

Concentration of carbonatite indicator minerals using a Wilfley gravity shaking table: A case history from the Aley carbonatite, British Columbia, Canada

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Recommended citation: Mackay, D.A.R., Simandl, G.J., Luck, P., Grcic, B., Li, C., Redfearn, M., and Gravel, J., 2015. Concentration of carbonatite indicator minerals using a Wilfley gravity shaking table: A case history from the Aley carbonatite, British Columbia, Canada. In: Geological Fieldwork 2014, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-1, pp. 189-195.

Abstract

A Wilfley shaking table was used to concentrate specialty metal indicator minerals, with an emphasis on Nb- and REE-bearing minerals. This paper presents an assessment of the Wilfley shaking table using a synthetic sample and natural samples from the Aley carbonatite drainage area. The Wilfley shaking table successfully concentrated key indicator minerals from stream-sediment samples from the Aley carbonatite drainage area. The key carbonatite indicator minerals (in order of importance) are: pyrochlore, columbite-(Fe); fersmite, REE-fluorocarbonates; monazite; apatite; and possibly magnetite, Na- and K-amphibole, and Na pyroxene. The concentrations of these minerals correlate with the concentrations of pathfinder elements (Nb, Ta, LREE [La, Ce, Pr, and Nd], Ba, Sr, P, U, and Th) in the Aley stream sediments. Relative to unprocessed sediments, the Wilfley table concentrated Nb by 4.8 times, Ta by 3.6 times, and LREE by 3.9 times. This indicates that heavy minerals previously identified as potential indicators were successfully concentrated by the Wilfley shaking table. High coefficients of determination ($R^2 > 0.85$) between the raw stream sediment and Wilfley concentrates for Nb, Ta, LREE, Y, Th, U, and Fe content indicate the targeted heavy minerals were consistently concentrated and Wilfley table treatment preserves the carbonatite geochemical signature.

Keywords: indicator minerals, heavy mineral separation, carbonatite, niobium, tantalum, rare-earth elements, specialty metals

1. Introduction

Indicator minerals are effective tools to explore for covered or poorly exposed ore deposits, and methods for their use in regional studies are well established (McCurdy et al., 2006, 2009; McClenaghan, 2011). The 250 μm –2.0 mm size fraction is commonly examined, and Wilfley-type tables are used to pre-concentrate minerals before heavy liquid separation, isodynamic magnetic separation, and hand picking (McClenaghan, 2011).

Indicator minerals for carbonatite-related specialty metal deposits are: Nb-bearing minerals (pyrochlore, columbite-[Fe], and fersmite), monazite, zircon, REE-fluorocarbonates (bastnaesite and synchysite), apatite, sulphates (barite-celestine) and potentially, magnetite, Na-K amphiboles, Na-pyroxenes, and allanite (Table 1). Herein we use sediment samples from streams draining the Aley carbonatite (Fig. 1) to determine if Wilfley tables can effectively concentrate carbonatite indicator minerals to a degree that additional processing is unnecessary before using Quantitative Evaluation of Minerals by SCANning electron microscopy (QEMSCAN) to establish quantitative mineralogy.

2. Aley carbonatite

The Aley carbonatite is 290 km north of Prince George, British Columbia (Fig. 1), and outcrops over a 3 x 3.5 km



Fig. 1. Location of the Aley carbonatite (yellow star) in British Columbia, Canada.

area (Mäder, 1986; McLeish, 2013). The Aley carbonatite is the most important Nb-deposit in the Canadian Cordillera with

Table 1. Potential carbonatite indicator minerals. Expected ranges in pathfinder element content (oxide Wt.%) are for minerals from carbonatites. From Bühn et al. (2001), Belousova et al. (2002a, b), Atencio et al. (2010), Anthony et al. (2014), and Mackay and Simandl (2014c).

