Carbonatites of the World, Explored Deposits of Nb and REE—Database and Grade and Tonnage Models

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Introduction

This report is based on published tonnage and grade data on 58 Nb– and rare-earth-element (REE)–bearing carbonatite deposits that are mostly well explored and are partially mined or contain resources of these elements. The deposits represent only a part of the known 527 carbonatites around the world (Woolley and Kjarsgaard, 2008), but they are characterized by reliable quantitative data on ore tonnages and grades of niobium and REE.

Grade and tonnage models are an important component of mineral resource assessments. Carbonatites present one of the main natural sources of niobium and rare-earth elements, the economic importance of which grows consistently. A purpose of this report is to update earlier publications (Singer, 1986a, 1986b, 1998; Orris and Grauch, 2002). New information about known deposits, as well as data on new deposits published during the last decade, are incorporated in the present paper. The compiled database (appendix 1) contains 60 explored Nb– and REE–bearing carbonatite deposits—resources of 55 of these deposits are taken from publications. In the present updated grade-tonnage model we have added 24 deposits comparing with the previous model of Singer (1998). Resources of most deposits are residuum ores in the upper part of carbonatite bodies.

Mineral-deposit models are important in exploration planning and quantitative resource assessments for two reasons: (1) grades and tonnages among deposit types vary significantly, and (2) deposits of different types are present in distinct geologic settings that can be identified from geologic maps. Mineral-deposit models combine the diverse geoscience information on geology, mineral occurrences, geophysics, and geochemistry used in resource assessments and mineral exploration. Globally based deposit models allow recognition of important features and demonstrate how common different features are. Well-designed deposit models allow geologists to deduce possible mineral-deposit types in a given geologic environment, and the grade and tonnage models allow economists to estimate the possible economic viability of these resources. Thus, mineral-deposit models play a central role in presenting geoscience information in a useful form to policy makers. The foundation of mineral-deposit models is information about known deposits. This publication presents the latest geologic information and newly developed grade and tonnage models for Nb– and REE –carbonatite deposits in digital form. The publication contains computer files with information on deposits from around the world. It also contains a text file allowing locations of all deposits to be plotted in geographic information system (GIS) programs. The data are presented in FileMaker Pro as well as in .xls and text files to make the information available to a broadly based audience. The value of this information and any derived analyses depends critically on the consistent manner of data gathering. For this reason, we first discuss the rules used in this compilation. Next, the fields of the database are explained. Finally, we provide new grade and tonnage models and analysis of the information in the file.

Rules Used

A mineral deposit is a mineral occurrence of sufficient size and grade that might, under the most favorable circumstances, be considered to have economic potential (Cox and others, 1986). Deposits sharing a relatively wide variety and large number of attributes are characterized as a "type," and a model representing that type can be developed.

Nb– and REE–carbonatite deposits consist of plugs, oval intrusions, dikes, veins, and stockworks generally restricted to large alkaline intrusive complexes or to their locally highly metamorphosed country rocks. They commonly have parts containing altered fenitized rocks. Deposits that may be derived from, or affected by, hypogene and supergene processes are included in the models.

An important consideration at the data-gathering stage is the question of what the sampling unit should be. Grade and tonnage data are available to varying degrees for districts, deposits, and mines. For the deposits in this model, the following rule was used to determine which ore bodies were combined. All mineralized rock or altered rock within two (2) kilometers was combined into one deposit. Some examples illustrate the effects of the application of this rule: (1) Salitre I and II deposits in Brazil and (2) Upper Fir and Fir in Canada. Carbonatite deposits are remote from one another.

Data Fields

The information on the explored Nb– and REE–carbonatite deposits included in the database and grade and tonnage models is contained in the files of2009-1139_carbonatite.fp7, of2009-1139_carbonatite.xls, and of2009-1139_carbonatite.tab.txt, which are FileMaker Pro 7, Excel, and tab-delineated text files, respectively. The fields in all files are described below. The “n.d.” abbreviation in various fields indicates “no data,” “not detected,” or “not defined.”

Deposit Name

The most recent deposit name is used in the “NameDeposit” field. There is another field, "OtherNames," which contains alternative names that have been used for the deposit. A third field, "Includes," provides the names of deposits that have been combined with the primary deposit as a result of the two-kilometer minimum separation rule.

Locations

A number of fields are provided to show the deposit's location. "Country" and "StateProvince" are used for general locations. "CountryCode" is an abbreviated version of the country information (table 1). Degrees, minutes, and seconds of longitude and latitude are provided in the separate fields. Decimal degrees of latitude ("LatitudeDecimal") and longitude ("LongitudeDecimal") are calculated from the degrees, minutes, and seconds fields. Southern latitudes and western longitudes are negative values. Longitudes and latitudes of all localities were checked and corrected using the "Google Earth 5." Deposits included in the database and tonnage and grade models are located on the world map (fig. 1) and are plotted on the "Google Earth 5" image using the of2009-1139_carbonatite.kmz file.

