LONDONITE, A NEW MINERAL SPECIES: THE Cs-DOMINANT ANALOGUE OF RHODIZITE FROM THE ANTANDROKOMBY GRANITIC PEGMATITE, MADAGASCAR

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ABSTRACT

Londonite, $(Cs,K,Rb) Al_4 Be_4 (B,Be)_{12} O_{28}$, is the Cs-dominant analogue of rhodizite. It occurs with rhodizite at Antandrokomby, a dike of granitic pegmatite in the Manandona valley, Antsirabe region, and at Ampanivana and Antsongombato, in the Betafo region south of Mahaiza, all in Madagascar. Londonite occurs in the inner zones and in miarolitic cavities of highly evolved pegmatites rich in red tourmaline. Associated minerals include microcline, quartz, albite, tourmaline (elbaite – liddicoatite – schorl series), Cs-rich beryl, spodumene, danburite, Mn-rich fluorapatite, hambergite, microlite, manganocolumbite, manganotantalite, béhierite, and hafnian zircon, among others. Londonite occurs as equidimensional crystals a few millimeters across, and exceptionally up to 7 cm. The dominant morphology is dodecahedral {110} and rare deltoid dodecahedral {221}, modified by tristetrahedral {211}, tetrahedral {111} and very rare cube {100} faces. Crystals are colorless to white to yellow, with a white streak. The luster is vitreous. Crystals are translucent to transparent. Optically, the mineral is isotropic, with an index of refraction of 1.693. Mohs hardness is 8. It has no cleavage or parting, and is brittle with a conchoidal fracture. Its density is 3.34 g/cm^3 (meas.) and 3.42 g/cm^3 (calc.). Londonite is isometric with space group $P\bar{4}3m$. The cell parameters are: a 7.321 (1) Å, V 392.30 $Å^3$, and $Z = 1$. The three strongest X-ray powder-diffraction lines measured for londonite [d in Å(I)(hkl)] are 2.9898(100)(211), 2.1132(70)(222), and 2.4410(50)(300,221). Electron-microprobe analyses reveal a wide range of K and Cs contents and an overall low abundance of Rb. The empirical formula based on 28 atoms of oxygen and calculated from an average of five analyses from Antandrokomby is: $(Cs_{0.48}K_{0.38}Rb_{0.09}Na_{0.03}Ca_{0.02}Mn_{0.01})_{\Sigma1.01} (Al_{3.98}Li_{0.02}Fe_{0.01})_{\Sigma4.01} Be_4 [(B_{10.99}Si_{0.01})_{\Sigma11.00} Be_1]_{\Sigma12.00} O_{28}$, with the proportion of B and Be fixed by stoichiometry. The mineral is named after David London, Professor of Geology and Geophysics, University of Oklahoma, in recognition of his experimental studies of evolved granitic melts and his contributions to our understanding of the origin of granitic pegmatites.

Keywords: londonite, new mineral species, cesium potassium aluminum beryllium borate, rhodizite, Antandrokomby, Ampanivana, Antsongombato, Madagascar.

SOMMAIRE

La londonite, $(Cs,K,Rb) Al_4 Be_4 (B,Be)_{12} O_{28}$, correspond au pôle césique équivalent de la rhodizite. On la trouve avec la rhodizite dans un filon de pegmatite granitique à Antandrokomby, dans la vallée de Manandona, région d'Antsirabe, de même qu'à Ampanivana et Antsongombato, dans la région de Betafo, au sud de Mahaiza, au Madagascar. La londonite se présente dans les zones internes et les cavités miarolitiques de massifs de pegmatite fortement évoluée, riche en tourmaline rouge. Lui sont associés microcline, quartz, albite, tourmaline (série elbaïte – liddicoatite – schorl), béryl césique, spodumène, danburite, fluor-apatite manganifère, hambergite, microlite, manganocolumbite, manganotantalite, béhierite, et zircon hafnifère, entre autres. Les cristaux sont équidimensionnels, quelques millimètres de taille, et atteignant jusqu'à 7 cm. Les formes dominantes sont dodécaédrique {110} et (rarement) dodécaédrique deltoïde {221}, telles que modifiées par les faces tristétraédrique {211}, tétraédrique {111} et, très rarement, cubique {100}. Les cristaux sont incolores ou blancs à jaunâtres, avec une rayure blanche. L'éclat est vitreux. Les cristaux sont translucides ou transparents. Optiquement, ils sont isotropes, avec un indice de réfraction de 1.693. La dureté de Mohs est 8. Il n'y a pas de clivage ou de plan de séparation; le minéral est cassant, avec une fracture conchoïdale. La densité est 3.34 g/cm^3 (mes.) et 3.42 g/cm^3 (calc.). La londonite est isométrique, groupe spatial $P\bar{4}3m$. Le

