

Rare earth elements in Québec, Canada: Main deposit types and their economic potential



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1. Introduction

Rare earth elements (REE) are strategic metals vital to global economic growth because they are used in a wide range of high-technology industries (e.g., energy, transport, and telecommunications; Walters et al., 2011). The world production and reserves are mainly owned by China. In 2008, the Chinese government introduced export quotas on rare metals, which led to a global search for new sources of REE. Québec has substantial REE resources (Simandl et al., 2012), which may contribute to future production.

Gosselin et al. (2003) and Boily and Gosselin (2004) inventoried rare metals (REE, Zr, Nb, Ta, Be, and Li) occurrences and deposits in Québec and, based mainly on lithological association, subdivided them into seven types: 1) deposits associated with peraluminous granitic complexes; 2) deposits associated with carbonatite complexes; 3) deposits associated with peralkaline complexes; 4) deposits associated with placers and paleoplacers; 5) iron oxide, Cu, REE, and U deposits; 6) deposits associated with granitic pegmatites, migmatites, and peraluminous to metaluminous granites; and 7) deposits associated with calc-silicate and metasomatized rocks or skarns. Herein we review REE mineralization in the province, adopting a more genetic scheme based on the classification of Walters et al. (2011). The REE occurrences and deposits are subdivided into primary deposits, formed by magmatic and/or hydrothermal processes, and secondary deposits, formed by sedimentary processes and leaching. Primary deposits are then subdivided into four types: 1) carbonatite complex-associated; 2) peralkaline igneous rock-associated; 3) REE-bearing Iron-Oxide-Copper-Gold (IOCG) deposits; and 4) hyperaluminous/metaluminous granitic pegmatite-, granite-, and migmatite-associated deposits, and skarns. Secondary deposits are subdivided into two deposit types: 1) placers and paleoplacers and 2) REE-bearing ion-adsorption clays.

2. Definition and characteristics

According to the International Union of Pure and Applied Chemistry (IUPAC), the REE comprise of 17 metals with similar chemical properties, including the lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), Sc,

and Y. The REE are not rare in the Earth's crust. They occur in trace amounts in most rocks, some more abundant than others. The relative abundance of REE in the Earth's crust varies according to two main factors: 1) the predominance of even-numbered chemical elements relative to their odd-numbered neighbours in the solar system, because of the greater stability of their atomic nuclei (Oddo-Harkins effect); and 2) the predominance of light REE (LREE: La to Eu) compared to heavy REE (HREE: Gd to Lu) in the Earth's crust, since LREE are more incompatible than HREE (Walters et al., 2011). The REE occur in a wide range of mineral species, such as silicates, carbonates, oxides, phosphates, and clays. However, REE contents of these minerals are variable and only a few of them are of economic interest. For a REE-bearing mineral to be economically viable, it should, for example, contain easily extractable metals, form large-tonnage deposits, and have low radioactive and toxic elements content (e.g., Th, U). The REE (except Sc) belong to the list of critical raw materials defined by the European Union in 2010 (European commission, 2010) and updated in 2014 (European commission, 2014). Of the REE included in this category, Eu, Tb, Nd, Pr, and Dy are predominant in the global REE market in terms of demand and value (Lehmann, 2014).

3. World production and reserves

China is the largest producer of REE, with 85% of global REE production in 2014 (Gambogi, 2015). Chinese deposits are mostly associated, directly or indirectly, with carbonatites (e.g., Bayan Obo Fe-REE-Nb deposit; Maoniuping REE deposit) and to ion-adsorption clays (e.g., Ganzhou deposits rich in HREE). The United States is the second largest producer of REE, far behind China, with 6% of the world's REE production in 2014 (Gambogi, 2015). US production comes mainly from the carbonatite-hosted Mountain Pass deposit, which is rich in LREE. In Canada, no REE mine is currently in operation, although several projects have reached advanced stages of exploration and development (e.g., Hoidas Lake, Saskatchewan; Thor Lake, Northwest Territories; Strange Lake, Québec).

Global reserves of rare earth oxides are also predominantly

in China (44% of known world reserves), followed by Brazil (17%), Australia (3%), India (2%), and USA (1%) (Gambogi, 2015). The remaining 33% are spread across other countries, although detailed data on these are currently not available. If NI-43-101 standards were uniformly applied worldwide Canada's and Australia's proportion of global reserves would be higher (Simandl, 2014).

4. Classification of REE occurrences and deposits

4.1. Primary occurrences

4.1.1. Deposits associated with carbonatite complexes

Most carbonatite complexes are formed in intracratonic anorogenic or post-orogenic extensional settings and are commonly spatially related to major crustal structures (Woolley and Kjarsgaard, 2008). Carbonatites form composite intrusive complexes associated with alkaline rocks, sills, dikes, and isolated masses with various shapes. The carbonatite complexes display evidence of hydrothermal remobilization and metasomatism (Chakhmouradian and Zaitsev, 2012). The metasomatic alteration leads to the formation of a halo around the igneous complexes with sodic and/or potassic rocks, called fenites, and the formation of veins and veinlets rich in alteration minerals.

