23. PERALKALINE ROCK-ASSOCIATED RARE METALS

23. PERALKALINE ROCK-ASSOCIATED RARE METALS

D.G. Richardson and T.C. Birkett

INTRODUCTION

Commodities associated with peralkaline rocks are diverse and include a variety of metals and industrial rocks and minerals. The elements of economic interest in peralkaline rock-associated rare metal deposits include zirconium (Zr), niobium (Nb), beryllium (Be), uranium (U), thorium (Th), tantalum (Ta), rare-earth elements (REEs), yttrium (Y), and gallium (Ga). Commonly several elements are concentrated in a deposit.

Peralkaline rocks are characterized by a molar excess of alkali elements (Na_2O+K_2O) over aluminum (Al_2O_3). Mineralogically, this chemical distinction is commonly manifested in the presence of alkali amphiboles and pyroxenes. Aluminous minerals such as topaz and biotite, which are more typically associated with peraluminous rocks (i.e. molar $CaO+K_2O+Na_2O>Al_2O_3$), are generally absent. Peralkaline rocks span the range of silica saturation, from granites through syenites to feldspathoid-bearing undersaturated rocks. Deposits of rare metals in peralkaline rocks occur in all rock types without regard for silica activity. Silica-saturated to silica-undersaturated rocks concentrate similar suites of elements, although some of the silica-undersaturated, carbonatite-associated rocks of the Kola Peninsula also contain large deposits of apatite.

Richardson, D.G. and Birkett, T.C.
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The mineralizing processes within peralkaline igneous rocks can be subdivided conceptually into magmatic and metasomatic end members. In nature, however, these systems commonly pass without interruption from magmatic to postmagmatic (hydrothermal) conditions. Three Canadian examples illustrate the behaviour of peralkaline systems. The Strange Lake deposit, Quebec-Labrador, and the Mann #1 occurrence, Labrador can be described as end member magmatic deposits, whereas the Thor Lake deposits, Northwest Territories, cross the magmatic-metasomatic transition. The locations of these deposits are shown on Figure 23-1.

Important foreign examples of deposits associated with peralkaline rocks include the Zr-Y deposits of the Ilimaussaq complex in southwestern Greenland, the giant apatite, Nb and Zr deposits of the Khibiny and Lovozero complexes in the Kola Peninsula of Russia, the Y-Zr-REE Brockman deposit, Western Australia, the Kvanefjeld and Motzfeldt Centre deposits in southern Greenland, deposits in apogranites in Russia, and numerous deposits in Saudi Arabia.

The Kipawa deposit (Quebec, Fig. 23-1) is a small Y-Zr deposit in a highly deformed and partly metasomatized alkaline complex which includes peralkaline granites, as well as carbonate rocks of indeterminate origin. Intense deformation and high grade metamorphism have obscured the origin of the mineralization.

In terms of end members, magmatic deposits consist of identifiable igneous units; the principal rare metal-bearing minerals are typically disseminated throughout the ore-forming unit and represent essential constituents that crystallized with their host rocks. Hydrothermal alteration associated with the deposits, if present, is generally late deuteric and local in nature; characteristically there are no extensive zones of alteration surrounding the deposits.

Metasomatic deposits occur in or near peralkaline igneous rocks, and are superimposed on pre-existing rocks. The deposits are related to the cooling and fluid release of intrusions; hydrothermal alteration may be extensive.

IMPORTANCE

Peralkaline rocks contain large resources of rare metals, including Nb, Ta, Be, Zr, Y, and REEs. These resources are generally undeveloped, except in Russia where about 2300 t of Nb_2O_5 are produced annually from the mining of loparite in the Lovozero complex, Kola Peninsula (I.G. Argamakov, pers. comm., 1992). In comparison, the equivalent of about 20 000 t of Nb_2O_5 was produced in market-economy countries in 1991 (Cunningham, 1991).

During the period 1957 to 1964, the Bokan Mountain deposit in Alaska produced a small amount of uranium. No significant production of rare metals has taken place from deposits of this class in Canada, although deposits such as Strange Lake and Thor Lake represent important potential sources of Be, Y, Nb, Ta, and Zr. Related deposits of fluorite in, and surrounding, peralkaline granites in Newfoundland have been a significant source of fluorite production in Canada (3.43 Mt of 70-95% CaF_2 concentrate from 1933 to 1978; Collins and Strong, 1985).

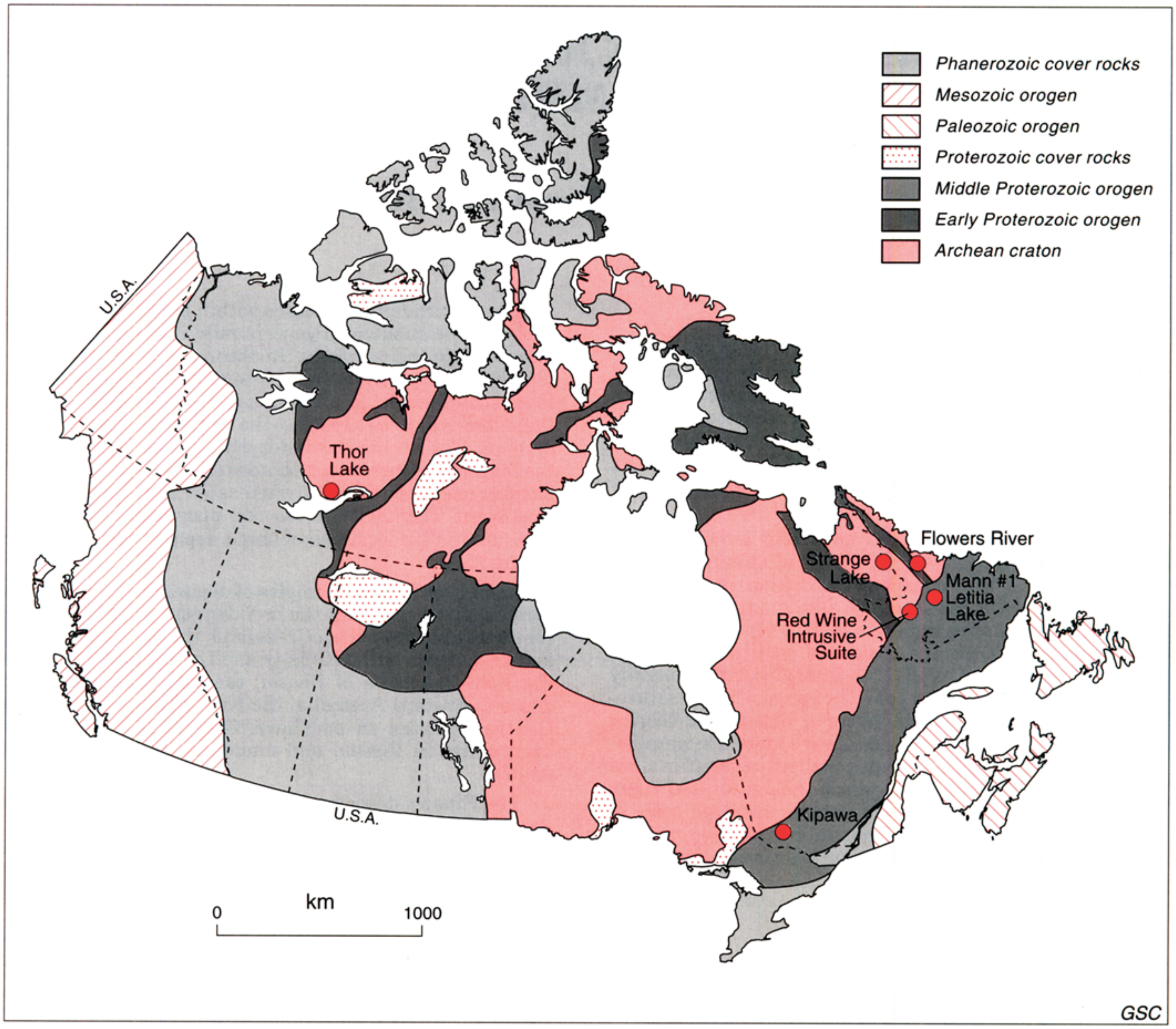

Figure 23-1. Locations of selected Canadian peralkaline rock-associated rare metal deposits/occurrences discussed in the text.

SIZE AND GRADE OF DEPOSITS

Peralkaline rock-associated rare metal deposits range widely in size, from less than one million tonnes to hundreds of millions of tonnes. Grades of Nb, Ta, Be, Y, and REEs are generally less than 1%; Zr typically ranges from 1 to 5%. The sizes and grades of Canadian peralkaline rock-associated rare metal deposits and selected other deposits worldwide are listed in Tables 23-1 and 23-2, respectively.

Grade-tonnage relationships of peralkaline rock-associated rare metal deposits are shown in Figure 23-2.

GEOLOGICAL FEATURES

Geological setting

Magmatic and metasomatic rare metal deposits generally occur within specific phases of peralkaline complexes. Drysdall et al. (1984), Miller (1989), and Pollard (1989a, b) have all noted that in deeper level environments, rare metal deposits associated with peralkaline rocks are commonly most closely associated with small satellite phases of the batholiths (e.g., Ghurayyah, Saudi Arabia); in some cases they occur within relatively fine grained marginal facies varieties of large plutons (e.g., Jabal Tawlah, Saudi Arabia).

Table 23-1. Production/reserves of selected Canadian peralkaline rare metal deposits/occurrences.

