Portable X-ray fluorescence to optimize stream sediment chemistry and indicator mineral surveys, case 2: Carbonatite-hosted REE deposits, Wicheeda Lake, British Columbia, Canada

Duncan A.R. Mackay[1] and George J. Simandl[1, 2, a]

[1] University of Victoria, School of Earth and Ocean Sciences, Victoria, BC, V8P 5C2
[2] British Columbia Geological Survey, Ministry of Energy and Mines, Victoria, BC, V8W 9N3
[a] corresponding author: George.Simandl@gov.bc.ca

Abstract

The Wicheeda carbonatite-hosted deposit is one of the most promising rare earth element (REE) prospects within the British Columbia alkaline province. Portable X-ray fluorescence (pXRF) allows for determination of several pathfinder elements (Nb, Ta, REEs, Th, Ba, and Sr) in stream sediment samples collected downstream of this deposit. These samples are expected to contain indicator minerals derived from the main carbonatite complex such as monazite, REE-bearing carbonates and fluorocarbonates, pyrochlore, columbite-(Fe), barite-celestine, apatite, and others. Study of these samples indicates that the + 250 μm, + 125 μm, and + 63 μm size fractions contain high concentrations of Nb, La, Ce, and Th relative to other size fractions. The + 125 μm fraction was chosen for systematic chemical analyses and pathfinder element studies. Although there is no noticeable decreasing trend in pathfinder elements with increasing distance downstream, there is co-variation of Nb, Ta, La, Ce, Pr, Nd, Y, and Th. This reflects the presence of multiple mineral phases including pyrochlore, monazite-(Ce), REE-fluorocarbonates, and REE-carbonates. Mineralogical studies using optical microscopy, scanning electron microscopy (SEM), electron microprobe (EMP), and Quantitative Evaluation of Materials by Scanning electron microscopy (QEMSCAN) are required to identify and quantify minerals and their distributions downstream of the deposit.

Keywords: Indicator minerals, pathfinder elements, rare earth elements, specialty metals, portable x-ray fluorescence, carbonatite

1. Introduction

Increased use of REE in consumer and green technologies has spurred demand and made these elements a focus of economic and strategic mineral development in the past few years (Tse, 2011). With 95% of world production of REE in China, from deposits such as the carbonatite-related Bayan Obo, and recent export restrictions, western industrialised nations are faced with supply uncertainties (Tse, 2011). Hence, increased exploration for and development of REE mineral deposits is taking place outside of China.

The Wicheeda carbonatite complex and carbonatite and syenite dikes are 80 km northeast of Prince George, British Columbia (Fig. 1). The Wicheeda carbonatite complex was originally explored for its base metal potential. Between 1979 and 1987 the complex was the subject of 1:5000-scale geological mapping and trenching (Betmanis, 1987), soil sampling and stream silt sampling (Lovang and Meyer, 1987), and geophysical surveying (Bruland, 2011). Spectrum Mining Corporation (Spectrum) acquired the claims that cover the Wicheeda carbonatite complex and conducted diamond drilling in 2008 and 2009 (Graf et al., 2009; Lane, 2009).

The main objectives of this study are to determine the best size fraction in stream sediments for indicator mineral and geochemical exploration programs, and to characterize the geochemical gradients of Nb, Ta, REEs, Ba, Sr, and Th in

sediments downstream of the Wicheeda carbonatite complex using pXRF. These will help assess geochemical and indicator minerals methods for Wicheeda-type carbonatite-hosted REE deposit exploration.

2. Geological setting

The Wicheeda carbonatite complex is part of a series of carbonatite, syenite, and alkaline rock complexes forming the British Columbia alkaline province, which coincides with the approximate margin of the Laurentian craton (Pell, 1994). Carbonatites in British Columbia were emplaced during three main periods of extensional tectonics ca. 800-700 Ma, 500 Ma, and 360-340 Ma (Pell, 1994; Millonig et al., 2012). Subsequent phases of deformation and sub-greenschist to amphibolite grade metamorphism between ~ 155 and 50 Ma overprint the carbonatites along this trend (Pell, 1994; Millonig et al., 2012).

