of possible magmatic origin and were deposited due to mixing with an external calcium-(strontium-barium)-bearing fluid in a shear zone. The Riddle Creek Sr-Ba-REE-F showing demonstrates the potential for REE exploration opportunities outside the Alkaline Province, particularly in "slab window" tectonic settings of the type represented in the Penticton Tertiary outlier.

Keywords: Riddle Creek, Rare Earth Element prospect, alkaline volcanics, hydrothermal concentration, shear zone, REE-enriched barite-celestite, REE chloride complex, fluid mixing

1. Introduction

The Riddle Creek prospect is an unusual Sr-Ba-REE-F occurrence in the Okanagan Valley, approximately 16 km west of Summerland, outside the British Columbia Alkaline Province, which hosts most of the known rare earth element (REE) mineralization in British Columbia (Fig. 1). The area of the prospect has been explored intermittently since the 1970s for uranium and precious metals. However, its REE potential was recognized relatively recently (Morrison, 2001; Church, 2007; Simandl et al., 2012). The prospect is characterized by low concentrations of U and Th, and is not spatially associated with any U-Th mineralization. Further study may elucidate why this REE prospect is nearly uranium-free, despite its location in a uranium district. Herein we present field, petrographic, SEM, and geochemical data to better document mineralization on the property.

2. Geologic setting

The nature and distribution of REE prospects in British Columbia have been documented in specialty metals compilations (Simandl et al., 2011, 2012). These publications show that the prospects occur predominantly in the NW-SE-trending British Columbia Alkaline Province (Fig. 1), which is largely confined to the Rocky Mountain Trench (Pell, 1994; Simandl, 2011). The Riddle Creek Sr-Ba-REE-F prospect is an exception, and occurs west of this igneous province in alkaline rocks of the Challis-Kamloops belt of south central British Columbia (Church, 2002 and references therein). This belt formed adjacent to a "Kula-Farallon" slab window, and includes the Tertiary Penticton outlier, which comprises the Springbrook, Marama, White Lake, and Marron formations (Church, 1973; Dostal et al., 2003; Church, 2007). The Marron Formation hosts the Riddle REE



Fig. 1. Location of the Riddle Creek Sr-Ba-REE-F prospect.

mineralization, and consists of predominantly Tertiary volcanic rocks that are considered to be coeval with the nearby Coryell syenite plutons (Church, 1971; Church, 1973; Currie, 1976; Souther, 1991). The REE mineralization occurs in the Yellow Lake rhomb porphyry of the Marron Formation (Fig. 2), which consists of anorthoclase and pyroxene phenocrysts in a largely devitrified matrix (Fig. 3). In the area of the prospect, exposure is poor (Fig. 4). However, trenching (Fig. 5) has revealed that the mineralized rocks are in a narrow, steeply dipping zone (Figs. 6 and 7) interpreted to have formed by shearing.

3. Petrography

Near the REE-mineralized zone, fresh rocks of the Yellow Lake rhomb porphyry are greyish-green; weakly altered rocks are light purple. The unaltered rocks contain phenocrysts of primary anorthoclase (40-60%), and rare hornblende (<1%) in a devitrified matrix of clinopyroxene (15-25%), anorthoclase (5-15%), apatite (1-5%), and hornblende and biotite (<1%). Anorthoclase forms subhedral grains up to 0.1 mm long and is commonly replaced by dolomite (20%) and radiating blades of albite (cleavelandite). Outside the shear zone, the Yellow Lake rhomb porphyry shows evidence of propylitic alteration in the form of epidote (1-5%), chlorite (1-5%), and pyrite (1-5%). Within the shear zone, the rocks have been strongly altered. This alteration is evident mainly as secondary fluorite and barite-celestite, which are restricted to the matrix, and dolomite, which also occurs as a rare sieve-textured alteration of anorthoclase. The only primary rock-forming minerals remaining are anorthoclase and rare hornblende and biotite. The altered rocks are purple cataclastic rocks consisting of fine-grained to microcrystalline sericitized anorthoclase (25%), fluorite (20-35%), barite-celestite (15-25%), dolomite (5-15%), lesser quartz (5%), hematite (1-5%), rare biotite (<1%) and hornblende (<<1%). Anorthoclase occurs as angular

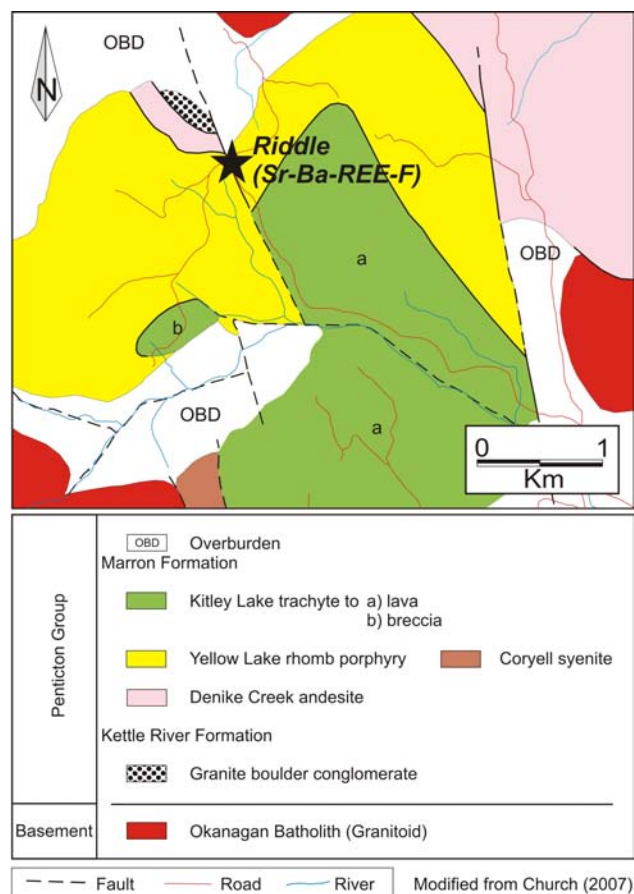


Fig. 2. Geological setting of Riddle Creek Sr-Ba-REE-F prospect (at 49.562N, 119.888W). After Church (2007).

