# Carbonatites and related exploration targets

George J. Simandl<sup>1, 2, a</sup>

<sup>1</sup> British Columbia Geological Survey, Ministry of Energy and Mines, Victoria, BC, V8W 9N3

<sup>2</sup> School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, V8P 5C2

<sup>a</sup> corresponding author: george.simandl@gov.bc.ca

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### 1. Introduction

Mineralized carbonatite systems are multi-commodity, highly sought after, but poorly understood exploration targets (Mariano, 1989a, b; Pell, 1996; Birkett and Simandl, 1999). They are the main sources of niobium and rare earth elements (REE), which are considered critical metals for some key economic sectors (European Commission, 2014), and have become popular exploration targets for junior mining companies worldwide. Carbonatites also contribute to our understanding of the Earth's mantle (e.g., Bell and Tilton, 2001, 2002).

Herein, we discuss the definition and classification of carbonatites; summarize information pertinent for carbonatite exploration such as tectonic setting, shape, geophysical signature, associated rocks, alteration, and temporal distribution; and highlight the multi-commodity aspect of carbonatiterelated exploration targets and mineral prospectivity.

## 2. Definition and classification

Carbonatites are defined by the International Union of Geological Sciences (IUGS) as igneous rocks containing more than 50% modal primary carbonates (Le Maitre, 2002). Depending on the predominant carbonate mineral, a carbonatite is referred to as a 'calcite carbonatite' (sövite), 'dolomite carbonatite' (beforsite) or 'ankerite carbonatite'. If more than one carbonate mineral is present, the carbonates are named in order of increasing modal concentrations, for example a 'calcite-dolomite carbonatite' is composed predominately of dolomite. If non-essential minerals (e.g., biotite) are present, this can be reflected in the name as 'biotite-calcite carbonatite'.

Where the modal classification cannot be applied, the IUGS chemical classification is used (Fig. 1). This classification subdivides carbonatites into calciocarbonatites, magnesiocarbonatites, and ferrocarbonatites. For calciocarbonatites, the ratio of CaO/(CaO+MgO+FeO +Fe<sub>2</sub>O<sub>3</sub>+MnO) is greater than 0.8. The remaining carbonatites are subdivided (based on wt.% ratios) into magnesiocarbonatite [MgO > (FeO+Fe<sub>2</sub>O<sub>3</sub>+MnO)] and ferrocarbonatite [MgO < (FeO+Fe<sub>2</sub>O<sub>3</sub>+MnO)] (Woolley and Kempe, 1989; Le Maitre, 2002). If the SiO<sub>2</sub> content of the rock exceeds 20%, the rock is referred to as silicocarbonatite.

When the IUGS chemical classification is used, care



Fig. 1. IUGS classification of carbonatites (Le Maitre, 2002).

should be taken to ensure that magnetite and hematite-rich calciocarbonates or magnesiocarbonatites are not erroneously classified as ferrocarbonatites (Gittins and Harmer, 1997).

A refinement to the IUGS chemical classification based on molar proportions (Gittins and Harmer, 1997), introduced 'ferrugineous' carbonatites (Fig. 2). The boundary separating calciocarbonatites from magnesiocarbonatites and 'ferrugineous' carbonatites is set at 0.75, above which carbonatites contain more than 50% calcite on a molar basis. Although not universally accepted, Gittins and Harmer's classification is commonly used in studies of carbonatitehosted ore deposits. A mineralogical-genetic classification of carbonatites was proposed by Mitchell (2005). His paper points to pitfalls of the IUGS classification and subdivides carbonatites into 'primary carbonatites' and 'carbothermal residua'. The introduction of the term 'carbothermal residua' is significant as it alerts mantle specialists to fundamental processes involved in the formation of many carbonatite-related deposits, and reduces rifts between camps of ore deposit geologists, petrologists, and mantle specialists. From the exploration perspective, the current IUGS classification is too restrictive.





Fig. 2. Carbonatite classification according to Gittins and Harmer (1997).