DEPOSIT	PRODUCTION/RESERVES/GRADE	COMMENTS/REFERENCES
Flowers River Igneous Suite, Labrador Lat. 55°35′ N Long. 61°05′ W	None	0.05 to 0.24% Y_2O_3 and 0.67 to 2.84% ZrO_2 occur in peralkaline aphyric quartz-poor lithic ash-flow tuffs and breccias of the Nuiklavik volcanics (Miller, 1993, 1994).
Mann # 1 Showing, Letitia Lake Group, Labrador Lat. 54°14′ N Long. 62°25′ W	1.8 Mt; 0.35-0.40 BeO, 0.24% Nb_2O_5	Volcanic-subvolcanic complex containing several Be and Nb occurrences. At Mann #1, beryllium minerals include barylite and eudidymite; niobium minerals are niobophyllite and pyrochlore. Limited drilling indicates irregular mineralization is contained in a lenticular oversaturated peralkaline body (2.0 km by 0.5 km) to a vertical depth of 60 m (Evans and Dujardin, 1961; Miller, 1987, 1988)
Red Wine Intrusive Suite, Labrador Lat. 54°05′ N Long. 62°35′ W	None; however, disseminated REE mineralization is reported in eudialyte near the boundaries of the complex	Eudialyte occurs within high-level, silica-undersaturated peralkaline phases of the North and South Red Wine plutons (Currie, 1976; Curtis and Currie, 1981; Hill and Miller, 1991).
Strange Lake/ Lac Brisson peralkaline complex Labrador-Quebec Lat. 56°18′ N Long. 62°05′ W	Open pit mineable reserves: 52 Mt; 2.93%ZrO_2, 0.31% Y_2O_3, 0.38% Nb_2O_5, 0.54% REEs, 0.08% BeO High grade zone within reserve (tonnage not published to date) contains 3.25% ZrO_2, 0.66% Y_2O_3, 0.56% Nb_2O_5	Highest grade mineralization occurs in a later stock and associated zoned pegmatite-aplite lens situated in the central part of a Middle Proterozoic arfvedsonite-aegirine peralkaline granite (Miller, 1985, 1986, 1990; Zajac et al., 1984).
Kipawa syenite gneiss complex, Quebec Lat. 46°48′ N Long. 78°30′ W	No tonnage reported but grades of $\geq$ 0.1% Y_2O_3, 0.5-1.2% ZrO_2 occur in a continuous zone 1300 m long and 30 m to 100 m wide	Mineralized zone consists of three higher grade, crudely defined subzones, termed the eudialyte, mosandrite, and britholite subzones. These subzones appear to be conformable with lithological contacts in the alkalic complex (Allan, 1990, 1992). Textural relations demonstrate that amphibolite-grade metamorphism, deformation, and possibly emplacement of an igneous alkaline protolith were roughly coeval (Currie and van Breemen, 1994).
Thor Lake, Northwest Territories Lat. 62°06′ N Long. 112°35′ W	North T- zone: 0.46 Mt; 1.11% BeO, 0.17% Y_2O_3, 0.58% Nb_2O_5 and 0.51 Mt; 0.28% $(REE)_2O_3$ 200 000 t of polylithionite South T-zone: 1.13 Mt; 0.62% BeO, 0.1% Y_2O_3, 0.2% $(REE)_2O_3$, 0.46% Nb_2O_5 Lake zone: 64 Mt; 0.04% Ta_2O_5, 0.57% Nb_2O_5, 1.99% $(REE)_2O_3$, 4.73% ZrO_2	The T-zone deposits are greisenized/metasomatized deposits hosted by oversaturated peralkaline members of the Blatchford Lake Intrusive Complex. The Lake zone deposit represents mineralization associated with a large metasomatized/altered breccia zone (Černý and Trueman, 1985; Highwood Resources, Limited Annual Report 1987; Pedersen and LeCouteur, 1990).

Table 23-2. Production/reserves of selected foreign peralkaline rare metal deposits/occurrences.

DEPOSIT	PRODUCTION/RESERVES/GRADE	COMMENTS/REFERENCES
Thabayadiotsa, Pilanesberg, South Africa	Estimated reserves: 13.5 Mt; 0.7% $(REE)_2O_3$ + ThO_2	The Pilanesberg alkaline complex consists of volcanic rocks intruded by a sequence of green and white foyaites, red syenite, and tinguaite disposed in concentric rings around a central core of red foyaite. Disseminations, irregular veinlets and sheet-like subzones rich in britholite occur on or near the contact of tinguaite with green trachytoidal foyaite (Lurie, 1986).
Brockman, Western Australia	Indicated resources: 8.97 Mt; 1.027% ZrO_2, 0.116% Y_2O_3, 0.437% Nb_2O_5, 0.036% Ta_2O_5, 0.038% HfO_2, 0.01% Ga, 0.105% $(REE)_2O_3$	Extremely fine grained minerals (< 20 micrometres) containing Zr, Hf, Y, and Ga in an ash-flow tuff (Niobium Tuff). Bastnaesite (± parisite and synchysite) and bertrandite occur in late-stage calcite veins. Mineralization is thought to be the result of alteration and remobilization of magmatic precursor minerals such as columbite and zircon by F-rich deuteric solutions that were retained in the tuff unit. Silicification and muscovitization are associated with this alteration (Industrial Minerals, February 1990; Ramsden et al., 1993).
Pocos de Caldas Alkaline Complex, Osamu Utsumi mine, Brazil	Reasonably assured reserves: 25.7 Mt; 0.0847% U_3O_8 Estimated (inferred) ores: 22.7 Mt; 0.11% MoO_3 21.3 Mt; 0.81% ZrO_2	Reserves, delineated to a depth of 370 m, are contained in a zone 1240 m long by 440 m wide, in the south-central portion of the largest known peralkaline complex in Brazil (1000 km^2). Zr-, Mo-, and U-bearing minerals (pitchblende, uraninite, coffinite, phosphuranylite, and uranothorianite) are disseminated in tuffaceous phonolites and foyaites. Uranium occurs mainly in refractory minerals, especially zircon. Genetically, mineralization is closely related to postmagmatic hydrothermal activity. Associated alteration products include clay (kaolinite and halloysite), sericite, pyrite, and fluorite (Loureiro and Dos Santos, 1988).
Pajarito Mountain, Otero County, New Mexico, U.S.A.	Known resources: 2.4 Mt; 0.18% Y_2O_3, 1.2% ZrO_2	Eudialyte contained in Proterozoic peralkaline riebeckite granite-quartz syenite complex (Mining Engineering, 1989; Mariano, 1989).
Bokan Mountain (Kendrick Bay), Alaska, U.S.A.	Tonnage mined from the Ross-Adams deposit: 89 000 t; 1% U_3O_8, 3% ThO_2	Thorium and REE-rich rock containing uranothorite, uraninite, and generally < 2% sulphides, is associated with a Late Jurassic peralkaline granite ring-dyke complex. Wall rock alteration within and adjacent to orebodies consists of pervasive hydrothermal albite and lesser amounts of chlorite, fluorite, calcite, quartz, sericite, and tourmaline. Specular hematite is present in the outer-distal parts of the ore zone. The pod-like Ross-Adams deposit appears to have formed during regional faulting synchronous with magma crystallization and subsequent hydrothermal events (Thompson, 1988).
Lovozero complex, Russia	Tonnage figures not published	Unique 650 km^2 (surface area) layered funnel (lopolithic) shaped multiphase intrusive massif of peralkaline composition with a determined depth of 6-8 km. Identified intrusive phases include: Phase I - pegmatoid poikilitic and porphyritic nepheline and hydrosodalite syenites; Phase II - loparite-bearing lujavrite-foyaite-urtite; Phase III - eudialyte lujavrites and murmanite (lovozerite) lujavrites; Phase IV - veins and dykes of porphyritic murmanite-bearing lujavrite.
Phase II rocks: Stratified loparite-bearing lujavrite-foyaite-urtite series	Reserves are very large, on the order of billions of tonnes; 0.30% Nb_2O_5, 0.8-1.5% $(REE)_2O_3$	Loparite-bearing (Phase II) rocks comprise 75% of the volume (1650 m thickness) of the massif. They consist of numerous (>203), persistent, comparatively thin, rhythmically alternating layers which in turn have been subdivided into 65 units, all of which dip gently (8-16°) towards the centre of the massif. Economic concentrations of loparite are generally found in the basal portion (1-2 m) of each of the 65 units; however, significant concentrations can be found as thin (0.4-0.5 m) layers in the upper parts of the units. With depth there is a marked increase in the number and thickness of ore horizons (i.e. 3.7 m) and grade (Vlasov, 1966; Ginzburg and Fel'dman, 1977; Kogarko, 1987).
Phase III rocks: Eudialyte lujavrites, murmanite lovozerite lujavrites	Eudialyte lujavrites: 3.45% $(Zr,Hf)O_2$, 0.28% $(Nb,Ta)_2O_5$, 0.30 $(REE)_2O_3$ Eudialyte-rich zones: 1.37% TiO_2, 6.26-8.68% $(Zr, Hf)O_2$, 0.39-0.93% $(Nb,Ta)_2O_5$, 1.01-1.68% $(REE)_2O_3$	Rhythmically layered eudialyte-bearing lujavrite sill-like bodies, (150 to 500 m thick) with steep sided/vertical contacts, are contained within Phase II rocks. The lenticular, almost monomineralic, eudialyte-rich zones are nest-like, and range in thickness from 1 to 75 m in the basal portion of the eudialyte-bearing lujavrites. The ore horizons are made up of 50-80% (modal) euhedral eudialyte crystals (Vlasov, 1966; Kogarko, 1987, 1990).
	Lovozerite lujavrites; 1.7-2.4% ZrO_2, 0.17-0.33% $(Nb,Ta)_2O_5$, 0.14-0.39% $(REE)_2O_3$	Porphyritic lovozerite lujavrites occur in a 1 km^2 area (Vlasov, 1968).