to sub-rounded brecciated grains (40 to 600 μm in diameter) in a fine-grained, foliated matrix of fluorite, barite-celestite, dolomite, and quartz (Fig. 8). Hematite occurs as small reddish crystals (10 μm). Based on their cataclastic textures, these foliated rocks are interpreted to represent a shear zone. The high permeability of these rocks resulted in the shear zone becoming a conduit for the passage of hydrothermal fluids and the associated alteration and concentration of the REE.

4. REE mineralogy

No minerals in which REEs are major components were identified, despite a careful search using a SEM equipped with an energy dispersive detector. However, barite-celestite, which occurs as angular grains up to 200 μm in diameter in a fine-grained matrix of fluorite, was shown to contain elevated concentrations of lanthanum and cerium (Fig. 9). The fluorite also contains significant amounts of these elements, but in lower concentrations than in the barite-celestite. Quantitative analyses will be conducted in the near future to determine the REE contents of these minerals.

5. Geochemistry

Twenty-four samples of the Yellow Lake rhomb porphyry and the REE mineralized zone were analysed by ALS Laboratories in Vancouver for bulk and trace element compositions. All samples were ground using a



Fig. 3. Fresh surface of the Yellow Lake rhomb porphyry.



Fig. 4. Riddle Creek prospect. The measuring tape coincides with the base line of Fig. 5.

steel mill. The major element chemistry was determined using lithium metaborate fusion followed by Inductively Coupled Plasma Emission Spectrometry (ICPES). Loss on ignition (LOI) was determined during the sample fusion (at 1000°C). Total carbon and sulphur contents were determined using the LECO combustion method. The other trace elements were analyzed by lithium metaborate fusion followed by Inductively Coupled Plasma Mass Spectrometry (ICPMS). Sample locations are plotted on Fig. 5, and results of the analyses are summarized in Table 1 and illustrated in Figures 10-13.

An immobile element diagram (Winchester and Floyd, 1977) was used to provide information on the

primary nature of the rocks (Fig. 10). Based on their Zr/Ti and Nb/Y ratios, both the Yellow Lake rhomb porphyry and the REE-mineralized zone classify mainly as trachyte and trachyandesite. However, the REE-mineralized samples have higher Zr/Ti ratios, and more of them plot in the trachyte field.

The alteration history of these rocks was traced on a Total Alkali-Silica (TAS) diagram. As expected from their trachyte or trachyandesite composition, all the samples analyzed plot in the alkaline field (Fig. 11). The Yellow Lake rhomb porphyry has been altered; hydrothermal fluids have modified its composition by leaching alkalis and silica in a roughly constant ratio (Fig. 11). Thus, compositions of the Yellow Lake rhomb porphyry are displaced from the trachyandesite field to fields of more mafic alkaline rocks. The same observation applies to the REE-mineralized rocks, except that the leaching was more extreme, yielding rocks with very low alkali and silica contents. This latter alteration reflects pervasive replacement of the host rock by fluorite and barite-celestite. In addition to undergoing extreme leaching of the alkalis and Si, the REE-mineralized rocks experienced extreme leaching of Al and Mg, and moderate leaching of Fe (Table 1 and Fig. 12). These losses were compensated by large additions of Ba, Sr, Ca, F, and sulphate.

The chondrite-normalized REE profiles of samples of the Yellow Lake rhomb porphyry and the REE-mineralized zone are very similar, although the overall REE contents of the REE-mineralized samples are significantly higher (Fig. 13). Both sets of profiles are characterized by light rare earth enrichment and the absence of a europium anomaly. The REE-mineralized samples however, are more enriched in the light REE with a La/Lu ratio of 359 compared to 153 in the Yellow Lake rhomb porphyry. The TREO (Total Rare Earth Oxide) concentration of the seven REE-mineralized samples averages 0.7 wt.% and ranges between 0.6 and 0.8 wt.%. Cerium and lanthanum concentrations reach 0.4 wt.% and 0.3 wt.%, respectively. The absence of a europium anomaly suggests that there was little fractionation of plagioclase during evolution of the magma.

A correlation matrix was generated to evaluate relationships of Ce with elements in the host rocks that may have influenced its concentration (Table 2). As Ce was demonstrated to be an important trace element in barite-celestite, we expected a high correlation coefficient for the Ce-Ba pair. The correlation coefficient for this pair however, is relative modest (0.61). In contrast, the correlation coefficient for the pair Ce-Sr is 0.95. This suggests that Ba must also be present in significant concentrations in another REE-poor mineral, possibly celsian ($\text{BaAl}_2\text{Si}_2\text{O}_8$), a conclusion that is consistent with the relatively modest correlation coefficient of 0.57 between Ba and Sr. Cerium concentration also correlates strongly with that of F (correlation coefficient of 0.87) and Ca (correlation coefficient of 0.81), consistent with the observation that the fluorite contains elevated

