24. CARBONATITE-ASSOCIATED DEPOSITS

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D.G. Richardson and T.C. Birkett

INTRODUCTION

Carbonatite-associated deposits include a variety of mineral deposits that occur both within and in close spatial association with carbonatites and related alkalic silicate rocks. Carbonatite-associated deposits are mined for rare-earth elements (REEs), niobium, iron, copper, apatite, vermiculite, and fluorite. Byproducts include barite, zircon or baddeleyite, tantalum, uranium, and in the unique Palabora carbonatite of South Africa, platinum group elements, silver, and gold. In some complexes, calcite-rich carbonatite is mined as a source of lime to produce Portland cement, and in Europe, carbonatites have provided lime and iron for hundreds of years (Dawson, 1974; Deans, 1978; Bowden, 1985).

Carbonatites are igneous rocks which contain at least 50% modal carbonate minerals, mainly calcite, dolomite, ankerite, or sodium- and potassium-bearing carbonates (nyerereite and gregoryite). Other minerals commonly present include diopside (in early carbonatites – e.g., Bond zone, Oka, Quebec), sodic pyroxenes or amphiboles, phlogopite, apatite, and olivine. A large number of rare or exotic minerals also occur in carbonatites. Definitions of rock names used in describing carbonatite-associated deposits are provided in Table 24-1 and chemical formulae of some less common minerals are given in Table 24-2.

Carbonatites occur mainly as intrusive bodies of generally modest dimensions (as much as a few tens of square kilometres), and to a lesser extent as volcanic rocks (flows and derived deposits), which are associated with a wide range of alkali silicate rocks (syenites, nepheline syenites, nephelinites, ijolites, urtites, pyroxenites, etc.) (Bowden, 1985; Barker, 1989). Although carbonatites are invariably associated with alkalic rocks, the inverse relationship does not necessarily hold (Möller, 1989b). Carbonatites are generally surrounded by an aureole of metasomatically altered rocks called fenites produced by reaction of country rock with peralkaline fluids released from the carbonatite complex (Morogan, 1994).

Carbonatite-associated deposits can be subdivided into magmatic and metasomatic types. Magmatic deposits are formed through processes associated with the crystallization of carbonatites, whereas metasomatic deposits form by the reaction of fluids released during crystallization with pre-existing carbonatite or country rocks. Spatially distinct niobium and rare-earth element (REE) mineralization at the Niobec mine, Quebec, are examples of magmatic and metasomatic mineralization, respectively.

The Aley (British Columbia); Oka, Crevier, and Niobec (Quebec); and Argor, Manitou Islands, Lackner Lake, and Nemegosenda Lake (Ontario) deposits are Canadian carbonatite-associated deposits (Fig. 24-1). Significant foreign carbonatite-associated deposits include Palabora (South Africa), Kovdor (Russia), Siilinjärvi (Finland), Sarfartôq (Greenland), Tapira and Jacupiranga (Brazil), the Mountain Pass bastnaesite deposit (California), the Kangankunde Hill monazite deposit (Malawi), Bayan Obo (People's Republic of China), and Amba Dongar (India).

IMPORTANCE

Carbonatite-associated deposits contain the majority of the known reserves of niobium in the world. The Niobec mine near Chicoutimi, Quebec, accounts for approximately 10% of western world niobium production, and is the only underground niobium mine (Scales, 1989). Production from this deposit makes Canada the world's second largest

Table 24-1. Definitions of rock names used in describing carbonatite complexes (compiled from: Sørensen, 1977; Bates and Jackson, 1987; Le Bas, 1987; Woolley and Kempe, 1989; Rock, 1991; Sage, 1991; A.N.Mariano, pers. comm., 1994).

bebedourite	Diopside-salite $(Ca(Mg,Fe)Si_2O_6)$ pyroxenite with low acmite and hedenbergite contents. The pyroxenite may contain biotite, with accessory perovskite, apatite, and titanomagnetite (from the classic locality – the Bebedoure Mountains of Salitre, Minas Gerais, Brazil).
magnesiocarbonatite/ dolomitic carbonatite/ beforsite	Magnesiocarbonatite contains >50% carbonate minerals and has $MgO>FeO + Fe_2O_3 + MnO$; beforsite = hyabyssal dolomitic carbonatite.
fenite	A rock that has been altered by alkali (Na/K) metasomatism.
ferrocarbonatite	A ferroan calcite to ankerite calcite carbonatite that is strongly enriched in some or all of REEs, Ba, Mn, Fe, Zn, F, and U, with possible lower limits of 1.0% MnO, 5000 ppm REEs, and 5000 ppm Ba. This rock type is very rare, but is the main source for mineralization of these elements in carbonatites. Ferrocarbonatites usually have $FeO + Fe_2O_3 + MNO>MgO$
glimmerite/biotitite	Igneous rock composed almost entirely of bitoite ± calcite ± zeolite ± magnetite ± REEs.
ijolite	A nepheline-pyroxene rock with a nepheline content between 30 and 70%. Rocks containing more than 70% nepheline are classified as **urtite** and those with less than 30% as **melteigite.** Some specimens may contain significant amounts of biotite in place of pyroxene. Potassium feldspar content is 10% or less and those rocks with 10% or less nepheline are classified as **pyroxenite. Nephelinite** is a fine grained or porphyritic extrusive or hypabyssal rock, of basaltic character, but primarily composed of nepheline and pyroxene (especially titanaugite), and lacking feldspar.
jacupirangite	An ultramafic plutonic rock that is part of the ijolite series, and is composed chiefly of titanaugite and magnetite, with a smaller amount of nepheline. Considered to be a nepheline-bearing clinopyroxenite.
malignite	A melanocratic nepheline syenite. In general, nepheline, pyroxene, and potassium feldspar occur in roughly equal proportions. The potassium feldpsar content must exceed 10% or the rock is classified as belonging to the ijolite suite. Both the nepheline and pyroxene content must exceed 10% or the rock would be classified with the syenites. This rock group is transitional between the ijolites and overlaps the syenitic rock group.
natrocarbonatite	Fine grained carbonatite lava composed of sodium-potassium-calcium carbonates (i.e., predominantly nyerereite and gregoryite).
phoscorite/foskorite/ kamaforite	Magmatic rock consisting predominatly of three major rock-forming minerals – olivine (forsterite), magnetite, and apatite. Accessory phases include variable amounts of calcite, baddelyite, and sulphides. Variations in the relative proportions of the three essential mineral components results in a variety of rock types in the phoscorite series, including: forsteritite (rock composed almost entirely of forsterite olivine), magnetitite (rock composed almost entirely of magnetite), nelsonite (magnetite-apatite [oxide-phosphate] rock), and apatitite (rock composed almost entirely of apatite).
rauhaugite	A carbonatite that contains ankerite or dolomite.
silicocarbonatite	A sövite-type of carbonatite rock containing 50% or more oxide and silicate minerals. Where silicate or oxide mineralogy exceeds 90%, various other rock names are applied (i.e. ijolite, pyroxenites, etc.).
sövite/calciocarbonatite	Coarse grained carbonatite rock composed of 50% or more calcite that displays adcumulate texture. If it is medium- or fine-grained the rock is a micro-sövite. Various mineralogical modifiers are used to classify the sövite (e.g., apatite-magnetite sövite, olivine-amphibole sövite, etc.). An alvikite is medium- to fine-grained type of sövite enriched in incompatible elements such as REEs, Ba, Mn, Zn, and commonly Nb. The boundary between sövite and alvikite is uncertain but may be set at 0.4% MnO, 1500 ppm Ba, and 200 ppm REEs. The calcite of an alvikite is slightly ferroan. Calciocarbonatites contain >80% CaO.
tinguaite	A textural variety of phonolite (extrusive equivalent of nepheline syenite), typically found in dykes, and characterized by conspicuous acicular crystals of acmite arranged in radial or criss-cross patterns in the groundmass. The phenocrysts are equigranular alkali feldspar and nepheline.
melilite series/melilitolite	A group of extrusive/plutonic, usually olivine-free, mafic rocks composed of melilite and augite or other mafic minerals that comprise more than 90% of the rock. This rock type may contain minor amounts of feldspathoids, apatite, calcite, anatase, and sometimes plagioclase and phlogopite. The melilite series includes **uncompahgrite. Ultramafic lamprophyres** correspond broadly to melililites and melilite-nephelinites, but are considerably enriched in volatile elements (H_2O, CO_2, F, Cl) and large-ion lithophile elements (K, Rb, Ba, Mg, Cr, Ni, etc.).

Table 24-2. Formulae of some of the less common minerals mentioned in the text.