The regional geology was originally mapped at a scale of 1:253,440 by Armstrong et al. (1969). The Wicheeda Lake carbonatite is immediately west of the Rocky Mountain Trench and intrudes Lower to Middle Paleozoic platformal successions deposited on the western margin of Laurentia. These rocks consist of limestone, argillite, and calcareous siltstone of the Kechika Formation (Cambrian to Early Ordovician; Fig. 2; Armstrong et al., 1969). The Kechika Formation is in fault contact with limestone, slate, siltstone, and argillite of the
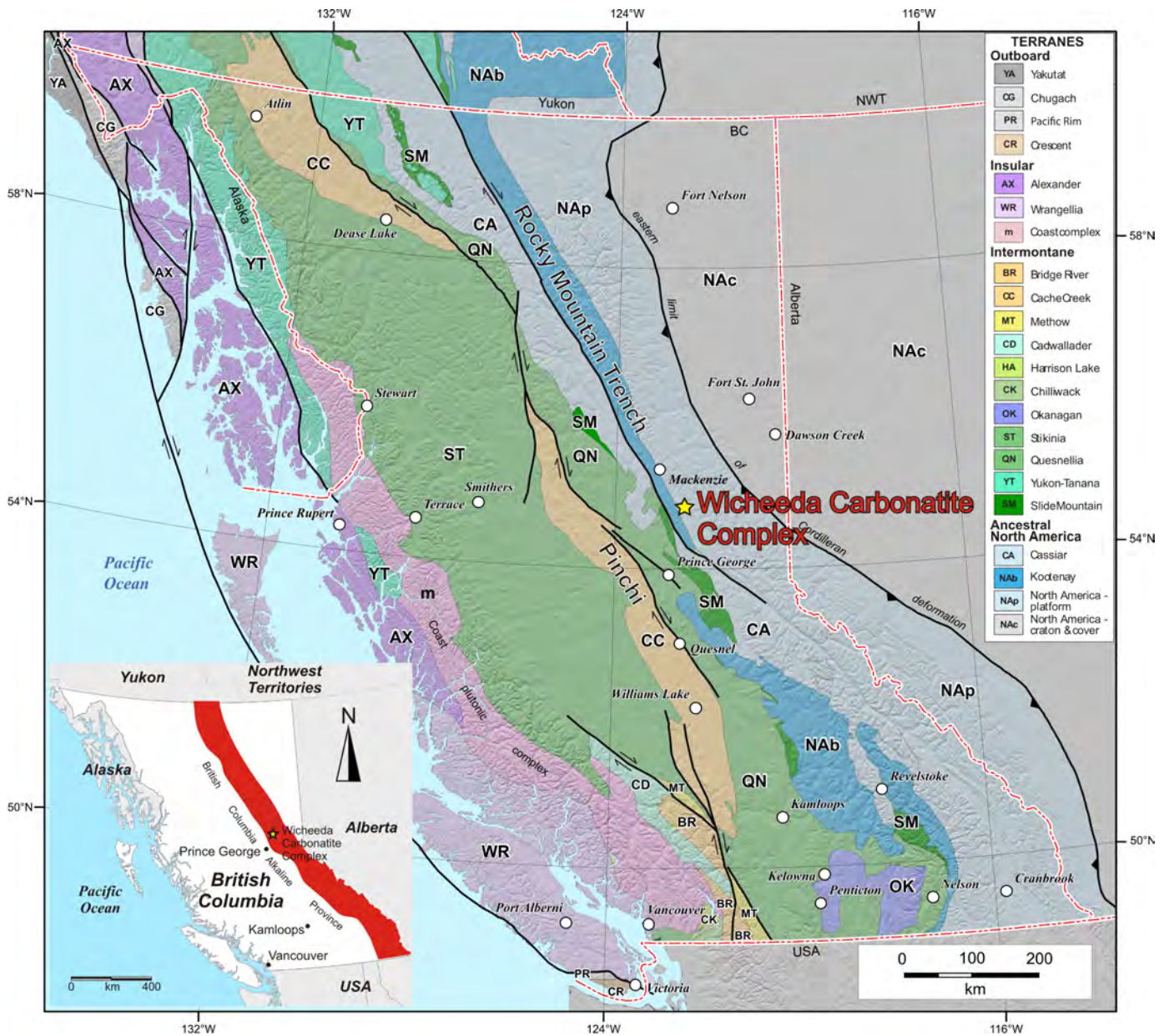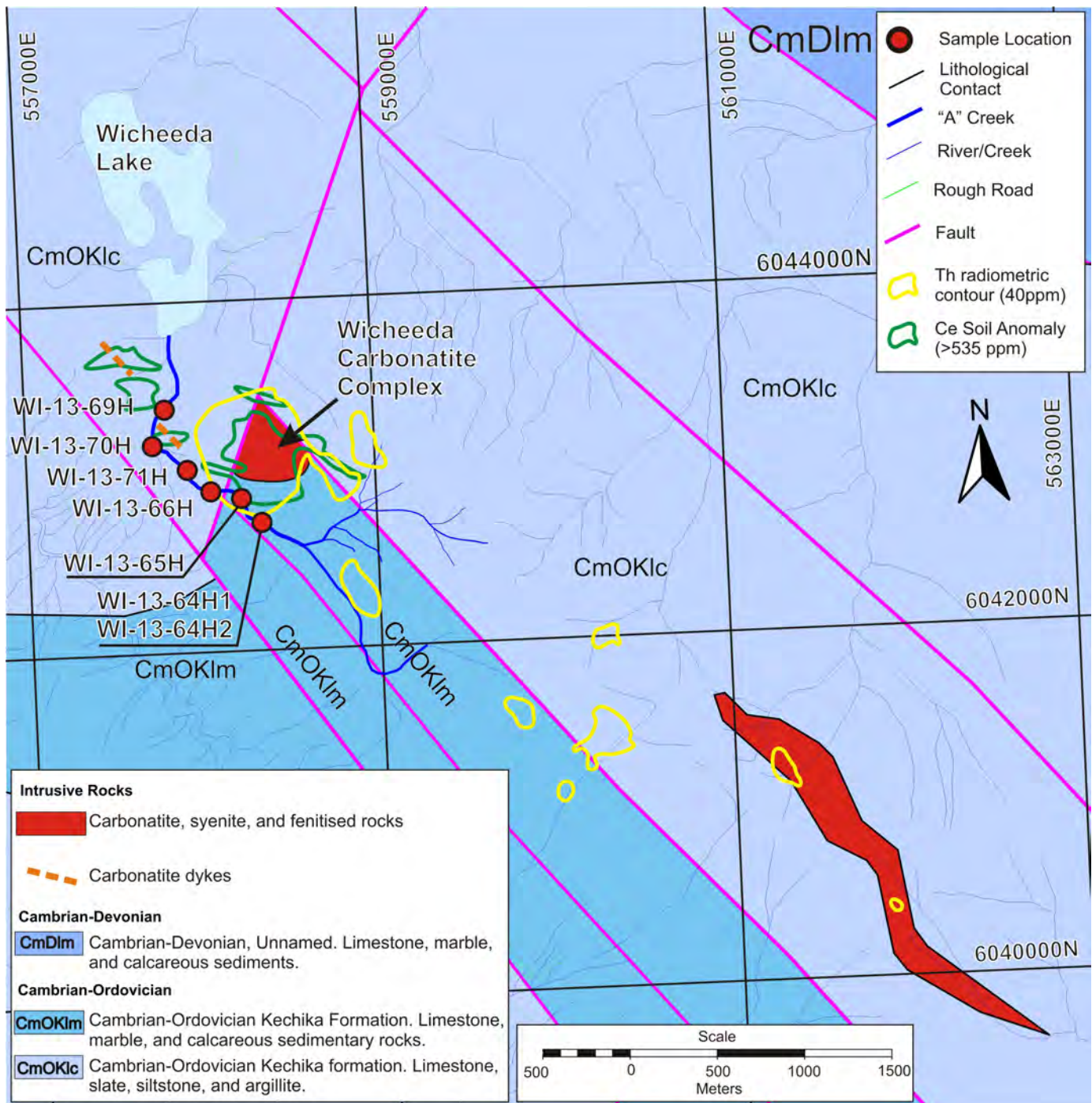
Fig. 1. Tectonic setting of the Wicheeda carbonatite complex (yellow star). British Columbia alkaline province shown in red (inset map). Municipalities are denoted by white circles. Modified after Pell (1994).

Gog Group (Neoproterozoic) and unassigned Devonian to Permian felsic volcanic rocks to the west, and unassigned Cambrian to Devonian carbonates, slates, and siltstones to the east (Armstrong et al., 1969; Lane, 2009). Lower greenschist grade regional metamorphism overprints the country rocks (Lane, 2009). Faulting in the area follows the major northwest-southeast trend of the Rocky Mountain Trench.

Dalsin (2013) reported a Sm-Nd whole rock isochron age of 316 ± 36 Ma for samples from the carbonatite dikes ~ 3 km southeast of the main Wicheeda carbonatite complex. The carbonatite and syenite dikes and the Wicheeda complex follow the same northwest-southeast structural trend and are assumed to be related.

3. Geology of the Wicheeda carbonatite complex

The shape of the Wicheeda carbonatite complex is not well defined. It is sub-circular in plan (< 500 m in diameter), based on previous mapping and a Th radiometric anomaly (Lovang and Meyer, 1988; Mäder and Greenwood, 1988; Lane, 2009; Bruland, 2011). Reconnaissance fieldwork suggests that its emplacement was controlled by the intersection of two faults (Fig. 2). Drilling in 2008 and 2009 intersected high-grade zones consisting of 3.55% total rare earth oxide (TREO) over 48.6 m, 2.2% over 144 m, and 2.9% over 72 m; other high grade intersections are near the top of drill holes in weathered dolomite carbonatite zones (Graf et al., 2009; Lane, 2009). A series of carbonatite dikes has been identified northwest of

196

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Fig. 2. Geological setting of the Wicheeda carbonatite complex, associated dikes, and locations of stream sediment samples. Base map modified after Massey et al. (2005). Thorium radiometric anomalies from Bruland (2011) shown by yellow traces. Cerium soil anomaly from Lane (2009) shown by green traces. UTM zone 10, NAD 83.

the main carbonatite complex near Wicheeda Lake; a larger syenite-carbonatite dike complex is ~ 3 km to the southeast (Fig. 2).