| Mineral Name | Chemical Formula | Density (g/cm ³) | Nb ₂ O ₅ | Ta ₂ O ₅ | TREO | Y ₂ O ₃ | P ₂ O ₅ | ThO ₂ | SrO | BaO | U ₃ O ₈ | ThO ₂ |
|----------------|--|------------------------------|--------------------------------|--------------------------------|-----------|-------------------------------|-------------------------------|------------------|-----------|-----------|-------------------------------|------------------|
| Pyrochlore | (Ca,Na) ₂ (Nb,Ti,Ta) ₂ O ₆ (O,OH,F) | 4.2-6.4 | 34.2-86.8 | tr-4.3 | 2.6-6.0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Columbite-(Fe) | (Fe ²⁺ ,Mn)(Ta,Nb) ₂ O ₆ | 5.3-7.3 | 46.8-81.2 | tr-31.2 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Fersmite | (Ca,Ce,Na)(Nb,Ta,Ti) ₂ (O,OH,F) ₆ | 4.69-4.79 | 66.0-70.1 | tr-16.9 | 4.8 | 2.9 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Monazite | (Ce,La,Nd,Th)PO ₄ | 4.8-5.5 | n.a. | n.a. | 59.2 | n.a. | 27.4 | 11.6 | n.a. | n.a. | 0.4 | 11.6 |
| Zircon | ZrSiO ₄ | 4.6-4.7 | n.a. | n.a. | 0.1-4.4 | n.a. | n.a. | n.a. | n.a. | n.a. | tr | n.a. |
| Bastnaesite | Ce(CO ₃)F | 4.95-5.00 | n.a. | n.a. | 73.6-78.1 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Synchysite | Ca(Ce,La)(CO ₃) ₂ F | 3.90-4.15 | n.a. | n.a. | 47.8 | 0.5 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Apatite | Ca ₅ (PO ₄) ₃ (OH,F,Cl) | 3.16-3.22 | n.a. | n.a. | 0.5-5.5 | n.a. | 35.7-40.4 | tr-0.1 | 0.4-4.5 | tr-1.0 | n.a. | tr-0.1 |
| Barite | BaSO ₄ | 4.48 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 65.4-65.7 | n.a. | n.a. |
| Celestine | SrSO ₄ | 3.9-4.0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 56.2-56.4 | n.a. | n.a. | n.a. |
| Magnetite | Fe ²⁺ Fe ³⁺ ₂ O ₄ | 5.1-5.2 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Arfvedsonite | Na ₃ [(Fe ²⁺ ,Mg) ₄ Fe ³⁺]Si ₈ O ₂₂ (OH) ₂ | 3.44-3.45 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Richterite | Na(Ca,Na)(Mg,Fe ²⁺) ₅ Si ₈ O ₂₂ (OH) ₂ | 3.09 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Aegirine | NaFe ³⁺ Si ₂ O ₆ | 5.50-5.54 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Allanite | (Ce,Ca,Y) ₂ (Al,Fe ²⁺ ,Fe ³⁺) ₃ (SiO ₄) ₃ (OH) | 3.3-4.2 | n.a. | n.a. | 32.0 | 5.5 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |

n.a. = not applicable; tr = trace; TREO = total rare earth oxides

a measured plus indicated resource of 286 million tonnes at 0.37% Nb₂O₅, with a cut-off grade of 0.20% Nb₂O₅ (Simpson, 2012). It is hosted by greenschist-facies metasedimentary rocks. The main body of the Aley carbonatite is dolomitic and is surrounded by a volumetrically minor calcite-carbonatite rim (Mäder, 1986; McLeish, 2013). Minerals of economic interest include fersmite, columbite-(Fe), and pyrochlore; common accessories include apatite, pyrite, magnetite, biotite/phlogopite, and calcite (Mäder, 1986; Kressell et al., 2010; McLeish, 2013; Mackay and Simandl, 2014a). The carbonatite is surrounded by a zone of fenitized (Na and K hydrothermally altered) country rock containing richterite, arfvedsonite, aegirine, and albite.

3. Summary of previous work

Twelve stream sediment samples were collected from the stream draining the Aley carbonatite area (Mackay

and Simandl, 2014a). Samples were dry sieved into eight size fractions (>4 mm, 2–4 mm, 1–2 mm, 500 µm–1 mm, 250–500 µm, 125–250 µm, 63–125 µm and <63 µm). The dry sieved 125–250 µm size fraction (herein referred to as ‘raw sample’) was determined to be ideal for carbonatite exploration in British Columbia, based on high concentrations of carbonatite pathfinder elements relative to the other size fractions (Luck and Simandl, 2014; Mackay and Simandl, 2014a, b). An approximately 10 g split of each raw sample was milled, prepared in standard X-ray diffraction sample cups, and analyzed using a Thermo Scientific Niton® FXL-950 as described by Luck and Simandl (2014). Samples with large amounts of material (>300 g) in the 125–250 µm fraction were split for processing on the Wilfley table.