Mineral name	Formula
Silicates	
allanite	$(Ce,Ca,Y)_2(Al,Fe^{+3})_3(SiO_4)_3(OH)$
eckermannite	$Na_3(Mg,Fe^{+2})_4AlSi_8O_{22}(OH)_2$
kimzeyite	$Ca_3(Zr,Ti)_2(Si,Al,Fe^{+3})_3O_{12}$
niocalite	$(Ca,Nb)_{16}Si_8(O,OH,F)_{36}$
melanite (titanian andradite)	$Ca_3(Fe,Ti)(SiO_4)_3$
melilite	$(Na,Ca)_2(Mg,Al)(Si,Al)_2O_7$
monticellite	$CaMgSiO_4$
taeniolite	$K,Li,Mg_2Si_4O_{10}F_2$
Oxides	
aeschynite	$(LREE,Ca,Fe,Th)(Ti,Nb)_2(O,OH)_6$
baddeleyite	ZrO_2
brookite	TiO_2
columbite	$(Fe,Mn)(Nb,Ta)_2O_6$
latrappite	$(Ca,Na)(Nb,Ti,Fe)O_3$
loparite	$(Ce,Na,Ca)_2(Ti,Nb)_2O_6$
lueshite	$NaNbO_3$
fersmite	$(Ca,Na)(Nb,Ta,Ti)_2(O,OH,F)_6$
perovskite	$CaTiO_3$
pyrochlore	$(Na,Ca,Ce)_2(Nb,Ta,Ti)_2O_6(OH,F)$
uranothorianite	$(U,Th)O_2$
Carbonates/fluorides	
ancylite	$SrCe(CO_3)_2(OH) \cdot H_2O$
burbankite	$(Na,Ca,Sr,Ba,LREE)_6(CO_3)_5$
bastnaesite	$(LREE)(CO_3)F$
cordylite	$Ba(LREE,Ca,Sr)_2(CO_3)_3F_2$
gregoryite	$(Na,K)_2CO_3$
huanghoite	$Ba,LREE,(CO_3)_2F_2$
nyerereite	$(Na,K)_2Ca(CO_3)_2$
parisite	$(LREE)_2Ca(CO_3)_3F_2$
synchysite	$Ca(LREE)(CO_3)_2F$
Phosphates	
britholite	$(Ca,Ce)_5(SiO_4,PO_4)_3(OH,F)$
florencite	$(LREE)Al_3(PO_4)_2(OH)_6$
monazite	$(LREE,Y)PO_4$
xenotime	YPO_4

niobium producer, after Brazil. Apatite and magnetite, and byproduct baddeleyite or zircon, are also derived from magmatic carbonatite deposits. The Palabora carbonatite is unique in that it hosts large economic concentrations of copper (Palabora Mining Company Limited, Mine Geological and Mineralogical Staff, 1976; Eriksson, 1989).

Carbonatite-associated deposits account for a significant portion of world REE production and contain most known reserves. The Bayan Obo orebody is the world's largest known REE deposit, with published reserves of 37 Mt of contained rare-earth oxides (REO) (Möller, 1989a). Over the past few decades, Mountain Pass has consistently been the world's leading producer of REE concentrates (Möller, 1989a). The central metasomatic beforsite core of the St. Honoré (Niobec) carbonatite contains bastnaesite and monazite in veinlets. These rocks contain approximately 2% rare-earth oxides (REOs) to a depth of 460 m (E. Denommé, pers. comm., 1991). The fine grained nature of the REE mineralization has, however, been an impediment to the production of a REE concentrate (Sinclair et al., 1992).

A substantial inferred resource of phosphate (apatite) is present in the Aley carbonatite, British Columbia (Table 24-3). The Jacupiranga carbonatite in Brazil is unique in that it represents one of the lowest grade commercial phosphate deposits (5.3% P_2O_5), and is the only carbonatite in Brazil from which phosphate is recovered from fresh rock rather than from a weathered residuum (Gomes et al., 1990). Phoscorites contained within alkali silicate-carbonatite complexes are also a major source of phosphate and form the basis of domestic phosphate production in South Africa (Notholt, 1980). The Kovdor (Russia) phoscorite has produced iron ore (magnetite) and phosphate since 1962. Canadian examples of phoscorite occur at the Lackner Lake alkalic complex, northern Ontario (Sage, 1988a), and at the Howard Creek carbonatite, Blue River area, British Columbia (A.N. Mariano, pers. comm., 1994). Phoscorite deposits generally have grades of 6 to 10% P_2O_5, but the product can be beneficiated to high-grade concentrates of 36-40% P_2O_5 at relatively low cost (Krauss et al., 1984).

Other commodities produced more rarely from carbonatite-associated deposits include: fluorite (e.g., Amba Dongar, India; Okorusu, Namibia; and Mato Preto, Paraná State, Brazil), vermiculite (e.g., Palabora, South Africa; Kovdor, Russia), vanadium (e.g., Magnet Cove Complex, U.S.A.), and baddeleyite (e.g., Palabora and Kovdor). Some carbonatite deposits are enriched in U and Th, but low U/Th ratios generally make them uneconomic (Le Bas, 1987).

SIZE AND GRADE OF DEPOSITS

Many carbonatite-associated deposits are relatively small, on the order of tens of thousands to hundreds of thousands of tonnes. However, significant production of phosphate, niobium, and REOs is derived from larger, higher grade (>5.0% P_2O_5; >0.6% Nb_2O_5; >5.0% REOs) deposits in Brazil, Canada, and South Africa, which vary greatly in size and grade (4 Mt to 5000 Mt grading >5% to 15% P_2O_5; 0.05% to >0.6% Nb_2O_5; 6 to >25% REOs; 3 to 4% TiO_2; and 30 to >50% CaF_2). Published grades and tonnages of Canadian and world carbonatite-associated deposits are presented in Tables 24-3 and 24-4, respectively. The grade-tonnage relationships of these deposits are shown in Figure 24-2.

GEOLOGICAL FEATURES

Geological setting

Of the more than 330 alkali silicate-carbonatite complexes presently known, most occur in relatively stable, intraplate areas (Le Bas, 1987). The regional distribution of these complexes is controlled by major tectonic features. About one-half of known carbonatites are located in topographic highs or domes, which can be from tens of kilometres to thousands of kilometres in diameter, and are bounded by zones of crustal-scale faulting (Woolley, 1989). Other major controls on carbonatite emplacement are major faults, anorogenic rifts, and the intersections of major faults. The Niobec deposit, for example, is located along the northern border of the Saguenay-Lac St. Jean graben, a branch of the St. Lawrence rift zone (Gagnon, 1981). A few carbonatites are found near plate margins and may be linked with orogenic activity or plate separation, and an even smaller number (i.e., Canary Islands and Cape Verde Islands) are aligned with oceanic fracture/fault zones and appear to be emplaced in hybrid oceanic/continental lithospheric rocks (Bowden, 1985; Woolley, 1989; B.A. Kjarsgaard, pers. comm., 1994). Because carbonatites are generally localized in clusters or provinces that display episodic magmatic activity, Woolley (1989) has postulated that the physical and/or chemical properties of lithospheric plates exert some control on their location and genesis.
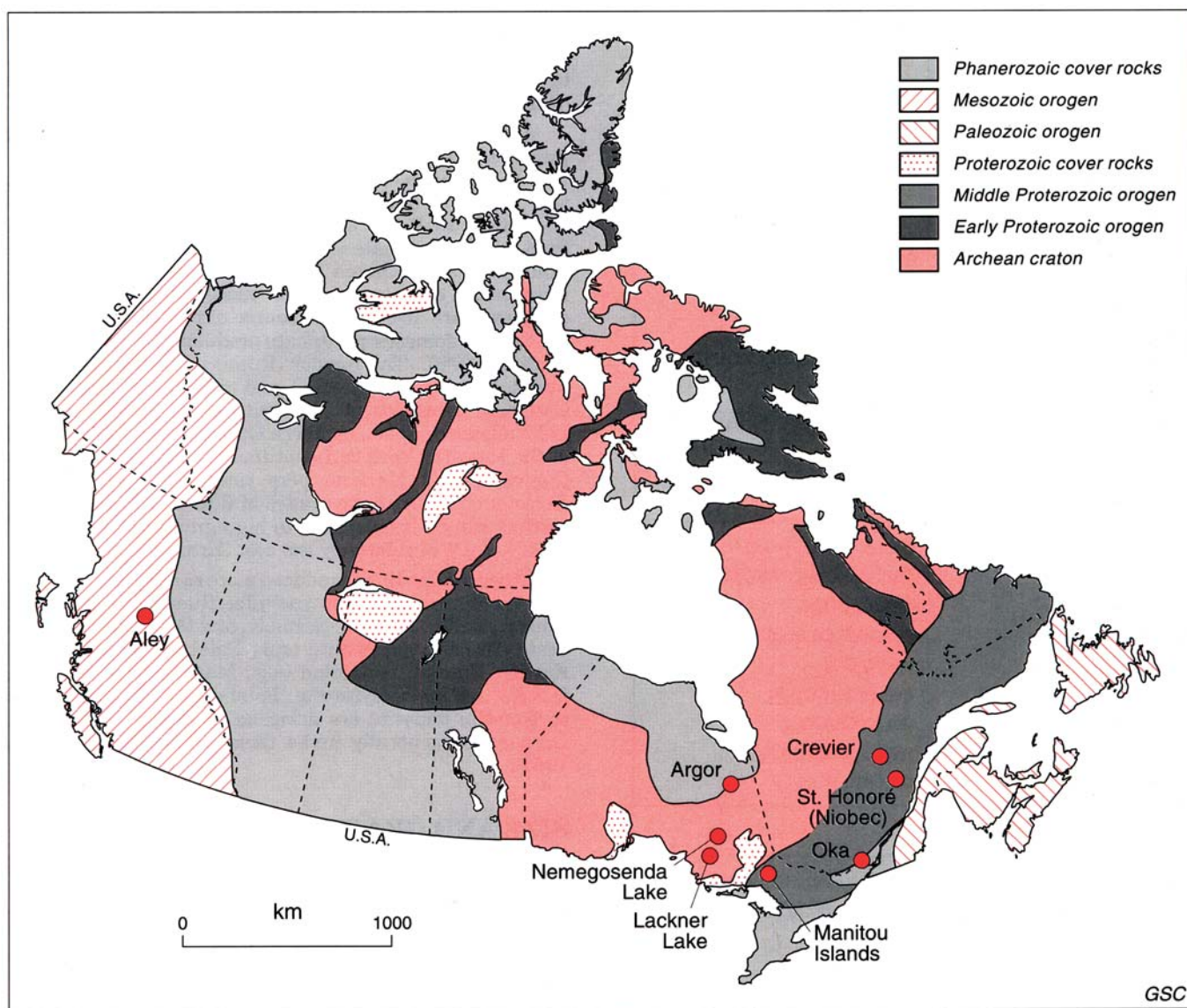

Figure 24-1. Locations of selected Canadian carbonatite-associated deposits and occurrences discussed in the text.