The main carbonatite complex consists of two main units: dolomite carbonatite; and fenitised zones formerly referred to as syenite breccias. Based on the work of Le Couteur (2008, 2009), Lane (2009), and observations from this study, the carbonatite consists mainly of dolomite (75-97%) ± ankerite. In general,

calcite, plagioclase, potassium feldspar, biotite, muscovite/ phlogopite, chlorite, and pyrite are minor constituents, and quartz, barite, strontianite, Fe-Ti oxides, molybdenite, galena, fluorite, apatite, and possibly powellite are present in trace amounts (Le Couteur, 2008, 2009; Lane, 2009). The main REE-bearing phases in the dolomite carbonatite are monazite [(Ce, La, Nd, Th) PO_4] and REE-bearing fluorocarbonates [such as bastnasite-(Ce), parisite-(Ce), and/or synchysite-(Ce)] and

197

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

carbonates (Le Couteur, 2008, 2009; Lane, 2009); however, it is expected some REEs form minor constituents in apatite, columbite, and possibly pyrochlore. The main Nb-bearing mineral is pyrochlore [(Na, Ca)$_2$ Nb$_2$ O$_6$(OH,F)]. Columbite [(Fe, Mn) Nb$_2$ O$_6$] and Nb-rutile [(Ti, Nb, Fe) O$_2$] may also be present. Calcite increases in abundance with depth. Le Couteur (2008, 2009) identified zones of predominantly calcite (85%), which contains biotite, strontianite, and magnetite.

The fenitised zones (albitised and potassic altered wall rock) observed in core contain abundant feldspar-rich (90%) xenoliths in a dolomite matrix. At the surface, patchy blue-green, Na-amphibole (± pyroxene)-bearing fenite is in contact with dolomite carbonatite. By definition potassium feldspar, plagioclase, micas, amphiboles, and other silicates are more abundant in fenitised rocks than in carbonatites. The carbonatite is overlain by a characteristic red soil or regolith horizon, 5 cm to more than 50 cm thick. Mineralogical and chemical characterisation of resistate minerals in this horizon are the subject of ongoing research.

4. Methods
4.1. Sample collection

Seven stream sediment samples along "A" creek adjacent to the Wicheeda carbonatite complex were collected during the 2013 field season (Figs. 2, 3, Table 1). Sample sites are spaced 200-300 metres apart. There is more than 160m elevation difference between sample WI-13-64H1 and WI-13-69H (Table 1). The streambed consists mainly of boulders, cobbles, and pebbles. Samples were collected in the lee of boulders and logs, and from inside stream bends, typically over areas < 1 m^2. Matrix material was wet sieved in the field through a + 8 mm screen; only the < 8 mm fraction was retained. Samples were contained in permeable canvas bags and stored in plastic pails. The dried samples weighed 1.1 to 5.4 kg (Table 1). Organic

Fig. 3. Location of stream sediment samples and local topography around the Wicheeda carbonatite complex. Samples are downhill of the Wicheeda carbonatite complex. Elevation contours denoted by brown lines (100 m contour interval). Modified after Massey et al. (2005).

material (conifer needles, leaves, and twigs) was scraped from the surface of samples sites. Not all of the organic material could be avoided during sample collection, and minor amounts were retained in the coarser fractions (+ 500 µm and coarser).
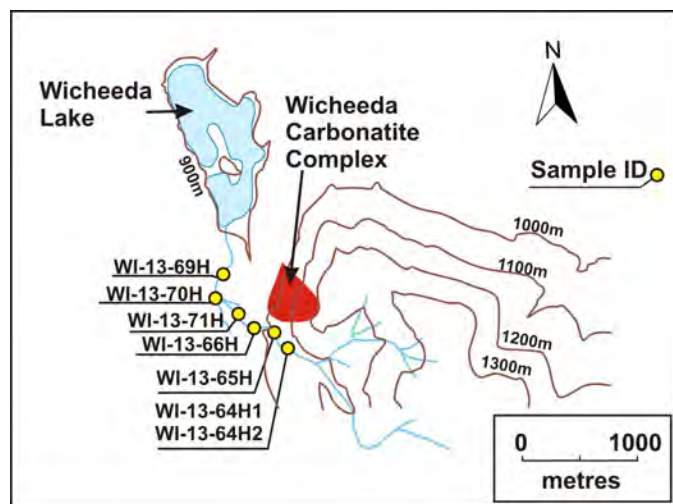
4.2. Sample preparation and pXRF analyses

Samples were dried in an oven at 40° C, weighed, and dry sieved into + 4 mm, 2 mm to 4 mm, 1 mm to 2 mm, 500 µm to 1 mm, 250 µm to 500 µm, 125 µm to 250 µm, 63 µm to 125 µm, and -63 µm fractions. No aggregates (clumps) were observed during the sieving process. Each size fraction was also weighed. Selected size fractions were split using a riffle splitter with portions retained for a witness sample, magnetic separation, and XRF analyses. Samples for XRF analyses were milled using ring and roller bowl tungsten carbide mills. Standard XRF sample pulp cups were then prepared and analysed by pXRF. Analyses were carried out using a portable Thermo Fisher Scientific Niton FXL-950 instrument. A complete description of equipment, sample preparation, and laboratory methods as well as information regarding the standards used, operating procedure, instrument settings, limits of detections, and data quality control are described by Luck and Simandl (2014). Relative major oxide and trace element concentrations analysed by pXRF have acceptable precision; however, pXRF data has not been recalibrated using results of standard laboratory analyses (as described in Simandl et al., 2013) to correct for analytical biases. Error bars for figures in this study are based on 2σ values for standards analysed multiple times by pXRF.

5. Results

Two samples (WI-13-66H and WI-13-71H) were chosen for detailed study. Sample WI-13-66H was collected ~ 175 metres downslope from the deposit (Fig. 3); WI-13-71H was collected 220 metres downstream of sample WI-13-66H, where "A" creek enters a cut block in an area of low topographic relief. In both samples, the + 125 µm size fraction contains higher concentrations of pathfinder elements relative to other size fractions (Fig. 4). The + 250 µm and + 63 µm fractions are the next most enriched. These results are similar to those from stream sampling near the Lonnie carbonatite (Luck and Simandl, 2014) and the Aley carbonatite (Mackay and Simandl, 2014). Based on these characteristics, the + 125 µm fractions of the remaining samples were analysed. Samples WI-13-66H and WI-13-71H show a grain-size distribution that is skewed toward coarse-grained material (Fig. 4).