In carbonatite complexes, REE mineralization is particularly rich in LREE compared to HREE (Linnen et al., 2014). These igneous complexes are also rich in high field strength elements (HFSE), like Nb and Ta, except in the case of the carbonatites emplaced in post-collision settings (Hou et al., 2006; Chakhmouradian et al., 2008). The ore minerals include the main components of carbonatites (e.g., calcite, dolomite, and apatite) and numerous REE-bearing carbonates (e.g., bastnaesite-(La) and bastnaesite-(Ce)), oxides (e.g., pyrochlore-(Nb)), phosphates (e.g., monazite-(Ce)), and silicates (e.g., allanite; Chakhmouradian and Zaitsev, 2012). REE mineralization may be: 1) magmatic and formed due to fractional crystallization or magma immiscibility; 2) hydrothermal and the result of precipitation from hydrothermal fluids; 3) hydrothermal and metasomatic; and 4) residual, derived from erosion and weathering of carbonatite complexes.

Québec REE occurrences and deposits hosted by carbonatite complexes (Figs. 1, 2) are mainly located along the Waswanipi-Saguenay structural corridor (e.g., Niobec mine within the St-Honoré carbonatite complex; Crevier deposit within the Crevier alkaline intrusion, containing carbonatite dikes; Montviel deposit; Lac Shortt deposit) and the Ottawa-Bonnechère graben (e.g., St. Lawrence Columbian mine and Niocan deposit within the Oka carbonatite complex). Other mineralization is also identified farther north in the Labrador Trough (e.g., Eldor deposit). These occurrences and deposits range in age from Neoproterozoic to early Cretaceous (Table 1).

4.1.2. Deposits associated with peralkaline igneous rocks

Peralkaline igneous rocks crystallize in anorogenic, continental extensional settings, in close spatial association with major crustal structures (Jaireth et al., 2014). They form

annular intrusive complexes, pegmatites, or subvolcanic massive bodies. The intrusions are commonly altered. The alteration includes albitization of the top of the intrusions, alteration by orthomagmatic fluids that causes F-leaching in the granitic rocks and destabilization and hematitization of amphibole and feldspar, alteration by Ca-rich low-temperature meteoric fluids that leads to the pseudomorphic replacement of Na-silicates by Ca-silicates, and silicification (Boily and Gosselin, 2004).

Rare earth deposits associated with peralkaline igneous rocks generally have large tonnages with low metal concentration. They are enriched in HREE relative to LREE, and are rich in HFSE like Nb and Zr (Castor and Hedrick, 2006). Beside rock forming minerals, the REE ore contain a range of REE-bearing silicates (e.g., eudialyte, gittinsite, mosandrite), phosphates (e.g., monazite, britholite), oxides (e.g., fergusonite, pyrochlore), carbonates (e.g., bastnaesite, synchysite), and fluoride (e.g., gagarinite). Rare earth mineralization results from magmatic and/or hydrothermal processes. However, hydrothermal remobilization appears to be essential for the formation of economic REE ore deposits (Linnen et al., 2014).

In Québec, the REE occurrences and deposits associated with peralkaline igneous rocks (Figs. 1, 3) are Mesoproterozoic and occur mainly in the Churchill and Grenville provinces (e.g., Strange Lake, Misery Lake, and Kipawa deposits; Table 1).

4.1.3. REE-bearing IOCG deposits

IOCG deposits are associated with late-orogenic and post-orogenic rifts in intracratonic, intra-arc, and back-arc extensional settings (Corriveau, 2007). These deposits form discordant masses, veins, dikes, tabular bodies, and stockworks and are emplaced along faults and other geological contacts. They are generally altered due to strong hydrothermal activity and are commonly surrounded by regional-scale sodic-calcic alteration zones and local-scale potassic and iron-oxides alteration zones (Corriveau, 2007). Alteration of the Kiruna-type (Fe±P) includes the formation of scapolite and albite, and the occurrence of actinolite and epidote in mafic wall rocks (Boily and Gosselin, 2004). Alteration of the polymetallic Olympic Dam-type (Fe±Cu±Au±U±REE) is more diverse and intense, with the formation of sericite and hematite at surface and chlorite and K-feldspar at depth (Boily and Gosselin, 2004).

Some IOCG deposits are mined for Fe, Au, and other metals but currently, REE are not recovered (Jaireth et al., 2014). Rare earths may be contained in a wide variety of REE-bearing minerals including apatite, allanite, monazite, xenotime, bastnaesite, britholite, florencite, kainosite, andradite, gadolinite, thorite, perovskite, pyrochlore, and uraninite. The formation of these deposits results from hydrothermal processes that have not yet been characterized precisely (Williams et al., 2005).