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DEPOSIT	PRODUCTION/RESERVES/GRADE	COMMENTS/REFERENCES
Midyan region, northwestern Saudi Arabia		
Ghurayyah	440 Mt; 8.6% Zr (zircon), 2.2% Nb (columbite-tantalite-pyrochlore), 0.13% Y (synchysite)	Disseminated Nb, Ta, Sn, Y, Th, U, and Zr minerals contained in a 0.9 km in diameter peralkaline microgranite with steeply dipping contacts that has intruded metavolcanic and metasedimentary rocks. Wall rocks show little alteration (Drysdall et al., 1984; Jackson, 1986).
Jabal Tawlah	Diamond drill indicated reserves to a depth of 65 m: 6.4 Mt; 0.34% Nb, 0.52% Y, 3.73% Zr	Disseminated Nb-Ta (columbite), Y-HREE (gagarinite, fergusonite, xenotime, and yttrium fluorite), Th (thorite), and Zr (zircon) contained in a composite sill up to 80 m thick with a strike length of 320 m. Wall rocks are in places silicified, feldspathized, and mineralized but elsewhere are apparently unaltered (Drysdall et al., 1984; Drysdall and Douch, 1986)
Hijaz region, central Saudi Arabia		
Jabal Sa'id	Potential reserves: 58 Mt; 0.33% Y, 0.108% Nb, 0.104% Ce, >1.9% Zr	Disseminated Nb, Ta, Sn, REE, Y, Th, U, and Zr minerals (zircon, thorite, bastnaesite, synchysite-(Y), monazite, thorian uraninite, pyrochlore) concentrated in the apical portion of a prominently layered, 150 m thick, aplite-pegmatite zone that extends for approximately 2.4 km along the contact between altered peralkaline microgranite and metavolcanic country rocks (Drysdall et al., 1984; Hackett, 1986; Jackson, 1986).
Umm al Birak	Reserve potential to 150 m below surface: High grade zone only - 6.6 Mt; 0.16% Nb, 0.51% Zr	Disseminated Nb, Ta, Sn, W, REE, Y, Th, and Zr minerals (zircon, monazite, bastnaesite, pyrochlore, scheelite, thorite) contained in a porphyritic, albite-microcline alkali microgranite stock (measuring 700 m by 400 m) and minor veins and pegmatites that are intrusive into metavolcanic rocks (Drysdall et al., 1984; Jackson, 1986).
Jabal Hamra	Reserve potential to 100 m below surface: 18 Mt; 0.17% Nb, 0.34% Ce, 0.16% Y, 1.33% Zr	Disseminated Nb, Ta, Sn, REE, Y, Th, and Zr minerals (monazite, bastnaesite, zircon, uraninite) contained in a 300 m long by 100 m wide, cresent-shaped stock of pervasively silicified and cataclasized silexite (rock composed essentially of quartz + hematite + alkali feldspar) (Drysdall et al., 1984; Jackson and Douch,1986).
Greenland alkaline complexes		
Ilimaussaq intrusion:		Ellipsoidal, 8 km by 14 km, approximately 1000 m thick differentiated peralkaline intrusion of nepheline syenite, naujaite, and lujavrite. In the southern part of the intrusion, stratified red, white, and black kakortokites occur among the lujavrites (these have a maximum thickness of 400 m in an area covering 35 km^2).
Kringlerne	Measured mineral resource: 14.5 Mt; 6% ZrO_2 19.5 Mt; 0.2% Y_2O_3 6.8 Mt; 3.0% $(REE)_2O_3$ 27.9 Mt; 0.2% Nb_2O_5	Estimation of the resources contained only in the eudialyte-rich (extremely high grade) red kakortokite igneous cumulates in the Kangerluarsuk fiord area of the complex (Sørensen, 1992; Kalvig and Appel, 1994).
Agpat	Estimated resources: 30 Mt; 1% ZrO_2, 0.1% Y_2O_3	Resource estimate based on examination by Highwood Resources of various types of lujavrite found at three sites adjacent to the Tunugdliarfik fiord (Sørensen, 1992).
Kvanefjeld	Reasonably assured resources to a depth of 200 m: 794 Mt; 0.00034% U 110 Mt; 0.36% Zr 73 Mt; 0.07% Nb 141 Mt; 0.8% REEs 131 Mt; 0.08% Y	The Kvanefjeld area (3 km^2 in size) on the northwestern margin of the Ilimaussaq intrusion has high concentrations of U, Th, Y (± REEs) in sheared and metasomatized sheets and masses of medium- to coarse-grained lujavrite, near the contact with overlying sheared volcanics/gabbros. Radioactive minerals are steenstrupine (a uranium-rich variety of monazite) and thorite. Zirconium appears to be enriched in the lower lujavrite levels. Niobium minerals, related to either a late water/volatile-rich magma or hydrothermal solutions, occur in veins and sheared masses located near the roof of the intrusion or along sheared xenolith contacts (Sørensen et al., 1974; Kunzendorf et al., 1982).
Igaliko Nepheline Syenite:		
Motzfeldt Centre	Indicated mineable resources in microsyenite: 80 Mt; 0.4-1.0% Nb_2O_5, 0.01-0.03% Ta_2O_5 and 1-2% ZrO_2 Additional resources in zones of altered microsyenite: 50 Mt; 0.03-0.1% Ta_2O_5	Peralkaline sheets of microsyenite, pegmatites, and hydrothermal alteration zones (characterized by the presence of hematitic alteration) are enriched in U-Nb-Ta-Zr-REEs contained in fine grained pyrochlore and subordinate amounts of columbite (Tukiainen, 1988; Sørensen, 1992; Kalvig and Appel, 1994).

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Peralkaline-rock associated REE deposits generally occur in cratonic, anorogenic settings. As noted by Pollard (1989a), the localization of individual igneous complexes in anorogenic regions is frequently controlled by regional scale fault systems, and the complexes are in many cases characterized by the presence of bimodal (basaltic and rhyolitic) magmatism. In shallow level environments, these plutons are commonly controlled by ring fractures, and intrude contemporaneous volcanic rocks within shallow level ring complexes (Pollard, 1989a). In some instances, both peralkaline and peraluminous magmas are spatially related (e.g. Arabian and Benin-Nigerian shields).

Form of deposits

Magmatic deposits assume the form of the host intrusive body. They may be irregular, following the contacts with country rocks or earlier intruded units, but can also be tabular, such as the rhythmically-layered kakortokite unit of the Illimaussaq complex.

Metasomatic rare metal deposits range in form from veins and stockworks to irregular replacement zones in which minerals are typically fine grained and widely disseminated, usually localized within the upper contact zones of small, steep-sided plutons, or within dome-shaped protuberances or cupolas (e.g., Jabal Sa'id, Saudi Arabia) or elongate, ridge-like structures on the upper surface of larger plutons (e.g., REE-rich zone, Motzfeldt Centre deposit, Igaliko complex, Greenland).

Subvolcanic and volcanic analogues of these intrusive deposits are also recognized. Jackson (1986) and Miller (1989) have suggested that some Nb-Zr-REE-bearing pegmatitic-aplite dykes and veins in Labrador and Saudi Arabia represent mineralization associated with vented roof zones of peralkaline intrusive bodies. In near surface environments, emplacement of late intrusive phases of magmatic complexes is in many cases controlled by ring fractures. Commonly, fine grained disseminated rare-metal mineralization occurs in contemporaneous volcanic rocks within ring complexes [e.g., Nb-Zr mineralization associated with peralkaline granites of the Nigerian ring complexes (Bowden, 1985; Bowden et al., 1987); REE+Th mineralization at the Thabayadiotsa deposit, Pilanesberg, South Africa (Lurie, 1986); and the Y-REE occurrences in the Flowers River Igneous Suite (Miller, 1993, 1994)].

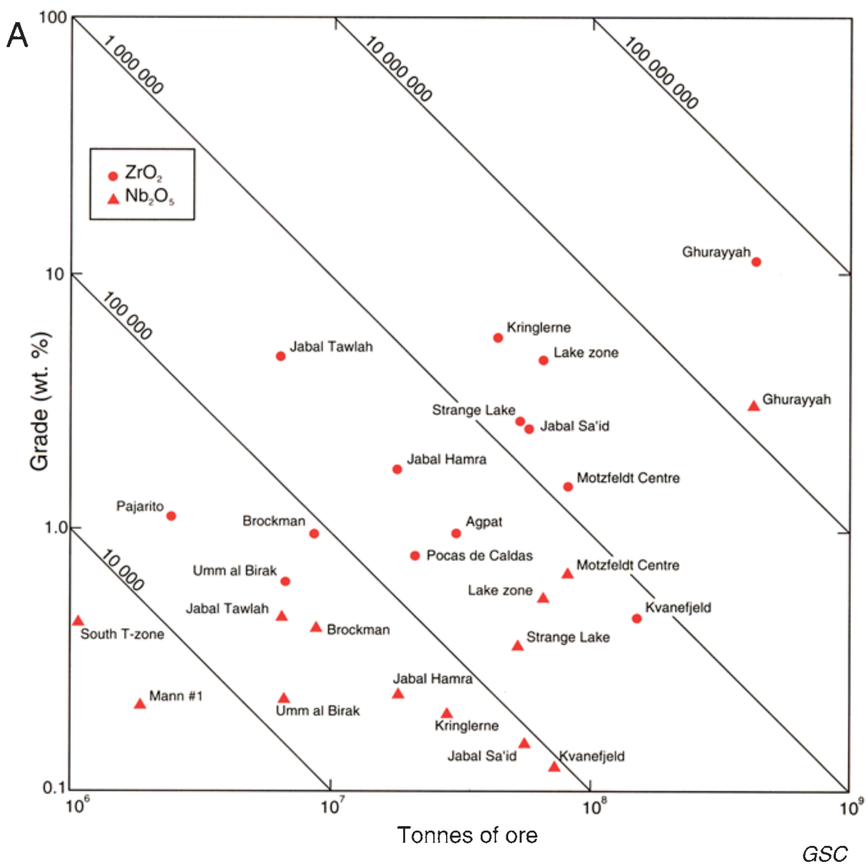
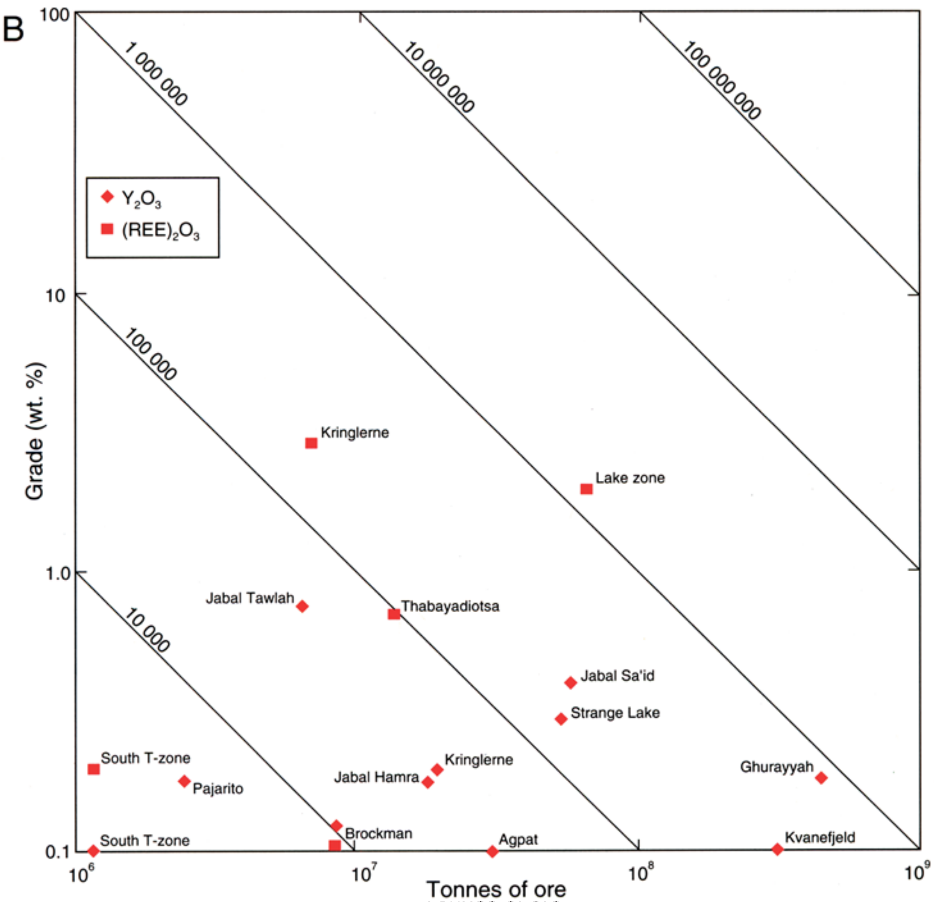