# **3.** Exploring for carbonatites: Where to look and what to look for

### 3.1. Tectonic setting, geometry, and geophysical signature

Most carbonatites are emplaced in continental extensional settings along large-scale, intra-plate fracture zones or rifts. Some are in orogenic belts. They may have been emplaced during post-orogenic extensional collapse or before a transition from rift to compressional tectonic regime. In rare cases, carbonatites are in oceanic environments (Woolley and Kjarsgaard, 2008a). Carbonatites are components of alkaline complexes, or occur as isolated pipes, sills, dikes, plugs, lava flows, and pyroclastic blankets. Where not severely deformed by post intrusive tectonic activity, many carbonatites display circular, ring, or crescent-shaped aeromagnetic and radiometric anomalies (Satterly, 1970; Thomas et al., 2011). Deformation, metamorphism, hydrothermal and supergene alteration may significantly change the shape or apparent shape of a carbonatite, the mineralogical, chemical, and textural characteristics of the ore and gangue minerals, and the shape and grade of the mineralized zone. Ore minerals stable in a surface environment may be concentrated by weathering.

### 3.2. Carbonatite-associated igneous rocks

Most intrusive carbonatite occurrences are spatially tied to one or more of seven intrusive silicate rock groups including melilitolites, ijolites, akali gabbros, feldspathoid syenites, syenites, kimberlites, and lamprophyres and/or their volcanic equivalents (Woolley and Kjarsgaard, 2008b). Peridotites and pyroxenites, commonly found near ijolites and melilitolites, are not considered as a distinct association because they are interpreted as cumulates (Woolley and Kjarsgaard, 2008a). Nevertheless, these rocks are important from the exploration point of view because they are most commonly observed in deeply eroded carbonatite complexes, providing indirect information about the depth of erosion and, by extension, about the mineralization potential of the complex (Frolov, 1970; Epshteyn and Kaban'kov, 1984). Phoscorites are "magnetite, olivine, apatite rocks usually associated with carbonatites" (Le Maitre, 2002). This definition is restrictive because olivine commonly retrogrades into pyroxene, amphibole, and serpentine. A much broader definition and classification of 'phoscorites' is anchored in Russian literature (e.g., Yegorov, 1993). Krasnova et al. (2004) proposed that phoscorite should be redefined as a "plutonic ultramafic rock comprising magnetite, apatite, and one of the silicates, forsterite, diopside, or phlogopite". According to Krasnova et al. (2004) most of the 21 phoscorite (sensu lato) occurrences that they were aware of are mineralized. If this broader definition were applied worldwide, the number of phoscorite occurrences would increase dramatically. For example, in British Columbia, the Aley carbonatite and several carbonatites in the Blue River area would be considered to contain phoscorite units.

In some cases, carbonatite represents only a small part of a carbonatite complex. Consequently, recognizing the spatial association of carbonatites to related intrusive silicate rocks and to phoscorite substantially increases the size of an exploration target (Fig. 3).

### 3.3. Alteration

A fenitization halo (typically desilicification with the addition of  $Fe^{3+}$ , Na, K,  $\pm$  Ca,  $\pm$  Al) surrounds carbonatites or carbonatite/alkaline complexes (Morogan, 1994; Smith, 2007; Le Bas, 2008; Williams-Jones and Palmer, 2002). Several generations of fenites may be present in the same complex and



**Fig. 3.** The average surface area of carbonatites is approximately 3 km<sup>2</sup>. In most cases the carbonatites are surrounded by alkali silicate rocks, which are in turn surrounded by a zone of fenitization. If a geologist recognizes the carbonatite, associated fenitized zone ( $\sim$ 5 km<sup>2</sup>), and associated silicate rocks ( $\sim$ 2 km<sup>2</sup>) the target area increases to 10 km<sup>2</sup>. The surface areas of the 27 carbonatite complexes used to prepare this figure vary from 0.01 to 78.5 km<sup>2</sup>.

may be genetically associated with the carbonatites and related alkaline igneous rocks. Depending on the size, orientation, and shape of the carbonatite intrusion, as well as the nature of the host rock, incorporating fenitization into the carbonatite model may more than double the surface area of an exploration target (Fig. 3). Fenitization may be manifested by the presence of Na- and K-amphiboles, aegerine-augite, wollastonite, nepheline, mesoperthite, antiperthite, pale brown mica, and albite. Intensity of fenitization may be used to vector towards a carbonatite (Simandl et al., 2013).