In Québec, REE mineralization in IOCG-type deposits (Figs. 1, 4) is Neoproterozoic and appears to be restricted to the Manitou area, in the Grenville Province. The most significant

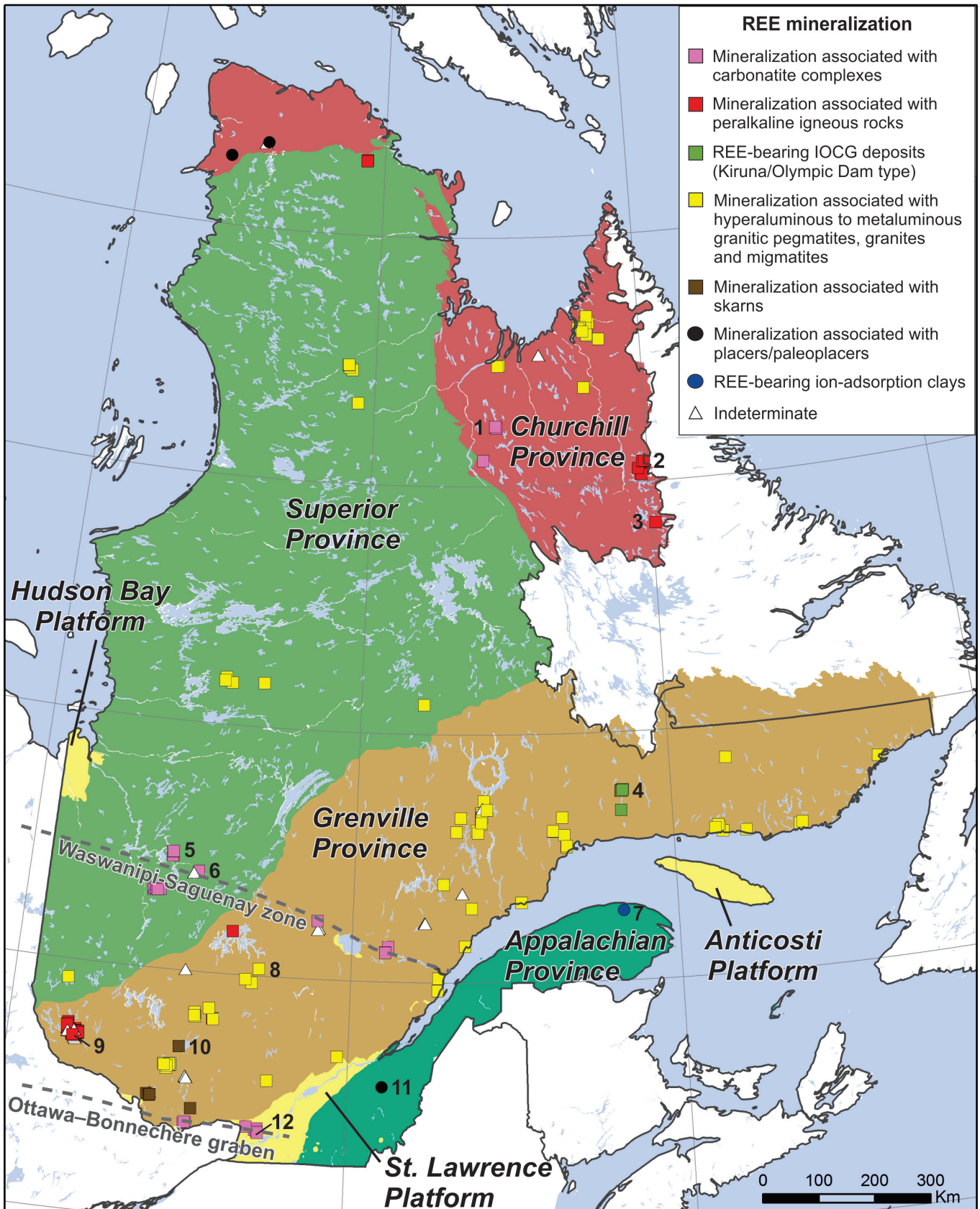


Fig. 1. Location of REE mineralization in Québec. 1- Eldor deposit, 2- Strange Lake deposit, 3- Misery Lake deposit, 4- Kwyjibo group of occurrences, 5- Montviel deposit, 6- Lac Shortt deposit, 7- Grande-Vallée deposit, 8- Haltaparche occurrence, 9- Kipawa deposit, 10- Baie-Mercier occurrence, 11- Wares occurrence, and 12- St. Lawrence Columbian mine and Niocan deposit.