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paramètre réticulaire est *a* 7.321 (1) Å, avec $V = 392.30$ Å^3 et $Z = 1$. Les trois raies les plus intenses du spectre de diffraction de la londonite [*d* en Å (*I*) (*hkl*)] sont 2.9898(100)(211), 2.1132(70)(222), et 2.4410(50)(300,221). Les résultats d'analyses à la microsonde électronique révèlent une série ayant des teneurs variables en K et Cs, tout en maintenant une teneur relativement faible en Rb. La formule empirique fondée sur 28 atomes d'oxygène et calculée à partir d'une moyenne des résultats de cinq analyses pour le matériau d'Antandrokomby serait: $(Cs_{0.48}K_{0.38}Rb_{0.09}Na_{0.03}Ca_{0.02}Mn_{0.01})_{\Sigma 1.01}$ $(Al_{3.98}Li_{0.02}Fe_{0.01})_{\Sigma 4.01}$ Be_4 $[(B_{10.99}Si_{0.01})_{\Sigma 11.00}Be_1]_{\Sigma 12.00}$ O_{28}, avec la proportion de B et Be fixée par stoéchiométrie. Le nom honore David London, professeur de géologie et de géophysique, Université de l'Oklahoma, et souligne ses travaux expérimentaux sur les liquides silicatés évolués et ses contributions à propos de l'origine des pegmatites granitiques.

(Traduit par la Rédaction)

Mots-clés: londonite, nouvelle espèce minérale, borate de béryllium, césium, potassium et aluminium, rhodizite, Antandrokomby, Ampanivana, Antsongombato, Madagascar.

Introduction

Recent investigations of new finds of rhodizite from granitic pegmatites in central Madagascar (Fig. 1) reveal the presence of a new mineral species (Pezzotta *et al*. 1997). Electron-microprobe analyses show a broad range in the abundance of the principal alkali cations K, Cs, and Rb. The results clearly show that both K- and Cs-dominant species exist in Madagascar. The K-dominant material is most abundant. We name the Cs-dominant analogue londonite. The name honors Dr. David London (b. 1953), professor of Geology and Geophysics at the University of Oklahoma, in recognition of his experimental studies of evolved granitic melts and his contributions to our understanding of the origin and patterns of crystallization of granitic pegmatites. The name londonite has been approved by the Committee on New Minerals and Mineral Names of the IMA (IMA number 1999–014).

Background Information

Rhodizite was first found as minute crystals on elbaite tourmaline in the Li-rich pegmatites around the villages of Sarapulka and Shaitanka, both near Murzinka, north of Yekaterinburg, in the Middle Urals, Russia. Historically, confusion exists in the literature as to the composition of rhodizite. None of the earliest reports gave Cs as the dominant alkali cation.

The first description of rhodizite by Rose (1834), based on material from the Urals, was qualitative and incomplete. Rose recognized the similarity between rhodizite and boracite. He gave the name rhodizite in allusion to the red color observed in flame tests, attributed to the presence of lithium. Of note was his failure to confirm lithium in solutions obtained by digestion of rhodizite. In the first quantitative chemical description of Russian rhodizite, Damour (1882) did not separate the heavy alkali ions (K, Rb, Cs), nor did he report the presence of Be or Li. As far as we have been able to determine, this was the last published composition of Russian rhodizite.

Subsequently, rhodizite was found in several locations in Madagascar (Fig. 1) including Antandrokomby near Mt. Ibity and at Manjaka in the Sahatany valley (Lacroix 1922). Results of the earliest analysis of rhodizite from Antandrokomby, Madagascar, by Pisani, were reported in Lacroix (1910) and Duparc *et al*. (1911). This composition contains 7.30 wt.% Li$_2$O; K, Rb, or Cs were not differentiated. Lacroix (1910) stated that the material analyzed by Pisani had admixed spodumene. However, from our calculations, we cannot rationalize a usable formula of rhodizite from this bulk composition after removing spodumene. Results of a second analysis of material from Manjaka, Madagascar, reported by Duparc *et al*. (1911), show 0.68 wt.% Li$_2$O; for the first time, the heavy alkali elements are distinguished. Duparc *et al*. (1911) obtained the formula $(Li, K, Cs, Rb, Na, H)_4$ Al_6 Be_7 B_{14} O_{39}. However, our recalculation removing spodumene yields Na-dominant rhodizite with K > Cs.

Lacroix (1922) proposed the formula $(Cs,Rb,K,Na,H)_8$ Al_6 Be_4 B_{12} O_{35}. It is unclear how he derived his formula, as it does not correspond to either of the two reported sets of results for Madagascar material. Strunz (1938) proposed the formula Na K Li$_4$ Al$_4$ Be$_3$ B$_{10}$ O$_{27}$, which he apparently obtained from the 1910 Li-rich bulk composition of Antandrokomby rhodizite as determined by M.E. Pisani.