Age

According to Woolley's (1989) compilation of carbonatite ages (Fig. 24-3), there has been a gradual increase in carbonatite magmatism with time, and the dates fall into groups that generally correspond to major orogenic and tectonic events. Identified age groups include: 1) a mid-Proterozoic group (1800-1550 Ma) that corresponds to the Hudsonian and Svecokarelian orogenies of North America and Europe, respectively; 2) a mid- to late Proterozoic group corresponding to the Grenville orogeny (peak at ~1100 Ma); 3) a group between 750 Ma and 500 Ma which includes early Caledonian dates from both northern Europe and North America, as well as some African localities; and 4) a major period starting at 200 Ma which is perhaps associated with the breakup of Pangaea (Woolley, 1989). A few carbonatites of

Table 24-3. Production and reserves of selected Canadian carbonatite-associated deposits and occurrences.

DEPOSIT	PRODUCTION/RESERVES/GRADE	COMMENTS/REFERENCES
Aley property, British Columbia Lat. 56°27'N Long. 123°45'W	Inferred open pit reserves: 20 Mt; 0.7% Nb_2O_5 Potential resources: 5 Gt; 3-5% P_2O_5	Eight Nb-bearing zones have been identified in the dolomitic carbonatite core, which consists of 80-95% dolomite and 5-15% apatite. Also minor REE-bearing zones (Pell, 1986, 1987; Mäder, 1987; Faulkner et al., 1992).
Argor, Ontario Lat. 50°45'N Long. 81°01'W	Diamond drill indicated reserves: 56.2 Mt; 0.52% Nb_2O_5	Deposit also has potential for byproduct apatite and possibly zircon. Columbite is related to fracturing and hematite alteration (Woolley, 1987; Sage, 1988b).
Lackner Lake, Ontario, Lat. 47°47'N Long. 83°06'W	Drill indicated/inferred reserves in zones 3, 4, 6, & 8 to a maximum depth of 243 m: 111 Mt; 0.23% Nb_2O_5	Pyrochlore mineralization occurs within nepheline syenite and mafic silicate phases as: 1) fine grains or irregular clusters in the ijolites and malignites (3 & 4 zones); 2) finely disseminated grains in massive titaniferous magnetite-apatite bodies (6 zone); and 3) scattered grains within ijolitic malignites (8 zone). Two dyke-like carbonatite bodies host part of the No. 8 zone (Woolley, 1987; Sage, 1988a, 1991).
Nemegosenda Lake, Ontario Lat. 48°00'N Long. 83°06'W	Drill indicated reserves/resources to a depth of 180 m: 18.1 Mt; 0.47% Nb_2O_5	Nb, present as pyrochlore, is found in all rock types, but appears to be concentrated in fenites and in plugs and breccia zones within the marginal zone of fenitization. There is a correlation of radioactivity with Nb content (Sage, 1976, 1987; Woolley, 1987).
Manitou Islands, Ontario Lat. 46°15'N Long. 79°35'W	Drill indicated reserves: 3.26 Mt; 0.627% Nb_2O_5; 0.032% U_3O_8	Five uranian pyrochlore deposits are confined to an aegirine-potassic feldspar fenite zone. Brownish crystals of uranian pyrochlore range from about 0.01 mm to 3.5 mm. The aegirine-potassic feldspar fenite also contains a few per cent magnetite, pyrite, and pyrrhotite (Lumbers, 1971; Currie, 1976; Woolley, 1987).
St. Honoré (Niobec), Quebec Lat. 48°33'N Long. 71°04'W	Total past production: 9.6 Mt; avg. 0.66% Nb_2O_5 Proven and probable reserves at Dec. 31, 1992: 10.1 Mt; 0.65% Nb_2O_5	Pyrochlore in two major zones in the southern section of the nearly circular St. Honoré complex. Production data from Canadian Mines Handbook 1977-78 to 1993-94; reserves from same source 1993-94.
Crevier-Lagorce townships, Quebec Lat. 49°29'N Long. 72°45'W	Drill indicated reserves: 15.2 Mt; 0.189% Nb_2O_5, 0.020% Ta_2O_5 (Société Quebecoise d'Exploration Minière Annual Report 1981-82)	Mineralization is in two zones: 1) disseminated apatite, magnetite, pyrochlore, betafite (uranpyrochlore), and chalcopyrite in carbonatite and carbonate-biotite-melanosyenite; 2) disseminated fine grained pyrochlore in porphyritic pegmatitic nepheline syenite dykes.
Oka carbonatite, Quebec Lat. 45°30'N Long. 74°01'W	Drill indicated reserves of all zones: 112.7 Mt; 0.44% Nb_2O_5 23.8 Mt; 0.20-0.50% REOs	Drilling indicated six potentially exploitable zones of niobium mineralization, consisting primarily of pyrochlore, niocalite, perovskite, and latrappite. Hydrothermal REE mineralization is in arcuate inward-dipping tabular bodies associated with cone-sheet fractures (Gold et al., 1967, 1986; Woolley, 1987; Mineral Policy Sector, 1989).

Table 24-4. Production and reserves of selected foreign carbonatite-associated deposits.

DEPOSIT	PRODUCTION/RESERVES/GRADE	COMMENTS/REFERENCES
Siilinjärvi, Finland	Inferred resources to a depth of 150 m: 470 Mt; 4% P_2O_5	Phosphate mineralization is confined to Archean glimmerite-carbonatite rocks. Locally apatite comprises 25-30% of the carbonatite (Notholt, 1979, 1980; Puustinen and Kauppinen, 1989).
Kovdor, Kola Peninsula, Russia	Indicated reserves 700 Mt; 6-7% P_2O_5	Economically important apatite-forsterite phoscorites surround an elongated core magnetite "ore complex" (as much as 50% magnetite and 16% apatite). Chalcopyrite is a persistent but minor accessory in the Kovdor carbonatites. Vermiculite in an olivine-phlogopite unit is mined from the central pyroxenite core (Deans, 1966; Notholt, 1980; Ilyin, 1989; Harben and Bates, 1990a).
Mountain Pass, California, U.S.A.	Proven reserves at end of 1986: 36.3 Mt; 7.67% REOs; 20-25% $BaSO_4$ Indicated reserves: 90.7 Mt; 5% REOs	REE mineralization is contained in a north-trending tabular carbonatite body (Sulphide Queen). The principal REE-bearing minerals are bastnaesite and parisite. The ore mined consists of 40-75% calcite, 15-50% barite, and 5-15% bastnaesite/parisite (Olsen et al., 1954; Woolley, 1987; Mariano 1989a, b; Möller, 1989a).
Magnet Cove Complex, Arkansas, U.S.A.	Estimated resources at the Christy deposit: 11.7 Mt; 0.0513% Nb 10.8 Mt; 0.83% V 10 Mt; 2.0% Ti	About 4700 t of rutile concentrate were produced 1934 to 1944 from veins hosted by altered phonolite/trachyte. The Christy Ti-V-Nb deposit is hosted in an interbedded chert-shale horizon (Arkansas Novaculite) adjacent to the Magnet Cove complex. It may have been formed by carbonatite-derived alkali-rich fluids that infiltrated the Arkansas Novaculite (Woolley, 1987; Flohr, 1994).
Powderhorn Complex (Iron Hill), Colorado, U.S.A.	Measured and indicated reserves: 223 Mt; 4.0% TiO_2 Inferred reserves: 123 Mt; 4.0% TiO_2	Perovskite and magnetite occur as irregular lens-like bodies and as accessory minerals in pyroxenite. Although the orebody is reported to contain 12% TiO_2, much of this is bound in augite, magnetite, mica, and leucoxene. The recoverable Ti mineral is perovskite (50% TiO_2) which comprises 8% of the orebody (Fantel et al., 1986; Woolley, 1987).
Sarfartôq, Greenland	Indicated reserve: 500 Mt; 3.5% P_2O_5 Drill indicated reserves of high grade Nb zone: 300 000 t; 10% Nb_2O_5	Apatite-bearing carbonatite sheets 2-30 m thick, and as much as 200-500 m in strike length, are situated within the outer carbonatite core. The veins and shear zones of the marginal zone are enriched in Nb, U, and LREEs contained in pyrochlore. The high grade pyrochlore zone is a semimassive replacement body (Woolley, 1987; Secher, 1989; Kalvig and Appel, 1994).
Qaqarssuk, Greenland	Drill indicated reserves: 4.0 Mt; 0.5% Nb_2O_5 3.4 Mt; 3.5-6% P_2O_5	Coarse grained apatite occurs in early calcitic and dolomitic carbonatite, which also contains minor phlogopite and magnetite. Pyrochlore is present in late stage calcitic carbonatites and in glimmerites, which locally contain zones consisting almost entirely of apatite-magnetite-pyrochlore. Lanthanides are locally present (Knudsen, 1989a, b; Kalvig and Appel, 1994).
Jacupiranga, São Paulo, Brazil	Estimated reserves: 200 Mt; 5.30% P_2O_5	Phosphate mineralization, as apatite, is generally contained in a carbonatite body that forms part of a complex of ultramafic rocks, ijolite, nepheline syenite, and carbonatite (Woolley, 1987; Born, 1989a; Gomes et al., 1990).
Ipanema, São Paulo, Brazil	Indicated reserves: 25 Mt; 7.5% P_2O_5	Apatite mineralization occurs primarily in glimmerite bodies and in a zone, 50-200 m wide, in enveloping fenites (Ulbrich and Gomes, 1981; Born, 1989b; Mariano, 1989b; Gomes et al., 1990).
Anitápolis, Santa Catarina, Brazil	Indicated reserves: 186 Mt; 4% P_2O_5	Apatite-rich calcitic carbonatite (sövite) forms a small plug in the complex, but is also present as dykes and veins (Ulbrich and Gomes, 1981; Woolley, 1987; Gomes et al., 1990).
Tapira, Minas Gerais, Brazil	Proven resources: 114 Mt; 1.2% Nb_2O_5 241 Mt; 8% P_2O_5	A pyroxenite phase is micaceous and rich in apatite and perovskite. A sövite core is rich in pyrochlore and apatite and is surrounded by an outer annulus composed of bebedourite and glimmerite (Woolley, 1987; Mariano, 1989b; Gomes et al., 1990; Eby and Mariano, 1992).