# **3.4.** Temporal patterns: Can carbonatite ages be used to screen explorations targets?

Frequency plots of carbonatites with well-established ages indicate a general trend with the number of carbonatites decreasing with age (Fig. 4). The reasons for this trend are unclear (Veizer, 1992; Woolley and Kjarsgaard, 2008a). The frequency of mineralized carbonatite occurrences follows a similar pattern, except for the interval between 150 and 0 Ma. Relatively shallow erosional levels may explain this divergence, because most carbonatite-related mineralization is spatially related to intrusive carbonatite phases,whereas nearsurface equivalents are commonly barren, unless subjected to supergene enrichment. In view of the broad temporal range of carbonatites, and the divergence within the 150 and 0 Ma interval, ages alone are of limited use in screening carbonatite exploration targets.

#### 4. Carbonatite-related ore deposits

Carbonatites, carbonatite complexes (including carbonatiterelated igneous rocks) and, in some cases, associated fenite zones and overlying regoliths (including zones of supergene enrichment) are favourable hosts of metallic and industrial minerals (Fig. 5). Reviews and compilations of carbonatiterelated mineralization are provided by Deans (1966), Heinrich (1980), Mariano (1989a, b), Pell (1996), Richardson and Birkett (1996a, b), Birkett and Simandl (1999), Woolley and Kjarsgaard (2008a), Berger et al. (2009), Simandl (2014), and Mackay and Simandl (2014, 2015).

Carbonatite complexes and carbonatite-related deposits are currently the main sources, and represent large resources of light rare earth elements (e.g., Bayan Obo, China; Maoniuping, China; Mountain Pass, USA; Mount Weld, Australia) and niobium (e.g., Catalăo, Brazil; Lueshe, South Africa; St. Honoré, Oka, and Aley, Canada) as summarized by Verwoerd (1986), Mariano (1989a, b), Berger et al. (2009), Simandl (2014), and Mackay and Simandl (2014). In terms of REE, the ore may consist of unweathered carbonatite rock such as at Mountain Pass, USA, (Castor, 2008) and St-Honoré, Canada, (Lafleur and Ayad, 2012) and/or overlying regolith such as at Mount Weld, Australia (Lynas Corp., 2015; Lottermoser, 1990). The REE mineralization tends to be concentrated in late carbonatite phases such as ferrocarbonatites or calciocarbonatites, forming central breccia zones, ring dikes, or cone sheets. However, they can also be distal to the carbonatite (e.g., Bayan Obo, China, Smith et al., 2015). Similarly, Nb ore may be part of a carbonatite rock unit (e.g., St-Honoré, Canada, Tremblay et al., 2015), carbonatite-associated alkaline rocks (e.g., Crevier deposit, Canada, Solgadi et al., 2015), fenitized zones, and/or in overlying regolith (e.g., Catalăo I, Brazil, Cordeiro et al., 2011; Araxá, Brazil, Issa Filho et al., 2015). Vermiculite and phlogopite deposits are predominantly hosted by mafic or ultramafic units of the carbonatite system (e.g., Northern pyroxenite at Palabora, South Africa, Heinrich, 1970; Fourie and De Jager, 1986), near the contacts of carbonatites with these rocks, or within mafic country rocks (e.g., Upper Fir carbonatite, Canada, Simandl et al., 2010). Most carbonatiterelated apatite deposits currently in production, such as Tapira, Brazil (Capponi et al., 2009), Ipanema, Brazil (Born, 1986), and Catalão I, Brazil (Carvalho and Bressan, 1986), were enriched



**Fig. 4.** The frequency of all known carbonatite occurrences with isotopic ages decreases with time. With the exception of carbonatites younger than 150 Ma, the frequency of mineralized carbonatite occurrences shows a similar decrease. Figure based on data from Woolley and Kjarsgaard (2008a), with minor updates.