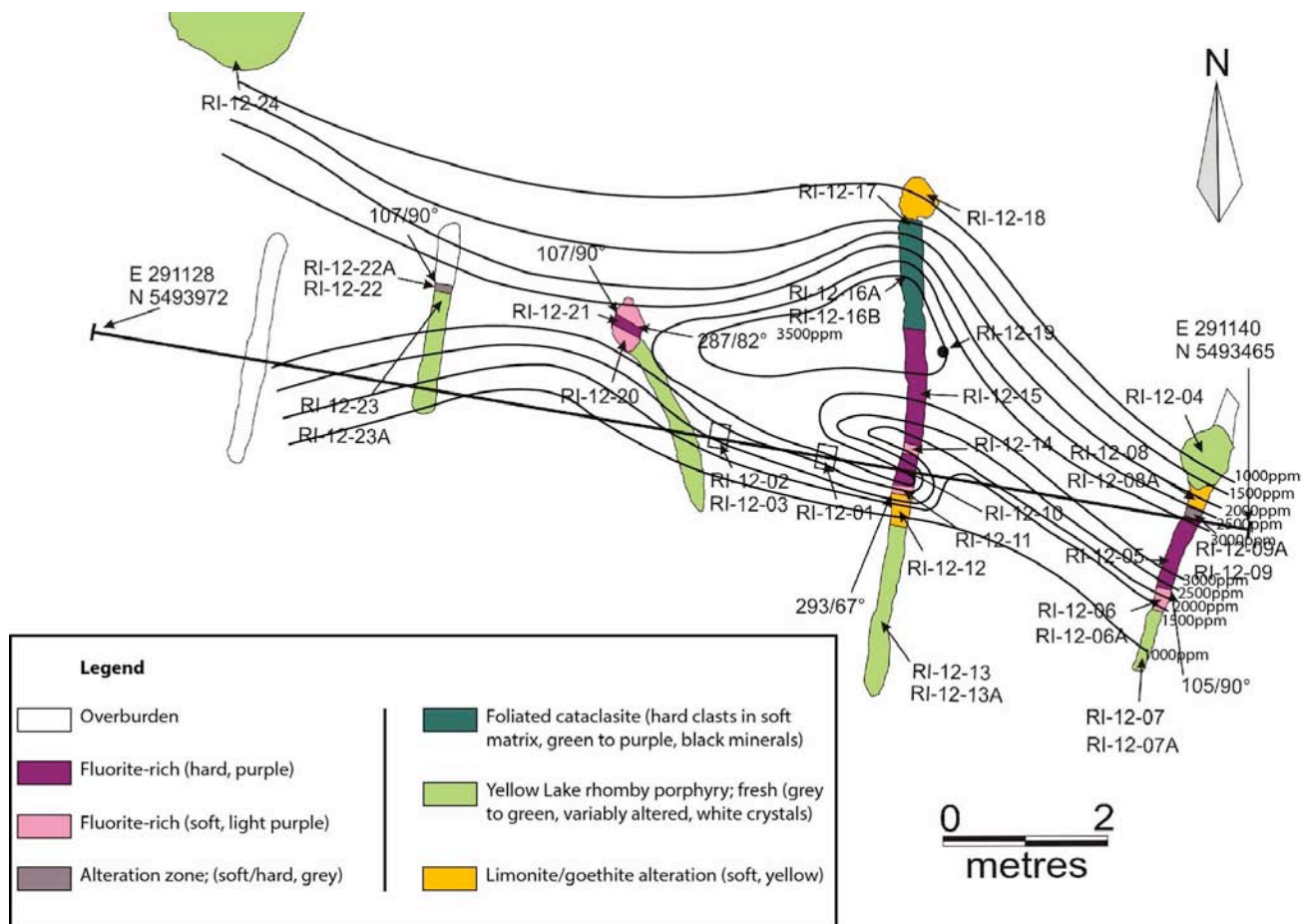


Fig. 5. Geology of the Riddle Creek Sr-Ba-REE-F prospect and isopachs of Ce concentration. The contour interval is 500 ppm.



Fig. 6. Central dark purple rock (mineralized zone; sample RI-12-10), adjacent pale purple rock (weakly mineralized contact zone; sample RI-12-11 and RI-12-14), and outer greyish green zone (fresh porphyry; sample RI-12-12). Pocket knife and measuring tape for scale. See Fig. 5 for sample locations.



Fig. 7. Contact between soft, pale purple and yellow zones; pencil for scale.

Table 1. Chemical composition of mineralized zone and host rocks.