Table 1. Country names and country codes used in this report

Country	StateProvince	CountryCode
Angola		ANGL
Australia	West Australia	AUWA
Brazil		BRZL
Burundi		BRND
Canada	British Columbia	CNBC
Canada	Ontario	CNON
Canada	Quebec	CNQU
China		CINA
Democratic Republic of Congo		DRCO
Gabon		GABN
India		INDA
Kenya		KNYA
Malawi		MLWI
Mauritania		MRTA
Mongolia		MNGL
Namibia		NAMB
Norway		NRWY
Russia		RUSA
South Africa		SAFR
Tanzania		TNZN
Turkey		TRKY
Uganda		UGND
United States	Arkansas	USAR
United States	California	USCA
United States	Colorado	USCO
Zambia		ZMBA

Activity

Where the discovery date is known, it is recorded in the "DiscoveryDate" field. The startup date of mining is listed in the "StartUp" field.

Grades and Tonnages

Data gathered for each deposit include the average grade of each metal or mineral commodity of possible economic interest and the associated tonnage on the basis of the total production, reserves, and resources at the lowest possible cutoff grade. All further references to tonnage follow this definition. All tonnages reported here ("Tonnage") are in millions of "metric tons" or "tonnes." Niobium ("Nb_2O_5 grade"), rare earth ("RE_2O_3 grade"), and phosphorus ("P_2O_5 grade") grades are reported as percents of the stated oxides. Grades not available (always for byproducts) are treated as zero. The "Comments" field contains supplementary information about some grades, such as thallium, uranium, and thorium when available. Three significant digits are used for tonnage and grades. The special field indicates sources of tonnage-grade data. If required, more detailed information about reserves, resources, and production is placed in "Comments."

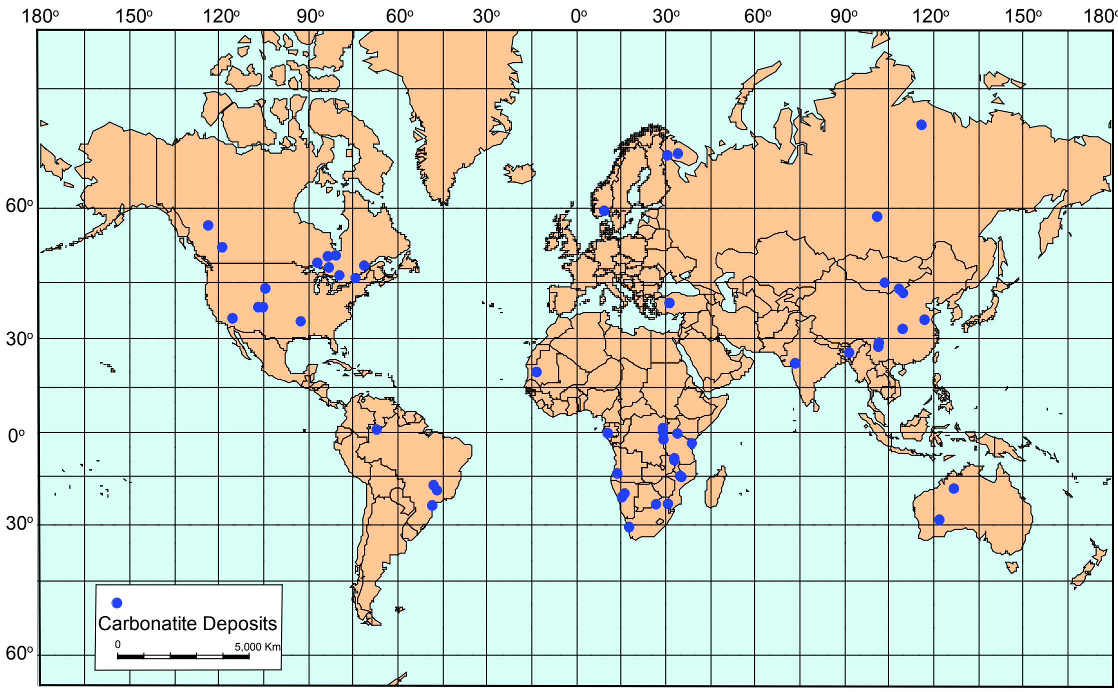

Figure 1. Location of explored Nb– and REE–carbonatite deposits included in the database and grade and tonnage models.