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Fig. 5. Vertical section of a hypothetical carbonatite mineralizing system, modified from Laznicka (2004).

by weathering. Exceptions are Siilinjärvi mine, Finland (O'Brien et al., 2015) and Cajati mine, Brazil (Alves, 2008). Copper, uranium, thorium, and baddeleyite (natural zirconia) were produced for decades from the Palabora carbonatite in South Africa (Heinrich, 1970; Clarke, 1981), but baddeleyite is currently produced only from the Kovdor deposit in Russia (Dickson, 2015).

Other materials produced from carbonatite or related deposits are: iron (Kovdor, Russia, Dickson, 2015; Bayan Obo, China, Smith et al., 2015; Palabora, South Africa, Heinrich, 1970); fluorite (Mato Preto, Brazil; Okorusu, Namibia; Amba Dongar, India; Hagni, 1999); carbonates for lime and cement production (Tororo, Uganda and Xiluvo, Mozambique, van Straaten, 2002; Jacupiranga, Brazil, Alves, 2008); and sodalite for use as dimension, ornamental and semi-precious stone (Swartboosdrift, Namibia, Menge, 1986; Cerro Sapo, Bolivia, Schultz et al., 2004). Some carbonatites, such as Tapira, Brazil (Swanepoel, 2014) and Powder Horn, USA (Van Gosen and Lowers, 2007), represent large resources of titanium minerals, and are being evaluated for future development.

### 5. Successful exploration and development of carbonatiterelated deposits: What are the odds?

As a rule of thumb, the exploration industry considers that less than one in 1,000 discoveries becomes a profitable mine (Marshall, 2012; Preston, 2015). According to the Ontario Mining Association (2015), the odds are even lower: "Only about one mineral exploration project in ten is taken to the drill stage, and one drill program in 1000 finds a viable mineral deposit".

Interpretation of data compiled by Woolley and Kjarsgaard (2008a) indicates that about 6% of known carbonatites host active mines, 3% hold historic mines, and 11% contain an established resource (Fig. 6). These numbers suggest that carbonatites have exceptional potential, and that a newly discovered carbonatite or carbonatite complex has a 9 out of 100 probability of hosting a mine.



**Fig. 6.** Prospectivity of newly discovered carbonatite. Interpretation based on data from Woolley and Kjarsgaard (2008a).

### 6. Conclusion

Carbonatite-related deposits are significant sources of Nb, LREE, Fe, Cu, baddeleyite, vermiculite, phlogopite, fluorite, apatite, calcium carbonate, and sodalite, and have historically provided U, and Th. Given that 9 out of 100 carbonatites contain currently producing or historic mines, carbonatite mineralizing systems represent outstanding multicommodity exploration targets. Identifying and incorporating carbonatite-related silicate igneous rocks and fenitites into carbonatite models results in increased size of exploration targets. Carbonatites range from Archean to Recent and hence age alone is not a valid prospectivity indicator, although within the same complex, the latest carbonatite pulses are commonly enriched in REE, and metasomatic overprinting may result in remobilization of these elements.