Frondel & Ito (1965) analyzed Cs-rich material from Manjaka, Madagascar, and reported the formula (Cs,K) Al_4 Be_4 B_{11} O_{25} $(OH)_4$. Buerger & Taxer (1966) refined the structure of rhodizite from Manjaka and obtained a structural formula of Cs Al$_4$ Be$_4$ B$_{12}$ O$_{28}$. This formula requires a neutral Cs atom. On the basis of an electron-spin-resonance spectrum, Donnay *et al*. (1966, 1967) determined that Cs could not be neutral and proposed the formula Cs Al$_4$ Be$_4$ B$_{11}$ O$_{26}$ (OH)$_2$.

Pring *et al*. (1986) gave a comprehensive review of the history of the composition of rhodizite and a detailed investigation of the crystal chemistry of rhodizite. They presented results of a new chemical analysis of K-dominant rhodizite from Ambatofinandrahana, Madagascar, that reduce to the formula $(K_{0.46}Cs_{0.36}Rb_{0.06}Na_{0.02})_{\Sigma 0.90}$ $Al_{3.99}$ Be_4 $(B_{11.35}Be_{0.55}Li_{0.02})$ O_{28}. They also refined the crystal structure and demonstrated that structurally bound H$_2$O is not present in rhodizite, as had been proposed by Frondel & Ito (1965) and Donnay *et al*. (1966).
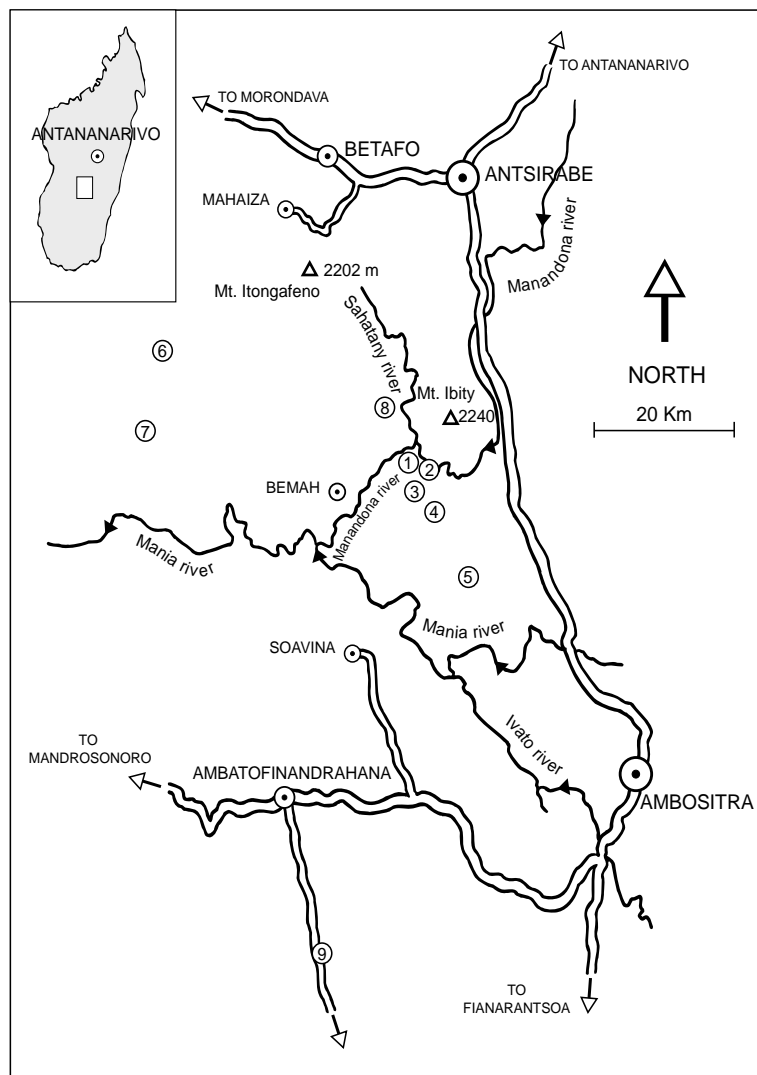
Fɪɢ. 1. Map showing locations of londonite–rhodizite-bearing pegmatites in the Betafo–Antsirabe region, Madagascar. The numbers refer to the following: 1) Antandrokomby, 2) Andasy, 3) Besesitra, 4) Ifasina, 5) Fiakarandava, 6) Antsongombato, 7) Ampanivana, 8) Manjaka, and 9) Ambalalehifotsy.