Age

In the field "DepositAge," ages are in standard divisions of geologic time or in millions of years when available. This field contains also common symbols of the dating method used (such as K-Ar, Ar-Ar, U-Pb) and whether the age was on the defined mineral or whole rock. Radiometric ages are reported in millions of years before the present ("AgeMY" field) based on defined radiological ages or midpoints of geologic time scale units (Remane, 1998). Table 2 illustrates grouping of the deposits and their tonnages by age intervals. The two youngest Cenozoic and Mesozoic groups in the two upper rows of the table contain half of the considered deposits with 59 percent of the total tonnage. Such a time-distribution of Nb– and REE–carbonatite deposits might be caused by an evolution of mantle-crust rifting activity within platforms and (or) by erosion of older deposits. However, this impressive tonnage proportion might change dramatically, if the problematic Cretaceous age of the Seis Lagos deposit, Brazil, the largest niobium deposit with 2.9 Gt of ore, were to be changed to Precambrian as was proposed by Antonini and others (2003).

Table 2. Grouping of deposits by age intervals
[n.d., not dated.]

Age MY groups (Ma)	Number of deposits	Percent of dDeposits %	Summary tonnage	Percent of tonnage %
10.4–100	15	24	4381	37
101–265	16	26	2553	22
344–520	6	10	1295	11
558–680	11	19	1310	11
1010–1400	7	12	1038	9
1655–2047	3	5	978	9
n.d.	2	4	194	1
Total	60	100	11,749	100

Geologic Setting

Geologic setting of the deposits is characterized in several data fields: tectonic setting, spatially associated rocks, shape of carbonatite bodies, and area occupied by carbonatites.

Tectonic setting

A majority of carbonatite deposits are localized within stable continental tectonic units, such as shields, cratons, and crystalline blocks, with well-developed old Earth crust. Inside these large regional structures, carbonatites are confined to alkaline magmatic provinces controlled by intracontinental rift and fault systems. There are few exceptions from such a predominant tectonic setting. The Carboniferous Aley deposit, British Columbia, Canada, is present in the Paleozoic foreland belt at the western margin of the North American continent (Pell and Höy, 1989). Two deposits, Cenozoic Dalucao and Maoniuping, Sichuan, China, are localized in the western margin of the Yangtze craton in the Cenozoic collision-related Himalayan Mianning-Dechang REE zone (Hou and others, in press). Meanwhile, this zone was superimposed on the Paleozoic longitudinal Panxi rift (Niu and others, 2003).

Rocks Associated with Carbonatites

Rocks in and around the carbonatite deposit are recorded here in the same terms used in the published maps and reports. We have used two fields in an attempt to provide some spatial information. The field "RocksInDeposit" is used for rocks that are only represented in the deposit itself and not observable on a regional map. This field includes listed magmatic and metasomatic rocks associated with carbonatites. Table 3 shows the frequency of these rocks in deposits. The rocks are divided into five groups: (1) *Carbonatitic rocks* that include, besides carbonatite itself, breccia in 30 percent of deposits and agglomerate in 12 percent of deposits; in many deposits the breccia is defined as “eruptive” and actually might be an analog of agglomerate; (2) *Alkaline rocks* ranging from syenite (33 percent) to relatively rare alkaline granite (5 percent); (3) *Alkaline nepheline-feldspathoid syenitic rocks* are also widespread mainly as nepheline syenite (35 percent) and ijolite (28 percent); (4) *Alkaline ultramafic and mafic rocks* are represented commonly by pyroxenite (28 percent), mainly bebedourite, combined with syenitic rocks of the two former groups; and (5) *Metasomatic rocks* contain mostly fenite (12 percent) and glimmerite (9 percent).

Table 3. Frequency of rocks associated with carbonatites
[Count is number of deposits; % is percentage of deposits with associated rock type. Many deposits associated with more than one rock type.]

Rock type	Count	%
Carbonatitic rocks		
carbonatitic breccia	18	30
carbonatitic agglomerate	7	12
Alkaline rocks		
syenite	20	33
trachyte	9	15
nordmarkite	4	7
alkaline granite, pegmatite	3	5
Alkaline nepheline-feldspathoid syenitic rocks		
nepheline-syenite	21	35
ijolite	16	27
melteigite	7	12
phonolite	5	8
foyaite	4	7
nephelinite	3	5
urtite	3	5
malignite	2	3
shonkinite	2	3
okaite	2	3
tephrite	1	2
melilitolite	1	2
Alkaline ultramafic and mafic rocks		
pyroxenite (incl. bebedourite)	17	28
lamprophyre, monchiquite, alnoite	9	15
phoscorite	7	12
jacupirangite	6	10
gabbro, diabase	6	10
peridotite	5	9
tuff	5	9
dunite	4	7
basalt	1	2
Metasomatic rocks		
fenite	7	12
glimmerite	5	8
albitite	3	5
silexite	1	2

Rock alteration type is shown also in the special field “AlterType;” in 85 percent of the deposits, it is fenite surrounding carbonatite-alkaline intrusive complexes. The width of such fenite rings ranges from 0.15 to 2.5 km (see the “Alteration Width” field).

With respect to associated rock types, the entire population of deposits can be roughly divided into two groups, 35 syenite-related deposits with total tonnage of 6.851 Mt and 25 ultramafic (±syenite)-related deposits containing 4,905 Mt. Statistical test showed insignificant difference in tonnage and grades between these two groups.