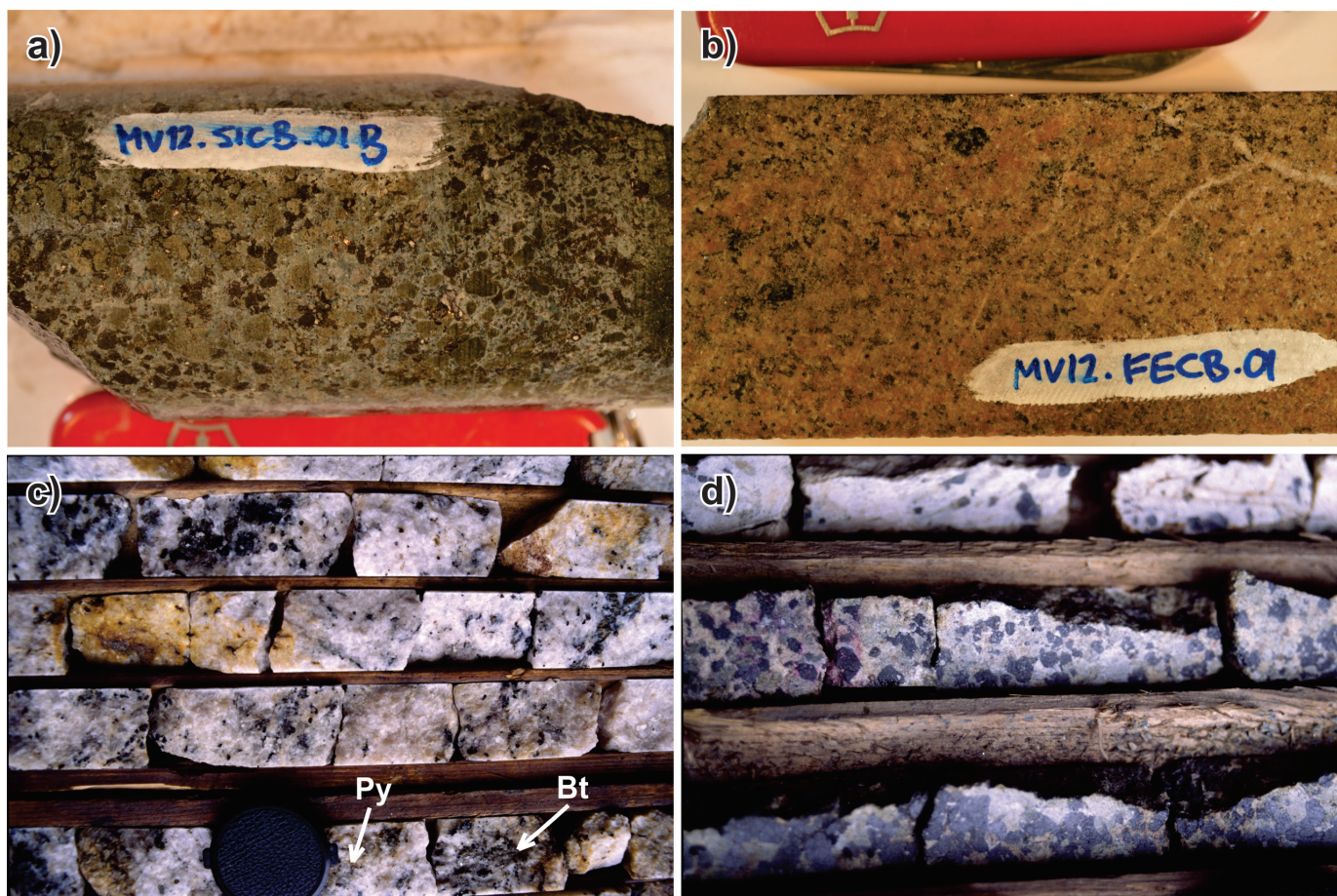


Fig. 2. Representative examples of carbonatite and skarn from carbonatite complex-related deposits. **a)** Silicocarbonatite from the Montviel carbonatite complex. The knife is ~9 cm long. Photo courtesy of O. Nadeau. **b)** Pervasively altered ferrocyanatite hosting REE-bearing minerals (e.g., cordylite-(Ce), kukharenkoite-(Ce), and qaqarssukite-(Ce)) from the Montviel carbonatite complex. The knife is ~9 cm long. Photo courtesy of O. Nadeau. **c)** Calcicocarbonatite with biotite (Bt) and, locally, disseminated pyrite (Py) from the Oka carbonatite complex. Core size is 3.6 cm in diameter. **d)** Calcic magnetite skarn in the S-60 mineralized zone from the Oka carbonatite complex. Core is 3.6 cm in diameter.

deposits are at the Kwyjibo property (Table 1).

4.1.4. Deposits associated with hyper- to metaluminous granitic pegmatite, granite, and migmatite, and skarns

The pegmatites, granites, and migmatites in this group are emplaced in continental orogenic environments during high-grade metamorphism and crustal anatexis resulting from post-collisional crustal thickening or underplating of mantle-derived mafic magmas at the base of the crust (Boily and Gosselin, 2004). Some pegmatites are derived directly from anatexis and emplaced in situ, and others are formed by magmatic differentiation of granitic melts (Boily and Gosselin, 2004). Skarns are emplaced in orogenic environments and form adjacent to felsic intrusions injected into calcareous sedimentary rocks (Jaireth et al., 2014). Granitic pegmatites form homogeneous to broadly zoned dike swarms, granites and granitic migmatites form heterogeneous masses, and skarns form irregular zones along intrusive contacts. In the pegmatites, granites, and migmatites, metasomatism results in albitization, chloritization, oxidation, and hydrous alteration of the intrusive rocks (Boily and Gosselin, 2004). In the skarns,

hornfels produced by contact metamorphism are commonly replaced by anhydrous or hydrous Ca-, Fe-, and Mg-silicates (Jaireth et al., 2014).