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### **References cited**

- Alves, P.R., 2008. The carbonatite-hosted apatite deposit of Jacupiranga, SE Brazil: styles of mineralization, ore characterization and association with mineral processing. MSc Thesis, Missouri University of Science and Technology, 140p. <http://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=7722&c ontext=masters theses> Accessed August 6, 2015.
- Bell, K., and Tilton, G.R., 2001. Nd, Pb and Sr isotopic compositions of east African carbonatites: evidence for mantle mixing and plume inhomogeneity. Journal of Petrology, 42, 1927–1945.
- Bell, K., and Tilton, G.R., 2002. Probing the mantle: the story from carbonatites. American Geophysical Union, Eos Transactions, 83, 273, 276–277.
- Berger, V.I., Snger, D.A., and Orris, G.J., 2009. Carbonatites of the world, explored deposits of Nb and REE – database and grade and tonnage models. U.S. Geological Survey Open-File Report 2009-1139, 17p. < http://pubs.usgs.gov/of/2009/1139/> Accessed August 4, 2015.
- Birkett, T.C., and Simandl, G.J., 1999. Carbonatite associated deposits: magmatic, replacement and residual. In: Simandl, G.J., Hora, Z.D., and Lefebure, D.V. (Eds.), Selected British Columbia Mineral Deposit Profiles, Vol. 3: Industrial Minerals and Gemstones. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia, Geological Survey, Open File 1999-10. <a href="http://www.empr.gov.bc.ca/Mining/Geoscience/MineralDepositProfiles/ListbyDepositGroup/Pages/NCarbonatites">http://www.empr.gov.bc.ca/Mining/Geoscience/MineralDepositProfiles/ListbyDepositGroup/Pages/NCarbonatites. aspx#n01> Accessed August 6, 2015.</a>
- Born, H., 1986. The Ipanema phosphate deposit, São Paulo, Brazil.
  In: Notholt, A.J.G., Sheldon, R.P., and Davidson, D.F., (Eds.),
  Phosphate Deposits of the World, Volume 2, Phosphate Rock
  Resource, Cambridge University Press, Cambridge, pp.116-119.

- Capponi, L., Peroni, R.D.L., Grasso, C.B., and Fontes, S.B., 2009. Sampling protocol review of a phosphate ore mine to improve short term mine planning. In: Fourth World Conference on Sampling and Blending. The Southern African Institute of Mining and Metallurgy, Paper 40, pp. 65-72.
- Carvalho, W.T., and Bressan, S.R., 1986. The phosphate deposit of Catalão I ultramafic alkaline complex, Goiás, Brazil. In: Notholt, A.J.G., Sheldon, R.P., and Davidson, D.F., (Eds.), Phosphate Deposits of the World, Volume 2, Phosphate Rock Resource, Cambridge University Press, Cambridge, pp.104-110.
- Castor, S.B., 2008. The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California. The Canadian Mineralogist, 46, 779-806.
- Clarke, G., 1981. The Palabora complex triumph over low grade ores. Industrial Minerals, No. 169, 45-62.
- Deans, T., 1966. Economic mineralogy of African carbonatites. In: Tuttle, O.F., and Gittins, J., (Eds.), Carbonatites, Wiley, New York, pp. 358-413.
- Cordeiro, P.F.O., Brod, J.A., Palmieri, M., de Oliveira, C.G., Barbosa, E.S.R., Santos, R.V., Gaspar, J.C., and Assis, L.C., 2011. The Catalão I niobium deposit, central Brazil: Resources, geology and pyrochlore chemistry. Ore Geology Reviews, 41, 112-121.
- Dickson, J.S., 2015. EuroChem reveals phosphate expansion plans at Kovdor and beyond. Industrial Minerals, May 2015. <a href="http://www.indmin.com/Article/3455925/EuroChem-reveals-phosphate-expansion-plans-at-Kovdor-and-beyond.htm">http://www.indmin.com/Article/3455925/EuroChem-reveals-phosphateexpansion-plans-at-Kovdor-and-beyond.htm</a> Accessed August 5, 2015.
- Epshteyn, Ye.M, and Kaban'kov, V.Ya., 1984. The depth of emplacement and mineral potential of ultramafic, ijolite, and carbonatite plutons. International Geology Review, 26, 1402-1415.
- European Commission, 2014. Report on critical raw materials for the EU. <a href="http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/crm-report-on-critical-raw-materials\_en.pdf">http://ec.europa.eu/enterprise/policies/raw-materials/ files/docs/crm-report-on-critical-raw-materials\_en.pdf</a> Accessed August 6, 2015.
- Fourie, P.J., and De Jager, D.H., 1986. Phosphate in the Phalaborwa complex. In: Anhaeusser, C.R., and Maske, S., (Eds.), Mineral Deposits of Southern Africa, II, The Geological Society of South Africa, pp. 2239-2253.
- Frolov, A.A., 1970. Vertical zonation in deposition of ore, as in ultrabasic-alkaline rocks and carbonatites: International Geology Review, v. 13, p. 685-695.
- Gittins, J., and Harmer, R.E., 1997. What is ferrocarbonatite? A revised classification. Journal of African Earth Sciences, 25, 159-168.
- Hagni, R.D., 1999. Mineralogy of beneficiation problems involving fluorspar concentrates from cabonatite-related fluorspar deposits. Mineralogy and Petrology, 67, 33-44.
- Heinrich, E.W.M., 1970. The Palabora carbonatitic complex a unique copper deposit. The Canadian Mineralogist, 10, 585-598.
- Heinrich, E.W.M., 1980. The geology of carbonatites. Robert E. Kreiger Publishing Company, Huntington, New York, 585p.
- Issa Filho, A., Riffel, B.F., and de Faria Sousa, C.A., 2015. Some aspects of the mineralogy of CBMM niobium deposit and mining and pyrochlore ore processing – Araxá, MG – Brazil. < http:// www.cbmm.com.br/Repositorio/Media/site/internas/operations/ minerologyaspectsniobiumdeposit.pdf>. Accessed: October 27, 2015.
- Krasnova, N.I., Petrov, T.G., Balaganskaya, E.G., Garcia, D., Moutte, J., Zaitsev, A.N., and Wall, F., 2004. Introduction to phoscorites: occurrence, composition, nomenclature and petrogenesis. In: Wall, F., and Zaitsev, A.N., (Eds.), Phoscorites and Carbonatites from Mantle to Mine: the Key Example of the Kola Alkaline Province: The Mineralogical Society, London, pp. 1-36.
- Lafleur, P.J., and Ayad, A.B., 2012. NI 43-101 technical report to present the mineral resources of the rare earth elements zone Niobec Mine – IAMGOLD Corporation. 145p. <www. sec.gov/Archives/edgar/data/1203464/000119312512119663/