Subsequent to the work of Pring *et al.* (1986), most modern mineralogists (Nickel & Nichols 1991, Gaines *et al.* 1997, Mandarino 1999) consider rhodizite to be a K-dominant species, and use the Pring *et al.* (1986) formula of $(K,Cs) Al_4 Be_4 (B,Be)_{12} O_{28}$.

Oᴌᴅ ᴀɴᴅ Nᴇᴡ Lᴏᴄᴀʟɪᴛɪᴇs ᴏғ Rʜᴏᴅɪᴢɪᴛᴇ

Rhodizite occurs at four localities. It is found in Russia (Rose 1834, 1836), the United Kingdom (Rob-

erts *et al.* 1990), the United States (Falster & Simmons 1989), and in Madagascar (Lacroix 1910, 1922), where it is found in many pegmatites in the Betafo–Antsirabe area of the central highlands.

Recent field studies in 1995–1999 by one of the authors (F.P.) led to the sampling of rhodizite crystals in many of the locations mentioned in the previous literature (Lacroix 1922, Béhier 1960) and to the discovery of several new occurrences (Pezzotta *et al.* 1997).

The rhodizite crystals analyzed in this study are representative of these old and new localities in Madagascar (Fig. 1). All these localities are in the Betafo–Antsirabe area: Antandrokomby (two dikes), Andasy, Besesitra and Ifasina in the Manandona Valley, Fiakarandava, south of the Manandona Valley, Manjaka, in the Ibity Valley, Antsongombato, 25 km southwest of Mahaiza, and Ampanivana, 15 km south of Antsongombato in the Mania Valley. An additional crystal of rhodizite from the exhausted occurrence of Ambalalehifotsy, reported by Béhier (1960), was taken for analysis from sample MSNM M 31114 housed at the Museum of Natural History of Milan.

Occurrence of Londonite and Its Associated Minerals

The rhodizite crystals studied from the localities listed above revealed a great range in the proportion of K and Cs, depending on the degree of evolution of the host pegmatite. The highest Cs contents typify the crystals collected in the geochemically more evolved pegmatites at Antandrokomby, Ampanivana, Antsongombato, and Manjaka. The dikes of Besesitra and Ifasina, with an intermediate degree of evolution, yield rhodizite crystals with moderate Cs content, and the less evolved dikes at Andasy and Fiakarandava contain rhodizite crystals with a lower Cs content. All these pegmatites are hosted in dolomitic marbles and typically are virtually mica-free.

The data acquired indicate that Cs dominates over K in many of the crystals occurring in the central units and in the miarolitic cavities of the Antandrokomby, Antsongombato, and Ampanivana pegmatites. Individual crystals typically have a Cs-rich rim but exhibit an overall patchy, heterogeneous distribution of Cs-dominant and K-dominant zones in interior portions of crystals.

In addition to the typical rock-forming minerals of pegmatites, such as microcline, albite and quartz, londonite is associated with spodumene, tourmaline (elbaite – liddicoatite – schorl series), danburite, Cs-rich beryl, pollucite, manganoan fluorapatite, hambergite, microlite, xenotime-(Y), monazite-(Ce), native arsenic, scheelite, manganocolumbite, manganotantalite, hübnerite, béhierite, and hafnian zircon, among other species.

Appearance and Physical Properties

The crystals of londonite from Antandrokomby, Ampanivana, and Antsongombato show subtle morphological differences. At Antandrokomby (Fig. 2A), londonite occurs in saccharoidal albite or in cavities as milky white to pale yellow crystals up to one centimeter across. The crystals exhibit a variety of forms, including dodecahedron {110}, tristetrahedron {211}, tetrahedron {111} and rare cube {100} faces. At Ampanivana (Fig. 2B), londonite forms white and pale

yellow dodecahedral crystals up to one centimeter across, occurring only in cavities on large crystals of red-purple tourmaline. At Antsongombato (Figs. 2C, D), the crystals are exceptionally large (up to 7 cm across) with lustrous faces, locally gemmy portions, and a color ranging from white to vivid sulfur yellow. The morphology includes dodecahedra {110} modified by deltoid dodecahedral {221}, tristetrahedral {211} and tetrahedral faces {111} with, in rare cases, additional cube {100} faces.

The crystals have a white streak. The luster is vitreous. Optically, the mineral is isotropic with an index of refraction $n_D = 1.693(1)$. The index of refraction was measured by immersion in Cargille oils. Many crystals show patchy areas of anomalous birefringence. Crystals show a weak yellow-green fluorescence under short-wave ultraviolet light (253.7 nm). The Mohs hardness is 8. The mineral has no cleavage or parting, and is brittle with a conchoidal fracture. Density, as measured with a Berman balance, is 3.34 g/cm^3. Using the composition of londonite from Antandrokomby, as given in Table 1, the calculated density is 3.42 g/cm^3. The lower measured density is likely due to the presence of numerous fluid inclusions and the fact that the measured value represents an average of the whole crystal fragment, which is a heterogeneous mixture of high- and low-Cs zones. Gladstone–Dale calculations for londonite give a compatibility index of 0.023. This value is regarded as excellent (Mandarino 1981).