Country Rocks

Country rocks that are recorded both in the deposits and on a regional map are placed in the field "RocksOnMapInDeposit," which also contains the geologic age of the rocks (in parentheses after rock definitions). In table 4, the country rocks are divided into two categories. Among *Metamorphic rocks*, gneiss, schist, and quartzite are dominant. Most are Archean (28 percent), Proterozoic (29 percent), and undivided Precambrian (31 percent) complexes. Prevailing old ages of metamorphic rocks correspond to craton-related “Tectonic Setting” described above. *Sedimentary and magmatic rocks* of Paleozoic (13 percent) and Mesozoic (3 percent) ages are not typical for the country rocks of carbonatite deposits. A part of sedimentary country rocks pertains to Precambrian complexes.

Table 4. Frequency of country rocks of the carbonatite deposits
[Count is number of deposits; % is percentage of deposits with associated rock type. Many deposits associated with more than one rock type.]

Rock	Count	%
Metamorphic rocks		
gneiss, granite gneiss, granulite	40	67
schist	13	22
quartzite	13	22
shale, phyllite	10	17
metamorphic mafic and ultramafic rocks (amphibolite, serpentinite, etc.)	6	10
metavolcanic rocks	5	9
Sedimentary and magmatic rocks		
clastic rocks (sandstone, siltstone, conglomerate)	21	35
carbonate rocks (dolomite, limestone, marble)	11	18
felsic volcanics	4	7
mafic volcanics	5	9
granitoids	14	25
gabbro	1	2

Shape of Carbonatite Intrusions

The "CarbonatiteShape" field illustrates configuration of single carbonatite intrusions and alkali-carbonatite intrusive complexes. The generalized types of occurrences and proportions of their sizes ("CarbonatiteArea") and ore tonnage limits are shown in table 5. In order to consistently capture information about the size and shape of carbonatites as presented in two-dimensional projection to the surface, the shortest dimension (b axis) is measured as the distance between parallel lines that just touch the object. After the short dimension is determined, the long axis is measured perpendicular to the b axis using the same criteria. Many carbonatite intrusions can be well represented by an ellipse. Where published estimates of the projected area of the body are not available we estimated the area using the standard formula for area of an ellipse (area = 3.14159 a b / 4).

Simple circular or oval carbonatite plugs with or without mapped alkaline intrusive rocks are dominant, composing 45 percent of deposits. Maximum tonnage of 2,898 Mt is indicated in the Seis Lagos niobium deposit, Brazil; minimum tonnage of 0.2 Mt is known in the Karonge deposit, Burundi. Alkali-carbonatite intrusive complexes are larger and, as a rule, contain carbonatite only as subordinate intrusions forming conic circular sheets, lenses, and small plugs among surrounding alkaline and ultramafic rocks. The third group consists of fissure-filling carbonatite dikes, veins, and stockworks partially of hydrothermal origin (Mitchell, 2005). Statistical tests do not show significant correlation between area and tonnage of deposits in these three groups.

Table 5. Range of tonnages and alteration areas by configuration of carbonatite deposits [Mt, million tonnes; n.d., no data]

Configuration	Number of deposits	%	Carbonatite area, sq. km		Tonnage limits, Mt	
			from	to	from	to
Plug	27	45	12.6	0.3	2898	0.2
Alkali-carbonatite complex	18	30	1327	1.4	1255	11
Dike, vein	15	25	15.8	0.6	455	0.03
n.d.	1	2	n.d.		0.1	

Mineralogical Subtypes of Carbonatite Deposits

Carbonatites are divided into three main mineralogical subtypes ("MineralType") by dominant carbonate mineral compositions and textural features. These subtypes are determined from the original sources for each deposits with respect to general "Carbonatite nomenclature" by Kresten (1983). (1) Sövite and alvikite have been defined as calcitic carbonatites; this subtype is most widespread (26 deposits, 43 percent). (2)

Beforsite and (or) rauhaugite indicate dolomite-ankeritic carbonatites; this subtype has been observed in 9 deposits (16 percent). Alvikite and beforsite are fine-grained “hypabyssic equivalents” of carbonatites mostly composing dikes, veins, and sheets. (3) A combination of sövite and beforsite (±rauhaugite) is recognized in 23 deposits (38 percent). (Besides these main varieties, Fe-(ankerite, siderite)-carbonatite is noted as a considerable component in 5 sövite deposits and Si-(quartz)-carbonatite in 2 sövite deposits). Statistical tests of three main mineralogical subtypes—sövite, beforsite, and combined sövite-beforsite—did not reveal any significant differences in tonnages and grades.