d317389dex991.htm> Accessed August 4, 2015.

Laznicka, P., 2004. Total Metallogeny-Geosites. AMF, Adelaide, 740 p and poster.

Le Bas, M.J., 2008. Fenites associated with carbonatites. The Canadian Mineralogist, 46, 915-932.

- Le Maitre, R.W., 2002. Igneous Rocks: A Classification and Glossary of Terms. Cambridge University Press, Cambridge, U.K., 236 p.
- Lottermoser, B.G., 1990. Rare-earth element mineralisation within the Mt. Weld carbonatite laterite, Western Australia. Lithos, 24, 151-167.

Lynas Corp., 2015. Mount Weld mineral resource and ore reserve update 2015. <a href="https://www.lynascorp.com/PublishingImages/Pages/Mt-Weld-Resources-and-Reserves/ASX%20">https://www.lynascorp.com/PublishingImages/Pages/Mt-Weld-Resources-and-Reserves/ASX%20</a> Announcement%20-%20Ore%20Reserves%20and%20 Resources%20FINAL%20051015.pdf>. Accessed October 27, 2015.

Mackay, D.A.R., and Simandl, G.J., 2014. Geology, market and supply chain of niobium and tantalum-a review. Mineralium Deposita, 49, 1025-1047.

Mackay, D.A.R. and Simandl, G.J., 2015. Niobium and tantalum: Geology, markets, and supply chains. In: Simandl, G.J. and Neetz, M., (Eds.), Symposium on Strategic and Critical Materials Proceedings, November 13-14, 2015, Victoria, British Columbia. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-3, pp. 13-22.