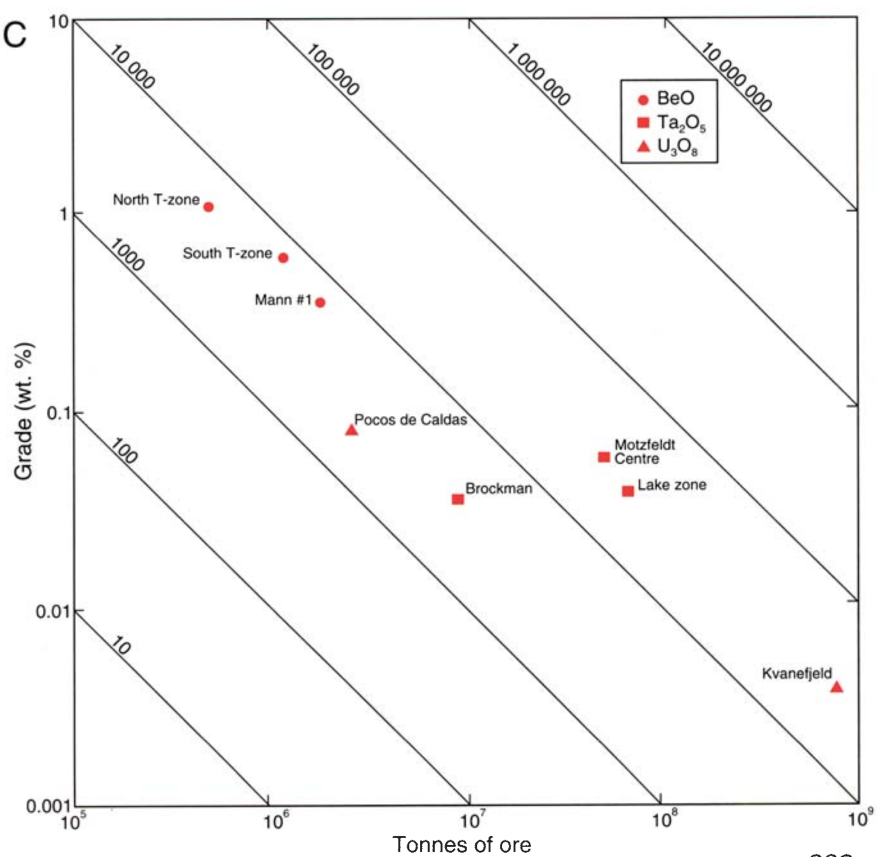
Figure 23-2. Grade-tonnage relationships for peralkaline rare metal deposits. Grades of the deposits are expressed in weight per cents. The diagonal lines indicate the quantity, in tonnes, of the contained commodity in the deposit. Data from Tables 23-1 and 23-2.

B


100
10
1.0
0.1
Grade (wt. %)
1 000 000
10 000 000
100 000 000
100 000
10 000
Y2O3
(REE)2O3
Kringlerne
Lake zone
Jabal Tawlah
Thabayadiotsa
Jabal Sa'id
Strange Lake
South T-zone
Pajarito
Jabal Hamra
Kringlerne
Ghurayyah
Brockman
South T-zone
Agpat
Kvanefjeld
10^6
10^7
10^8
10^9
Tonnes of ore

GSC

C


10
1
0.1
0.01
0.001
Grade (wt. %)
10 000
100 000
1 000 000
10 000 000
1000
100
10
BeO
Ta2O5
U3O8
North T-zone
South T-zone
Mann #1
Pocos de Caldas
Motzfeldt Centre
Lake zone
Brockman
Kvanefjeld
10^5
10^6
10^7
10^8
10^9
Tonnes of ore

GSC

Table 23-3. Formulae of some of the unusual minerals mentioned in the text.

Mineral name	Formula
Silicates:	
allanite-(Ce)	$(Ce,Ca)_2(Al,Fe^{3+})_3(SiO_4)_3(OH)$
aenigmatite	$Na_2Fe^{2+}{}_5TiSi_6O_{20}$
armstrongite	$CaZrSi_6O_{15} \cdot 3H_2O$
astrophyllite	$(K,Na)_3Fe^{2+}{}_7Ti(Si_8O_{24})(O,OH,F)_7$
barylite	$BaBe_2Si_2O_7$
bertrandite	$Be_4Si_2O_7(OH)_2$
calcium catapleiite	$CaZrSi_3O_9{\cdot}2H_2O$
coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
chkalovite	$Na_2BeSi_2O_6$
dalyite	$K_2ZrSi_6O_{15}$
elpidite	$Na_2ZrSi_6O_{15}{\cdot}3H_2O$
eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn,Y)ZrSi_8O_{22}(OH,Cl)_2$
eudidymite	$NaBeSi_3O_7(OH)$
gadolinite (Ca-rich)	$Be_2(Ca,REE,Fe)_3Si_2O_{10}$
gittinsite	$CaZrSi_2O_7$
helvite	$(Fe,Mn,Zn)_4(BeSiO_4)_3S$
kainosite	$Ca_2(Y,Ce)_2Si_4O_{12}(CO_3){\cdot}H_2O$
leifite	$Na_2(Si,Al,Be)_7(O,OH,F)_{14}$
lovozerite	$Na_2Ca(Zr,Ti)Si_6(O,OH)_{18}$
milarite	$K_2Ca_4Al_2Be_4Si_{24}O_{60} {\cdot}H_2O$
mosandrite (rinkite)	$(Na,Ca,Ce)_3Ti(SiO_4)_2F$
murmanite	$Na_2(Ti,Nb)_2Si_2O_9{\cdot}nH_2O$
narsarsukite	$Na_2(Ti,Fe^{3+})Si_4(O,F)_{11}$
niobophyllite	$(K,Na)_3(Fe^{2+}, Mn)_6(Nb,Ti)_2Si_8(O,OH,F)_{31}$
phenakite	Be_2SiO_4
polylithionite	$KLi_2AlSi_4O_{10}(OH,F)_2$
thorite	$(Th,Fe,Y,P,Ca)SiO_4$
titanite	$CaTiSiO_5$
uranothorite	$(U,Th)SiO_4$
vlasovite	$Na_2ZrSi_4O_{11}$
zircon	$ZrSiO_4$
Oxides:	
aeschynite-(Nd)	$(Nd,Ce,Ca)(Ti,Nb)_2(O,OH)_6$
columbite	$(Fe,Mn, Ti,Ta)Nb_2O_6$
fergusonite-(Y)	$(Y,Ce,U,Th)(Nb,Ta,Ti)O_4$
loparite	$(Na,Ca,REE)_2(Ti,Nb)_2O_6$
pyrochlore	$(Na,Ca)_2Nb_2O_6(OH,F)$
uraninite (pitchbende)	UO_2
uranothorianite (thorian uraninite)	$(U,Th)O_2$
Carbonates/fluorides:	
bastnaesite-(Ce)	$(Ce,La)(CO_3)F$
gagarinite -(Y)	$NaCaY(F,Cl)_6$
parisite-(Ce)	$Ca(Ce,La)_2(CO_3)_3F_2$
synchysite-(Ce)	$Ca(Ce,La)(CO_3)_2F$
roentgenite-(Ce)	$Ca_2(Ce,La)_3(CO_3)_5F_3$
Phosphates:	
britholite	$(Ca,Ce,Y)_5(SiO_4,PO_4)_3(OH,F)$
monazite-(Ce)	$(La,Ce,Nd,Th)PO_4$
phosphuranylite	$Ca(UO_2)_3(PO_4)_2(OH)_2{\cdot}6H_2O$
xenotime-(Y)	YPO_4

Age of deposits

Peralkaline igneous complexes with rare metal deposits range in age from Proterozoic to Tertiary, although a large number are mid-Proterozoic (1400 to 1000 Ma) in age (Currie and Gittins, 1993). Deposits in the Arabian Shield are related to late Proterozoic, post-tectonic peralkaline granite complexes that range in age from about 610 Ma to 510 Ma (Stoeser, 1986). Castor (1990) postulated that most of the world's Proterozoic REE deposits are associated with an axial zone of anorogenic magmatism that existed on a Proterozoic supercontinent. Anorogenic peralkaline complexes and associated rare metal deposits in Nigeria are primarily Jurassic in age (Kinnaird et al., 1985). The Lake zone at Thor Lake has been dated at 2094 ± 10 Ma (Sinclair et al., 1994).

Mineralogy

In most rare metal deposits, the principal Nb- and Ta-bearing minerals are columbite-tantalite and pyrochlore, although loparite is the source of the Nb and REE currently recovered from the Lovozero complex. In many deposits, Zr occurs mainly in eudialyte, which in some cases contains REEs. In addition, rare metal deposits associated with alkalic rocks can also contain a wide variety of unusual or rare minerals. Formulae of some of the unusual minerals found in peralkaline rock-associated rare metal deposits are given in Table 23-3.