TABLE 1. CHEMICAL ANALYSES OF LONDONITE AND RHODIZITE

	Ldn 1	Rdz 2	Ldn 3			Ldn 1	Rdz 2	Ldn 3
SiO₂ wt.%	0.07	0.08	n.d.	Si *apfu*		0.01	0.01	n.d.
B₂O₃ (calc.)	47.39	49.60	47.66	B		10.99	10.99	11.00
Al₂O₃	25.10	26.35	25.28	Σ		11.00	11.00	11.00
Fe₂O₃	0.06	0.02	n.d.					
MnO	0.05	0.03	n.d.	Be		5.00	5.00	5.00
BeO (calc.)	15.49	16.21	15.57					
MgO	n.d.	n.d	n.d.	Al		3.98	3.99	3.98
CaO	0.14	0.04	n.d.	Fe³⁺		0.01	0.00	n.d.
Na₂O	0.11	0.19	0.43	Li		0.02	0.02	0.03
K₂O	2.21	5.03	2.12	Σ		4.01	4.01	4.01
Rb₂O	1.04	0.51	1.48					
Cs₂O	8.37	1.70	7.32	Mn		0.01	0.00	n.d.
Li₂O	0.04	0.03	0.06	Ca		0.02	0.01	n.d
				Na		0.03	0.05	0.11
Total	100.07	99.79	99.92	K		0.38	0.82	0.36
				Rb		0.09	0.04	0.13
				Cs		0.48	0.09	0.42
				Σ alkalis		1.01	1.01	1.02

Atoms per formula unit (*apfu*) based on 28 atoms of oxygen. The proportion of B and Be is obtained by stoichiometry: B + Si is set equal to 11.000 *apfu*, and Be, to 5.000 *apfu*. n.d : not detected. Column 1: londonite from Antandrokomby, average result of five analyses. Column 2: rhodizite from Andasy, average result of seven analyses. Column 3: londonite from Antsongombato.

The type specimen on which londonite occurs is in the mineralogical collection of the Museum of Natural History of Milan, Italy, number MSNM M31115. This specimen was collected from the pocket zone of the Antandrokomby pegmatite, near Mt. Ibity, south of the Sahatany Valley, Madagascar. Londonite occurs as two well-formed white crystals 1 cm across on the type specimen. The londonite is associated with well-formed crystals of quartz, albite and red tourmaline, along with massive microcline and corroded danburite. Half of one of these crystals was used to obtain the chemical and physical data published in this work. Some of the fragments of this crystal are now in the mineralogical collection of the Department of Geology and Geophysics, University of New Orleans.

ANALYTICAL METHODS

X-ray diffraction

Powder X-ray-diffraction results were obtained using a Scintag XDS 2000 X-ray diffractometer; the samples were pulverized with an agate mortar and pestle and run using a step scan with 0.015° steps and a three-second dwell time per step over a range of 10° to 75° 2θ. The instrument was calibrated using purified quartz, which was run before and after the unknowns. Cell dimensions were determined using CELL, a modified version of the least-squares indexing program by Appleman & Evans (1973).

Electron-microprobe analysis

Samples were encased in epoxy, ground and polished, and carbon-coated. Representative samples from each of the sites were analyzed on an ARL–SEMQ electron microprobe, operated at an acceleration potential of 15–25 kV, a current of 15 nA, and a beam diameter of 2–3 μm. Standards used included: pollucite (Cs$L\alpha$), Rb-substituted leucite (Rb$L\alpha$), albite (Si$K\alpha$, Na$K\alpha$), sillimanite (Al$K\alpha$), orthoclase (K$K\alpha$), rhodizite (Mn$K\alpha$), and clinopyroxene (Fe$K\alpha$, Ca$K\alpha$).