The REE occurrences contained in hyper- to metaluminous pegmatites, granites, and migmatites, and in skarns are characterized by low tonnages and relatively low concentrations of REE-bearing minerals (Chakhmouradian and Zaitsev, 2012). Common ore minerals are monazite, xenotime, apatite, allanite, zircon, gadolinite, thorite, fergusonite, and uraninite. In granitic pegmatites, granites, and migmatites, REE mineralization is mainly magmatic in origin. However, metals are commonly remobilized and concentrated during metamorphism and hydrothermal alteration. In skarns, mineralization forms where fluids react with carbonate rocks to introduce alumina, silica, magnesium, as well as REE and Mo. Locally, mineralization may be remobilized by later fluids formed during regional metamorphism or leaching (Jaireth et al., 2014).

In Québec, these mineral occurrences (Figs. 1, 5) are mainly in the Grenville Province and include the Haltaparche occurrence hosted by a granitic pegmatite (MERN, 2014) and the Baie-Mercier occurrence primarily associated with

Table 1. Selected REE occurrences and deposits in Québec, their deposit type, age, and grade and tonnage information.

Occurrence/Deposit ^a	Type	Age	Commodity grade and tonnage
Eldor deposit [1]	Carbonatite complex	1874 Ma (Wright et al., 1998)	Inferred mineral resources of 117.3 Mt at 1.74% TREO using a 1.25% TREO cut-off grade (Laferrière, 2011)
Strange Lake deposit (B-Zone) [2]	Peralkaline igneous complex	1240 Ma (Miller et al., 1997)	Indicated mineral resources of 278.1 Mt at 1.92% ZrO ₂ , 0.93% TREO, and 0.18% Nb ₂ O ₅ and inferred mineral resources of 214.4 Mt at 1.71% ZrO ₂ , 0.85% TREO, and 0.14% Nb ₂ O ₅ using a 0.50% TREO cut-off grade (Gowans et al., 2014)
Misery Lake deposit [3]	Peralkaline igneous complex	1410 Ma (David et al., 2012)	Up to 8.56% TREO, 3.05% ZrO ₂ , and 0.72% Nb ₂ O ₅ (Petrella, 2012)
Kwyjibo property [4]	IOCG deposit	~972 to 951 Ma (Gauthier et al., 2004)	7.0 m thick-interval with 7.04% TREO and 0.19% Cu (Focus Graphite Inc., 2013)
Montviel deposit [5]	Carbonatite complex	1894 Ma (David et al., 2006)	Indicated mineral resources of 82.4 Mt at 1.51% TREO and inferred mineral resources of 184.2 Mt at 1.43% TREO using an economic cut-off of CA\$180 per tonne (Belzile et al., 2015)
Lac Shortt deposit [6]	Carbonatite complex	2652 Ma (Thorpe et al., 1984; Morasse, 1988)	Up to 2.2% REO (Quirion, 1991)
Crevier deposit ^b	Carbonatite complex	957.5 Ma (Groulier et al., 2014)	Indicated mineral resources of 12.9 Mt at 0.19% Nb ₂ O ₅ and 234 ppm Ta ₂ O ₅ and inferred mineral resources of 15.4 Mt at 0.17% Nb ₂ O ₅ and 252 ppm Ta ₂ O ₅ using a 0.10% Nb ₂ O ₅ cut-off grade (Duplessis and Girard, 2010)
Niobec mine ^b	Carbonatite complex	565 Ma (Doig and Barton, 1968)	Total production of 1.8 Mt at 0.61% Nb ₂ O ₅ (MRNF, 2010)
Grande-Vallée deposit [7]	Ion-adsorption clay	Cambrian (Raffle et al., 2013)	Indicated mineral resources of 1.0 Gt at 563 ppm REE and rare metals using a 18% Al ₂ O ₃ cut-off grade (Doran et al., 2012b)
Haltparche occurrence [8]	Granitic pegmatite	-	3950 ppm Ce, 2040 ppm La, and 1520 ppm Nd (MERN, 2015)
Kipawa deposit [9]	Peralkaline igneous complex	1033 Ma (van Breemen and Currie, 2004)	Indicated mineral resources of 13.4 Mt at 0.36% TREO and inferred mineral resources of 3.3 Mt at 0.31% TREO using a 0.20% TREO cut-off grade (Saucier et al., 2013)
Baie-Mercier occurrence [10]	Skarn	-	2800 ppm Ce, 1200 ppm La, and 810 ppm Nd (Lapointe et al., 1993)
Wares occurrence [11]	Paleoplacer	Cambrian (Gauthier et al., 1989)	1540 ppm Ce, 917 ppm La, and 568 ppm Nd (MERN, 2015)
St. Lawrence Colubium mine ^c [12]	Carbonatite complex	135 to 113 Ma (Chen, 2014)	Total production of 6.2 Mt at 0.31% Nb ₂ O ₅ between 1961 and 1976 and mineral reserves of 25.0 Mt at 0.44% Nb ₂ O ₅ (Trudel, 1983; Lavergne, 1985)
Niocan deposit ^c [12]	Carbonatite complex	135 to 113 Ma (Chen, 2014)	Indicated mineral resources of 6.4 Mt at 0.65% Nb ₂ O ₅ and inferred mineral resources of 3.2 Mt at 0.61% Nb ₂ O ₅ using a 0.40% Nb ₂ O ₅ cut-off grade (Niocan Inc., 2015)