Mineralogy

Information on the mineralogy of the deposits varies widely in quantity and quality. Depending on the purpose of a study and the researcher's interest, a report on a mineral deposit might contain a detailed list of alteration minerals and a mention of unnamed phosphate, rare earth, thorium, and uranium minerals; a detailed list of ore minerals and mention of alteration in broad terms; a complete list of all minerals; or a sparse list of minerals. In some studies, the author attempted to list the relative or absolute amounts of each mineral. Unfortunately, these attempts are not common and frequently not comparable among reports because of different standards. Thus, it was decided to use only the presence or absence of ore and gangue minerals ("Ore Minerals" and "GangueRock Minerals") in this file. General frequencies of minerals of both fields are presented in tables 6, 7, 8, and 9. Main ore minerals are listed in table 6, showing pyrochlore as a major source of Nb; Nb–rutile and Nb–ilmenite also are essential in some deposits. Monazite, bastnaesite, and synchysite are the most important source of REE elements. Predominance of calcite and dolomite among gangue minerals (tables 8, 9) corresponds to the main mineral subtypes of carbonatites.

Table 6. Frequency of main ore minerals
[Count, number of deposits; %, percentage of deposits containing the mineral]

Minerals	Count	%
apatite	57	95
pyrochlore, Ba-, Ce-, Sr-, U-	53	88
barite, Sr-barite	45	75
magnetite	44	73
pyrite	40	67
monazite, monazite-(Ce)	36	60
fluorite	28	47
rutile, Nb-rutile, ilmenorutile	27	45
bastnaesite, bastnaesite-(Ce)	25	42
zircon	25	42
ilmenite, Nb-ilmenite	24	40
hematite	23	38
perovskite, perovskite-(Ce)	21	35
galena	19	32
pyrrhotite	18	30
strontianite	18	30
goethite	16	27
synchysite, synchysite-(Ce)	16	27
titanite	16	27
chalcopyrite	15	25
anatase	14	23
parisite, -(Ce), -(Nd)	14	23
columbite	13	22
sphalerite	13	22
baddeleyite	11	18
florencite, florencite-(Ce)	10	17
ancyllite, ancyllite-(Ce)	9	15
goyazite	9	15
crandallite, Ce-crandallite	9	15
gorceixite	9	15
allanite	8	13
celestite, Ba-celestite	8	13
limonite	8	13
thorite	8	13
sphene, Nb-sphene	8	13
molybdenite	7	12
thorianite, U-thorianite	7	12

Table 7. Frequency of minor and rare ore minerals
[Count, number of deposits; %, percentage of deposits containing each mineral of the group]

Minerals	**Count** (for each mineral)	**%**
carbocernaite, -(Ce); pyrolusite; xenotime, -(Y), -(Ce)	6	10
aeschynite, Nb-aeschynite; alloy Cu-Zn, Sn-Cu, Sn-Zn; burbankite; cerianite, -(Ce); fergusonite, -(Nd), -(Ce), -(Y); fersmite; psilomelane, zirconolite	5	8
britholite, britholite-(Ce); brookite, chevkinite, chevkinite-(Ce); rhabdophane, rhabdophane-(Ce); wulfenite	4	7
betafite; Nb-brookite; calzirtite; cebaite-(Ce), cebaite-(Nd); copper; cordylite, cordylite-(Ce); daqingshanite, -(Ce); eudialyte; gold, electrum; isokite; pentlandite, Ag-, Co-; uraninite; zirkelite	3	5
bornite; cerussite; chalcocite; cheralite; chromite; churchite; fluocerite; götzenite; huanghoite-(Ce); röntgenite-(Ce); samarskite, -(Y); tin	2	3
aenigmatite; azurite/malachite; bafertisite; baotite; betekhtinite; beudantite; bismuth; braunite; bravoite; cabriite; cassiterite; cerite; chondrodite; cubanite; dingdaohengite-(Ce); froodite; hessite; hibonite; iron; jalpaite; juonniite; kainosite-(Y); kimzeyite; kobeite-(Y); kukharenkoite-(Ce); küstelite; lanthanite; lead; leucoxene; loparite-(Ce); lusungite; mackelveyite-(Y); mackinawite; majakite; manganite; maoniupingite-(Ce); marcasite; marianoite; millerite; naummanite; niocalite; parkerite; perrierite-(Ce); pyromorphite; pyrophanite; REE-carbonate; REE-phosphate; sahamalite-(Ce); sellaite; shadlunite; siegenite; silver; sperrylite; Sr-Ba carbonate; Sr-REE carbonate; stromeyerite; talnakhite; tetrahedrite; thortveitite; tongxinite; valleriite; villiaumite; violarite; witherite; wittichenite; wöhlerite	1	2

Table 8. Frequency of main gangue minerals
[ount, number of deposits; %, percentage of deposits containing the mineral]