The magmatic deposits of the Illimaussaq intrusion of southern Greenland contain alkali silicate minerals with essential components of the ore metals, including chkalovite, eudialyte, and vlasovite, and oxides and phosphates such as pyrochlore and monazite.

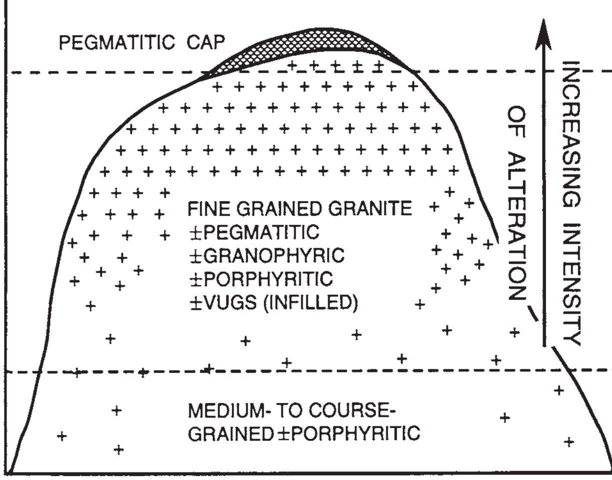
Alteration

As noted by Bowden (1985), Kinnaird (1985), Jackson (1986), Bowden et al. (1987), and Pollard (1989a, b), despite differences in primary magma compositions, the distribution of alteration and textural zones associated with rare metal deposits are similar, with a medium- to coarse-grained microcline-rich zone at the deepest levels succeeded upwards by an intermediate fine grained albite-rich zone and an upper pegmatitic zone of greisenization. In the case of peralkaline systems, greisenization is rare and alteration is dominated instead by albitization (sodium metasomatism). For example, albite-rich zones host the mineralization at Bokan Mountain, U.S.A. (Thompson, 1988) and at Thor Lake, Northwest Territories (Trueman et al., 1988). Pollard (1989a) noted that regardless of whether zones of intense albitization are magmatic or metasomatic, they generally occur in the top 50 m, and the grade of mineralization decreases gradually, laterally and vertically away from the apex of the intrusion. The development of U-Nb-Ta deposits and associated alteration at Pocos de Caldas, Brazil, and at Kvanefjeld and Motzfeldt Centre, Greenland seems to be related to the remobilization of rare metals by volatile-rich, deuteric fluids and their concentration in the carapace of the related intrusion. Primary geochemical haloes in the rocks hosting peralkaline rare metal deposits are typically absent, but, if present, are generally not extensive. The typical textural features of rare metal peralkaline rock-hosted deposits are illustrated and described in Table 23-4.

GENETIC MODEL

The formation of magmatic peralkaline rare metal deposits is related to igneous differentiation of intrusive complexes under closed conditions. Rare metal concentrations in the magmas increase through crystal fractionation, possibly supplemented by vapour-phase transport. Layering, such

Table 23-4. Schematic representation and summary of textural features typically associated with peralkaline and peraluminous rare metal deposits (compiled from: Bowden, 1985; Kinnaird, 1985; Jackson, 1986; Bowden et al., 1987; Pollard, 1989a, b).



TEXTURAL ZONE	SPATIAL LOCATION	THICKNESS	DESCRIPTION OF POSSIBLE FEATURES
Marginal pegmatite facies (stockscheider)	Upper cupola/apex/ upper contact zone of pluton	Variable thickness. If present, however, from few centimetres to >5 m. Thickness decreases away from apex of intrusion.	- Development of subhorizontal quartz-feldspar pegmatite interlayered with fine grained granite. - Development of downward branching (plumose) alkali feldspar in matrix of fine grained granite. - Presence of "brain rock" - narrow (<1 cm) alternating layers of microgranite and oriented quartz. - Development of layering parallel to upper contact of the main granite (i.e., individual quartz-rich and amphibole-rich zones within a network matrix of K-feldspar).
Fine grained granite	Upper contact zone/roof zone of pluton	In large plutons, zone is typically 10-100 m thick, but may be dominant rock type in small isolated plutons	- Presence of segregations of coarse grained pegmatite as much as a metre in diameter. - Miarolitic cavities are a common feature and are frequently infilled with hydrothermal minerals. - Presence of granophyric quartz-feldspar intergrowths within a network of coarser grained quartz-feldspar-mica pegmatite.
Medium- to coarse-grained ±porphyritic	Deeper levels of pluton	May possibly extend 200-300 m below pluton apex	- Development of microcline "porphyroblasts" adjacent to incipient fractures.

as that seen at the Lovozero complex, Russia and Kringlerne, Greenland, forms by crystal accumulation and by injection of residual magma into a semiconsolidated crystal mush. Pegmatites and magmatic-hydrothermal fluids are also formed from residual magmas. The pegmatites share the mineralogy of the surrounding rocks, but commonly have higher concentrations of rare metals (e.g., Strange Lake, Quebec-Labrador).

Disseminated Nb-Zr-Be-U-Th-REE-bearing minerals in pegmatite-aplite dykes and adjacent rocks in Labrador (Flowers River, Mann #1) and South Africa (Thabayadiotsa) are thought to represent subvolcanic- and volcanic-hosted mineralization associated with nearby peralkaline intrusive bodies (Lurie, 1986; Miller 1987, 1994).

The concentration of F (and possibly of CO_2) is fundamental in the development of magmatic and metasomatic peralkaline rock-associated rare metal deposits. Fluorine expands the temperature interval between liquidus and solidus, lowers viscosity of magmas, and, through complexing, assists in the transport of elements, including those of economic interest. Deposits form through relatively simple concentration of elements during crystallization (Strange Lake, Ilimaussaq intrusion), possibly with some transport of material by fluids (supra-solidus alteration).

In some deposits, such as Thor Lake, mineralization results from the upward migration of postmagmatic fluids rich in F and CO_2, probably in excess of H_2O. The timing and nature of fluids exsolved from peralkaline magmas probably exercise a fundamental control on the subsequent mineralization.

Pollard (1989b) suggested that rare metals may be concentrated through scavenging by postmagmatic, metasomatic fluids, and the mineralization at Thor Lake is a good illustration of the potential for transport and concentration of rare metals by metasomatic processes. Fluids not related to the igneous event (for example groundwaters) are not generally considered to be involved in the mineralizing processes.

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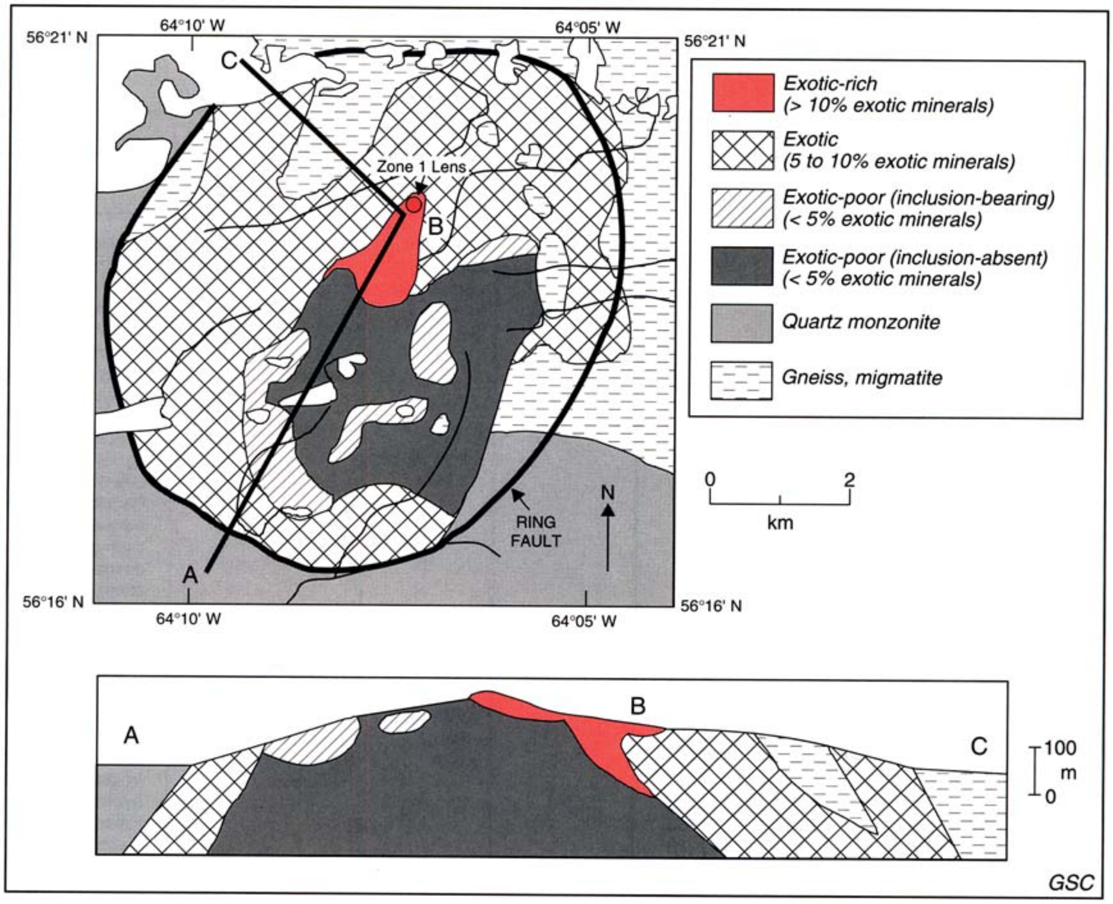

Figure 23-3. Generalized geology and south-north cross-section A-B-C of the Strange Lake peralkaline complex (after Miller, 1990; Hill and Miller, 1991). The term 'exotic' in the legend is used to define the main mineralogical phases of the Strange Lake Granite. These phases are distinguished on the basis of the modal abundances of an unusual suite of minerals that includes the Zr-bearing minerals zircon, gittinsite, armstrongite, vlasovite, elpidite, catapleiite, and dalyite, together with pyrochlore, kainosite, and gadolinite, as well as titanite, fluorite, monazite, thorite, narsarsukite, astrophyllite, and aenigmatite. The 'exotic-poor' granite is further subdivided on the basis of whether or not it contains host rock inclusions.