^a Numbers in brackets correspond to the numbers identifying deposits in Figure 1

^b In the Crevier deposit and Niobec mine, REE are minor substances subordinate to Nb

^c In the St. Lawrence Colubium mine and Niocan deposit, REE are major substances, but REE resources are unknown
Abbreviation: TREO = total rare earth oxide, REO = rare earth oxide

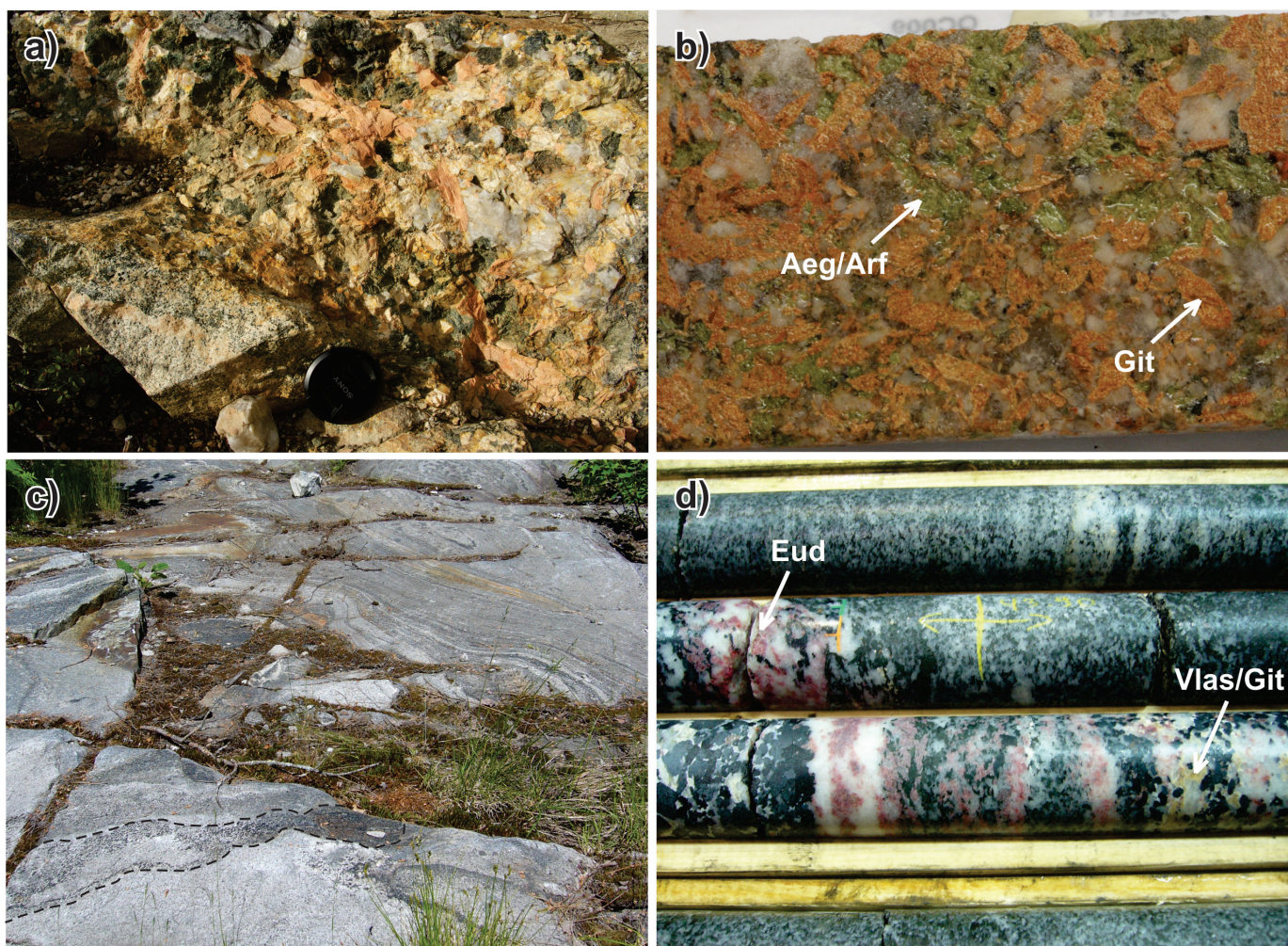


Fig. 3. Representative examples of pegmatite and syenite from peralkaline igneous rock-associated deposits. **a)** Pegmatite intruding subsolvus granite from the B-Zone of the Strange Lake intrusive complex. Lens cap is ~6 cm in diameter. Photo is courtesy of A. Williams-Jones. **b)** Pegmatite core with gittinsite (Git) and aegirine (Aeg)/arfvedsonite (Arf) from the B-Zone of the Strange Lake intrusive complex. Core is 4.7 cm in diameter. Photo courtesy of A. Williams-Jones. **c)** Syenite gneiss from the Kipawa Alkaline complex, crosscut by a 4 m-wide coarse-grained mesocratic syenite band with eudialyte and mosandrite (bottom of the picture). Photo courtesy of F. Fleury. **d)** Foliated syenite with eudialyte (Eud) and vlasovite (Vlas)/gittinsite from the Kipawa Alkaline complex. Core is 4.7 cm in diameter. Photo courtesy of F. Fleury.