Minerals	Count	%
calcite, Sr-, Mn-	56	93
dolomite	43	72
phlogopite, Ba-, Fe-	42	70
biotite	37	62
quartz	31	52
aegerine, aegerine-augite, augite	29	48
ankerite	20	33
K-feldspar	20	33
pyroxene, diopside	19	32
garnet, melanite	17	28
olivine	16	27
vermiculite	15	25
siderite, Mn-siderite	14	24
amphibole	13	22
riebeckite, Mg-riebeckite	12	20
chlorite	11	18
kaolinite, dickite	9	15
wollastonite	7	12

Table 9. Frequency of minor and rare gangue minerals
[Count, number of deposits; %, percentage of deposits containing each mineral of the group]

Minerals	**Count** (for each mineral)	%
albite	6	10
cancrinite; epidote; muscovite; nepheline; serpentine; spinel	5	8
arfvedsonite; barytocalcite; montichellite; norsethite; zeolite	4	7
crocidolite, Mg-crocidolite; gypsum; melilite; pectolite, Mn-pectolite; tremolite	3	5
actinolite; bömite; gibbsite; hematite; hornblende; rhodochrosite; strontianite; svanbergite; talc; vesuvianite;	2	3
alstonite; alunite; benstonite; breunnerite; brucite; clinohumite; corundum; dawsonite; eckermannite; edingtonite; hauyne; hercynite; hydromica; hyalophane; jacobsite; leucite; magnesite; montmorillonite; natrolite; pyrophyllite; richterite; sanidine, scapolite; staurolite; vivianite	1	2

Spatially related deposits

Here we record other deposits by type that are within 5 km ("Assoc Deposits less 5km") and within 10 km ("Assoc Deposits less 10km") of a carbonatite deposit. In many situations, these other spatially related deposits are merely occurrences and not economic mineral deposits. Nevertheless, many of these occurrences can be typed and their types might provide important information about the possible association with carbonatite deposits. Each deposit type is coded with the deposit type number and deposit type as listed in U.S. Geological Survey Bulletins 1693 (Cox and Singer, 1986) and 2004 (Bliss, 1992). Within 5 km, 13 thorium-rare-earth veins closely associated with carbonatite (Model 11d, described by Staatz, 1992), 3 carbonatite (Model 10), 3 apatite-magnetite, and 1 titanium deposits are known. Within 10 km, 7 carbonatite and 1 apatite deposits are noted. These data accentuate the separate grouping of Nb– and REE–carbonatites that are generally located in large regional alkaline provinces and belts mainly far from other mineral deposits.

Preliminary Analysis

Grade and Tonnage Models

Grade and tonnage models of mineral deposits are useful in quantitative resource assessments and exploration planning. Having some idea of the possible values of alternative kinds of deposits that might be sought is critical to good exploration planning. In quantitative resource assessments, these models play two roles: (1) grade and tonnage models can help classify the known well-explored deposits in a region into types and therefore aid in delineation of areas permissive for types and (2) the models provide information about the potential value of undiscovered deposits in the assessment area, a key to economic analyses of these resources. Construction of grade and tonnage models involves multiple steps. The first is the identification of a group of well-explored deposits that are believed to belong to the mineral deposit type being modeled. "Well-explored" here means completely drilled in three dimensions. After deposits are identified, data from each are compiled. These data consist of average grades of each metal or mineral commodity of possible economic interest and tonnages based on the total production, reserves, and resources at the lowest available cutoff grade. Here we use the deposits that have tonnages recorded in the "Tonnage" field. We exclude deposits with grades and tonnages only in the "Comments" field because of indications that more exploration is needed for these deposits.

Relations among grade and tonnage variables are important for simulations of resources. These relations also affect our understanding of how deposits form and our assumptions about resource availability. Tonnage is correlated with REE grade ($r = -0.48^{**}$, $n = 35$). (** means significant at the 1-percent level). 15 deposits of 55 deposits with tonnages have no Nb grades reported.

Frequency distributions of the tonnages and niobium, REE, and phosphorus grades for the deposits of the well-explored carbonatite deposits reported in the file can be employed as models of the grades and tonnages of undiscovered deposits. Here these frequencies are plotted in figures 2–5 and are summarized in table 10. Grade and tonnage models are presented in a graphical format in order to easily compare deposit types and to display the data. The grade and tonnage plots show the cumulative proportion of deposits versus the tonnage or grade of the deposits. Individual symbols represent the deposits, and intercepts for the 90th, 50th, and 10th percentiles are plotted. Percentiles of grades that contain unreported values, such as Nb, REE, and P, were based on the observed distributions. Based on the Shapiro-Wilk W test, tonnage, Nb, and P grades are not significantly different from the lognormal distribution at the 1-percent level. Using the same test, the distribution of REE is significantly different from lognormal at the 1-percent level because of a single low-grade deposit.

Table 10. Grade and tonnage models of carbonatite deposits
[Mt, million tones. See also figures 2-5.]