DEFINITIVE CHARACTERISTICS

Peralkaline rock-associated rare metal deposits have several common features, including:

1. Elevated contents of rare metals, such as Nb, Zr, Y, REEs, U, and Th, and of the volatiles F and CO_2.
2. Rare-earth elements are usually contained in oxides or silicates of Nb, Ti, Zr, Al, Be, and Na; Ca-phosphates and Ca-fluorocarbonates, such as bastnaesite; or yttrium members such as synchysite (Möller, 1989c). Niobium is primarily contained in pyrochlore, rather than columbite-tantalite.
3. Associated intrusive, subvolcanic, and volcanic rocks are peralkaline in composition (molar proportions Na_2O+K_2O/Al_2O_3 >1), and they may be either silica-undersaturated or silica-saturated.
4. Distinction between magmatic and metasomatic deposits is clear in cases in which extensive hydrothermal alteration activity has been inhibited (e.g. Strange Lake, Kringlerne, Illimaussaq intrusion, Greenland), but becomes arbitrary in cases in which the mineralizing system has passed continuously from magmatic to hydrothermal conditions (e.g., Thor Lake deposits, Northwest Territories; Motzfeldt Centre, Igaliko complex, Greenland).

SYNOPSIS OF CANADIAN DEPOSITS AND OCCURRENCES

Strange Lake deposit

Geological setting

The Strange Lake deposit, located on the Newfoundland-Quebec border, is part of a post-tectonic, peralkaline granite complex dated at 1240 ± 2 Ma (R.R. Miller, L.M. Heaman, and T.C. Birkett, unpub. data, 1994), which has intruded along the contact between older gneisses and monzonite of the Churchill Province of the Canadian Shield. The complex is subcircular, and consists of generally concentric, high level granitic intrusions bounded by sharp contacts with the country rock (Zajac et al., 1984; Miller, 1985, 1986, 1990). Ring faults, at or near the contact of the alkalic complex, dip outward at low to moderate angles (20-35°) (Miller, 1985). At the geometric centre of the complex is a small (approximately 1.5 km^2) stock of medium grained, generally nonporphyritic granite 'exotic-rich' granite on Fig. 23-3), with very high overall values of zirconium, niobium, and yttrium. Rooted within this medium grained granite stock are dykes of aplite-pegmatite that contain very high values of rare metals. The principal deposit outlined to date is the 'Zone 1 lens', a flat-lying aplite-pegmatite dyke located just north and east of the granite stock (Miller, 1990). This dyke is as much as 20 m thick and has a surface expression of 0.75 km^2. The basal portion of the dyke is a fine grained aplitic rock with flow-aligned phenocrysts which impart a directional fabric (Miller, 1986, 1990). Overlying the fine grained portion is a coarse grained, generally massive pegmatite of broadly similar composition. Occurrences of similar aplite-pegmatite dykes are known in other parts of the Strange Lake alkalic complex, but have not been systematically explored.

Mineralogy

Early hypersolvus granites at Strange Lake contain sodium-rich minerals such as narsarsukite, aenigmatite, astrophyllite, sodic amphibole and pyroxene, elpidite, leifite, and vlasovite, in addition to pyrochlore, fluorite, quartz, and feldspar. In later subsolvus granites, calcium-rich phases appear, such as gittinsite, calcium-catapleiite, armstrongite, kainosite, titanite, milarite, pyrochlore, prehnite, and an unusual calcium-rich member of the gadolinite group. Magnesium is generally present in clay minerals.

The potential ore minerals at Strange Lake include Be- and Y-bearing minerals such as the gadolinite group Ca-rich silicate minerals, an unnamed Ca-Y silicate and kainosite; the Zr-bearing mineral gittinsite; and Nb-bearing minerals such as pyrochlore and titanite.

Genetic model

Magmatic evolution within the Strange Lake complex led to enrichment of Ca and Mg, as well as of the elements of interest. Whether or not concentration of these elements in the apical portions of the pluton was assisted by volatile transport is not clear. Within the deposit, reaction of earlier formed minerals with magmatic and postmagmatic fluids has led to local metasomatic reaction and pseudomorphous replacement of earlier formed minerals. The absence of veins within and around the deposit is noteworthy.

Mineralization of the Letitia Lake Group and Flowers River Igneous Suite, Labrador

Mann #1 occurrence, Letitia Lake Group

The Mann #1 occurrence, in the Letitia Lake area of Labrador, has been described by Evans and Dujardin (1961), Thomas (1981), and Miller (1987, 1989). Mineralization is present in a variety of rare Be-, Nb-, and Y-bearing minerals, including barylite, eudidymite, niobophyllite, and pyrochlore (Miller, 1987, 1988). According to Miller (1988, 1989), high grade Nb-Be mineralization at the Mann #1 occurrence is contained in: 1) subvolcanic veins (i.e., aegirine-feldspar veins and albite-rich felsic veins) associated with fine- to medium-grained, massive, equigranular peralkaline aegirine-riebeckite±quartz syenite; and 2) disseminations in near-vent peralkaline trachytes (i.e., banded feldspar-riebeckite volcanic rocks and massive aegirine-feldspar volcanic rocks) that overlie, and are probably coeval with, the peralkaline syenite. Although most Nb-Be showings in the Letitia Lake area are associated with the emplacement of the peralkaline syenite, significant mineralization has not been discovered near all of the mapped syenites (Miller, 1988). Miller (1988) also noted that peralkaline granites in the area, which have similar mineralogy to the syenite, except that quartz and astrophyllite are more abundant and riebeckite and aegirine are less abundant, do not appear to host mineralization, although they are enriched in many of the rare metals.

Flowers River Igneous Suite

The Mid-Proterozoic Flowers River Igneous Suite includes the Nuiklavik felsic volcanic rocks and associated predominantly peralkaline granites. The Nuiklavik volcanic rocks, approximately 340 m thick and exposed in several partially eroded nested calderas, have been subdivided into five major units: 1) basal tuff; 2) amphibole-bearing porphyry; 3) lower crystal-rich ash flow; 4) crystal-poor and quartz-phyric ash-flow; and 5) upper ash-flow (Miller, 1993). Anomalous Zr and Y (2000-12 000 ppm Zr, 400 to 2000 ppm Y) are found in the crystal-poor and quartz-phyric ash-flow unit (Abdel-Rahman and Miller, 1994). Miller (1993) documented the presence of a thin sequence (about 4 m thick) of mineralized volcanic rocks (300-1900 ppm Y and >4000 ppm Zr) over an area of 14 km^2. In one locality, this unit is 32 m thick. Although mineralization is associated with Na-depleted peralkaline volcanic rocks, trace element data suggest that REE mineralization is magmatic in origin (Miller, 1994).

Thor Lake deposits

Geological setting

The Thor Lake rare metal deposits are centrally located within the Aphebian Blatchford Lake Intrusive Complex, which has intruded metasedimentary rocks of the Archean Yellowknife Supergroup. The complex consists of a western series of gabbroic, granitic, and syenitic rocks; to the east, these rocks are cut by a larger subcircular body of peralkaline granite (Grace Lake Granite) that encloses a central syenite body (Thor Lake Syenite) (Davidson 1978, 1981, 1982). Gravity studies by Birkett et al. (1994) suggest that

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the peralkaline rocks form a subhorizontal, relatively thin (extending to a depth of 1.5 to 1 km) lobe that appears to be centred over a subsided block of Yellowknife Supergroup metasedimentary rocks. Pinckston (1989) and Pinckston and Smith (1991) identified nepheline-bearing rocks as the youngest phase at Blatchford Lake, and have suggested they were emplaced as a ring complex.

The six Thor Lake mineral deposits shown in Figure 23-4 (Fluorite zone, Lake zone, R zone, S zone, North T-zone, and South T-zone), which at one time may have been contiguous, are separated by vertical faults (Trueman, 1986). Although the R, S, and Fluorite zones represent important mineralized areas, only the Lake Zone and both the North and South T-zone deposits are of economic interest (Schiller, 1985). Schematic geological cross-sections of the Be-Y-rich North T-zone are shown in Figure 23-5.

The T-zone deposits form a peralkaline pegmatite system which was emplaced as an intrusive, dyke-like body. In contrast, the Lake zone deposit consists of disseminated Nb-, Ta-, and Zr-bearing minerals contained in a large core of hydrothermally altered syenite breccia or pseudobreccia.

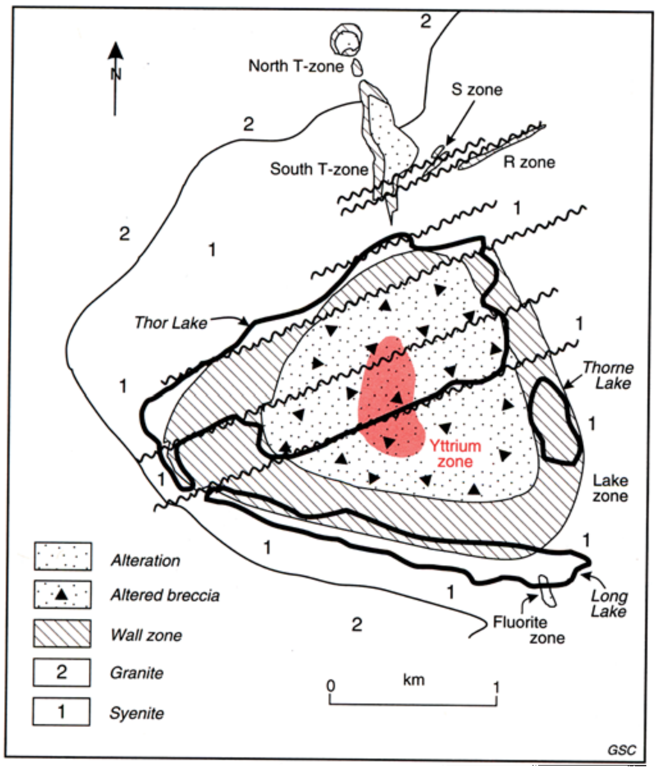

Figure 23-4. General geology of the Thor Lake area, showing the location of the North and South T-, Lake-, R-, S- and Fluorite zones, after Trueman et al. (1988). Area colored in red denotes approximate location of the high grade yttrium zone in the Lake zone deposit as determined by diamond drilling (Highwood Resources Limited, Annual Report, 1987). The heavy black lines outline lakes.

The T-zone and Lake zone deposits are linked by an albitized wall zone, which envelopes the T- and Lake zones. The two portions, however, are quite distinct.