4. Wilfley mineral separator

Wilfley shaking tables separate silt and sand sized material

based on mineral density (e.g., Sivamohan and Forssberg, 1985; Stewart, 1986; McClenaghan, 2011). Testing and optimization of operating conditions for the Mine & Smelter Supply Co. Wilfley shaking table (#13 table, 457 x 1016 mm) was performed using a synthetic standard, which contained 500 g of material made up of magnetite (40 g), garnet (30 g), fluorite (60 g), and quartz (370 g). Magnetite was selected as a proxy for heavy minerals targeted as carbonatite indicators. Synthetic standard components were milled to the same grain size range (125–250 μ m) as identified previously for testing (Luck and Simandl, 2014; Mackay and Simandl, 2014a, b). Several runs with synthetic standards were performed, and operating parameters were optimized based on magnetite concentrations (a magnet was used to recover magnetite from concentrate). The main operating parameters for a Wilfley shaking table are: table inclination and slope, wash-water flow rate, material feed rate, table speed, and stroke amplitude (Razali and Veasey, 1990; Manser et al., 1991). Separation of material is also affected by feed grade and feed density. The table was set with an 8° incline, 3° slope, 10 mm stroke, and

table speed of 250 rpm for all samples. Water flow was kept constant for all samples at 18 L/min based on optimization using synthetic standards. Optimized parameters increased the magnetite yield by 3.7 times.

4.1. Processing procedure

Dry sieved (125–250 μ m size fraction) stream-sediment samples varying from 380.4–938.4 g (Table 2) were mixed into a slurry with water and gradually washed from a container into the sample feeder (Fig. 2) using a water hose. Material moves in the direction of shaking across the table surface and diagonally down the table slope. Denser material (concentrate) is carried farthest left along the table ridges, while the least dense material is washed off the bottom of the table (Fig. 3). Launder trays were positioned to collect the concentrate, middlings, and tailings. Suspended particles were allowed to settle and excess water was decanted from concentrates, middlings, and tailings. Samples were dried overnight at 90°C then weighed for quality control, allowing samples to be reconstituted and reprocessed if needed. After processing, concentrate, middlings, and tailings