	Number deposits	10th percentile of deposits	50th percentile of deposits	90th percentile of deposits
Tonnage (Mt)	55	650	49.0	0.58
Nb_2O_5 grade (%)	55	2.0	0.23	0.0
RE_2O_3 grade (%)	55	4.6	0.61	0.0
P_2O_5 grade (%)	55	16.0	0.0	0.0

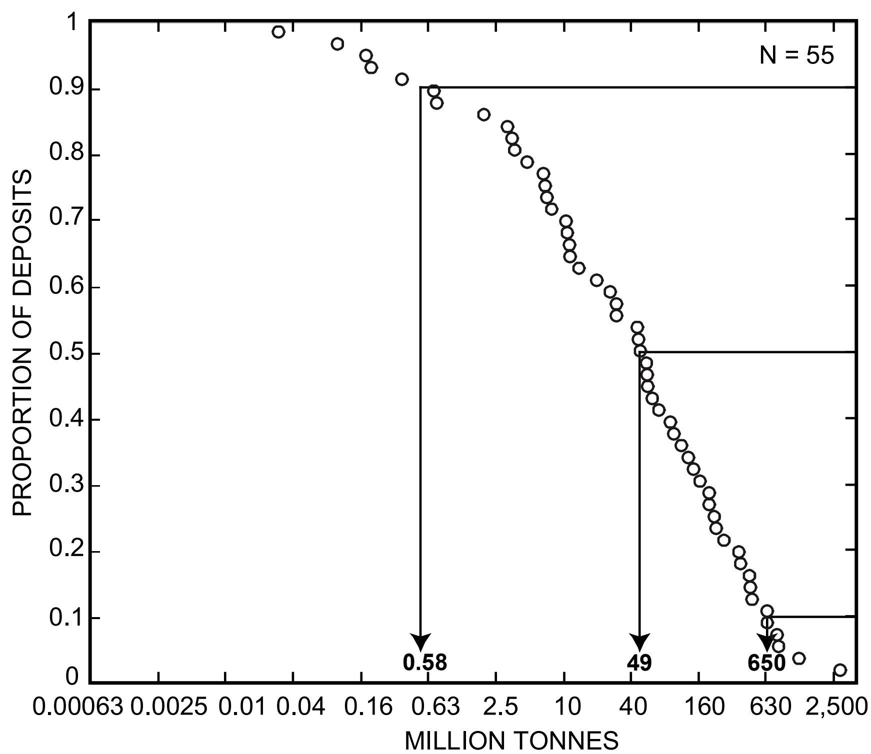

Figure 2. Cumulative frequency of ore tonnage of Nb– and REE–carbonatite deposits. Each circle represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the observed distribution are provided.

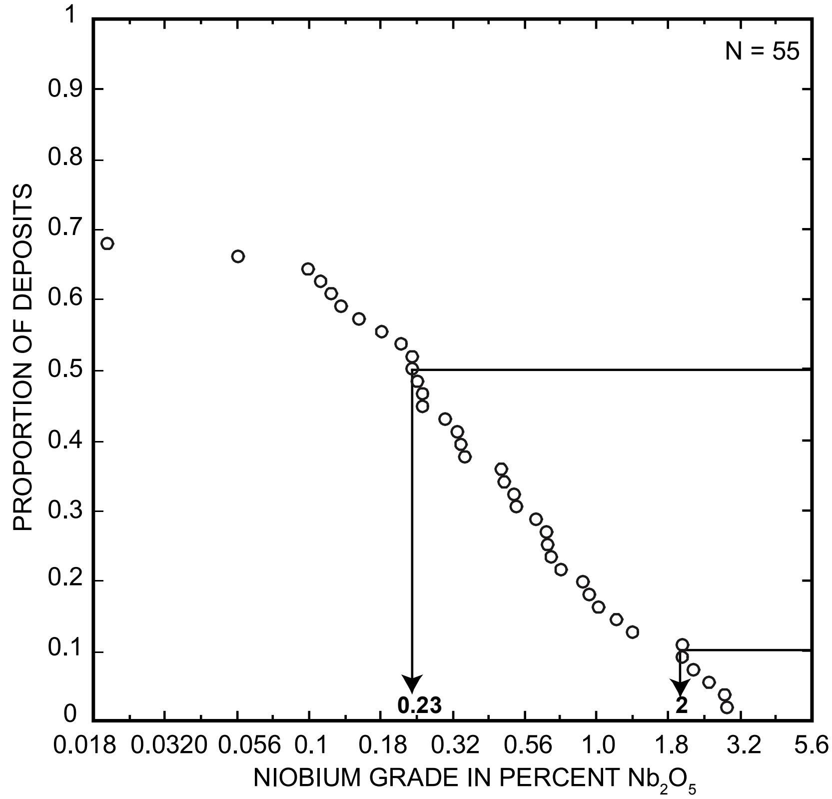

Figure 3. Cumulative frequency of Nb_2O_5 grade of Nb– and REE–carbonatite deposits. Each circle represents an individual deposit. Intercepts for the 50th and 10th percentiles of the observed distribution are provided.