Concentrations of major oxides (Table 2) range from 42.8 to 57.9 wt% SiO$_2$, 16.3 to 23.4 wt% Al$_2$O$_3$, 4.5 to 7.0 wt% Fe$_2$O$_3$, 2.1 to 8.2 wt% CaO, 0.4 to 0.9 wt% TiO$_2$, 1.8 to 2.4 wt% MgO, and 4.5 to 6.9 wt% K$_2$O. Trace element concentrations (Table 2) range from 57 to 283 ppm Nb, <22 to 34.7 ppm Ta, 19 to 46 ppm Y, 117 to 887 ppm La, 215 to 1301 ppm Ce, 167 to 482 ppm Nd, 97 to 225 ppm Pr, 806 to 1805 ppm Ba, 190 to 328 ppm Sr, < 5 to 7 ppm U (only 4 samples are above detection

198

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1
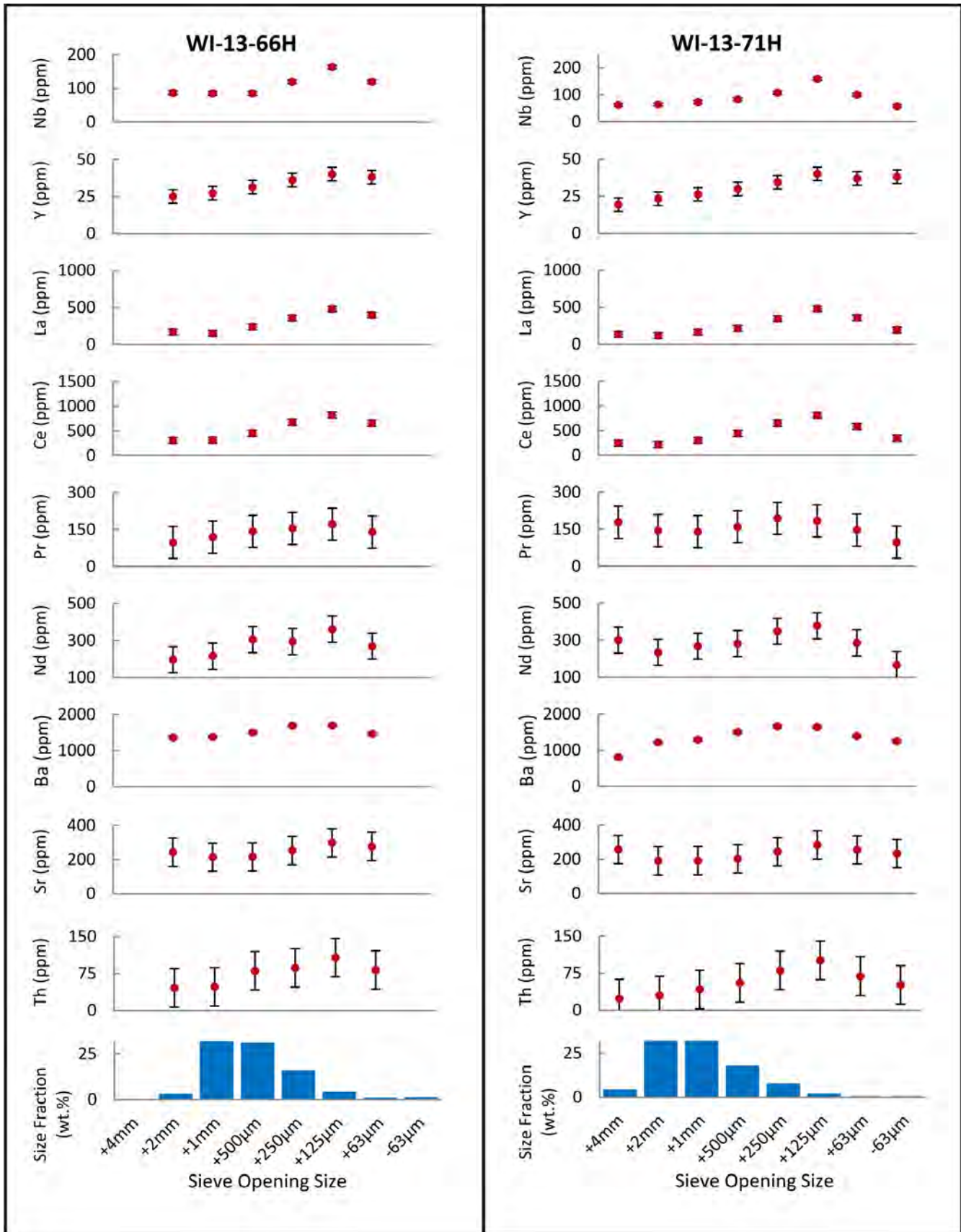
Fig. 4. Portable XRF analyses for selected trace elements and grain size fraction distributions of samples WI-13-66H and WI-13-71H. The + 250 μm, + 125 μm, and + 63 μm size fractions are enriched in Nb, La, Ce, and Th relative to other size fractions.

199

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Table 1. Characteristics of stream channel and sample sites. Samples are in order of increasing distance downstream of the Wicheeda carbonatite complex. UTM zone 10, NAD 83.

| | Location | | Elevation | Channel Characteristics | | | Clast Size (cm) | | Dry wt. (< 8 mm diameter) | Sample Site Characteristics |
Sample ID	Northing	Easting	(m)	Width (m)	Depth (m)	Flow	Average	Max.	(kg)	
WI-13-64H1	6042772	558279	1077	1.5	0.10	rapid	0.5-1.5	5-7	1.7	Lee of fallen trees; steep-sided gully, upstream of trail; predominantly shale, siltstone, and carbonate clasts.
WI-13-64H2	6042772	558279	1077	1.5	0.10	rapid	0.5-1.5	5-7	1.1	2-3 m upstream of WI-13-64H1.
WI-13-65H	6042901	558198	1015	2.0	0.20	rapid	0.5-1.5	5-10	2.6	Inside of stream bend; steep-sided gully; grey slate clasts predominant.
WI-13-66H	6042929	558020	973	2.0	0.30	rapid	0.5-1.5	5-7	1.5	Pools below rapids (protected by fallen tree); steep sided gully; grey slate clasts predominant.
WI-13-71H	6043031	557916	935	1.5	0.15	slow	2-5	35	5.4	Lee of fallen tree; low relief topography; grey slate and limestone predominant.
WI-13-70H	6043178	557731	920	1.5	0.10	slow	1-2	10	2.6	Sample from matrix between cobbles; low relief topography; grey slate and limestone predominant; upstream of trail.
WI-13-69H	6043384	557792	911	1.0	0.15	moderate	0.2-0.5	5-7	2.8	Sample from matrix between cobbles; low relief topography; grey slate and limestone predominant; upstream of trail.