Ore compositions and zoning of ore

The Thor Lake deposits display large-scale zonation, with Be, REEs, and Y concentrated in the northern portions of the system (the T-zone deposits) and Ta and Zr concentrated in the southern part, (the Lake zone). Trueman et al. (1988) and Pedersen and LeCouteur (1990) have documented more detailed patterns of metal distribution at Thor Lake, including:

1. The five Be-enriched zones outlined in the North T-zone show a trend to phenakite enrichment upward and a concomitant decrease in the proportion of Be as bertrandite and the minor Be-bearing minerals gadolinite and helvite.
2. Phenakite mineralization is richest in the North T-zone and values decrease downward and southward in the South T-zone where bertrandite (±gadolinite and helvite) predominate. Beryllium is not concentrated in the Lake zone; however, anomalous values have been detected along its eastern contact.
3. Yttrium, present in xenotime and Th-Y silicates, occurs in the central portion of the Lake zone and to a lesser degree in the central and lower portions of the North T-zone, where it may or may not be associated with Be mineralization (Fig. 23-4 and 23-5).
4. Cerium and lanthanum, present in the REE fluorocarbonates bastnaesite, parisite, synchysite, and roentgenite, attain their highest values in the upper North T-zone where they form a discrete upper quartz-bastnaesite zone (Fig. 23-5). This zone contains 60 000 t grading approximately 8% rare-earth oxides (REOs) (Sinclair et al., 1992).
5. Niobium (columbite and pyrochlore) follows a similar pattern to Be and Y, showing extreme enrichment in the North T-zone and decreasing southward into the Lake zone. Schiller (1985) reported that a portion of the Wall zone of the North T-zone contains a separate zone grading 1.0% Nb_2O_5 and 0.05% Ga.
6. In the Lake zone, Ta and Nb, contained in ferrocolumbite, pyrochlore group minerals, and aeschynite group minerals, are accompanied by enrichment of LREE (allanite-(Ce), monazite-(Ce), bastnaesite-(Ce)) and Y (fergusonite-(Y), xenotime, zircon).
7. Zirconium, almost absent in the T-zone deposits, attains significant concentrations in the Lake zone (>3.5% Zr in zircon).

   Detailed descriptions of the zones, subzones, and mineralogies of the significant Thor Lake deposits are provided in Table 23-5.

Genetic model

The T-zone deposit is thought to have evolved by magmatic crystallization upward and inward from the walls. The main stage of mineralization was formed by the reaction of the residual liquids of the system (possibly with the addition of more fluids from below) with the already-solidified

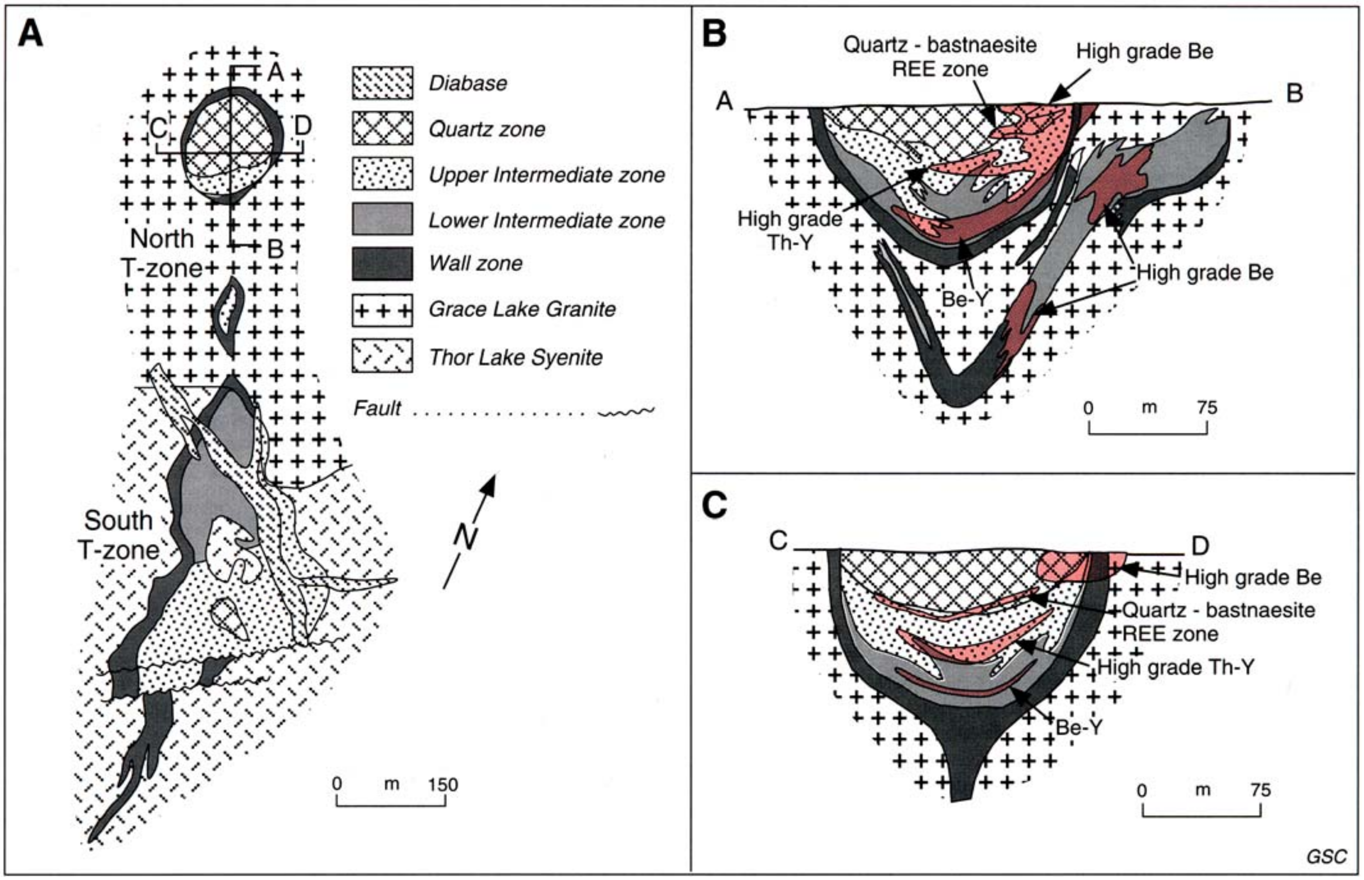

Figure 23-5. Plan of the T-zone deposit showing the major rock types **A)**; cross-sections AB **B)** and CD **C)** are from the North T-zone deposit, modified from Trueman et al. (1988). Areas shaded red denote zones of high-grade Be, high grade Th-Y, Be-Y, and quartz-bastnaesite REE mineralization (after Trueman et al., 1984; Schiller, 1985; and Pedersen and LeCouteur, 1990).

minerals. The progressive development and upward migration of the various zones, is thought to be analogous to the formation of a chromatogram, where various chemical compounds are separated and then subsequently deposited into a distinct zonal pattern. Alteration patterns and mineralization at Thor Lake, which include relic granite and syenite protoliths; albitites; microclinites; quartz-fluorite-polylithionite-phenakite greisens; and a massive quartz core, are indicative of superimposed potassic, sodic, and Fe-rich greisen metasomatism on an original peralkaline pegmatite (Pinckston and Smith, 1988, 1991; Trueman et al. 1988; and Trueman, 1989).

Uranium-lead zircon and monazite geochronology by Sinclair et al. (1994) suggests that Thor Lake mineralization substantially postdates the peralkaline phases of the Blatchford Lake Intrusive Complex (the Grace Lake Granite and Thor Lake Syenite). The presence of REE-bearing minerals such as zircon, cerianite-(Ce), britholite-(Ce), and thorite in the upper parts of the as yet undated, late stage undersaturated nepheline syenite body below the Thor Lake deposits led Pinckston (1989) and Pinckston and Smith (1991) to suggest that Thor Lake mineralization may be related to the crystallization and cooling of this syenite. However, an outstanding problem with this hypothesis concerns the derivation of the relatively siliceous wall zone rocks that envelope the deposits (Birkett et al., 1990).

RELATED DEPOSIT TYPES

Felsic anorogenic rocks commonly evolve to compositions enriched in the rare elements without regard to peralkalinity or silica activity. The gradation of composition between peralkaline and peraluminous rocks commonly results in members of the two classes being closely related in space and time. Thus lithophile element mineralization associated with peraluminous and metaluminous granitic rocks, such as Sn-W vein and stockwork, porphyry Mo-W, and pegmatitic and vein-hosted Li-Ta-Nb-Be deposits, are related to the peralkaline rock-associated deposits (see Types 18, 19, and 21, respectively). The Sn-Nb (columbite type) mineralization associated with peraluminous biotite granites in the 1250 km long belt of ring complexes extending across Niger and Nigeria (Kinnaird et al., 1985; Pollard, 1989a), as well as certain Sn-W deposits associated with peraluminous to metaluminous, postorogenic granites

Table 23-5. Summary of geology/mineralogy of the T-zone and Lake zone deposits, Thor Lake, Northwest Territories (compiled from: Černý and Trueman, 1985; Trueman et al., 1988; Pedersen and LeCouteur, 1990; and Trueman, 1990).