Mariano, A.N., 1989a. Economic geology of rare earth minerals. In: Lipman, B.R., McKay, G.A., (Eds.), Geochemistry and mineralogy of rare earth elements. Mineralogical Society of America, Chantilly, Reviews in mineralogy v. 21, pp. 303–337.

Mariano, A.N., 1989b. Nature of economic mineralization in carbonatites and related rocks. In: Bell, K., (Ed.), Carbonatites: genesis and evolution. Unwin Hyman, London, pp. 149–176.

Marshall, L., 2012. Hitting paydirt. Mines, Colorado School of Mines Magazine. <a href="http://minesmagazine.com/6211/">http://minesmagazine.com/6211/</a>> Accessed August 5, 2015.

Menge, G.F.W., 1986. Sodalite carbonatite deposits of Swartbooisdrif, South West Africa/Namibia. In: Anhaeusser, C.R., and Maske, S. (Eds.), Mineral Deposits of Southern Africa, II. The Geological Society of South Africa, pp. 2261-2268.

Mitchell, R.H., 2005. Carbonatites and carbonatites. The Canadian Mineralogist, 43, 2049-2068.

Morogan, V., 1994. Ijolite versus carbonatite as sources of fenitization. Terra Nova, 6, 166-176.

O'Brien, H., Heilimo, E., and Heino, P., 2015. The Archean Siilinjärvi carbonatite complex. In: Maier, D.W., Lahtinen, R., and O'Brien, H., (Eds.), Mineral Deposits of Finland, Elsevier, pp. 327-343.

Ontario Mining Association, 2015. Mining 101. <http://www.oma. on.ca/en/ontariomining/Mining101.asp?hdnContent=> Accessed August 5, 2015.

Pell, J., 1996, Mineral deposits associated with carbonatites and related alkaline igneous rocks. In: Mitchell, R.H., (Ed.), Unsaturated alkaline rocks: Mineralogy, petrogenesis, and economic potential. Mineralogical Association of Canada, Short Course Series, v. 4, pp. 271-310.

Preston, G., 2015. Roundup takeaway 1: outsmart tough odds. Mining.com. <a href="http://www.mining.com/web/roundup-takeaway-1-outsmart-tough-odds/">http://www.mining.com/web/roundup-takeaway-1-outsmart-tough-odds/</a>> Accessed August 5, 2015.

Richardson, D.G., and Birkett, T.C., 1996a. Carbonatite associated deposits. In: Eckstrand, O.R., Sinclair, W.D., and Thorpe, R.I., (Eds.), Geology of Canada 8: Geology of Canadian deposit types. Geological Survey of Canada, pp. 541-558.

Richardson, D.G., and Birkett, T.C., 1996b. Residual carbonatiteassociated deposits. In: Eckstrand, O.R., Sinclair, W.D., and Thorpe, R.I., (Eds.), Geology of Canada 8: Geology of Canadian mineral deposit types. Geological Survey of Canada, pp. 108-119.

Satterly, J., 1970. Aeromagnetic maps of carbonatite-alkalic

complexes in Ontario. Ontario Department of Mines and Northern Affairs, Preliminary Map no. P452 (revised).

- Schultz, F., Lehmann, B., Tawackoli, S., Rössling, R., Belyatsky, B., and Dulski, P., 2004. Carbonatite diversity in the Central Andes: the Ayopaya alkaline province, Bolivia. Contributions to Mineralogy and Petrology, 148, 391-408.
- Simandl, G.J., 2014. Geology and market-dependent significance of rare earth element resources. Mineralium Deposita, 49, 889-904.
- Simandl, G.J., Paradis, S., Simandl, L., and Dahrouge, J., 2010. Vermiculite in the Blue River Area, East-Central British Columbia, Canada. In: Geological Fieldwork 2009, British Columbia Ministry of Energy, Mines and Natural Gas, British Columbia Geological Survey Paper 2010-1, pp. 83-91.