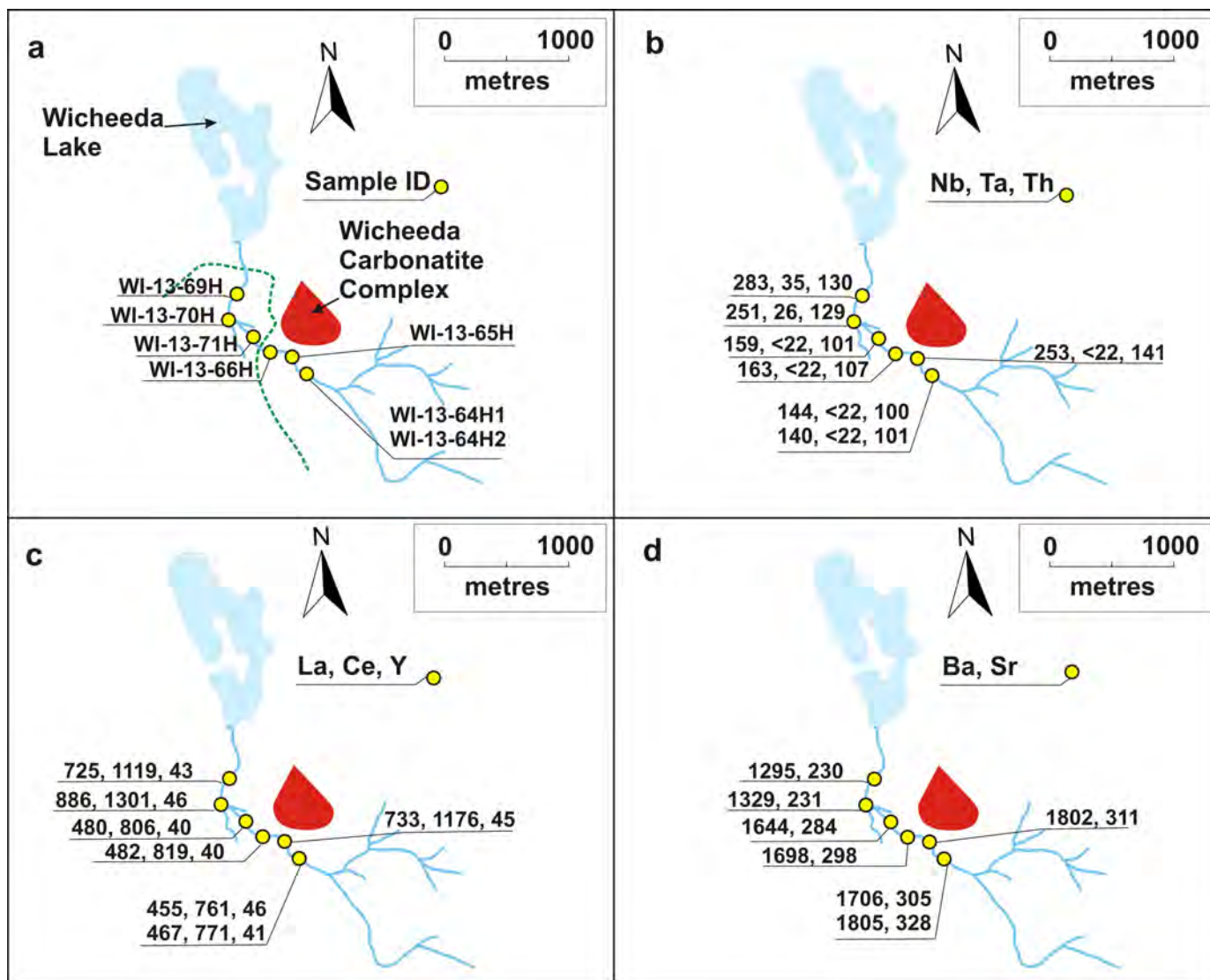limits), and 24 to 141 ppm Th. All samples have P values of < 90 ppm.

6. Discussion

High concentrations of key pathfinder elements (Nb, Ta, REEs, Th, Ba, and Sr) suggest the presence of prospective indicator minerals in the +125 μm size fraction. Barium and to a lesser extent Sr concentrations decrease from southeast to northwest (Figs. 5, 6). Their source is probably upstream of the deposit. This may reflect input of material from other carbonatite-related showings in the area, or be related to sediment influx from limestones and marbles of the Kechika Formation. A slight decreasing trend in CaO with increasing distance downstream is observed, while the opposite is observed for SiO_2. This is probably due in part to a change in lithology across a fault from predominantly limestone and

200

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Table 2. Relative major oxide and trace element concentrations analysed by pXRF. This pXRF data has acceptable precision; however, it has not been recalibrated using results of standard laboratory analyses (as described in Simandl et al., 2013) to correct for matrix effects and analytical biases to improve accuracy. Portable XRF is not a substitute for conventional laboratory analyses. Eight size fractions reported for sample WI-13-71H. Six size fractions reported for WI-13-66H. The +125 μm fraction is reported for all other samples. Results are in ppm except where otherwise noted. Samples are in order of increasing distance downstream of the Wicheeda carbonatite complex.

Sample	Size Fraction (mm)	Nb	Ta	Y	La	Ce	Nd	Pr	Ba	Sr	P	U	Th	% SiO$_2$	% CaO
WI-13-64H1	+0.125	144	<22	46	455	761	319	172	1707	305	<90	<5	100	47.68	6.27
WI-13-64H2	+0.125	140	<22	41	467	771	344	148	1805	328	<90	5	101	49.42	4.80
WI-13-65H	+0.125	253	<22	45	733	1176	442	192	1802	311	<90	<5	141	52.15	4.70
WI-13-66H	+2.00	87	<22	25	171	310	196	97	1363	243	<90	7	46	50.10	4.87
WI-13-66H	+1.00	85	24	27	151	315	216	119	1379	214	<90	<5	48	50.24	3.95
WI-13-66H	+0.500	85	<22	31	239	455	305	142	1501	216	<90	7	80	52.70	3.06
WI-13-66H	+0.250	119	<22	36	358	671	294	154	1690	253	<90	<5	86	52.60	3.41
WI-13-66H	+0.125	163	<22	40	482	819	361	172	1698	298	<90	<5	107	53.69	4.77
WI-13-66H	+0.063	119	<22	38	396	655	269	139	1463	277	<90	5	82	50.09	5.01
WI-13-71H	+4.00	62	23	19	135	244	300	178	806	257	<90	<5	24	47.78	8.20
WI-13-71H	+2.00	64	22	23	117	215	234	144	1216	190	<90	<5	30	51.49	4.10
WI-13-71H	+1.00	73	25	26	164	305	268	140	1291	192	<90	<5	42	51.88	3.74
WI-13-71H	+0.500	83	<22	30	214	444	282	160	1506	203	<90	<5	55	52.20	3.32
WI-13-71H	+0.250	108	<22	34	344	648	348	194	1661	244	<90	<5	80	52.87	3.66
WI-13-71H	+0.125	159	<22	40	480	806	378	184	1644	284	<90	<5	101	53.13	4.69
WI-13-71H	+0.063	100	<22	37	358	581	286	146	1391	255	<90	<5	69	51.56	4.65
WI-13-71H	-0.063	57	<22	38	193	341	167	97	1250	233	<90	<5	51	42.76	5.09
WI-13-70H	+0.125	251	26	46	886	1301	482	225	1329	231	<90	<5	129	55.86	3.06
WI-13-69H	+0.125	283	35	43	725	1119	424	191	1295	230	<90	<5	130	57.92	2.07

201

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Fig. 5. Selected trace element concentrations in stream sediment samples. **a)** Sample numbers. **b)** Nb, Ta, and Th. **c)** La, Ce, and Y. **d)** Ba and Sr concentrations in ppm. The edge of the cut block and the area of low topographic relief are denoted by the green dotted line.

marble in the southeast to a predominantly pelitic assemblage in the northwest (Fig. 6).