Direct-coupled plasma spectrometry

Direct-coupled plasma (DCP) spectrometry was used to analyze for Li, Be, and B. Four aliquots of 200 mg of finely pulverized londonite from the type material as well as three additional samples of londonite–rhodizite from the Antsongombato and Andasy pegmatites in the Betafo–Antsirabe region were fused with 400 mg of sodium carbonate + sodium hydroxide (1:1). The resultant cake was dissolved in dilute nitric acid and diluted to a volume of 50 mL for Li and 500 mL for B and Be. Solutions were run on a Spectrometrics Spectrascan V DCP unit against standard solutions of Li, B and Be. Standard solutions were adjusted to contain similar ion contents as the unknowns by adding Al, B, Be, K, and Cs to the solutions to yield a concentration corresponding to $(Cs_{0.5}K_{0.5})$ Al_4 Be_5 B_{11} O_{28}. Sodium also was added to the standard solutions in an amount corresponding to the amount of Na added by the flux. The B standards contained the elements Cs, K, Be, Al and Na; the Li standards contained the elements Cs, K, Be, B, Al and Na, and the Be standards contained Cs, K, Al, B and Na.

Scanning electron microscopy

An Amray 1820 digital scanning electron microscope equipped with a back-scattered electron and energy-dispersion X-ray detector was operated at 25 kV acceleration potential, working distance of 18 mm, and a final aperture of 300 μm.

CRYSTALLOGRAPHY

X-ray powder-diffraction patterns for rhodizite from the Andasy dike and londonite from the Antandrokomby pegmatite are shown in Table 2. The composition of these samples is given in Table 1. The londonite pattern compares favorably with the pattern of rhodizite from the Andasy dike and with JCPDS pattern 18–327. Londonite is isometric and, by analogy with rhodizite, has space group $P\bar{4}3m$. The cell parameter a is equal to 7.3205(3) Å, V is 392.30(5) Å^3, and $Z = 1$.

CHEMICAL COMPOSITION

Electron-microprobe analyses of all the londonite–rhodizite samples reveal a wide range of K (2.10 to 5.10 wt.% K_2O) and Cs contents (1.50 to 8.60 wt.% Cs_2O), with a low overall abundance of Rb (0.44 up to 1.37 wt.% Rb_2O). Na, Ca, Mg, Fe, and Mn have been found in trace amounts only. All of the analyzed londonite–rhodizite crystals exhibit striking heterogeneity under back-scattered electron imaging, although individual crystals may have a Cs-rich rim. Oscillatory and patchy patterns of zonation are common (Fig. 3). Cs-enriched portions of the londonite–rhodizite crystals occur in four main types: as primary growth zoning, as irregular patchy areas, as exsolution-like lamellae, and as late-stage fracture-controlled veins (Fig. 3). Cs-enriched portions are abundant in the crystals from the center of the Antandrokomby and Antsongombato pegmatite and the cavities of the Ampanivana dike.

DCP analyses revealed only small amounts of Li (0.02–0.06 wt.% Li_2O) confirming that Li is not an essential constituent of londonite or rhodizite. DCP results for B and Be are slightly lower than the expected concentrations (47.39 wt.% B_2O_3, 15.49 wt.% BeO) in londonite. Measured B_2O_3 concentrations ranged from 46.02 to 46.48 wt.%, and measured BeO concentrations ranged from 14.97 to 15.05 wt.%. The shortfall is be-