	Detection Limit	RI-12-04	RI-12-05	RI-12-06	RI-12-07	RI-12-08	RI-12-09	RI-12-10	RI-12-11	RI-12-12	RI-12-13	RI-12-13A	RI-12-14
%													
SiO ₂	0.01	50.3	4.83	38.3	42.6	50.4	17.35	3.02	41.7	43.2	47.9	48.3	30.7
Al ₂ O ₃	0.01	14.95	0.58	12.1	13.3	15.3	4.25	0.61	14.95	13.8	13.95	15.7	11.7
Fe ₂ O ₃	0.01	6.47	2.36	7.06	4.93	6.26	2.75	2.19	9.29	5.15	6.03	6.82	8.29
CaO	0.01	6.05	19.8	6.1	6.61	3.02	14.5	20.9	4.64	6.19	6.2	5.5	6.91
MgO	0.01	3.85	0.36	2.63	3.05	3.28	1.4	0.3	3.56	3.27	3.39	3.62	2.26
Na ₂ O	0.01	2.46	<0.01	0.22	0.42	1.77	<0.01	<0.01	0.36	0.45	0.62	0.69	0.1
K ₂ O	0.01	3.75	0.15	3.23	3.73	4	0.87	0.14	3.77	3.68	3.91	4.28	3.34
Cr ₂ O ₃	0.01	0.01	0.01	0.02	0.01	0.02	0.01	<0.01	0.02	0.02	0.01	0.01	0.01
TiO ₂	0.01	0.97	0.05	0.81	0.91	1.01	0.28	0.04	1.01	0.93	0.91	1.05	0.77
MnO	0.01	0.16	0.18	0.09	0.13	0.17	0.09	0.06	0.13	0.13	0.12	0.12	0.12
P ₂ O ₅	0.01	1.31	4.14	2.79	1.76	1.43	4.37	4.84	1.49	1.62	1.57	1.45	3.2
SrO	0.01	0.58	22	5.9	4.12	0.75	14.3	20.3	2.25	2.94	2.45	1.18	6.24
BaO	0.01	0.71	14.1	5.11	2.37	0.81	13.25	15.4	1.43	1.71	1.59	0.63	6.96
LOI	0.01	8.13	5.12	10.25	12.25	9.44	7.09	2.12	11.45	12.1	9.86	9.82	10.6
Total		99.7	73.68	94.61	96.19	97.66	80.51	69.92	96.05	95.19	98.51	99.17	91.2
C	0.01	0.8	1.07	0.06	0.79	0.27	0.09	0.09	0.41	0.79	0.85	0.66	0.13
S	0.01	0.19	9.29	2.83	1.68	0.26	7.27	9.77	0.87	1.13	0.98	0.35	3.52
F	0.01	0.41	7.18	1.88	0.83	0.54	6.14	10.05	0.95	0.79	0.67	0.63	2.21
ppm													
Nb	1	59.6	114.5	80.3	68.8	64.2	114	117.5	61.3	63.5	66.9	65.7	105
Th	1	46.9	25.2	50.5	46.7	47.8	36.8	29.2	44.7	46.5	46.4	51.9	44.9
U	1	7.51	30.2	20.5	14.75	12.15	35.1	27.1	17.8	12.85	14	9.81	45.5
Zr	10	330	20	280	310	340	120	30	310	320	330	370	300
La	0.5	275	2360	944	520	408	2320	2660	409	434	467	314	1315
Ce	0.5	475	3010	1335	790	633	3010	3420	638	691	741	563	1625
Pr	0.03	54.5	251	123.5	77.2	69.1	257	284	63.5	69	73.8	59.5	145.5
Nd	0.1	189	684	380	249	233	726	781	204	223	236	197.5	403
Sm	0.03	25.9	60.9	42.1	29.7	30.1	67.3	69.7	24.9	27.9	29.2	26.8	45.3
Eu	0.03	6.03	16.8	10.1	7.52	7.39	18.7	20.4	6.21	6.83	7.23	6.24	12.75
Gd	0.05	13.45	20.2	17.35	14.25	14.85	23.2	23.7	12.15	13.85	13.65	14.05	20.3
Tb	0.01	1.39	1.97	1.78	1.45	1.5	2.22	2.29	1.29	1.42	1.39	1.43	1.98
Dy	0.05	5.87	8.47	7.8	6.13	6.54	9.83	9.8	5.6	6.13	6.17	6.19	8.04
Ho	0.01	0.96	1.36	1.27	1.02	1.08	1.61	1.61	0.92	1	1.01	1.01	1.3
Er	0.03	2.26	3.18	2.99	2.41	2.56	3.82	3.81	2.2	2.35	2.44	2.38	3.17
Tm	0.01	0.29	0.46	0.41	0.33	0.34	0.54	0.54	0.3	0.31	0.32	0.31	0.48
Yb	0.03	1.82	3.17	2.62	2.1	2.18	3.82	3.83	1.87	2	2.08	1.89	3.11
Lu	0.01	0.28	0.56	0.42	0.33	0.32	0.69	0.72	0.3	0.3	0.31	0.28	0.5
Y	0.5	27.4	47.4	39.5	30.4	30.9	54.4	55.7	27.1	29	30	28.3	45.1
ΣREY		1079.15	6469.47	2908.84	1731.84	1440.86	6499.13	7337.1	1397.34	1508.09	1611.6	1222.88	3630.53

Table 1. Continued.