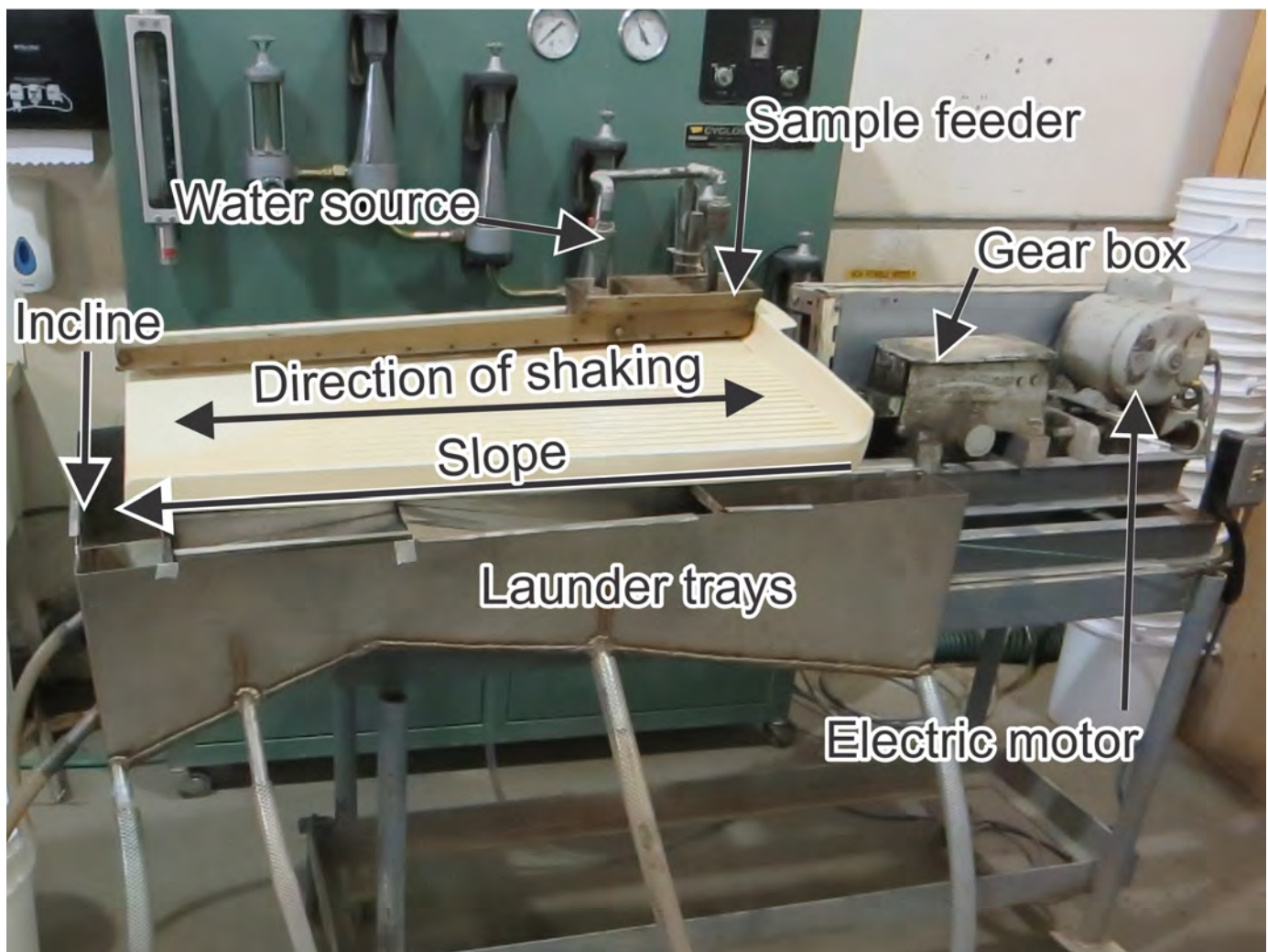


Fig. 2. Wilfley shaking table with adjustable launder trays. Slope and incline axes (angle from horizontal) are shown.