Simandl, G.J., Reid, H.M., and Ferri, F., 2013. Geological setting of the Lonnie niobium deposit, British Columba, Canada. In: Geological Fieldwork 2012, British Columbia Ministry of Energy, Mines and Natural Gas, British Columbia Geological Survey Paper 2013-1, pp. 127-138.

Smith, M.P., 2007. Metasomatic silicate chemistry at the Bayan Obo Fe-REE-Nb deposit, Inner Mongolia, China: Contrasting chemistry and evolution of fenitizing and mineralizing fluids. Lithos, 93, 126-148.

Smith, M.P., Campbell, L.S., and Kynicky, J., 2015. A review of the genesis of the world class Bayan Obo Fe-REE-Nb deposits, Inner Mongolia, China: Multistage processes and outstanding questions. Ore Geology Reviews, 64, 459-476.

Solgadi, F., Groulier, P.-A., Moukhsil, A., Ohnenstetter, D., André-Mayer, A.-S., and Zeh, A., 2015. Nb-Ta-REE mineralization associated with the Crevier alkaline intrusion. In: Simandl, G.J. and Neetz, M., (Eds.), Symposium on Strategic and Critical Materials Proceedings, November 13-14, 2015, Victoria, British Columbia. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-3, pp. 69-74.

Swanepoel, E., 2014. Iluka in Brazil titanium deal with Vale. Creamer Media's Mining Weekly. <a href="http://www.miningweekly.com/print-version/iluka-in-brazil-titanium-deal-with-vale-2014-06-04">http://www.miningweekly.com/print-version/iluka-in-brazil-titanium-deal-with-vale-2014-06-04</a>> Accessed August 6, 2015.

Thomas, M.D., Ford, K.L., and Keating, P., 2011. Exploration Geophysics for intrusion-hosted rare earth metals. Geological Survey of Canada, Open File 6828 (Poster). <<u>http://ftp2.cits.rncan.gc.ca/pub/geott/ess\_pubs/288/288092/of\_6828.pdf</u>> Accessed Oct. 30, 2015.

Tremblay, J., Bédard, L.P., and Matton, G., 2015. A petrographic study of Nb-bearing minerals at the Saint-Honoré niobium deposit. In: Simandl, G.J. and Neetz, M., (Eds.), Symposium on Strategic and Critical Materials Proceedings, November 13-14, 2015, Victoria, British Columbia. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-3, pp. 75-81.

Van Gosen, B., and Lowers, H., 2007. The Iron Hill (Powderhorn) carbonatite complex, Gunnison County, CO – a potential source of several uncommon mineral resources. Proceedings of 2007 SME Annual Meeting, Denver, Colorado, Society for Mining, Metallurgy, and Exploration, pp.298-305.

van Straaten, P., 2002. Rocks for Crops: Agrominerals of sub-Saharan Africa. ICRAF, Nairobi, Kenya, 338p.

Veizer, J.E.A., 1992. Temporal distribution of carbonatites. Geology, 20, 1147–1149.

Verwoerd, W.J., 1986. Mineral deposits associated with carbonatites and alkaline rocks. In: Anhaeusser, C.R., and Maske, S., (Eds.), Mineral Deposits of Southern Africa, II. The Geological Society of South Africa, pp. 2173-2191.

Williams-Jones, A.E., and Palmer, D.A.S., 2002. Fluid evolution of the Amba Dongar carbonatite complex, India. Chemical Geology, 185, 283-301.

Woolley, A.R., and Kempe, D.R.C., 1989. Carbonatites: nomenclature, average chemical compositions and element distribution. In: Bell, K., (Ed.), Carbonatites: Genesis and Evolution. Unwin Hyman, London, pp. 1-14.

- Woolley, A.R., and Kjarsgaard, A., 2008a. Carbonatite occurrences of the world: map and database. Geological Survey of Canada, Open File 5796, 22p.
- File 5796, 22p. Woolley, A.R., and Kjarsgaard, A., 2008b. 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.
- Yegorov, L.S., 1993. Phoscorites of the Maymecha-Kotuy ijolitecarbonatite association. International Geology Review, 35, 346-358.