TABLE 2. X-RAY POWDER-DIFFRACTION DATA
FOR LONDONITE AND RHODIZITE

Rhodizite Andasy[1]				Londonite Antandrokomby[1]				Rhodizite JCPDS-18-327		
I/I_0	D_{obs}	d_{calc} (Å)	h k l	I/I_0	D_{obs}	d_{calc} (Å)	h k l	I/I_0	d(Å)	h k l
30	7.158	7.300	1 0 0	17	7.342	7.320	1 0 0	20	7.31	1 0 0
5	5.143	5.158	1 1 0	5	5.190	5.176	1 1 0	12	5.17	1 1 0
								4	4.23	1 1 1
5	3.633	3.647	2 0 0	10	3.663	3.660	2 0 0	12	3.67	2 0 0
35	3.250	3.262	2 1 0	35	3.276	3.274	2 1 0	50	3.27	2 1 0
100	2.9673	2.9781	2 1 1	100	2.9898	2.9886	2 1 1	100	2.983	2 1 1
5	2.5719	2.5791	2 2 0	5	2.5896	2.5882	2 2 0	4	2.575	2 2 0
40	2.4279	2.4279	3 0 0, 2 2 1	50	2.4410	2.4402	3 0 0, 2 2 1	50	2.440	3 0 0
45	2.1953	2.1995	3 1 1	30	2.2076	2.2072	3 1 1	20	2.205	3 1 1
70	2.1031	2.1058	2 2 2	70	2.1132	2.1132	2 2 2	35	2.111	2 2 2
5	2.0202	2.0232	3 2 0	3	2.0308	2.0303	3 2 0	4	2.025	3 2 0
35	1.9568	1.9565	3 2 1	35	1.9568	1.9565	3 2 1	20	1.956	3 2 1
50	1.8226	1.8237	4 0 0	20	1.8304	1.8301	4 0 0	20	1.829	4 0 0
40	1.7686	1.7693	4 1 0, 3 2 2	40	1.7759	1.7755	4 1 0, 3 2 2	25	1.775	4 1 0
25	1.7189	1.7194	3 3 0, 4 1 1	15	1.7255	1.7254	3 3 0, 4 1 1	18	1.724	3 3 0
								2	1.675	3 3 1
5	1.6314	1.6312	4 2 0	5	1.6371	1.6369	4 2 0	4	1.635	4 2 0
5	1.5926	1.5919	4 2 1	5	1.5980	1.5975	4 2 1	12	1.597	4 2 1
10	1.5551	1.5553	3 3 2	5	1.5606	1.5607	3 3 2	16	1.560	3 3 2
				3	1.4940	1.4943	4 2 2	2	1.492	4 2 2
5	1.4598	1.4590	4 3 0, 5 0 0	3	1.4641	1.4641	4 3 0, 5 0 0	4	1.463	5 0 0
15	1.4314	1.4306	5 1 0, 4 3 1	10	1.4356	1.4357	5 1 0, 4 3 1	10	1.434	5 1 0
10	1.4051	1.4039	5 1 1, 3 3 3	8	1.4088	1.4088	5 1 1, 3 3 3	12	1.407	5 1 1
5	1.3556	1.3546	5 2 0, 4 3 2	5	1.3594	1.3594	5 2 0, 4 3 2	6	1.358	5 2 0
5	1.3332	1.3319	5 2 1	3	1.3365	1.3365	5 2 1	8	1.336	5 2 1
45	1.2909	1.2896	4 4 0	20	1.2938	1.2941	4 4 0	16	1.294	4 4 0
								2	1.274	4 4 1
								4	1.254	5 3 0
								2	1.219	6 0 0
				5	1.1875	1.1875	6 1 1, 5 3 2	12	1.187	6 1 1
				8	1.1430	1.1433	5 4 0, 6 2 1	4	1.143	5 4 0
				3	1.1294	1.1296	5 4 1	2	1.130	5 4 1
								2	1.117	5 3 3
				3	1.1037	1.1036	6 2 2	2	1.104	6 2 2
				3	1.0911	1.0913	6 3 0, 5 4 2	4	1.092	6 3 0

[1] X-ray data for samples analyzed in Table 1.

lieved to be related in part to loss of B during fusion and in part to the analytical error associated with the dilutions and additions of ions to the standard solutions. Thus, the B and Be results are considered to be only semiquantitative and are presented only as confirmation of the approximate B and Be concentrations expected for members of the londonite–rhodizite series. For the compositions given in Table 1, B and Be were assumed to be present in stoichiometric concentrations.

In terms of the three principal alkali-site cations, Cs, K, and Rb, samples with the highest proportion of Cs plot in the londonite field (Fig. 4). Results of electron-microprobe analyses of the crystal from Antandrokomby used as the holotype are shown in Table 1. According to the structural characterization of Pring *et al.* (1986), one Be atom is disordered among the B sites in rhodizite. We have followed this formulation for londonite and assigned the minor Li to the six-coordinated Al site and the minor Si content to the tetrahedral B site (*i.e.,* 11–Si = B). The sum B + Si + Be is set equal to 12 atoms per formula unit (*apfu*). Accordingly, with 5 Be and 11 (B + Si) *apfu*, the empirical formula of londonite, calculated on the basis of 28 atoms of oxygen, is: $(Cs_{0.48}K_{0.38}Rb_{0.09}Na_{0.03}Ca_{0.02}Mn_{0.01})_{\Sigma1.01}$ $(Al_{3.98}Li_{0.02}Fe_{0.01})_{\Sigma4.01}$ Be_4 $[(B_{10.99}Si_{0.01})_{\Sigma11.00}Be]_{\Sigma12.00}$ O_{28}.