a carbonatite horizon (Lapointe et al., 1993; Table 1). A few occurrences have been discovered in the Superior Province and in the Churchill Province (Labrador Trough). Pegmatites, granites, migmatites, and skarns containing REE appear to be mostly Archean to Proterozoic.

4.2. Secondary deposit-types

4.2.1. Placers and paleoplacers

Placers and paleoplacers with REE mineralization are formed near continental margins rich in reworked siliciclastic sediments, and near Mesozoic to Cenozoic volcanic arcs (Boily and Gosselin, 2004). They are found in alluvial fan, eolian, fluvial, glacial, glaciofluvial, beach, and seafloor settings. Continental deposits form thin and discontinuous lenses; coastal marine deposits form thin elongate bodies of limited lateral extent (Boily and Gosselin, 2004).

Generally, placers and paleoplacers lack major concentrations of REE-bearing minerals and contain high levels of U and Th (Castor and Hedrick, 2006). In these deposits, REE are extracted as by-products of ilmenite and zircon mining (Castor and Hedrick, 2006). The predominant REE ore minerals are monazite and xenotime. These heavy minerals are derived from erosion of a range of primary sources, including ore deposits and igneous rocks.

In Québec, the most important placer REE occurrences (Fig. 1) are in the Ungava and Appalachian orogens (e.g., Wares occurrence; Table 1). Several paleoplacers rich in Fe and Ti, which contain low concentrations of REE, have been reported in Pleistocene sands in the Basse-Côte-Nord area, along the St. Lawrence River (e.g., Natashquan deposit; Boily and Gosselin, 2004). Placers and paleoplacers containing REE mineralization are Cambrian to Holocene in age.

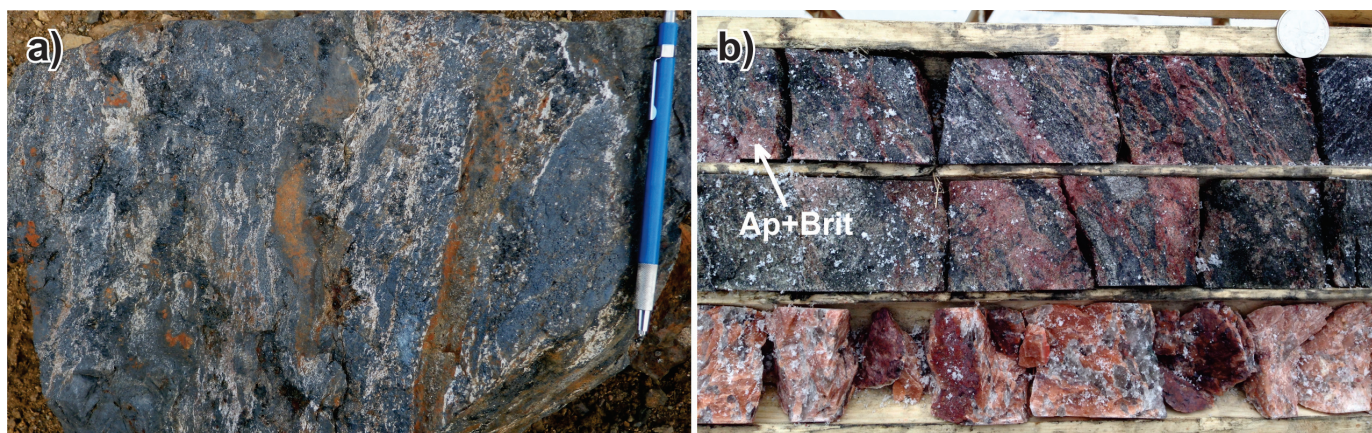


Fig. 4. Representative examples of mineralization from REE-bearing IOCG deposits. **a)** Veins with calc-silicate minerals and REE-bearing minerals (e.g., apatite, britholite, allanite), veinlets of magnetite, and fragments of massive magnetite from the Josette deposit in the Kwyjibo property. The pen is ~15 cm long. **b)** Altered biotite-hornblende-plagioclase-magnetite gneiss brecciated by veins/veinlets of apatite (Ap) and britholite (Brit) from the Josette deposit in the Kwyjibo property. The coin is 2.4 cm in diameter. Photos courtesy of S. Perreault.