Excluding Ba and Sr, samples WI-13-71H and WI-13-66H have consistently lower concentrations of pathfinder elements than the samples immediately upstream and downstream (WI-13-65H and WI-13-70H; Fig. 6). Calcite carbonatite dikes are reported by Lane (2009) northeast of the main carbonatite complex; during mapping in the summer of 2013, outcropping calcite carbonatite was observed near sample WI-13-70H (Fig. 2). Carbonatite boulders were also observed near the location of a dike reported by Lane (2009). Drilling in 2009 intersected one dike near sample WI-13-70H. These observations coincide with Ce soil and Th radiometric anomalies in the area (Fig. 2). Input of material from these occurrences probably contributes to increased pathfinder element concentrations in samples WI-13-69H and WI-13-70H (Fig. 7). Co-variation in pathfinder element concentrations between Nb, La, Ce, Nd, and Th (Fig. 7) is probably related to the presence of multiple indicator

minerals in stream sediments. These minerals may have originated from multiple sources.

High Ta concentrations (samples WI-13-69H and WI-13-70H) coincide with two of the highest Nb values (Fig. 7) and suggest the presence of Nb-Ta-bearing minerals such as pyrochlore or columbite. Samples WI-13-69H and WI-13-70H are downstream of the inferred position of the calcite carbonatite dikes (Fig. 7). This may reflect a difference in mineralogy between the main carbonatite complex and carbonatite dikes near Wicheeda Lake. High Nb:Ta ratios are expected in carbonatites based on typical composition of Nb-bearing mineral phases.

Correlations of pathfinder elements observed in the +125 μm size fraction (Fig. 8) can be used to predict indicator minerals found in stream sediments. Strong correlations between Ce and La ($R^2 = 0.99$), Nd ($R^2 = 0.94$), and Pr ($R^2 = 0.74$) is expected due to ready substitution of these elements in the same minerals. Cerium and Th ($R^2 = 0.87$; Fig. 8a) linear dependency indicates
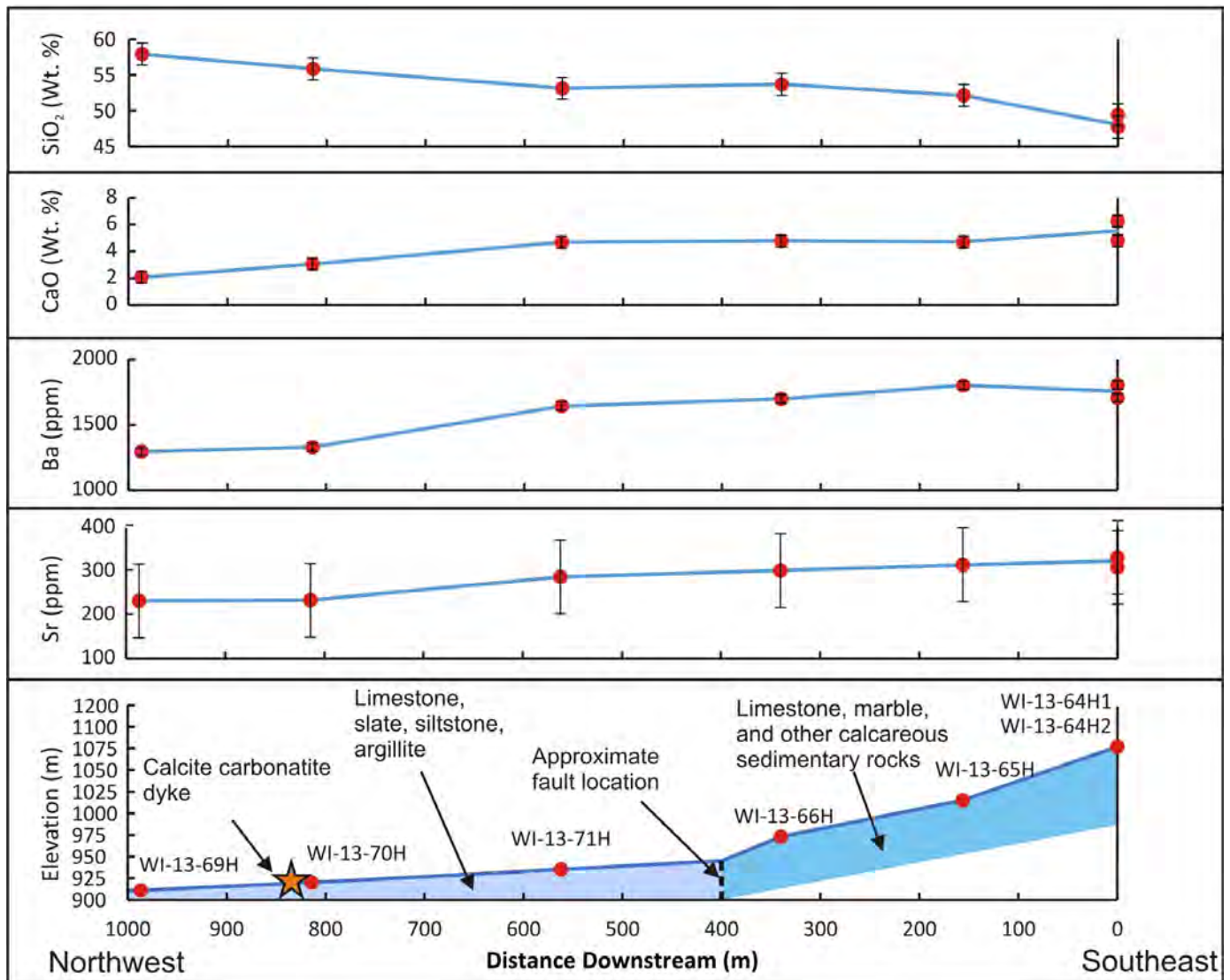
202

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Fig. 6. Profiles of SiO_2, CaO, Ba, and Sr concentrations in the + 125 μm size fraction; elevation (m above sea level). The approximate position of the calcite carbonatite dike outcrop is projected onto the profile.

that monazite-(Ce) is also a prospective indicator mineral. The co-variation of pathfinder elements is consistent with observed mineralogy for the Wicheeda carbonatite complex (Le Couteur, 2008, 2009; Lane, 2009); REE mineralisation in the main carbonatite is predominantly in monazite-(Ce) and REE-fluorocarbonates and carbonates. All P readings are below detection limits and pXRF does not measure F, hindering identification of these minerals in sediment samples. Phosphorus, a relatively light element (atomic weight 30.97), has to be present in higher concentrations than other pathfinder elements if it is to be detectible by pXRF.

Poor correlation between Ce and Y ($R^2 = 0.34$) reflects input of indicator minerals that are strongly enriched in light REEs relative to heavy rare earth elements including Y (HREY) in the carbonatite complex. No meaningful relationship exists between Th and U.

Strong dependence between Nb-Ce ($R^2 = 0.85$; Fig. 8b) and Nb-La ($R^2 = 0.82$) probably indicates co-occurrence of

Nb- and REE-bearing minerals. This is expected as REE-fluorocarbonates [such as bastnasite-(Ce), parisite-(Ce), or synchysite-(Ce)], monazite-(Ce), and pyrochlore have similar densities (4.0-5.0 g/cm^3, 4.5-5.5 g/cm^3, and 4.2-6.4 g/cm^3 respectively) and probably, settling velocities.