	Detection Limit	RI-12-15	RI-12-16A	RI-12-16B	RI-12-17	RI-12-18	RI-12-20	RI-12-22	RI-12-23	RI-12-23A	RI-12-24	RI-12-26	RI-12-28
%													
SiO ₂	0.01	9.15	14.7	20.3	40.1	43.7	21.4	5.5	48.2	49.8	50.6	54.6	55
Al ₂ O ₃	0.01	2.66	1.6	5.9	14.8	19.15	8.07	0.31	14.4	14.55	15.2	16.45	16.05
Fe ₂ O ₃	0.01	3.28	1.88	3.85	8.01	7.25	6.96	2.3	7.33	7.04	7	6.27	6.32
CaO	0.01	17.25	8.15	10.35	4.56	2.12	11.4	18.85	6.63	6.28	7.13	4.53	5.55
MgO	0.01	0.87	0.39	1.4	2.8	1.65	1.72	0.21	3.11	2.94	4.32	3.33	3.62
Na ₂ O	0.01	<0.01	<0.01	<0.01	0.37	0.29	<0.01	<0.01	1.33	1.54	3.16	4.06	4.61
K ₂ O	0.01	0.92	0.17	1.32	4.79	3.79	2.36	0.05	4.33	4.43	4.23	4.3	4.53
Cr ₂ O ₃	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
TiO ₂	0.01	0.17	0.04	0.28	0.98	1.17	0.51	0.02	0.97	0.98	0.96	0.98	0.93
MnO	0.01	0.07	0.05	0.16	0.6	0.03	0.08	0.06	0.16	0.14	0.15	0.11	0.09
P ₂ O ₅	0.01	4.43	1.88	5.8	2.76	2.5	3.97	4.38	1.18	1.31	1.1	1.12	0.94
SrO	0.01	17.85	21	12.45	2.56	2.55	10.5	21.4	0.78	0.63	0.46	0.45	0.38
BaO	0.01	14.25	19.85	14.1	4.64	1.74	10.05	14.5	0.47	0.39	0.36	0.4	0.34
LOI	0.01	2.79	3.25	6.05	9.41	13.4	8.91	2.59	9.5	8.86	6.77	3.78	2.76
Total		73.7	72.97	81.97	96.4	99.36	85.94	70.18	98.4	98.9	101.45	100.39	101.13
ppm													
C	0.01	0.07	0.04	0.09	0.06	0.14	0.12	0.38	0.92	0.81	0.88	0.13	0.07
S	0.01	8.67	10.65	7.08	1.59	1.24	5.37	9.94	0.18	0.12	0.02	0.02	0.01
F	0.01	7.87	4.06	2.38	1	0.85	4.39	8.1	0.59	0.52	0.3	0.31	0.22
ppm													
Nb	1	90.5	58.9	109.5	85.4	70.9	118.5	96.6	57.7	55.8	56.1	58.7	84.6
Th	1	34.8	28	46.4	51.2	55.3	39.4	26.7	46.4	44.8	44.2	46.9	61
U	1	29.6	67	54.1	39.2	45.8	28.5	26.3	8.06	7.15	7.65	8.9	12.7
Zr	10	110	100	150	240	140	160	<20	310	290	320	340	410
ppm													
La	0.5	2500	2990	2720	1080	468	1940	2540	260	254	211	222	214
Ce	0.5	3170	3570	3450	1495	748	2500	3150	461	463	400	419	391
Pr	0.03	269	296	297	139.5	70	217	267	45.9	47.3	44.1	46.7	41.9
Nd	0.1	758	788	830	392	233	581	730	164	170	150.5	158	142.5
Sm	0.03	70.2	67.7	76.6	45.8	29.3	58.1	62.6	24.2	24.6	21.1	22.2	19.75
Eu	0.03	16.75	15.85	19.35	11.7	6.49	15	17.5	5.2	5.07	4.89	5.07	4.53
Gd	0.05	25	23.7	30.3	23.8	14.8	25.3	25.1	13.6	13.05	10.95	11.25	10.7
Tb	0.01	2.48	2.44	2.98	2.41	1.55	2.48	2.46	1.4	1.33	1.16	1.18	1.18
Dy	0.05	9.82	9.82	11.4	9.18	6.43	9.15	9.05	5.62	5.36	5.09	5.17	5.29
Ho	0.01	1.64	1.68	1.95	1.57	1.11	1.56	1.51	0.96	0.88	0.82	0.84	0.89
Er	0.03	4.11	4.52	4.9	3.98	2.91	3.93	3.84	2.38	2.2	1.97	2.02	2.15
Tm	0.01	0.62	0.74	0.7	0.53	0.41	0.57	0.58	0.31	0.28	0.26	0.26	0.29
Yb	0.03	4.48	5.62	4.61	3.44	2.64	3.71	3.71	1.94	1.76	1.66	1.62	1.84
Lu	0.01	0.83	1.11	0.82	0.53	0.39	0.61	0.65	0.28	0.25	0.24	0.24	0.27
Y	0.5	51.5	53.5	58.7	45.9	31.8	48	44.1	25.3	24.3	22.9	23.5	23.9
ΣREY		6884.43	7830.68	7509.31	3255.34	1616.83	5406.41	6858.1	1012.09	1013.38	876.64	919.05	

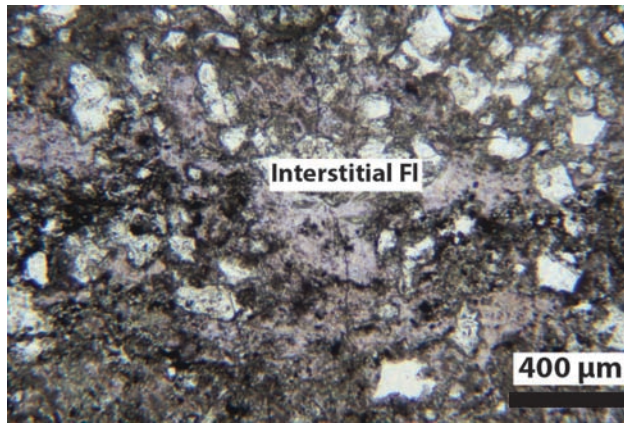


Fig. 8. Subhedral anorthoclase grains (grey) suspended in a pinkish fluorite-rich matrix (Sample RI-12-05).

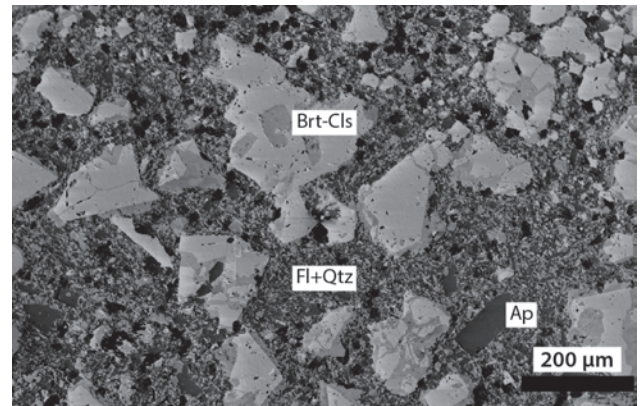


Fig. 9. SEI of sample RI-12-05 showing euhedral barite-celestite grains suspended in a fine-grained matrix of fluorite and silica.