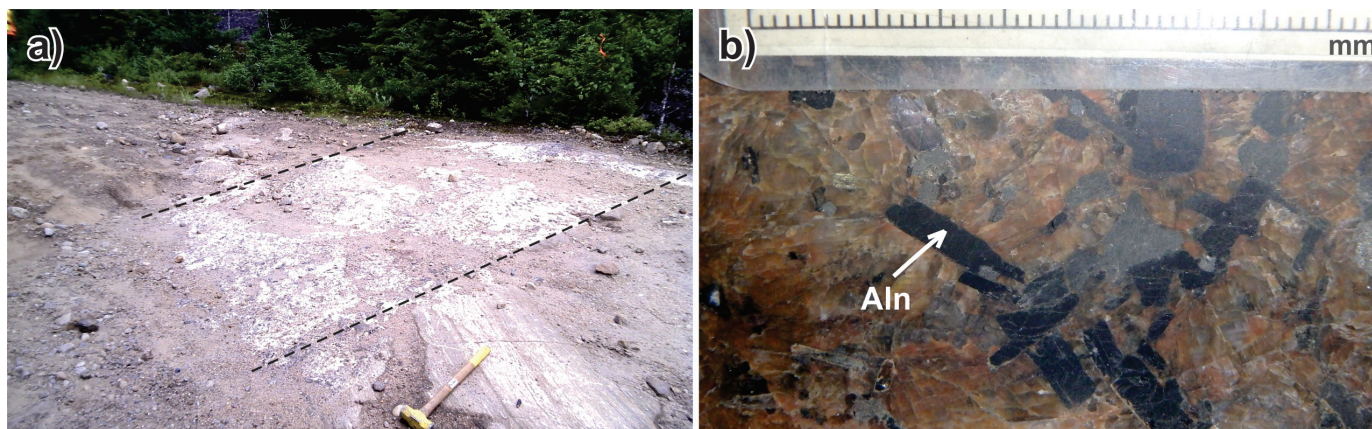


Fig. 5. Representative examples of pegmatite from hyperaluminous/metaluminous granitic pegmatite-related deposits. **a)** Dike of granitic pegmatite crosscutting the foliated charnockite of the Hibbard Plutonic suite in the Haltaparche occurrence area. The hammer is ~38 cm long. **b)** Granitic pegmatite with allanite (Aln) from the Haltaparche occurrence. Photos courtesy of F. Solgadi.

4.2.2. REE-bearing ion-adsorption clays

Rare earth element-bearing ion-adsorption clays commonly form in subtropical areas, where chemical weathering is intense, but can also be found in deep-marine settings. The clays can be unconsolidated to consolidated.

Rare earth element mineralization associated with ion-adsorption clays is characterized by low grades and large tonnages of metals and is typically rich in HREE and poor in radioactive elements. In addition, clay deposits contain REE that are easily extracted by open-pit mining and easily processed. In REE-bearing ion-adsorption clays, most of the REE are in the form of cations adsorbed on the surface of clay minerals. This REE mineralization derives from the chemical and mechanical weathering of rocks that contain a significant proportion of minerals rich in REE and sensitive to chemical alteration, like granites (Kynicky et al., 2012).

In Québec, only one REE occurrence has been identified in ion-adsorption clays (Fig. 1). This occurrence is associated with the Cambrian Grande-Vallée alumina deposit (Table 1), in the Appalachian orogen. The aluminous mudstone containing REE

mineralization is composed of kaolinite and probably gibbsite or boehmite, and was deposited in a deep-marine setting on a passive continental margin (Doran et al., 2012a, 2012b). REE contents of clays in the Grande-Vallée deposit are low, but REE can be recovered as by-products of alumina (Doran et al., 2012a, 2012b).

5. Economic potential

Among all the REE occurrences in Québec, the Proterozoic deposits formed by magmatic and hydrothermal processes and associated with carbonatite complexes, peralkaline igneous rocks and, to a lesser extent, IOCG deposits have the highest economic potential. They are numerous, have locally high REE contents, and are significant sources of the most abundant REE (e.g., La, Ce) and the most critical REE (e.g., Nd, Eu, Tb). Furthermore, several of these deposits appear to have substantial REE resources (Table 1) and are currently being evaluated. Good examples are Montviel (Belzile et al., 2015; Nadeau et al., 2015), Eldor (Wright et al., 1998; Laferrrière, 2011), Stange Lake (Gowans et al., 2014; Vasyukova and

Williams-Jones, 2014), Kipawa (van Breemen and Currie, 2004; Saucier et al., 2013), and Josette in the Kwyjibo property (Gauthier et al., 2004; Focus Graphite Inc., 2013).

6. Conclusion

Québec hosts numerous REE occurrences and deposits. Six main types of mineralization are recognized, according to their lithological association. Four of these types are primary and formed by igneous and/or hydrothermal processes. Two types are secondary and formed by weathering and sedimentary processes. The primary deposits are the most abundant in the province and are the main targets for exploration. They are associated with carbonatite complexes, peralkaline igneous rocks, IOCG deposits, or hyperaluminous/metaluminous igneous rocks and skarns. They vary from Archean to Mesozoic in age, and were emplaced mainly in extensional intracontinental settings near major crustal structures. In contrast, the secondary deposits are scarce. They are Paleozoic to Cenozoic in age and formed in continental and marine siliciclastic settings or in clays.

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