DEPOSIT	PRODUCTION/RESERVES/GRADE	COMMENTS/REFERENCES
Mato Preto, Paraná State, Brazil	Indicated resources: 4.3 Mt; 58% CaF_2	A small body consists of a feldspathic carbonatite breccia and a ferruginous carbonatite with uneconomic REEs, Th, and P. A larger sövite body contains abundant hydrothermal fluorite and pyrite veins (Woolley, 1987; Mariano, 1989b; Gomes et al., 1990).
Palabora, South Africa	Existing reserves in main (PMC) pit: 600 Mt; 7% P_2O_5 286 Mt; 0.69% Cu Apatite concentrate contains 0.5% REOs and total recoverable reserves are estimated at 2.16 Mt REOs. Vermiculite and baddeleyite are also mined.	Vermiculite ore grading 22% has been mined since 1963. Production was about 89 500 t/a. in the 1960s, but has been increased to about 180 000. Very coarse grained, locally pegmatitic phoscorite consists largely of serpentine-magnetite and apatite. Its minerals of economic interest are apatite, copper sulphides, and baddeleyite, as well as magnetite (most has >4 wt.% TiO_2). Banded carbonatite averages 6.5% P_2O_5 and also contains copper sulphides, magnetite, baddeleyite, and uranothorianite. A central carbonatite core has higher copper (1 wt.%), magnetite with lower Ti, and a lower apatite content (average 4.5% P_2O_5). Minor Ni, Au, Pt group metals, Ag, and Se are also recovered from the Cu ores (Palabora Mining Company Limited, Mine Geological and Mineralogical Staff, 1976; Clarke, 1981; De Jager, 1989; Eriksson, 1989; Mariano, 1989b; Verwoerd, 1989; Harben and Bates, 1990b).
Panda Hill (Mbeya), Tanzania	Drill indicated reserves: 113 Mt; 0.3% Nb_2O_5 High grade zone: 3.4 Mt; 0.79% Nb_2O_5	Disseminated pyrochlore-apatite and magnetite are in a sövite plug. The carbonatite has well developed flow structures accentuated by apatite-rich streaks and pyrochlore stringers. In places, pyrochlore is partially replaced by columbite (Bowden, 1985; van Straaten, 1989).
Gakara-Karonge, Burundi	United States Bureau of Mines estimated reserves: 907 t contained REOs. Intermittent mining occurred 1950 to 1981.	A stockwork and REE veins of massive bastnaesite, and lesser monazite, quartz, goethite, and barite, occur in four major zones within the Lake Tanganyika Rift. No associated carbonatite is known (van Wambeke, 1977; Roskill Information Services Limited, 1988; Mariano, 1989a).
Okorusu, Namibia	Drill indicated reserves: 7.9 Mt; 50% CaF_2	Hydrothermal fluorite mineralization occurs in sedimentary rocks, in part metasomatically altered, along the southern rim of the complex. Economic mineralization is a coarse mixture of fluorite and quartz, with minor calcite and apatite, in steeply-dipping fractures and vein-like fracture-filled breccia zones (Gittins, 1966; Kilgore et al., 1986).
Kangankunde Hill, Malawi	United States Bureau of Mines estimated the total monazite reserve contains 269 000 t REOs.	An ankeritic-dolomite carbonatite unit contains an average of 7% monazite. Other REE minerals associated with quartz are hydrothermal. Difficulty in separating monazite from waste rock has prevented the deposit from being exploited (Deans, 1978; Roskill Information Services Limited, 1988; Mariano, 1989a).
Bayan Obo, Inner Mongolia, People's Republic of China	Proven reserves: 37 Mt of REOs; 1 Mt of Nb (avg. grades: 6% REOs; 0.10% Nb)	This is the largest known REE deposit. It consists mainly of bastnaesite, monazite, parisite, xenotime, aeschynite, and allanite, and associated dolomite, fluorite, quartz, calcite, and apatite, in lenticular bodies of magnetite-hematite ore. REE-Nb-iron mineralization is considered to have a carbonatite, mantle-derived origin (Argall, 1980; O'Driscoll, 1988; Drew et al., 1989a, b; 1990; Mariano, 1989a; Philpotts et al., 1989; Zhongxin et al., 1992)
Amba Dongar, India	11.6 Mt; 30% CaF_2	Fluorite occurs principally around the outer margin of a calcitic carbonatite ring dyke as hydrothermal quartz-fluorite veins and replacements of the late stage dolomitic carbonatite plugs (locally also fluorite-bearing). The ore is associated with fenites along the contact between carbonatite and country rocks (Gittins, 1966; Deans, 1978; Mariano, 1989b).

Archean age are known (e.g., Lac Shortt carbonatite in the northwestern Abitibi region of Quebec, which has a U-Pb zircon age of 2691 +5/-3 Ma; A. Joanisse, pers. comm., 1994); however, Proterozoic and, in particular, Mesozoic and younger ages are much more abundant. Veizer et al. (1992) have cautioned that the latter interpretation may be misleading since the temporal distribution of carbonatites could in fact be a function of their preservation. Because the preservation of carbonatites decreases exponentially with increasing age of the crustal segments (i.e. Archean and earliest Proterozoic carbonatites would be eroded or buried by later sedimentation), these carbonatites would not be accounted for in Woolley's compilation, and therefore, the temporal distribution of carbonatites actually involves a combination of orogenic activity and erosional dispersal. Regardless of how the temporal distribution of carbonatites is interpreted, there does not appear to be a correlation between age of carbonatite intrusion and economic potential (Sage, 1986).

Relationships of ore to host rocks

Carbonatites may consist of a number of intrusive phases with different textural and mineralogical characteristics. Early phases typically consist mainly of calcite, do not contain peralkaline pyroxenes or amphiboles, except as overprinting phases, and contain associated apatite+magnetite±pyrochlore mineralization (e.g., Panda Hill and Palabora) (Bowden, 1985; Flohr, 1994). Later phases, which may contain dolomite, ankerite, and siderite, in addition to calcite, are commonly enriched in pyrochlore. At Niobec, the principal host rock for the niobium deposit is coarse grained dolomitic carbonatite, which is surrounded, in part, by barren calcitic carbonatite (Fig. 24-4, 24-5) (Fortin-Bélanger, 1981; Gagnon, 1981; Vallée and Dubuc, 1981). Many very late stage carbonatites contain only trace, or no, Nb mineralization, and are enriched in primary REE-bearing minerals (A.N. Mariano, pers. comm., 1994). This is the case at Niobec, where the core of the dolomitic carbonatite contains a zone rich in REEs (Fig. 24-4).
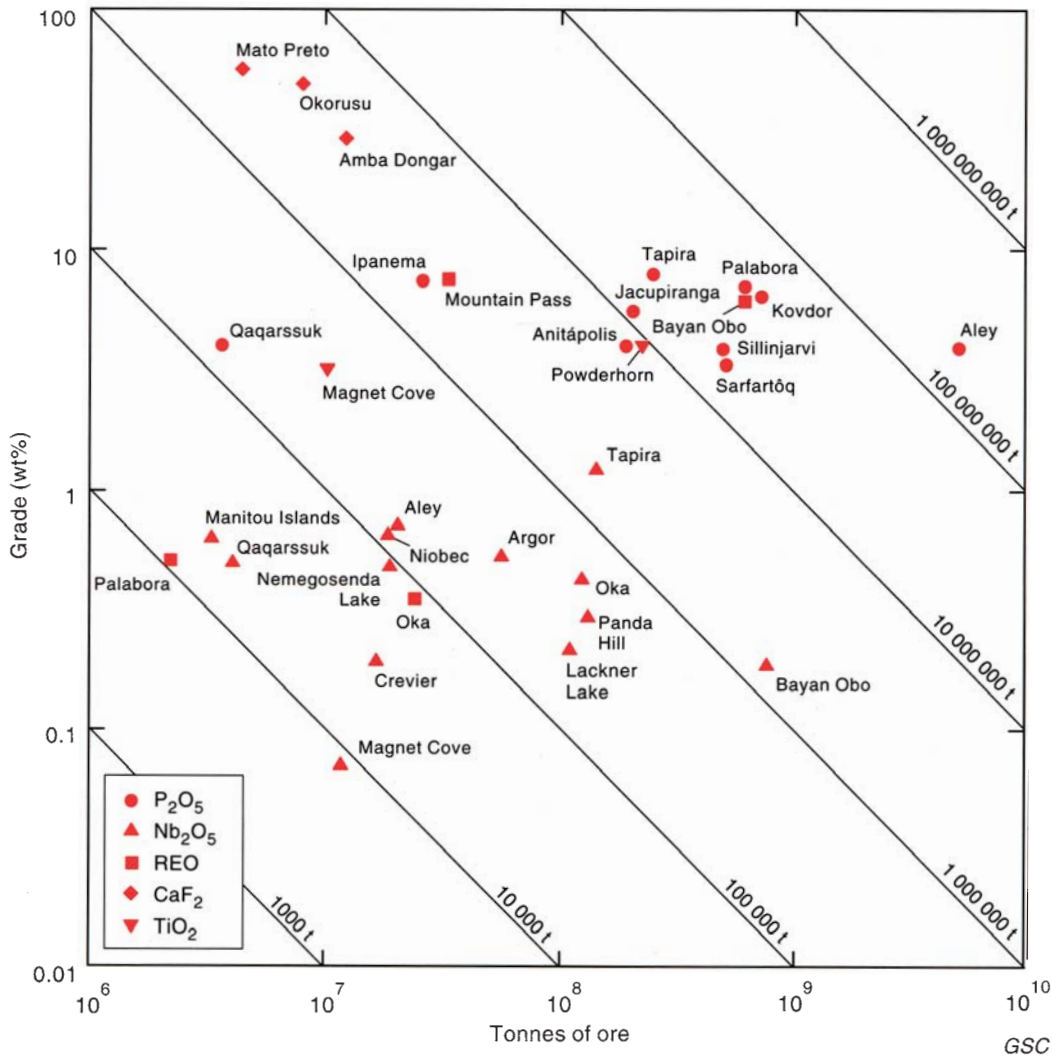