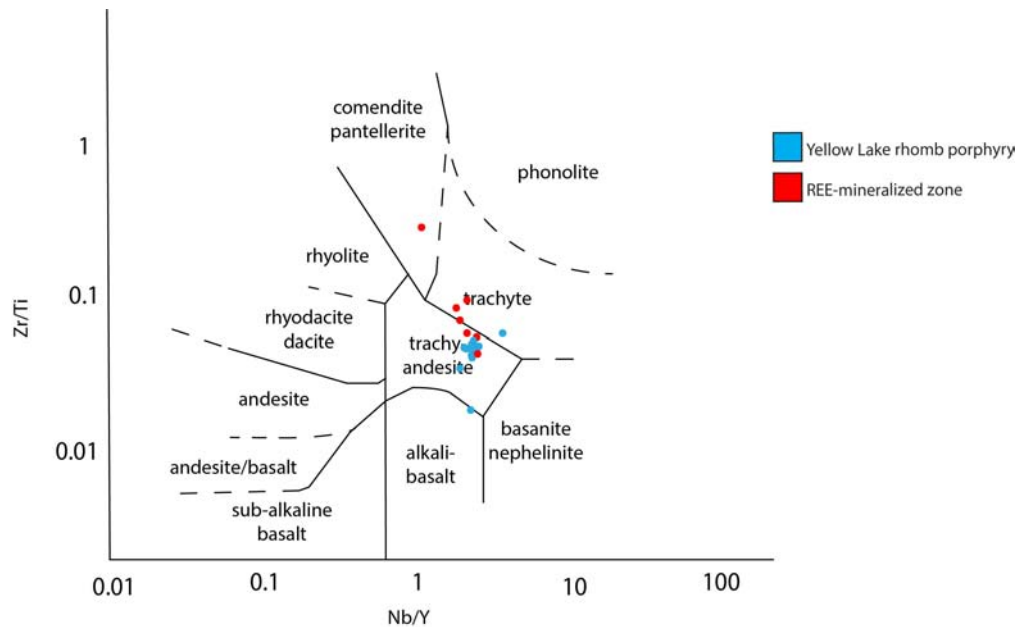


Fig. 10. Immobile element classification of the Yellow Lake rhomb porphyry and the REE-mineralized zone. Samples of both plot in the trachyte and trachyandesite fields. The Zr/Ti values of the REE-mineralized samples are elevated relative to those of the Yellow Lake rhomb porphyry. Modified from Winchester and Floyd (1977).

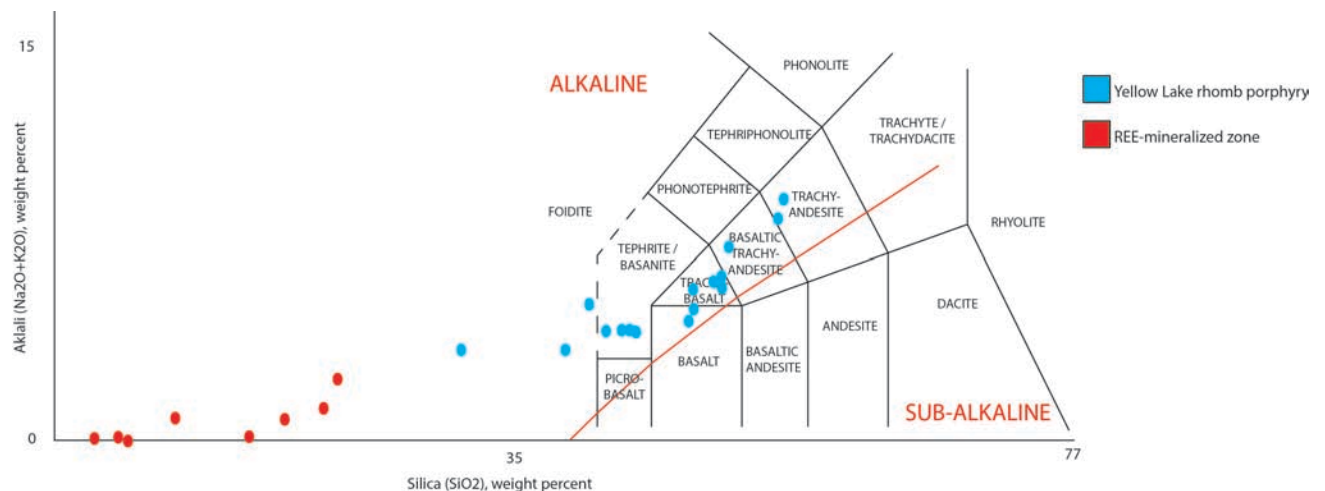


Fig. 11. TAS diagram illustrating the composition of samples of the Yellow Lake rhomb porphyry and the REE-mineralized zone.