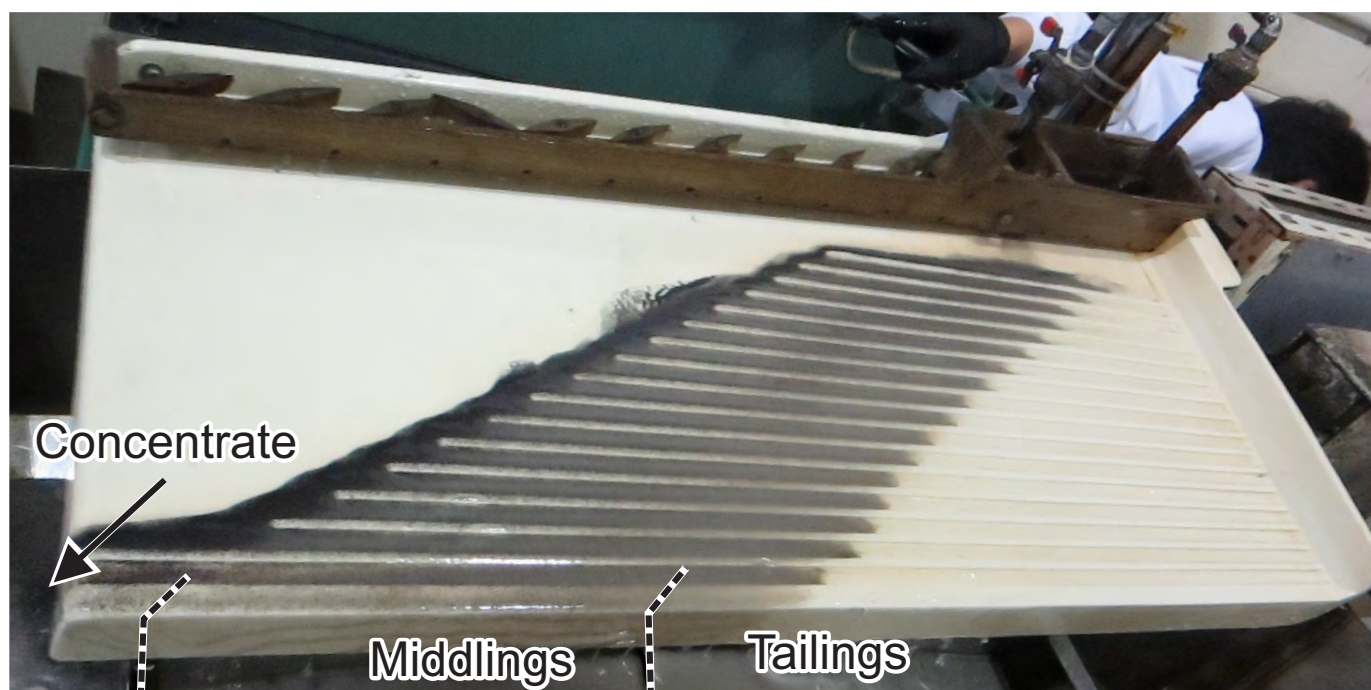


Fig. 3. Close-up of the Wilfley table. Heavy minerals (black) are separated from middlings and tailings as material moves from the top-right to bottom-left.

Table 2. Selected major and minor elemental composition (ppm) of the 125–250 μm size fraction of stream sediments from the Aley area, analysed by portable XRF. Phosphorous content was determined by lab analysis using fused bead, acid digestion, and ICP-AES analysis. Modified from Mackay and Simandl (2014a).

| Sample no. | Split Size (g) | Nb | Ta | LREE | La | Ce | Pr | Nd | Y | Ba | Sr | P* | U | Th | Fe | Ca |
|------------|----------------|------|-----|------|------|------|-----|------|-----|-----|-----|-------|----|-----|-------|--------|
| AL-13-01 | 380.4 | 3495 | 79 | 2602 | 596 | 936 | 346 | 724 | 72 | 670 | 711 | 10822 | 26 | 266 | 40852 | 78201 |
| AL-13-07 | 383.1 | 615 | 23 | 1690 | 316 | 505 | 289 | 580 | 34 | 244 | 688 | 6327 | 6 | 68 | 22375 | 160338 |
| AL-13-10 | 510.1 | 5543 | 110 | 4879 | 1280 | 1918 | 520 | 1161 | 104 | 505 | 944 | 14619 | 40 | 376 | 65852 | 154081 |
| AL-13-16 | 938.4 | 5246 | 101 | 4229 | 1083 | 1648 | 470 | 1028 | 93 | 910 | 745 | 12000 | 36 | 355 | 59782 | 156997 |
| AL-13-18 | 503.7 | 3311 | 78 | 2763 | 662 | 1025 | 355 | 721 | 71 | 688 | 747 | 10997 | 26 | 255 | 42845 | 166097 |

*Lab analysis by fused bead, acid digestion, and ICP-AES analysis

were analysed by portable X-ray fluorescence (XRF) using the method described by Luck and Simandl (2014) and Mackay and Simandl (2014a).

5. Results of Wilfley table separation and geochemical analysis

Wilfley table separation of the 125-250 μm size fraction of stream-sediment samples from the Aley carbonatite drainage produced a range in proportions of concentrates (10.0-18.3 wt.%), middlings (48.8-68.8 wt.%), and tailings (11.0-38.2 wt.%; Fig. 4). Due to minor loss of material during processing, the proportion of concentrate, middlings, and tailings do not total 100%. Relative to raw samples (Table 2), the Nb content of Wilfley concentrates (Table 3) increased by 3.9-5.6 times (average of 4.8; Fig. 5a). Similarly, Ta increased by 2.3-4.9

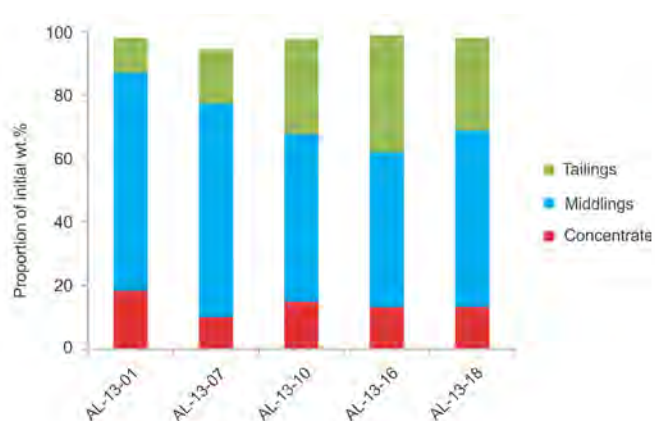


Fig. 4. Proportion of original wt.% in Wilfley table concentrates, middlings, and tailings for Aley carbonatite area stream sediments.