Figure 24-2. Grade-tonnage relationships for carbonatite-hosted and other carbonatite-associated deposits. Data from Tables 24-1 and 24-2.
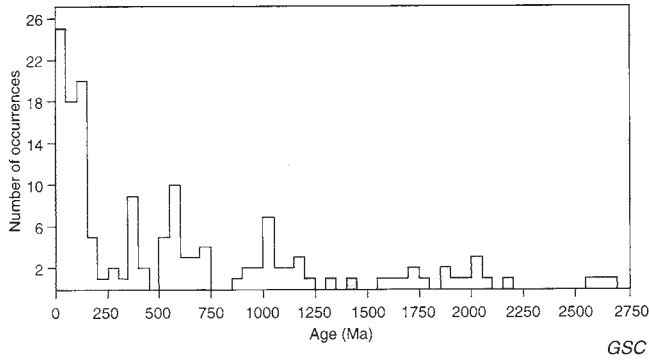
Figure 24-3. Frequency distribution diagram of carbonatite age dates (from Woolley, 1989).

In most complexes, iron-rich (ferro) carbonatites occur in minor quantities as thin brown dykes and veins with chilled margins against, and crosscutting relations to, earlier carbonatites. In some cases, late stage ferrocarbonatite magmas were highly enriched in volatiles (and REEs, F, Ba, U, Th). The ferrocarbonatites and associated minerals deposited by these volatile-rich magmas may replace earlier calcite and dolomite carbonatites (e.g., REE±U mineralization at both Niobec and Sarfartôq), or form dykes and veins in the roof zones of carbonatites (e.g. fluorite veins at Amba Dongar and Mato Preto). At Mountain Pass and Kangankunde Hill, however, bastnaesite, parisite, and monazite appear to have crystallized with calcite, barite, and dolomite as primary igneous minerals in a late stage carbonatite (Mariano, 1989a, b).
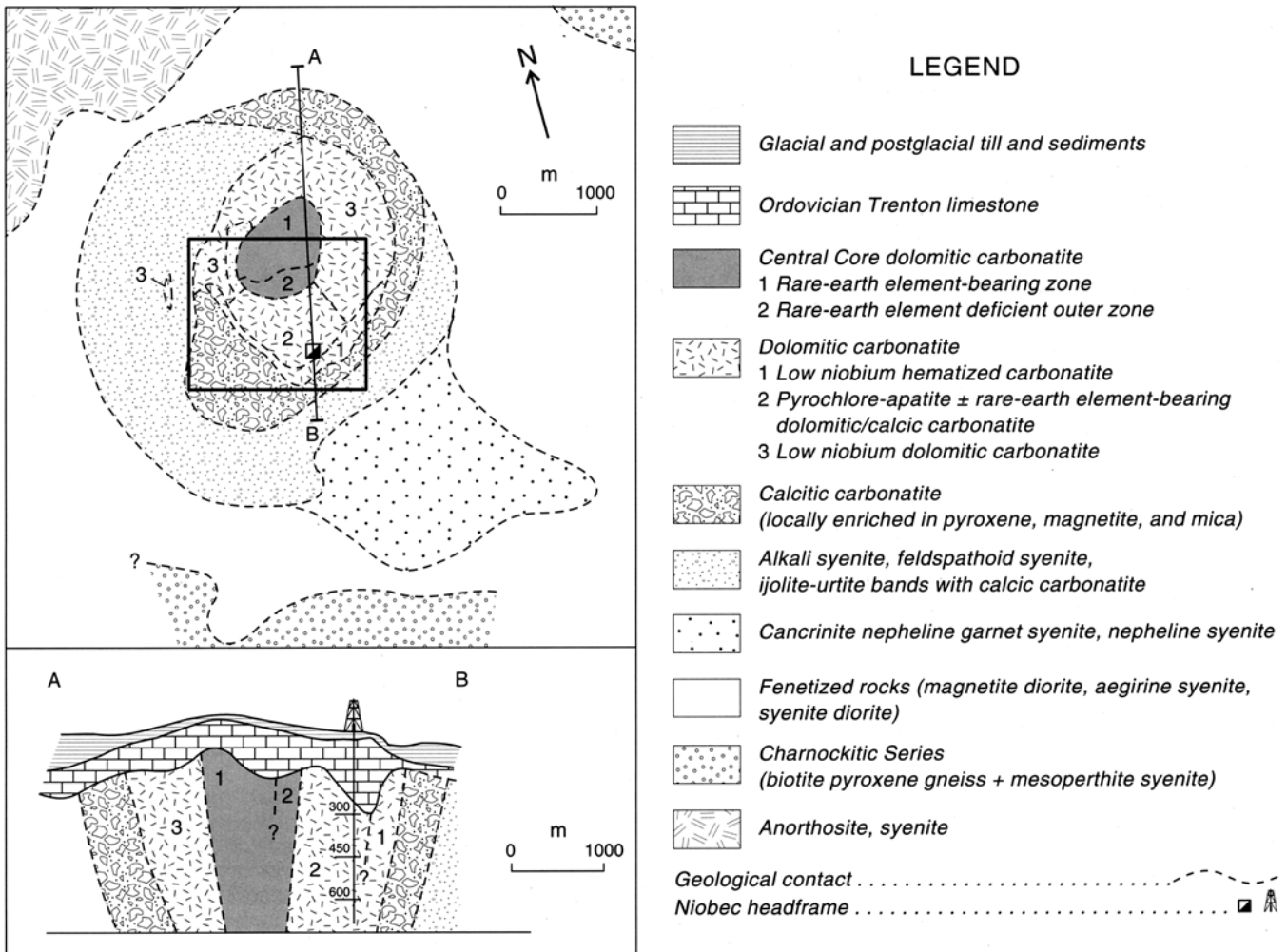

LEGEND

Glacial and postglacial till and sediments

Ordovician Trenton limestone

Central Core dolomitic carbonatite
1 Rare-earth element-bearing zone
2 Rare-earth element deficient outer zone

Dolomitic carbonatite
1 Low niobium hematized carbonatite
2 Pyrochlore-apatite ± rare-earth element-bearing dolomitic/calcic carbonatite
3 Low niobium dolomitic carbonatite

Calcitic carbonatite
(locally enriched in pyroxene, magnetite, and mica)

Alkali syenite, feldspathoid syenite, ijolite-urtite bands with calcic carbonatite

Cancrinite nepheline garnet syenite, nepheline syenite

Fenetized rocks (magnetite diorite, aegirine syenite, syenite diorite)

Charnockitic Series
(biotite pyroxene gneiss + mesoperthite syenite)

Anorthosite, syenite

Geological contact . . . .
Niobec headframe . . . .

Figure 24-4. Subsurface geology of the St. Honoré carbonatite complex below Ordovician Trenton limestone cover, and schematic north-south cross-section A-B (vertical exaggeration = 9) (after Gagnon, 1981; Thivierge et al., 1983). Area of Figure 24-5 is indicated by the bold outline.

Other carbonatite-associated deposits are hosted in a range of felsic to ultramafic alkali silicate plutonic rocks, the most important of which include: 1) the apatite-mica pyroxenite and apatite-forsterite-magnetite phoscorites of Palabora; 2) the perovskite-rich biotite pyroxenites of the Powderhorn Complex (Verwoerd, 1989); and 3) vermiculite deposits at Palabora, contained in hyrothermally altered pyroxenitic phases of ultramafic ring complexes.