There is an excellent linear dependence between Nb and TiO_2 ($R^2 = 0.98$; Fig. 8c). This relationship may indicate that pyrochlore contains significant amounts of Ti, or the presence of Nb-rutile within stream sediments. The moderate correlation between Nb and Fe_2O_3 ($R^2 = 0.73$; Fig. 8d) indicates the coincidence of magnetite and Nb-bearing mineral phases such as pyrochlore and Nb-rutile. Correlation between Nb and Ta is poor ($R^2 = 0.61$; including below detection limit data).

Linear dependence between Ba and Sr ($R^2 = 0.98$) may reflect the presence of both elements in a common mineral phase such as REE-bearing fluorocarbonates and/or a consistent composition for barite-celestine solid solution minerals in the area. Input of Sr-Ba sulphates from limestones and marbles of the Kechika
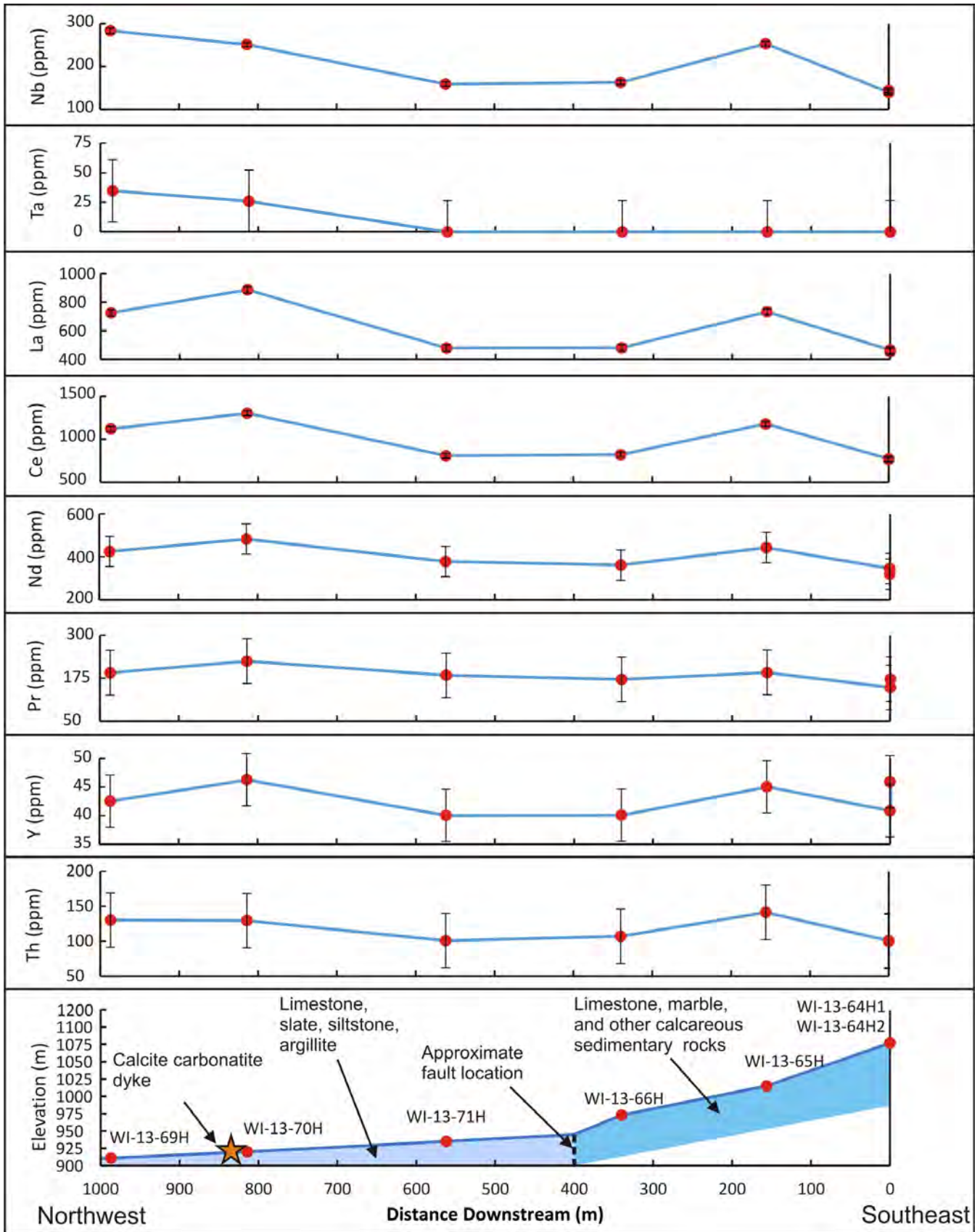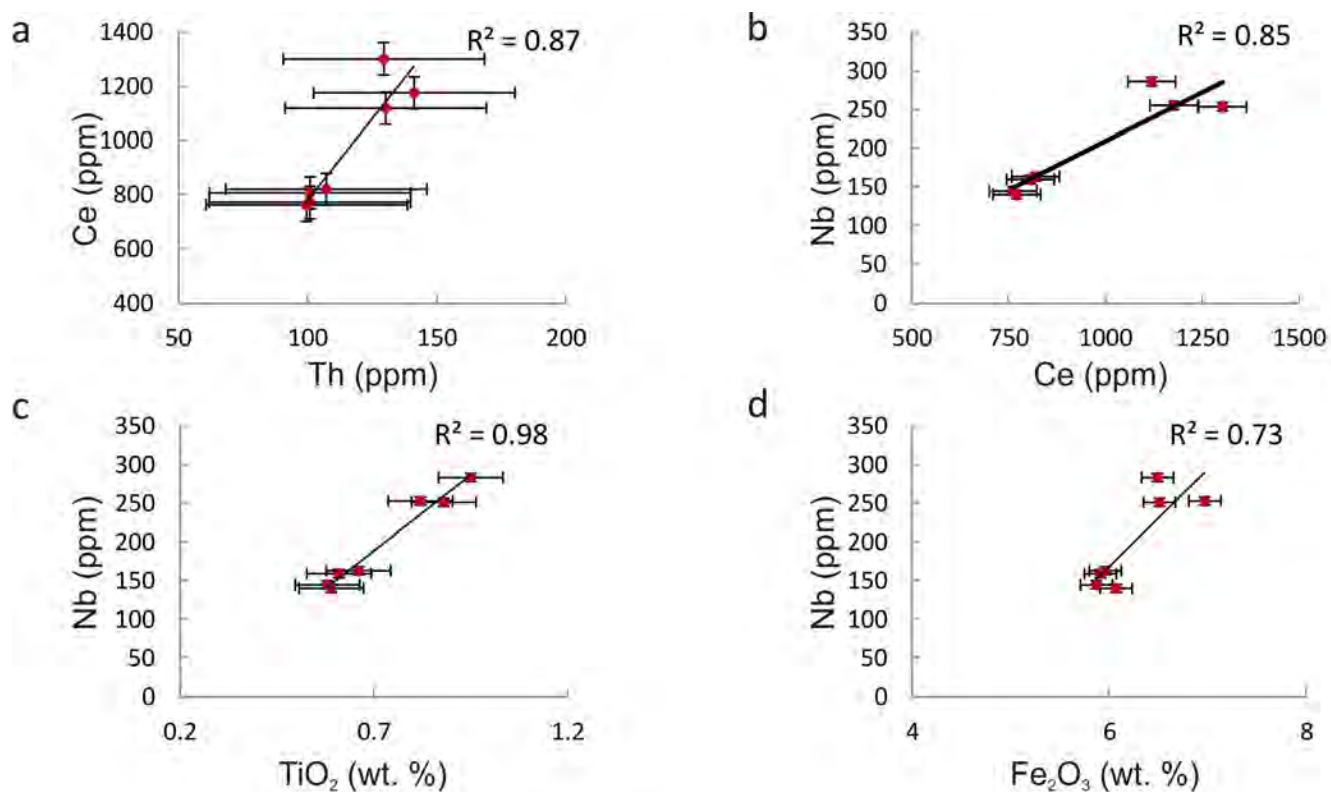
203

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Fig. 7. Profiles of key pathfinder elements concentration in the + 125 μm size fractions; and elevation (m above sea level). The approximate position of the calcite carbonatite dike outcrop is projected onto the profile.