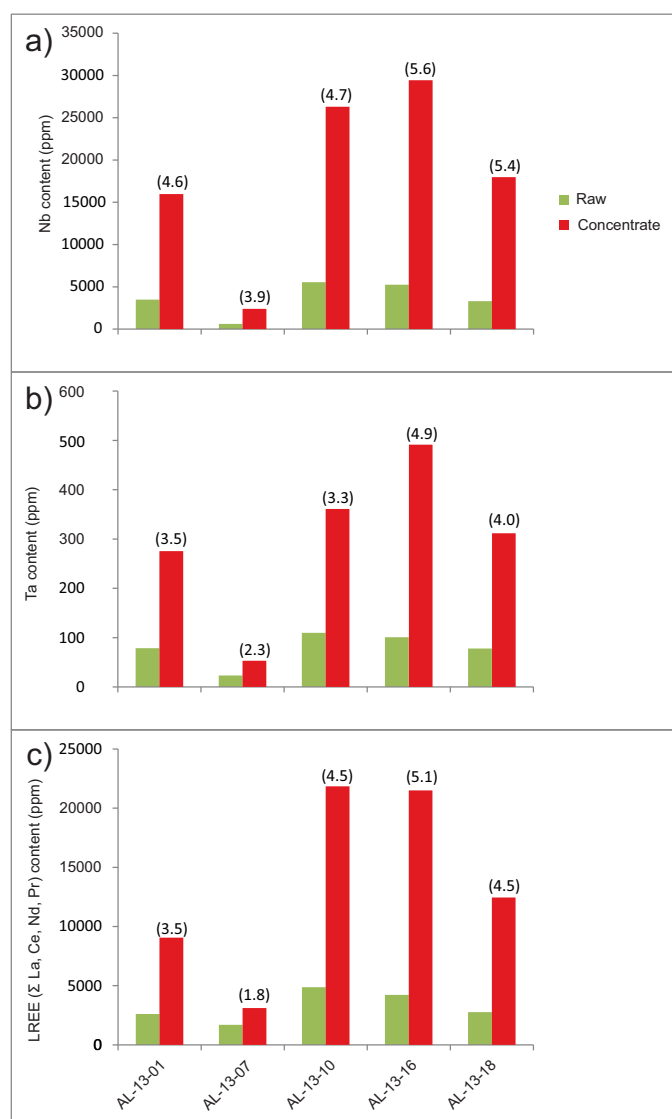


Fig. 5. Comparison of **a)** Nb, **b)** Ta, and **c)** LREE (Σ La, Ce, Nd, Pr) concentrations in Wilfley table concentrates relative to corresponding raw samples from Aley. Concentration factors for each element or group of elements for individual samples are shown in parentheses.

times (average of 3.6; Fig. 5b) and LREE content increased by 1.8-5.1 times (average of 3.9; Fig. 5c). The portable XRF used in this study reports phosphorous values above 10000 ppm as below detection limit, hence P was determined by fused bead, acid digestion and inductively coupled plasma atomic emission spectroscopy (ICP-AES; Tables 2 and 3). Phosphorous content of Wilfley concentrations increased by 1.8-2.4 times (average of 2.2) relative to raw samples.