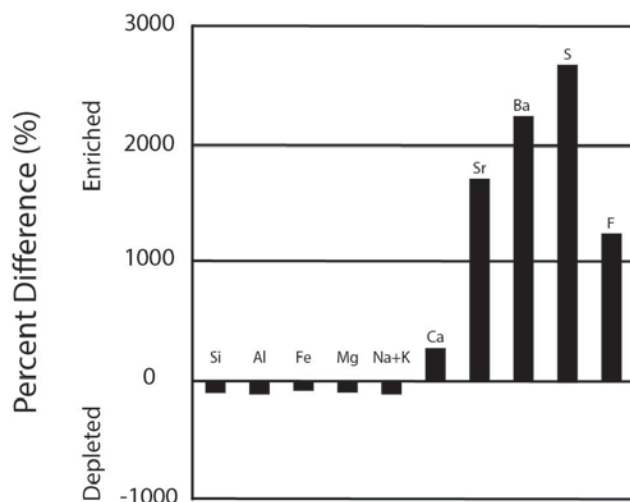


Fig. 12. Mass changes of average mineralized compositions (RI-12-05, RI-12-10, and RI-12-22) with respect to a fresh sample (RI-12-12) obtained from the Yellow Lake rhomb porphyry. Closed system behavior (i.e., constant mass) is assumed.

concentrations of the light REE. Finally, the high correlation coefficient of the Ce-P pair suggests that the rare apatite observed in both the Yellow Lake rhomb porphyry and the REE mineralized zone (Table 2) may have elevated REE contents.

5.1. Spatial distribution of REE

Isopach maps for Ce, Gd, and Y (e.g., Fig. 5) were generated to determine if there was any preferential mobility of individual REE that could be used as a vector towards the mineralization. These maps confirm that the highest REE concentrations coincide with mineralized zone. However, preferential mobility of particular REE was not discerned. The mineralized zone is easily identified by sharp, colour-based contacts from green through yellow and gray (fresh), to pale purple (weak mineralization), and dark purple (strong mineralization). This colour change provides an excellent vector to the mineralization.

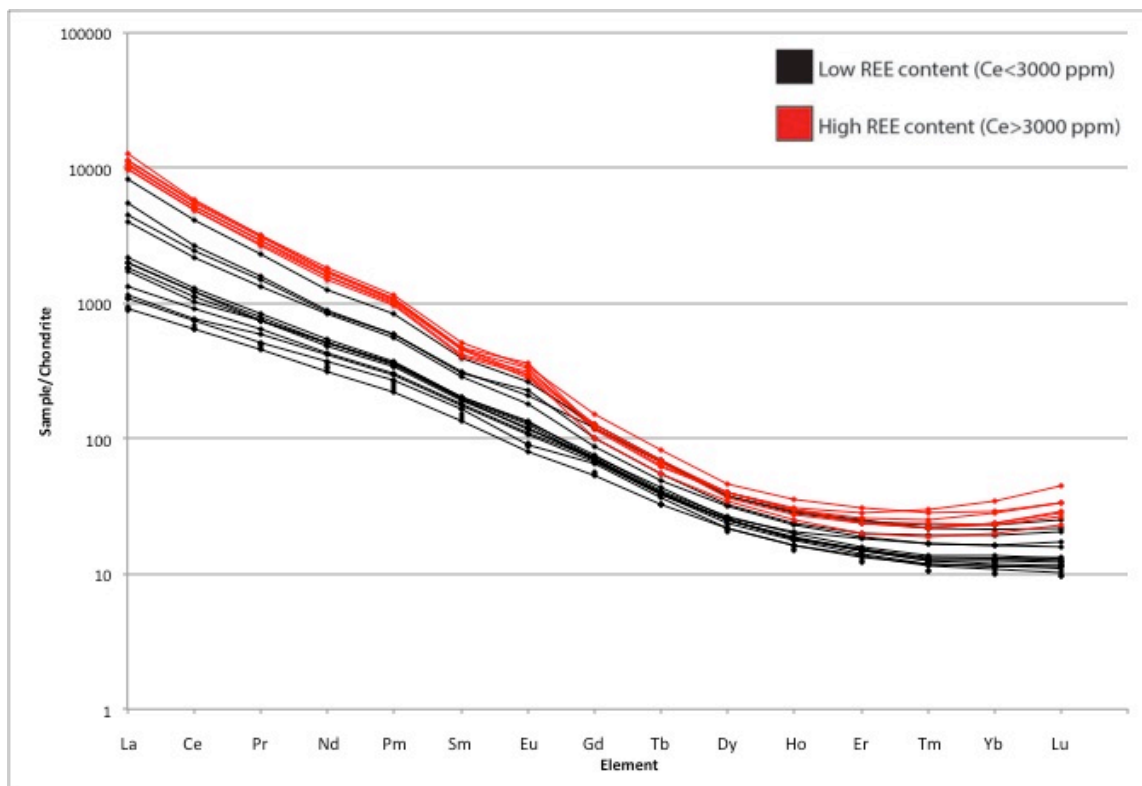


Fig. 13. Chondrite-normalized REE diagram illustrating the relative abundances of the different REE in samples of Yellow Lake rhomb porphyry and the REE-mineralized zone. The chondrite values were obtained from McDonough and Sun (1995).

Table 2. Correlation matrix of selected elements for samples obtained from the Riddle Creek REE prospect.

	Responding Element										
	Ba	Ce	La	Nd	Sm	Yb	Ca	P	Sr	S	F
Independent Element	Ba	1	0.61	0.62	0.64	0.62	0.37	0.64	0.57	0.99	0.50
	Ce	0.61	1	1.00	0.99	0.93	0.81	0.88	0.95	0.98	0.87
	La	0.61	1.00	1.00	0.98	0.94	0.80	0.86	0.95	0.98	0.86
	Nd	0.62	1.00	1	0.99	0.93	0.80	0.89	0.94	0.97	0.86
	Sm	0.64	0.99	0.99	1	0.94	0.77	0.91	0.91	0.94	0.84
	Yb	0.62	0.93	0.93	0.94	1	0.57	0.76	0.84	0.89	0.70
	Ca	0.37	0.81	0.80	0.77	0.57	1	0.81	0.88	0.85	0.94
	P	0.64	0.88	0.89	0.91	0.76	0.81	1	0.79	0.78	0.82
	Sr	0.57	0.95	0.94	0.91	0.84	0.88	0.79	1	0.99	0.97
	S	0.99	0.98	0.97	0.94	0.89	0.85	0.78	0.99	1	0.92
	F	0.50	0.87	0.86	0.84	0.70	0.94	0.82	0.97	0.92	1