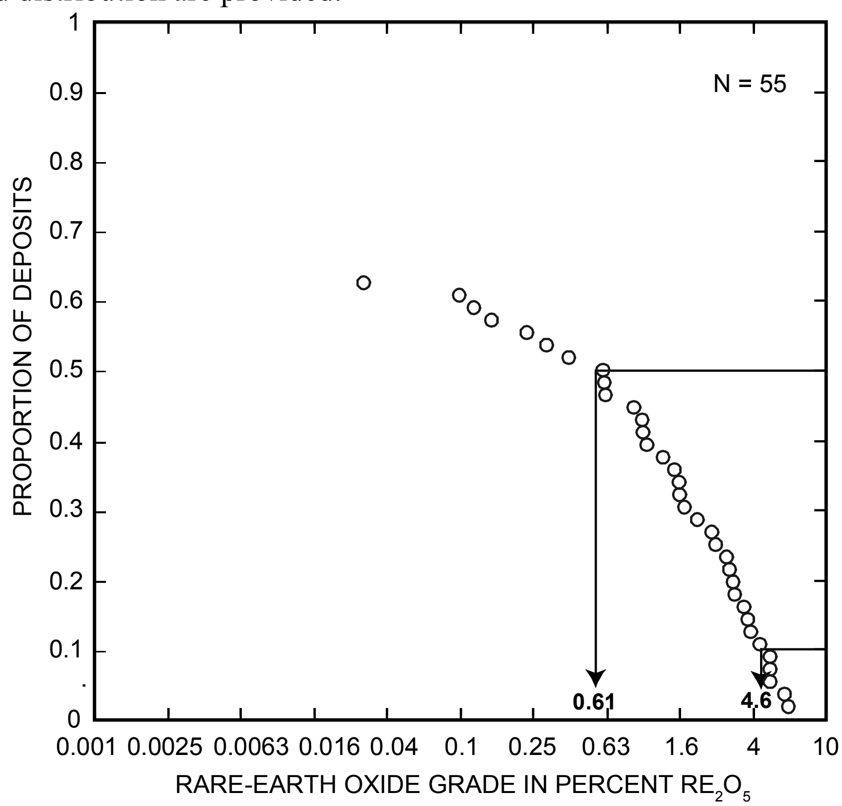

Figure 4. Cumulative frequency of RE_2O_3 elements grade of Nb– and REE–carbonatite deposits. Each circle represents an individual deposit. Intercepts for the 50th and 10th percentiles of the observed distribution are provided.

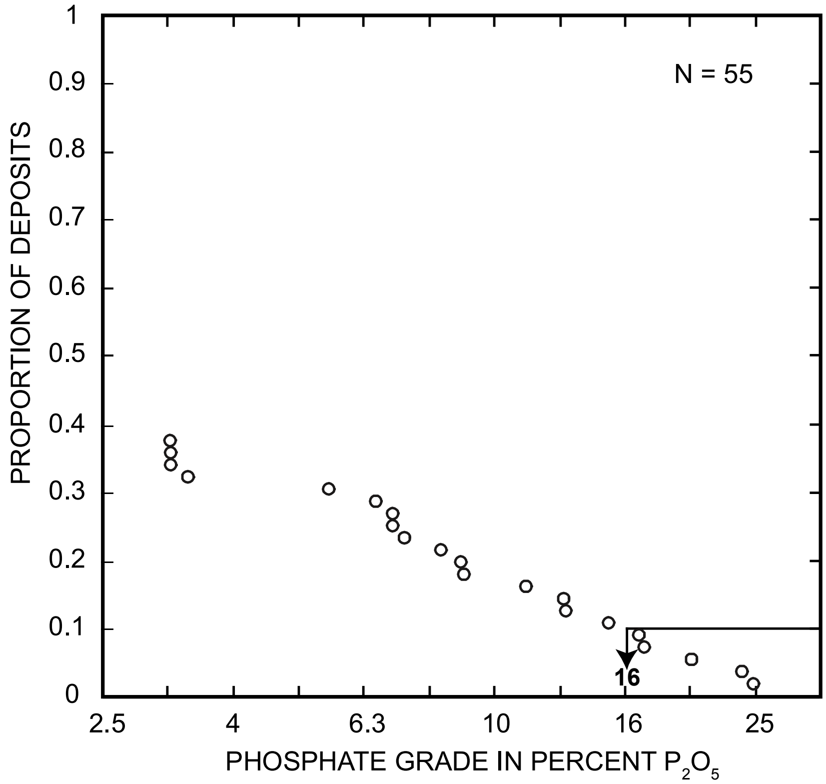

Figure 5. Cumulative frequency of P_2O_5 grade of Nb– and REE–carbonatite deposits. Each circle represents an individual deposit. Intercept for 10th percentile of the observed distribution is provided.

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