Form of deposit

Mineralized carbonatites are found in lava flows and tephra, plugs, cone sheets, dykes, and rare sills, but never in large homogenous plutons (Barker, 1989). Economic mineralization, however, is generally associated with plutonic carbonatitic phases, not with lavas. Magmatic carbonatite deposits generally occur in small (3-5 km) plug-like and crescentric bodies in composite plutons with
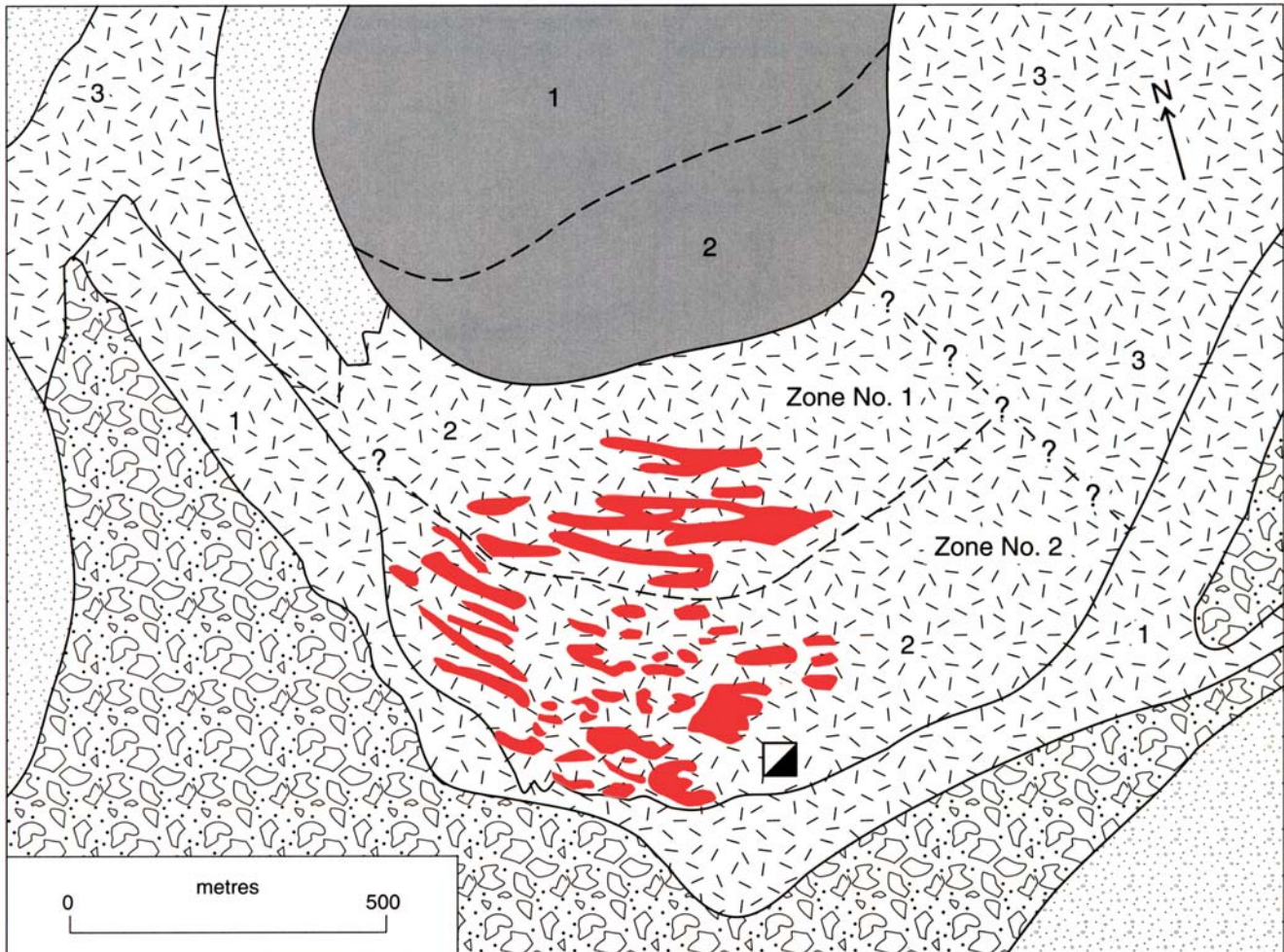

Figure 24-5. Vertical projection to surface of geology and ore lenses (solid red) containing Nb_2O_5 >0.5% from the 300 m and 450 m levels (after Gagnon, 1981). Zone 2 lenses, in the southern portion of the complex, differ from those in Zone 1 in that they: 1) are generally of higher grade; 2) have a more pinch-and-swell shape; 3) are contained in more calcitic carbonatite; 4) contain niobium almost exclusively in sodic pyrochlore, not columbite; 5) lack the paleosurficial ferruginous alteration layer associated with the carbonatite-Trenton contact; and 6) contain abundant biotite and a lower content of magnetite. Legend same as Figure 24-4, except that well-defined geological contacts are shown as solid lines, poorly-defined or gradational contacts are shown as dashed lines, and uncertain contacts are designated by dashed lines with question marks.

coeval silica-undersaturated mafic and/or ultramafic rocks (Notholt, 1980; Dawson and Currie, 1984; Barker, 1989). Mineralization is commonly related to magmatic layering and flow structures within the host rocks, defined by parallelism of xenoliths and by trains of apatite, oxides, and mafic silicates. The deposits are commonly groups of lenses or irregular ore shoots that, in plan, have crescent-shaped or annular forms. In section, these deposits generally have steep dips, parallel to the walls of the intrusive complex, and may extend to great depths. The niobium zones at Niobec are irregular, steeply dipping, east-striking lenses that are 12 to 60 m wide and of variable length. The largest mineralized lens has a maximum length of 305 m (Fig. 24-5). The lenses occur in two distinct zones which collectively occupy an area measuring 610 m x 760 m to a depth of at least 440 m (Gagnon and Gendron, 1981; Scales, 1989).

Metasomatic carbonatite deposits typically have the form of: 1) dykes and dilatant veins of ankerite or dolomite, with or without calcite; 2) thin hydrothermal veins; 3) stockworks; and 4) replacement bodies rich in calcite and dolomite or ankerite (Barker, 1989). Veins and dykes, which locally form radial or annular patterns, commonly crosscut consanguineous fenitized alkaline lithologies and adjacent country rocks (Gomes et al., 1990).

Phoscorites occur as: 1) stocks, stockworks, ring dykes, and linear dykes of widely variable thickness (i.e. from centimetres to hundreds of metres) that form a distinct component of the alkaline-carbonatite complex (e.g. Palabora); and 2) inclusions of various sizes and shapes in carbonatites (Yegorov, 1993).

Mineralogy and ore compositions

Ore minerals of magmatic carbonatite deposits include: 1) pyrochlore; 2) rare-earth fluorocarbonates or phosphates (e.g., bastnaesite, parisite, monazite) which are present as major rock-forming components with barite and strontianite; 3) perovskite-magnetite±loparite±lueshite±pyrochlore (e.g., Oka, Quebec, and Prairie Lake, Ontario – A.N. Mariano, pers. comm., 1994); and 4) apatite. The host rocks are typically calcite or dolomite carbonatite which contain accessory hematite, magnetite, apatite, zircon, allanite, sphene, and biotite. At Niobec, the principal ore minerals are finely disseminated pyrochlore and columbite; associated minerals include apatite, biotite, pyrite, pyrrhotite, zircon, ilmentite, sphalerite, barite, and traces of hydrocarbons (Gagnon, 1981).

The multiple dyke and vein complexes comprising late stage REE-rich metasomatic carbonatite deposits typically show strong enrichment in the light rare-earth elements (LREEs), Ba, and Sr, lack appreciable magnetite and pyrochlore, and contain quartz, sphene, zircon, allanite, sulphides, garnet, (±)perovskite, and fluorite as accessory phases (van Wambeke, 1977; Bowden, 1985; Le Bas, 1987, 1989). If phosphate is abundant in the carbonatite, REEs are typically concentrated in monazite; if phosphate is absent, economic minerals include bastnaesite, parisite, synchysite, ancylite, and britholite (Mariano, 1989a). At Niobec, the REEs occur mainly in bastnaesite and, to a minor extent, in monazite (Sinclair et al., 1992). Fluorite

mineralization, which is largely independent of REE mineralization, occurs in the roof zones of carbonatite complexes (Le Bas, 1987, 1989). The Mato Preto, Okorusu, and Amba Dongar vein deposits each consist of a relatively coarse mixture of fluorite and quartz with minor calcite, apatite, barite, magnetite±galena±pyrite±chalcopyrite±pyrrhotite (Kilgore, 1986; Mariano, 1989b; Gomes et al., 1990). Barite, which is present in nearly all carbonatite complexes, may be magmatic or metasomatic (Mariano, 1989b). Magmatic barite is typically associated with calcite, dolomite, bastnaesite, parisite, and strontianite.

Phoscorite deposits consist of apatite, forsterite olivine (serpentine), and magnetite, with subordinate amounts of calcite, vermiculite, baddeleyite, pyroxene, biotite, and phlogopite (Notholt, 1980).

Alteration

Carbonatites and related intrusions are typically surrounded by alkali metasomatized country rocks, referred to as fenites. Most fenite alteration haloes are characterized by desilicification, addition of ferric (Fe^{3+}) iron, sodium, potassium, and anomalous concentrations of LREEs, large ion lithophile (LIL), and other incompatible elements (Sage, 1991). Proximal to alkali silicate-carbonatite complexes, fenite aureoles are characterized by: 1) pervasive alteration/replacement of pre-existing minerals by alkali feldspars and sodic pyroxenes and amphiboles; 2) recrystallization of quartz and feldspar; and 3) partial recrystallization and incomplete assimilation of country rocks (Gomes et al., 1990). With increased distance from the intrusions, the distribution of fenite alteration is controlled by structural features (i.e., faults and fractures) (Sage, 1991). Although the extent of the fenite surrounding the St. Honoré (Niobec) complex has not been determined, it is characterized by: 1) presence of numerous red or green carbonate veinlets; 2) blue sodic amphiboles that have been altered to aegirine; 3) sericitization of feldspars in the vicinity of carbonate veinlets; and 4) the conversion of oligoclase-andesine to albite (Fortin-Bélanger, 1981).