6. Discussion

The results of the petrographic and geochemical analyses provide insights into the hydrothermal history of the Riddle Creek showing and the possible mechanism of REE enrichment. Mineralization appears to be in a cataclastic shear zone developed at the expense of the Yellow Lake rhomb porphyry (Fig. 10). The evidence of extreme leaching of the alkalis and Mg, and even of an element like Al, which is normally immobile, is strong evidence that the hydrothermal fluid was extremely acid ($\text{pH} < 2$); at low pH, dissolution of silica is pH independent but is favoured by high HF activity. A preliminary model is proposed in which the REE (preferentially the light-REE) were mobilized by a fluorine-sulphate-bearing, chloride-rich hydrothermal brine of possible magmatic origin. As HF is strongly associated at low pH, thereby restricting the availability of F^- , and REE-fluoride mineral solubility is very low, fluoride complexing of the REE is precluded (Williams-Jones et al., 2012). It is therefore proposed that the REE were transported as chloride complexes; such complexes transport the light REE preferentially. Sulphate complexes may also have played a role in REE transport, but would not have contributed to the observed light REE enrichment. Finally, it is proposed that deposition of the REE occurred as a result of mixing of the ore fluid with an external Ca-Sr-Ba-bearing fluid in a shear zone cutting the Yellow Lake rhomb porphyry; the very low solubility of fluorite, barite, and celestite require that their constituent components were transported separately. This mixing increased the pH of the fluid and ore mineral components, leading to supersaturation of barite-celestite and fluorite, and in turn, the concentration of the light REE by incorporating them in their structures.

7. Conclusions

The Riddle Creek Sr-Ba-REE-F prospect demonstrates the potential for REE exploration outside the Alkaline Province, particularly in “slab window” tectonic settings like those represented in the Penticton Tertiary outlier. Unlike most REE deposits, the rare earth elements are not concentrated in a REE-rich phase such as bastnäsite-(Ce) or monazite-(Ce). Instead, the REE occur mainly as a minor component in barite-celestite and to a much lesser extent in fluorite. The association of REE to fluorite (purple) provides a macroscopically observable colour-based pattern, which may be used as a vector to the ore. The Riddle prospect is also unusual by having anomalously low contents of U and Th relative to other occurrences in the district.

Acknowledgments

The authors wish to thank Alex Kaul and Rebecca Stone for their assistance in the field, and Alex Kaul for his preliminary drafting of the maps. This project received funding and support from Targeted Geoscience Initiative 4 (2010-2015), a Natural Resources Canada program carried out under the auspices of the Geological Survey of Canada.

References cited

- Church, B.N., 1971. The geology of the White Lake basin. In: *Geology, Exploration and Mining in British Columbia*, 1970, British Columbia Department of Mines and Petroleum Resources, pp. 396-402.
- Church, B.N., 1973. *Geology of the White Lake Basin*. British Columbia Department of Mines and Petroleum Resources, British Columbia Geological Survey Bulletin 61, 120 p.
- Church, B.N., 2002. *Geology of the Penticton Tertiary outlier*. B.C. Ministry of Mines and Energy Resources, British Columbia Geological Survey Geoscience Map 2002-5, scale: 1:50 000.
- Church, B.N., 2007. *Geological and geochemical evaluations of the Riddle Creek Claims, Riddle Creek, Osoyoos Mining Division, British Columbia*. British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Survey Branch Assessment Report 28970.
- Currie, K.L., 1976. The alkaline rocks of Canada. *Geological Survey of Canada Bulletin* 239, 229 p.
- Dostal, J., Breitsprecher, K., Church, B.N., Thorkelson, D., and Hamilton, T.S., 2003. Eocene melting of Precambrian lithospheric mantle: Analcime-bearing volcanic rocks from the Challis Kamloops belt of south central British Columbia. *Journal of Volcanology and Geothermal Research*, 126, 303-326.
- McDonough, W.F., and Sun, S.-s., 1995. The composition of the Earth. *Chemical Geology*, 120, 223-253.
- Morrison, M.S., 2001. *Geochemical assessment report on the Vent Claim Group Summerland area, Osoyoos Mining Division*; British Columbia Ministry of Energy Mines and Petroleum Resources. Assessment Report 26750, 33 p.
- Pell, J., 1994. Carbonatites, nepheline syenites, kimberlites and related rocks in British Columbia. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, Bulletin 88, 136 p.
- Simandl, G.J., Prussin, E.A., and Brown N., 2011. *Specialty (rare) metals in British Columbia, Canada*. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey GeoFile 2011-10, scale: 1:2 000 000.
- Simandl, G.J., Prussin, E.A., Brown N., Hancock, K. and Meredith-Jones, S., 2012. *Specialty (rare) metal-bearing deposits in British Columbia, with selected examples*. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey GeoFile 2012-2.
- Souther, J.G., 1991. Volcanic Regimes. In: Gabrielse, H., Yorath, C.J. (Eds.), *Geology of the Cordilleran Orogen in Canada*. Geological Survey of Canada, *Geology of Canada* 4 (also Geological Society of North America, vol. G-2), pp. 457-490.
- Williams-Jones, A.E., Migdisov, A.A., and Samson, I.M., 2012. Hydrothermal mobilization of the rare earth elements – a tale of “ceria” and “yttria”. *Elements*, 8, 355-360.
- Winchester, J.A., and Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, 20, 325-343.