6. Discussion of Wilfley table heavy mineral separation

Relatively high coefficients of determination in raw samples versus Wilfley table concentrates for Nb ($R^2=0.96$; Fig. 6a) and Ta ($R^2=0.85$; Fig. 6b) suggest consistent concentration of Nb- (\pm Ta) bearing minerals (pyrochlore, columbite-(Fe), and fersmite). Similarly, high coefficients of determination for LREE ($R^2=0.96$; Fig. 6c) and Y ($R^2=0.94$; Fig. 6d) suggest that REE-fluorocarbonates, monazite, and other REE-bearing minerals were successfully concentrated by the Wilfley table treatment. High coefficient of determination ($R^2=0.98$) between Zr and LREE content of Wilfley table concentrates indicates zircon is a possible LREE-bearing indicator mineral for carbonatite exploration. Iron also shows a high coefficient of determination ($R^2=0.97$) suggesting the effective concentration of magnetite, hematite, and columbite-(Fe). The low coefficient of determination ($R^2=0.01$; Fig. 6e) for Sr content in concentrates and raw samples and a low concentration factor (average of 1.2) from Wilfley table processing indicate that Sr in stream sediments was not concentrated in a predictable way. Coefficients for Ba ($R^2=0.93$; Fig. 6f), Th ($R^2=0.95$), and U ($R^2=0.95$) in raw samples and Wilfley table concentrates indicate that the carbonatite signature in stream sediments is preserved following Wilfley table concentration.

7. Conclusions

The Wilfley shaking table successfully concentrated carbonatite pathfinder elements in the 125–250 μ m size fraction of stream-sediment samples from the Aley carbonatite drainage. Niobium content of Wilfley table concentrates increased relative to raw samples by a factor of 4.8 (in the

Table 3. Selected major and trace element composition (ppm) of Wilfley table concentrates from the Aley area, analysed by portable XRF. Phosphorous was determined by fused bead, acid digestion, and ICP-AES analysis.

| Sample no. | Nb | Ta | LREE | La | Ce | Pr | Nd | Y | Ba | Sr | P* | U | Th | Fe | Ca |
|------------|-------|-----|-------|------|-------|------|------|-----|------|------|-------|-----|------|--------|--------|
| AL-13-01 | 15977 | 275 | 9058 | 2528 | 3885 | 769 | 1876 | 238 | 1473 | 988 | 25964 | 112 | 926 | 128372 | 164276 |
| AL-13-07 | 2387 | 53 | 3107 | 754 | 1156 | 374 | 823 | 71 | 251 | 888 | 14837 | 14 | 184 | 37174 | 206324 |
| AL-13-10 | 26293 | 361 | 21845 | 6692 | 10006 | 1367 | 3779 | 368 | 1055 | 943 | 26052 | 147 | 1209 | 265897 | 126498 |
| AL-13-16 | 29441 | 491 | 21493 | 6516 | 9902 | 1370 | 3706 | 396 | 3327 | 861 | 24743 | 162 | 1371 | 273248 | 118279 |
| AL-13-18 | 17983 | 312 | 12451 | 3621 | 5534 | 904 | 2392 | 274 | 1912 | 1006 | 26663 | 109 | 993 | 167279 | 155281 |