Both sodic (Na-rich) and potassic (K-rich) fenites can occur around a single alkali silicate-carbonatite complex (e.g., Amba Dongar). Sodic fenites are composed of albite, alkali feldspar, aegirine to aegirine-augite, magnesio-arfvedsonite to eckermannite, and biotite; whereas potassic fenite mineralogy is characterized by orthoclase, microcline, biotite-phlogopite, and iron-titanium oxides (Bowden, 1985). Le Bas (1989) has suggested that fenites are depth zone-related, with potassic fenitization characterizing high level emplacement, and sodic fenitization developing only at deeper levels.

Fenites enveloping carbonatites are distinct from the similar-looking syenitic fenites formed around ijolitic rocks, which consist of much higher temperature minerals (Le Bas, 1989; Morogan, 1994). The potassic fenite aureoles developed around pyroxenites and ijolites are commonly smaller than those around carbonatites (Dawson and Currie, 1984), and are characterized by extensive phlogopitization, feldspathization, and amphibolitization (Bowden, 1985; Gomes et al., 1990).

In addition to fenitization, late stage carbonatitic fluids are responsible for postmagmatic autometasomatic alteration and redistribution of incompatible elements. For example, REEs in magmatic fluorocarbonates may be leached and precipitated, with other minerals, in veins in the country rock (Möller, 1989b). Another common alteration feature produced by late stage fluids is the development of a distinctive biotite-rich rock commonly referred to as biotitite or glimmerite (Sage, 1991). Prominent glimmerite zones occur within the various lithostructural units of the Oka Complex (Gold et al., 1986). Considerable local Nb enrichment along contact zones, fractures, and faults can also be produced by mobilization of Nb by late alkaline fluids (e.g., Sarfartôq; Möller, 1989b). The development of rödberg, a low temperature, iron-rich hematite-dolomite-sövite, formerly mined for iron at the Fen complex in south Norway, has also been ascribed to late autometasomatic processes.

Supergene alteration of biotite and phlogopite leads to the development of economic concentrations of vermiculite (Harben and Bates, 1990b).

DEFINITIVE CHARACTERISITICS

Magmatic carbonatite deposits are igneous rocks which form small, volumetrically limited but integral portions of carbonatite complexes. They are generally contained in small (<3 to 4 km in diameter) rounded plug-like and crescent-shaped bodies or nested cone sheets that intrude larger bodies of felsic to ultramafic alkali silicate rocks (i.e., feldspathoid-bearing nephelinites, phonolites, nepheline syenites, urtite-ijolite-melteigite series, melilite/melilitolite-series rocks) (Barker, 1989; Sage, 1991). Deposits are characterized by: 1) a suite of incompatible rare elements and volatile components (i.e., Sr, Ba, REE(Y), Nb(Ta), P, ±Th) (Möller, 1989b); and 2) distinct mantle-derived isotopic signatures (i.e., ^{87}Sr:^{86}Sr <0.706, $\delta^{13}C$ = -1 to -9‰ PDB; $\delta^{18}O$ = +6 to +12‰ SMOW) (Barker, 1989; Möller, 1989b; Philpotts et al., 1989).

REE-bearing carbonatite deposits are strongly enriched in LREEs. Chondrite-normalized rare-earth patterns are characteristically steep and Eu anomalies are minor or absent (Bowden, 1985; Möller, 1989b).

Different types of mineralization are associated with the various textural and mineralogical varieties of carbonatite that commonly occur in a given complex. Early sövite phases, which generally form the largest carbonatite bodies in most complexes, are usually enriched in apatite and magnetite±pyrochlore (Bowden, 1985; Barker, 1989). Late stage magnesium- and iron-rich carbonatites contain deposits of various commodities including: fluorite, REE-fluorocarbonates, U and Th in silica-rich zones, and barite vein and microvein complexes (Le Bas, 1989).

Those carbonatite-associated deposits that are not hosted in carbonatites may be contained in distinct zones of phoscorite, pyroxenite, and ijolite-urtite that are components of steeply dipping alkaline ring complexes (Notholt, 1979, 1980).

The alkali silicate-carbonatite complexes that host carbonatite-associated deposits are usually surrounded by sodic and/or potassic fenitized aureoles of metasomatically altered rocks (Bowden, 1985; Le Bas, 1987, 1989; Barker, 1989).

GENETIC MODEL

Carbonatite-associated deposits are genetically related to host alkali silicate-carbonatite complexes. There are three competing hypotheses for the formation of carbonatites and related alkalic rocks: 1) carbonatite and alkaline magmas represent two distinct primary magmas; 2) carbonatites form by immiscible separation from silica-undersaturated carbonated nephelinitic magmas after prolonged differentiation at shallow crustal levels; and 3) carbonatites represent residual melts derived by fractional crystallization of a parent carbonated alkaline silicate magma (Barker, 1989; Möller, 1989b; Wyllie, 1989).

In general, the emplacement of carbonatites represents the final intrusive phase of most alkali silicate-carbonatite complexes. According to Barker (1989), the emplacement sequence of a typical complex, from periphery to core (i.e., oldest to youngest) is: nepheline syenite to nepheline-clinopyroxene rocks to carbonatite. Kapustin (1986) listed the sequence as dunite and/or clinopyroxenite to melilite-bearing rocks to nepheline-clinopyroxene rocks, nepheline syenite, and finally carbonatite. Kapustin's sequence is observable at Powderhorn (U.S.A.) and Tapira, Salitre I and II, Serra Negra, and Jacupiranga in Brazil (A.N. Mariano, pers. comm., 1994). The mechanisms controlling magma chemistry and the emplacement sequence are largely unknown; however, there are strong indications of magmatic differentiation in early-formed rock units with a corresponding progressive increase in alkalinity as successive units form (e.g., emplacement sequence at Mountain Pass: shonkinite (with no peralkaline pyriboles) – syenite (with Na-amphibole) – alkali granite – carbonatite bodies, dykes, and veins; Olsen et al., 1954; DeWitt et al., 1987). Although limited radiometric age studies have been performed on the different rock units comprising some South American alkali silicate-carbonatite complexes (i.e., Chiriguelo and Cerro Sarambi, Amamby and Concepción provinces, Paraguay, and Catalão I and II, Goiás Province, Brazil; Eby and Mariano, 1992), the temporal development of rock units, and carbonatite phases comprising worldwide alkali silicate-carbonatite complexes is not well understood.

Fractional crystallization and related differentiation of carbonatite magmas results in the various types of carbonatite deposits. The earliest crystals to precipitate from a carbonate melt are usually strontium-rich calcites that are accompanied by apatite, magnetite, phlogopite, zircon, sulphides (pyrrhotite), olivine, pyrochlore±perovskite cumulates (Le Bas, 1989; Möller, 1989a). The apatite+magnetite+pyrochlore association in magmatic deposits results from early crystallization of apatite which removes P_2O_5 and F from the magma, lowers niobium solubility, and results in the crystallization of pyrochlore (Mariano, 1989b). Rare-earth elements in deposits of apatite+magnetite+pyrochlore typically do not form fluorocarbonate minerals, but instead are incorporated into apatite and calcite. Recent studies of physical properties of carbonatite magmas have shown that carbonatite magmas have very low viscosities (similar to that of water) and heats of fusion, and high thermal diffusivities as compared to the more common silicate magmas (Treiman and Schedl, 1983; Treiman, 1989). Thus crystal settling is rapid, the grain size of cumulate phases is small, and flow systems (convective or other) are rapid and turbulent (Treiman, 1989).

Further fractionation of carbonatite magma can produce dolomitic/magnesiocarbonatites and ferrocarbonatites (beforsites and rauhaugites), and residual F-REE-Sr-Ba-U-Th-rich fluid (Le Bas, 1987, 1989). The late fluids promote partial'replacement of calcite by ankerite or dolomite and form late stage veins (Bowden, 1985; Le Bas, 1987, 1989; Barker, 1989; Möller, 1989a). Mineralization associated with the intrusion of late stage ferrocarbonatites that bear ankerite or ankeritic dolomite, and the introduction of associated end-stage metasomatic volatile phases, include REEs, fluorite, U, and Th, and is in many cases accompanied by silicification (Le Bas, 1987, 1989). Late stage F-enriched volatile carbonatitic phases also concentrate Ba and SO_4^{2-} as incompatible components (Le Bas, 1989). Andersen (1984) has postulated that the hematite contained in rödberg, unlike the iron in more typical carbonatite-associated magnetite-apatite deposits, formed by reactions involving a combination of both deuteric fluids and groundwater convecting in hydrothermal cells set up by the intrusion of the carbonatite and other intrusive phases. The degree to which meteoric fluids in the country rocks hosting other carbonatite-associated deposits have been involved in the formation of metasomatic deposits has not been determined.

Although vein and microvein metasomatic mineralization is usually spatially and temporally associated with late stage carbonatitic phases, in the presence of local structural controls, this mineralization may be distally deposited and direct evidence of a carbonatite association is obscured (e.g., Gakara-Karonge and Bayan Obo) (Mariano, 1989a, b).

Late stage fluids in some cases result in the alteration or remobilization of Nb and REEs in carbonatite-associated deposits. For example, although pyrochlore within the Niobec deposit was magmatic, columbite may have formed by metasomatism of pyrochlore (replacement of calcium in pyrochlore by iron; Gagnon, 1981). In contrast, however, the presence of karstic features at Niobec led Sage (1988b) to suggest that columbite replacement of pyrochlore may have been a supergene phenomenon. Fluid inclusion data obtained from calcite and dolomite within the dolomitic beforsite of the REE-zone at Niobec have provided evidence of postmagmatic hydrothermal activity and confirmed the mobility of REE in aqueous solutions (Heinritzi et al., 1989).