204

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Fig. 8. Correlations between the concentrations of selected elements in the + 125 μm size fraction of samples. **a)** Ce and Th. **b)** Nb and Ce. **c)** Nb and TiO₂. **d)** Nb and Fe₂O₃.

Formation cannot be ruled out as a possible source of Ba and Sr.

Further optical microscope and electron microprobe studies, supplemented by further stream sediment and soil sampling, are required to identify and determine the chemical composition of indicator minerals. The use of QEMSCAN could reconcile stream sediment and indicator mineral chemistry and may confirm the working hypothesis of different indicator mineralogy between calcite and dolomite carbonatites. Pre-concentration of heavy minerals by Frantz isodynamic separation or Wilfley shaker table may be required. The economics and effectiveness of QEMSCAN analyses relative to traditional indicator mineral methods involving hand-picking remains to be established. In combination with EMP and SEM analyses, QEMSCAN will provide quantitative information on indicator minerals and establish mineralogical differences between calcite and dolomite carbonatites in the area. Further sampling of stream sediments downstream of other mineralisation in the area and outside the influence of the Wicheeda carbonatite complex could strengthen the findings in this study.

7. Conclusion

Portable XRF is an effective tool to measure relative concentrations of pathfinder elements (Nb, Ta, La, Ce, Pr, Nd, Y, and Th) in stream sediments collected near the Wicheeda carbonatite complex. These elements are preferentially enriched in the + 125 μm size fraction relative to other sizes. Based on the mineralogy of the Wicheeda carbonatite complex

and detectable concentrations of Nb, Ta, La, Ce, Pr, Nd, and Y, monazite, REE-fluorocarbonates and carbonates, and pyrochlore (± columbite) are prospective indicator minerals for Wicheeda carbonatite-type REE deposits. Stream sediment samples collected near the Wicheeda carbonatite complex do decrease in pathfinder element and indicator mineral concentrations downstream. The economics and effectiveness of QEMSCAN analyses relative to traditional indicator mineral methods involving hand-picking, remains to be established.

References Cited

Armstrong, J.D., Tipper, H.W., and Hoadley, J.W., 1969. Geology of McLeod Lake, British Columbia. Geological Survey of Canada,

205

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1

Map 1204A; scale: 1:253 440.

Betmanis, A.I., 1987. Report on Geological, Geochemical, and Magnetometer Surveys on the Prince and George Groups, Cariboo Mining Division, B.C. British Columbia Ministry of Energy, Mines, and Petroleum Resources, Assessment Report 15944, 86 p.

Bruland, T., 2011. 2010 Helicopter-borne AreoTEM System Electromagnetic, Magnetic Survey and Radiometric Survey. British Columbia Ministry of Energy, Mines, and Petroleum Resources, Assessment Report 32439, 57 p.

Dalsin, M. L., 2013. The Mineralogy, Geochemistry and Geochronology of the Wicheeda carbonatite complex, British Columbia. MSc, University of British Columbia, 265 p.

Graf, C., Lane, B., and Morrison, M., 2009. The Wicheeda Carbonatite-Syenite Breccia Intrusive Complex Hosted Rare Earth Deposit. Conference Abstract, 5th Annual Minerals South Conference & Trade Show, Cranbrook, Canada. <http://www.slideshare.net/RareMetalBelt/abstract-on-the-wicheeda-rare-earth-property#> Accessed December 13, 2013.

Lane, B., 2009. Diamond Drilling Report on the Wicheeda Property, Cariboo Mining Division. British Columbia Ministry of Energy, Mines, and Petroleum Resources, Assessment Report 30873, 196 p.

Le Couteur, P.C., 2008. Petrographic Report on Four samples from the Wicheeda Property; unpublished company report, Spectrum Mining Corporation, 36 p.

Le Couteur, P.C., 2009. Petrographic Report on Four samples from the Wicheeda Property; unpublished company report, Spectrum Mining Corporation, 28 p.

Lovang, G., and Meyer, W., 1987. Report on Trenching, Stream Silt Concentrate and Soil Sampling on the George Group, Cariboo Mining Division. British Columbia Ministry of Energy, Mines, and Petroleum Resources, Assessment Report 16246, 18 p.

Luck, P., and Simandl, G.J., 2014. Portable X-ray fluorescence in stream sediment chemistry and indicator mineral surveys, Lonnie carbonatite complex, Canada. In: Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1, this volume.

Mackay, D.A.R., and Simandl, G.J., 2014. Portable x-ray fluorescence to optimize stream sediment chemistry and indicator mineral surveys, case 1: Carbonatite-hosted Nb deposits, Aley carbonatite, British Columbia, Canada. In: Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1, this volume.

Mäder, U.K., and Greenwood, H.J., 1988. Carbonatites and Related Rocks of the Prince and George Claims, Northern Rocky Mountains (93J, 93I): Geological Fieldwork 1987. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Paper 1988-1, pp. 375-380.

Massey, J.W.H., McIntyre, D.G., Dejardins, P.J., and Cooney, R.T., 2005. Digital geology map of British Columbia. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2005-2, DVD.

Millonig, L.J., Gerdes, A., and Groat, L.A., 2012. U-Th-Pb geochronology of meta-carbonatites and meta-alkaline rocks in the southern Canadian Cordillera: A geodynamic perspective. Lithos, 152, 202-217.

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., Fajber, R., Paradis, S., and Simandl, L.J., 2013. Exploration for sedimentary phosphate (±REE) deposits using handheld XRF – An orientation survey. Geochemistry: Exploration, Environment, Analysis. http://dx.doi.org/10.1144/geochem2012-180. Available online.

Tantalum-Niobium International Study Center, 2013. Niobium - Raw Materials and Processing. <http://tanb.org/niobium> Accessed July 17, 2013.

Tse, P.K., 2011. China's Rare-Earth Industry. United States Geological Survey, Open-File Report 2011-1042, 11 p.

Woolley, A.R., and Kjarsgaard, B.A., 2008. Paragenetic Types of Carbonatite as Indicated by the Diversity and Relative Abundances of Associated Silicate Rocks: Evidence from a Global Database. The Canadian Mineralogist, 46, 741-752.

206

Geological Fieldwork 2013, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2014-1