*Lab analysis by fused bead, acid digestion, and ICP-AES

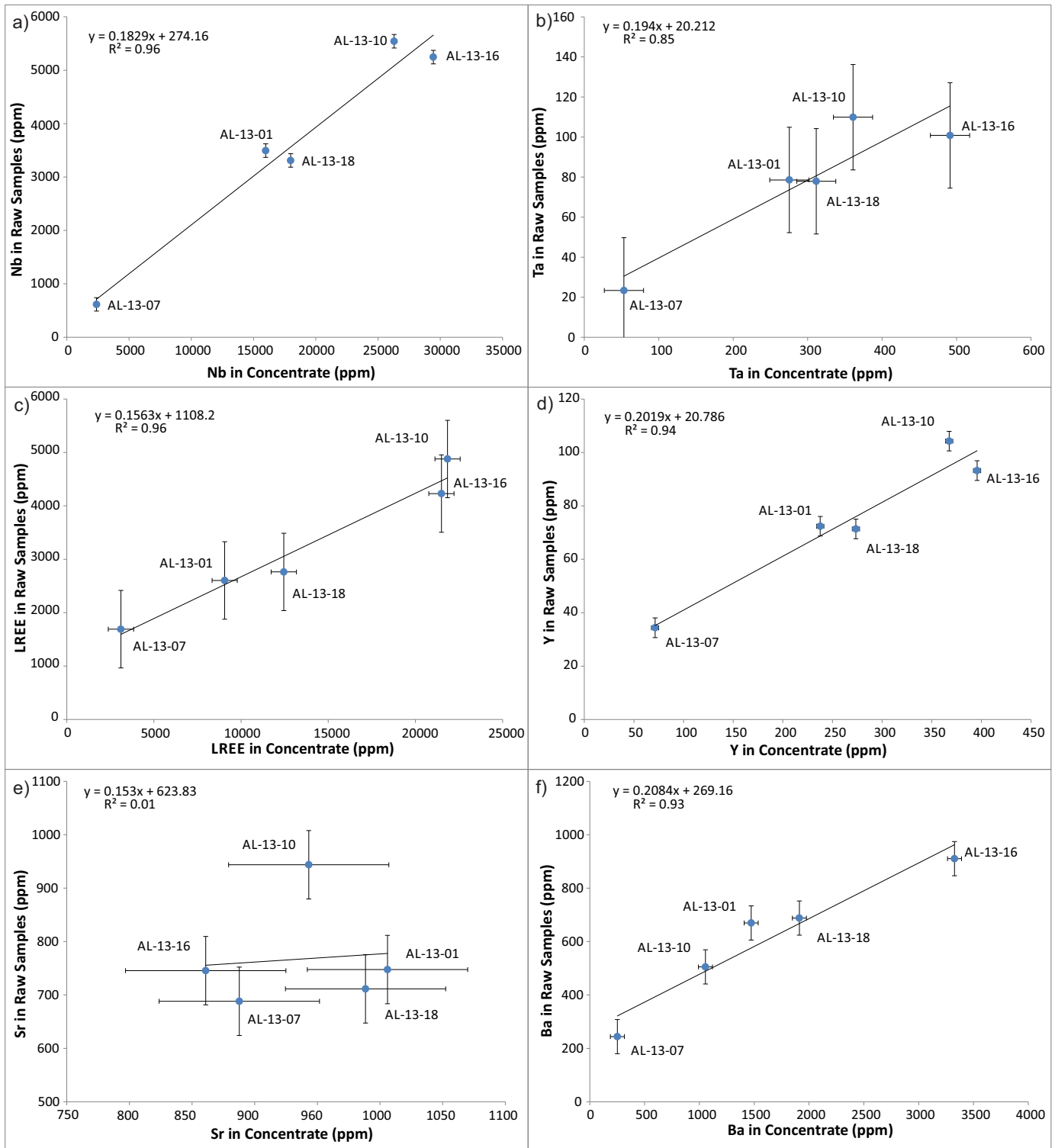


Fig. 6. Comparison of Wilfley table concentrates relative to raw samples from the Aley carbonatite. **a)** Nb. **b)** Ta; for raw samples Ta is near the lower detection limit, resulting in large errors relative to the concentrates. **c)** LREE; error propagation for \sum LREE results in larger margins relative to La, Ce, Pr, and Nd individually. **d)** Y. **e)** Sr. **f)** Ba. Error bars (2σ) are based on repeated analyses of standards as described in Luck and Simandl (2014).

range of 600–30000 ppm). Similarly, Ta increased by 3.6 times (in the range of 20–500 ppm), and LREE by 3.9 times (in the range of 1700–22000 ppm). This indicates that the

Wilfley table effectively concentrates the Nb-, Ta-, and LREE-bearing heavy minerals targeted by this study (e.g. pyrochlore, columbite-[Fe], fersmite, REE-fluorocarbonates, monazite,

zircon, apatite, and allanite). High coefficients of determination between pathfinder element concentrations in raw samples and Wilfley table concentrates suggests predictable relationships between indicator mineral counts in raw sediments and Wilfley table concentrates. A QEMSCAN study is in progress to test this.

Acknowledgments

This project was funded by the Targeted Geoscience Initiative 4 (2010–2015), a Natural Resources Canada program. The Specialty Metal component of this program was carried out collaboratively the Geological Survey of Canada and the British Columbia Geological Survey. Dr. Maria Holuszko (University of British Columbia, Norman B. Keevil Institute of Mining Engineering) provided many helpful and constructive comments and suggestions that improved the manuscript. Bureau Veritas Commodities Canada Ltd., Inspectorate Metallurgical Division and Acme Analytical Laboratories are thanked for access to laboratory equipment and the expert advice of their staff. Helicopter and logistical support during sampling from Taseko Mines Limited and a scholarship from Geoscience BC to the first author are also greatly appreciated.

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