DEPOSIT/ DIMENSIONS	HOST ROCK	ALTERATION/ MINERALIZED ZONE	DESCRIPTION	MINERALOGY
T-ZONE DEPOSITS 1 km long, 275 m wide, 150 m deep	**North T-zone** hosted by Grace Lake Granite	QUARTZ ZONE (QZ)	Monomineralic coarse grained quartz core as much as 35 m thick. Gradational with UIZ.	Patchy zones of green fluorite and separate zone of honey yellow sphalerite found near footwall boundary.
	South T-zone hosted by both Grace Lake Granite and Thor Lake Syenite	UPPER INTERMEDIATE ZONE (UIZ)	Transitional with QZ and LIZ and boundaries between these units are indistinct. Significant Be mineralization is contained in UIZ, along with some Y enrichment. Four pronounced subzones have been recognized.	<u>Subzone 1 - Quartz-mica/quartz-mica feldspar/quartz feldspar</u> Massive lenses and anastomosing stringers of euhedral polylithionite in a quartz matrix. Pink albite common, green fluorite and carbonate are common accessories. <u>Subzone 2 - Quartz-feldspar-mica-magnetite ± phenakite</u> Abundant phenakite intergrown with quartz, and large randomly oriented tabular crystals of magnetite and biotite. Fluorite and bastnaesite-group minerals are accessories <u>Subzone 3 - Quartz-bastnaesite</u> Quartz with "brick-red" bastnaesite group fluorocarbonates (bastnaesite-(Ce), parisite-(Ce), synchysite-(Ce), roentgenite-(Ce) with accessory fluorite. <u>Subzone 4 - Quartz-thorite-feldspar</u> Lower half of UIZ, anastomosing stringers and blebs of fine grained mixtures of "chocolate-brown" thorium minerals (thorite, Th-Y silicates) in dark grey, very fractured quartz. This subzone is highly enriched in Y and Be. Beryllium minerals include phenakite, lesser amounts of bertrandite, and minor gadolinite. Xenotime, columbite, and dark purple fluorite are common.
		LOWER INTERMEDIATE ZONE (LIZ)	Displays gradational contact with UIZ, and with WZ breccias. Abundant granite-syenite xenoliths are present, and exhibit varying degrees of alteration. Zone is enriched in Be, Y, and Nb. Five pronounced subzones have been recognized.	<u>Subzone 1 - Quartz-biotite/chlorite-feldspar</u> Upper boundary of LIZ, massive lenses and anastomosing stringers of euhedral biotite in quartz, with accessory fluorite and columbite. <u>Subzone 2 - Biotite/chlorite-feldspar-carbonate quartz</u> Found only in south T-zone, mineralogy is similar to LIZ subzone 1, but the subzone contains 25% grey dolomite. <u>Subzone 3 - Quartz-biotite/chlorite-feldspar (altered granite) and biotite/chlorite-feldspar± quartz (altered syenite)</u> Mineralogy similar to LIZ subzone 1, relict xenoliths of granite and syenite exhibit minor to complete alteration. <u>Subzone 4 - Quartz-magnetite-biotite/chlorite</u> Forms fairly continuous brownish black "envelope" between UIZ and the main LIZ alteration. Highly siliceous, rich in magnetite, and locally in Nb (columbite). <u>Subzone 5 - Quartz, feldspar, ± magnetite</u> Gradational with LIZ subzone 4, similar to UIZ Subzone 1, but less siliceous and is significantly enriched in Be (phenakite).
		WALL ZONE (WZ)	Forms outer feldspathic shell of the T-zone. Outer contact with host granite and syenite is sharp, but the inner brecciated boundary with the LIZ is gradational. Niobium is found in columbite, and Ga is enriched in feldspars. Can be subdivided into three distinct subunits.	<u>Subunit 1 - Feldspar-breccia</u> Found along inner boundary of WZ, partly to completely albitized large K-feldpar crystals in matrix of quartz and quartz-magnetite. <u>Subunit 2 - Microclinite, albitite</u> Central core of WZ, light pink coarse microcline partly to completely replaced by cleavelandite. <u>Subunit 3 - Banded aplite, albitite</u> Fine grained outer margin of WZ, contains disseminated fluorite and mafic accessories.
LAKE ZONE Triangular in shape (covers an area of about 2 km^2), has been delineated to a depth of 335 m	Hosted by Thor Lake Syenite	CORE ZONE BRECCIA	Core zone is surrounded by the wall zone.	Not a breccia sensu stricto; what appear to be syenite fragments often display diffuse boundaries, grading back into unaltered protolith. Core zone assemblage consists of crystals and fragments of K-feldspar, all in a matrix of fine- to coarse-grained mica and lesser magnetite and amphibole. The matrix contains fluorite, columbite, uraninite, bastnaesite, parisite, synchysite, xenotime, monazite-(Ce), apatite, allanite-(Ce), fergusonite- (Y), aeschynite- (Nd), and zircon.
		WALL ZONE	Zone consists of albitite, similar to that enveloping the T-zone deposits.	Outer part consists of fine grained albite and quartz; inner part is characterized by a diverse suite of rocks rich in mafic minerals such as aegirine, biotite, and Fe and Ti oxides. Inner part also contains fluorite, quartz, and coarse fragments of perthitic K-feldpar, and displays evidence of extensive albitization.

within the eastern Arabian Shield (Jackson, 1986; Du Bray et al., 1988), are examples of spatially and temporally related peralkaline and peraluminous deposits.

Mineralization associated with fluorine-rich silicic lava flows (e.g., Spor Mountain Be deposit) and subvolcanic equivalents (e.g., Mexican fumarolic Sn deposits; Burt and Sheridan, 1987; Ramsden et al., 1993) are linked through the essential involvement of F in volcanic and subvolcanic peralkaline rare metal deposits. Similarly, the Fe-Cu-U-Au-REE Olympic Dam deposit of southern Australia (Oreskes and Einaudi, 1990) and the Fe-REE-apatite deposits at Kiruna, Sweden are associated with felsic alkalic rocks rich in F (see deposit Type 22, Kiruna-Olympic Dam Fe-Cu-U). These deposits exhibit extensive metasomatism (Frietsch, 1978, 1989; Hauck et al., 1989; Oreskes and Einaudi, 1990). The iron-rich nature of these deposits could be due to the involvement of groundwaters in the hydrothermal system.

Mineralogical, geochemical, and petrogenetic similarities also exist between carbonatites and peralkaline rock-associated rare metal deposits. For example, Bowden (1985) noted that from a mineralogical point of view, there are many parallels, including the presence of sphalerite, REE minerals, zircon, complex titanium-zirconium silicate minerals, pyrochlore, columbite, and uranium and thorium minerals (see Type 24).

EXPLORATION GUIDES

Exploration guidelines for peralkaline rock-associated rare metal deposits include the following:

1. Broad-scale features: deposits occur principally in anorogenic tectonic settings in which magma generation and intrusion are associated with crustal extension (Pollard, 1989a, b). Mineralized plutons typically form steep-sided, ovoid to elongate bodies that range from less than one square kilometre to several tens of square kilometres, which generally constitute the final intrusive phases of multiple-staged batholiths (Pollard, 1989b). In the subvolcanic environment, these plutons are in many cases controlled by ring fractures, and have commonly intruded contemporaneous volcanic rocks within shallow level ring complexes. In deeper level environments, mineralized plutons generally form small satellite phases to the main pluton, and in some cases form relatively fine grained, marginal facies varieties of large plutons.
2. Mineralogy: undersaturated peralkaline intrusion-related deposits are characterized by the presence of colourful, relatively rare alkali-rich minerals, such as sodalite (dark blue), eudialyte (pink/red), acmite (brown/green), alkali-amphiboles (blue/black), rinkolite (red brown/yellow brown), and gadolinite (green/brown-black).

   In the Be-bearing metasomatic deposits, the prominent minerals are quartz and fluorite, whereas the primary beryllium minerals (phenakite, beryl, bertrandite, and helvite) are inconspicuous and easily overlooked. At Thor Lake, the beryllium potential of the T-zone deposit was not recognized until 1978 when phenakite was identified.

   The presence of U and Th in these deposits commonly results in fluorite being purple.
3. Geochemical approaches: peralkaline rocks associated with mineralization typically have high Rb/Sr values, and are anomalously enriched in Zr, Zn, Nb, Y, Th, U, LREE and HREE, F, Be, and Pb (Bowden, 1985). These elements provide strong contrasts to regional background concentrations. Geochemical surveys of lake water or till can effectively locate the peralkaline rocks likely to host deposits. In the Gardar igneous province in southern Greenland, the Nb content in the 0.1 mm fraction of stream sediments, collected at a reconnaissance scale (1 sample per 6.25 km^2) proved most effective in defining potentially economic mineralization associated with peralkaline and carbonatitic intrusive complexes (Steenfelt, 1991). Indicator minerals in heavy mineral concentrates from stream sediments include pyrochlore, chrysoberyl, helvite, and euclase.

   The Strange Lake deposit was discovered in 1979 as a result of exploration by the Iron Ore Company of Canada following regional lake water and sediment surveys that had revealed anomalous fluorine, uranium, and lead values (Geological Survey of Canada, 1979). Subsequent tracing of glacially transported mineralized boulders, initially recognized some 20 km from their source, led to the discovery of the deposit (Miller, 1985, 1986). Mapping of Quaternary deposits and geochemical studies have determined that anomalies associated with the Strange Lake deposit extend for 25 to 40 km in a down-ice direction from the mineralized source (McConnell et al., 1984; McConnell and Batterson, 1987; Batterson, 1989).

   Although not applicable in Canada, the leaves of hickory trees have been found to concentrate REEs to an extraordinary degree and can serve as a biogeochemical indicator of REE-Y mineralization (Möller, 1989b).
4. Geophysical approaches: in Canada and Greenland, airborne radiometric (K, U, Th) surveys at 1 km line-spacing have proven effective in delineating peralkaline-alkaline intrusions and their mineral deposits (Batterson and LeGrow, 1986; Steenfelt, 1991). According to A.N. Mariano (Geological Survey of Canada Logan Club, oral presentation, February 24, 1994) the presence of positive airborne radiometric anomalies and negative aeromagnetic signatures characterize the Strange Lake, Kipawa, and Pajarito Mountain deposits.

   Because most REE (Y) ores are somewhat radioactive, largely owing to the co-presence of Th, and to a lesser extent U, radiometric surveys may be useful for identifying parent granites, actual REE deposits, and other relevant features associated with mineralization (e.g., alteration, structural controls). A 1971 reconnaissance scale airborne radiometric survey carried out by the Geological Survey of Canada detected both U and Th anomalies over the area containing the Thor Lake deposits (Davidson, 1982). A subsequent detailed airborne radiometric/magnetic/VLF survey in 1988 by the Geological Survey of Canada of a 500 km^2 area at a line spacing of 250 m identified: 1) the major lithologies of the Blatchford Lake Intrusive Complex; 2) the Thor Lake deposits; and 3) potential sites of additional REE mineralization (Charbonneau and Legault, 1994).

Gravity surveys can be used to outline REE deposits in host rocks of contrasting density. Modelling of gravity data obtained over the Lake zone deposit by Highwood Resources Limited in 1983, suggests that the deposit has the form of an easterly-plunging cone (Trueman et al., 1988).

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