The evidence for either a hydrothermal or magmatic origin for the sulphides (bornite, chalcopyrite, and cubanite) in the Palabora carbonatite, which constitute a unique deposit, remains equivocal (Eriksson, 1989). Also, the origin of many carbonatite-associated phoscorite deposits and their relationship to carbonatites remains unclear (Yegorov, 1993). Nevertheless, whether they result from liquid immiscibility or from crystal accumulation, these rocks, although commonly affected by postmagmatic processes, are of magmatic origin (Yegorov, 1993).

RELATED DEPOSIT TYPES

The ore-forming environment of the giant Olympic Dam Cu-U-Au-Ag-REE deposit in southern Australia (see Type 22) has many similarities with carbonatite-associated deposits, including: 1) location in extensional environments, in late orogenic and anorogenic settings; 2) REE mineralization (i.e., bastnaesite, florencite, monazite, xenotime, and britholite) is associated with extensive hydrothermal alteration and metasomatism; 3) evidence that REE, and possibly Cu mineralization may in part be contributed from alkaline mafic/ultramafic magmas; and 4) apatite and fluorite as principal nonmetallic minerals (Gandhi and Bell, 1990; Oreskes and Einaudi, 1990). However, unlike carbonatite deposits which have a mantle source, the Olympic Dam deposit is thought to be a hydrothermal breccia complex formed in a subvolcanic environment as an integral part of a major crustal melting event triggered by mantle plume activity beneath continental crust (J.P. Johnson, unpub. data, Geological Survey of Canada, Minerals Colloquium, Ottawa, 1994).

The relationship between carbonatite and megacryst-bearing, olivine-rich and micaceous diamondiferous kimberlites (see subtype 25.1) has been in dispute for several decades. Both deposit types are characterized by: 1) the presence of high temperature calcite; 2) mantle isotopic signatures; 3) enrichment of the trace elements Cr, Ni, V, La, Li, Nb, Sr, and Y; and 4) similar morphology (i.e., deep-seated cyclindrical plug-like bodies) (Sage, 1983). Although a close kimberlite-carbonatite association can be observed in certain localities (e.g., Premier mine, South Africa; Barker, 1989), a worldwide relationship cannot be clearly established, and, except for the fact that both deposit types are magmatic and of mantle origin, there is no obvious genetic connection. However, the rare occurrence of diamonds in what were formerly called 'central complex' kimberlites (also known as alnöites/damtjernites/ultramafic lamprophyres), which commonly form part of alkali-silicate carbonatite complexes, is noteworthy (e.g., Île Bizard, Quebec; Alnö, Sweden) (Rock, 1991).

Mineralogical, geochemical, and petrogenetic similarities also exist between carbonatite deposits and peralkaline rock-associated rare metal deposits described in Type 23 of this volume. Most notable of these is the layered ijolitic (nepheline-aegirine-apatite-sphene) rocks of the very large (1327 km^2) Khibiny ultramafic alkaline complex in the Kola Peninsula of Russia, which contains the largest known accumulation of monomineralic apatite rock in the world (Notholt, 1980; Ilyin, 1989; Mariano, 1989a). The relationship between the recently discovered carbonatite/silicocarbonatite stock, located along the eastern periphery of the Khibiny intrusion, and the apatite-bearing silica-undersaturated rocks remains unclear (Kogarko, 1987; Ilyin, 1989).

Weathering of carbonatite-associated deposits, may, under favourable conditions, produce: residual apatite, pyrochlore, and anatase deposits; supergene REE deposits; and, as previously noted, supergene vermiculite from the conversion of phlogopite/biotite (for further details, see subtype 4.3, "Residual carbonatite-associated deposits").

EXPLORATION GUIDES

Exploration guidelines for carbonatite-associated deposits include the following:

Broad scale features

1. Individual carbonatites usually contain more than one mineral of potential economic interest. Therefore, each carbonatite should be considered as a multicommodity exploration target and should be thoroughly evaluated for Nb, REEs, U, P, and fluorite (Sage, 1986).

2. Carbonatites occur as irregular, centrally located, rounded masses or continuous to semicontinuous concentric rings and dykes, commonly within more extensive alkali-silicate complexes. These complexes themselves are notable for their relatively small size (surface area usually does not exceed 50 km^2), steeply dipping or vertical walls, and that most are of undetermined depth (Notholt, 1980). The alkaline rocks have variable compositions, felsic members include nepheline-syenites, mafic members, ijolites, ultramafic peridotites, mica pyroxenites, and jacupirangites (Notholt, 1980; Ulbrich and Gomes, 1981; Gomes et al., 1990).

3. Extrusive pyroclastic carbonatites can be laterally extensive. For example, the Mount Grace extrusive carbonatite in the Omineca Belt of the Canadian Cordilleran averages 2-5 m in thickness and has been traced and extrapolated for at least 100 km along the northwestern margin of the Frenchman Cap Dome (Pell, 1987; Pell and Höy, 1989).

4. Because carbonatite deposits are commonly contained in plug-like intrusive bodies or ring structures, many are associated with annular topographic features. In the absence of appreciable overburden, the characteristic circular patterns are still readily discernable on aerial photographs, even in the case of those having very subdued relief (Gold et al., 1967).

5. Because deposits associated with carbonatitic rocks are usually contained in specific lithologies, definition of igneous contacts among the various intrusive phases is an important exploration tool.

6. The presence of the characteristic carbonatite fenite facies may prove useful as a general guide in the detection of carbonatites and associated mineralization. Fenitization is generally characterized by desilicification; however, in certain REE-rich magnesiocarbonatites and ferrocarbonatites (e.g., Mountain Pass and Kangankunde Hill), mineralization is associated with enrichment in silica (Woolley and Kempe, 1989).

7. Both magmatic (e.g., Mountain Pass, U.S.A.) and metasomatic (e.g., Wigu Hill, Tanzania; Itapirapuá, Brazil; Adrounedj, Mali) REE-rich carbonatite deposits are low in P, Ti, Zr, and Nb relative to earlier carbonatite rock units (A.N. Mariano, Geological Survey of Canada, Logan Club presentation, February 24, 1994).

Geochemical approaches

Elements associated with carbonatite-associated deposits (i.e., Nb±Ta, Ba, Sr, U, Th, LREEs, Ti, F, and P) are usually contained in distinct, chemically resistant minerals (e.g., pyrochlore, monazite, perovskite) that can be detected through regional studies of heavy mineral suites from unconsolidated sediments. In western Greenland, for example, multi-element analysis of the fine fraction of stream sediments and U, F, and conductivity determinations of waters, collected at a very low density of 1 sample/30 km^2, successfully delineated the Sarfartôq and Qaqarssuk carbonatites (Steenfelt, 1991). A reconnaissance scale (1 sample /10 km^2) stream sediment survey completed in the vicinity of the Magnet Cove alkali silicate-carbonatite complex determined that REEs, Ti, and F in the 0.075 mm fraction were the best indicators for the presence of carbonatite (Sadeghi and Steele, 1989).

Geophysical approaches

Magnetic, radiometric, and gravimetric techniques can all be applied to carbonatite deposits. Because carbonatites commonly contain appreciable magnetite, they generally have a higher magnetic susceptibility than their host rocks, and appear on aeromagnetic maps as small-diameter (about 5 km) high-intensity, circular to elliptical positive magnetic anomalies (Gold et al., 1967; Sage, 1986). Associated magnetite-bearing alkalic rock complexes are commonly characterized by less intense, larger, circular to elliptical anomalies (Sage, 1986). However, because strong alkalinity associated with fenitization stabilizes iron in the ferric state due to the "alkali ferric-iron effect" (Carmichael and Nicholls, 1967), magnetite usually does not form in the fenite aureole, and these rocks have a negative or low magnetic response. The magnetite-poor fenites and carbonatitic phases of the magmatic Fen and Mountain Pass deposits display negative aeromagnetic responses (Saether, 1958; A.N. Mariano, pers. comm., 1994). Metasomatic REE-bearing carbonatite deposits may or may not have positive magnetic expression, depending on the presence of appreciable magnetite (A.N. Mariano, Geological Survey of Canada, Logan Club presentation, February 24, 1994).

Exposed carbonatites that contain radioactive minerals (e.g. thorian pyrochlore, monazite) have positive radiometric responses. The lack of penetration of the conventionally measured radiation (K, U, Th) detracts from the usefulness of radiometric techniques in areas of thick soil development or glacial overburden (Gold et al., 1967). Reconnaissance radiometric surveys in Canada (5 km line spacing, 120 m ground clearance survey over the 0.4 km^2 Allan Lake carbonatite) and Greenland (3 km line spacing, 100 m ground clearance over the 10 km^2 Sarfartôq and 15 km^2 Qaqarssuk carbonatites) successfully detected the carbonatites or their associated dispersion trains (Steenfelt, 1987, 1991; Ford et al., 1988).

The location of carbonatite deposits in regionally extensive fault zones, rift valleys, and crustal warps is fortuitous as these large scale structural features appear as pronounced linear features on regional gravity anomaly maps. At the deposit or intrusive complex scale, if the density contrast between country rocks and the lithologies comprising the alkaline-carbonatite complexes is sufficient, deep-rooted carbonatite bodies will be characterized by steep, high gradient gravity anomalies.

Case studies of the application of integrated exploration techniques to Canadian carbonatites have been documented for Niobec (Vallée and Dubuc, 1970), Allen Lake (Ford et al., 1988), and Oka (Gold et al., 1967).

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Authors' addresses

T.C. Birkett
SOQUEM
2600, boul. Laurier
Tour Belle Cour, bureau 2500
Sainte-Foy, Quebec
G1V 4M6

D.G. Richardson
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8