RESULTS AND DISCUSSION

Our studies show that there is a broad range in the alkali content of Madagascar londonite and rhodizite, and it is clear that both K-dominant and Cs-dominant species exist. Undoubtedly, this range of alkali composition explains some of the problems in the early studies of rhodizite. An additional complication is the strong heterogeneity of individual crystals, which further complicates bulk analyses. The alkali site of the londonite–rhodizite series contain principally Cs, K, and Rb, with only minor incorporation of Na. We are uncertain if the small amounts of Ca and Mn substitute for the alkali
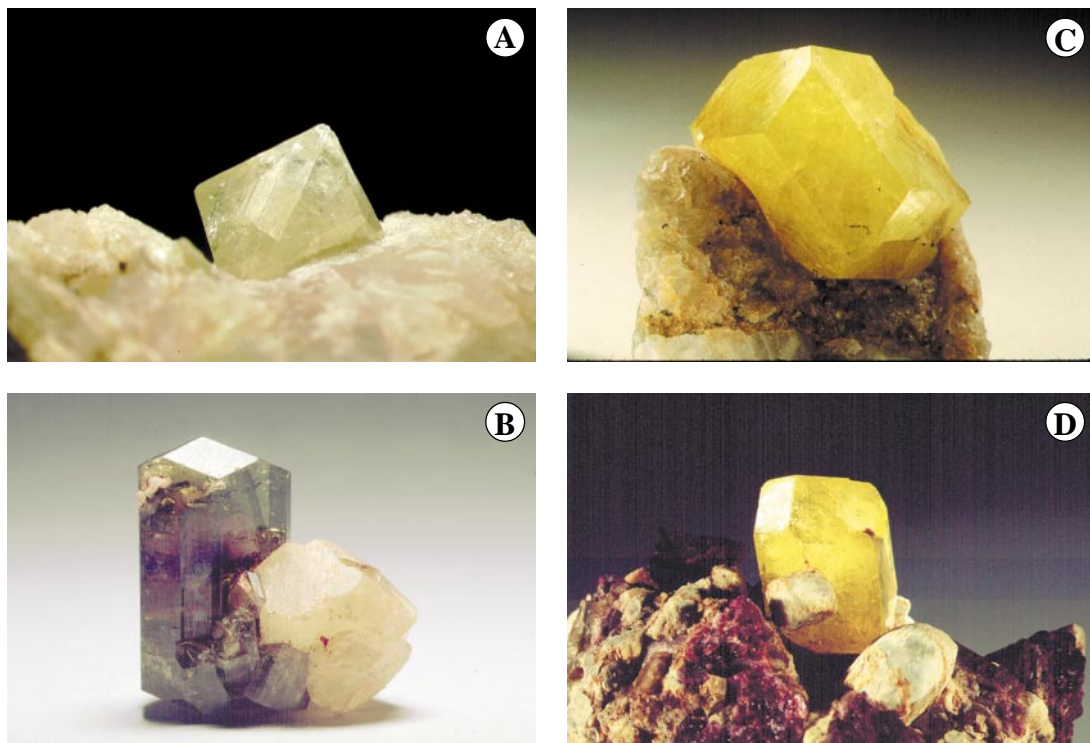
FIG. 2. Color photographs of the londonite crystals. A. A pale yellow-green crystal of londonite on saccharoidal albite from the Antandrokomby pegmatite, Madagascar. The crystal is 0.7 cm across and shows dodecahedron {110}, tristetrahedron {211}, and tetrahedron {111} faces (photo by R. Appiani). B. Milky pale yellow crystal of londonite (1 cm) on a crystal of liddicoatite from Ampanivana, Madagascar (photo by R. Appiani). C. Large, well-formed dodecahedral, sulfur-yellow londonite crystal (1.8 cm) from Antsongombato, Madagascar (photo by W. Wilson). D. An exceptionally large, gemmy, sulfur-yellow londonite crystal (3.5 cm) from Antsongombato, Madagascar (photo by F. Valoti).

ions in the alkali site. We have included them in the alkali site in Table 1. Li and Fe probably substitute for octahedrally coordinated aluminum. Our analyses confirm that Li is a minor component in Madagascar rhodizite and londonite crystals. The range in proportions of the three major alkali cations (Fig. 4) points to a strong correlation between Rb and Cs content, the proportion of Rb increasing with that of Cs. Cs/K values are lowest in rhodizite formed in primitive pegmatites rich in black tourmaline. Some of these samples approach the end-member composition of rhodizite. Cs/K values reach the highest levels in the most evolved pegmatite dikes.

Londonite occurs as both colorless and yellow crystals (Fig. 2). We note that no correlation exists between the color of the mineral and its alkali-site occupancy. Many crystals contain patchy zones of londonite and rhodizite that are only visible by back-scattered electron imaging (Fig. 3). The yellow color is most likely related to defects, which appear to be light-sensitive. At Antsongombato, londonite–rhodizite crystals collected from the dumps are white on the exposed surfaces of crystals and a darker yellow on the unexposed bottom surfaces. The association with pink tourmaline and blue apatite, and the occurrence within miarolitic cavities, are better guides to high-Cs content, but londonite cannot be identified visually. Quantitative chemical analyses are required to distinguish londonite from rhodizite.

The overall Cs and B content of the londonite–rhodizite-bearing pegmatite dikes in Madagascar is extraordinarily elevated, particularly considering the relatively small size of these dikes (centimeters to meters in width) compared with the Cs enrichment found in the much larger LCT-type pegmatites. The near-absence of mica minerals in the londonite–rhodizite-bearing pegmatite dikes is conspicuous and may relate to the conditions of formation of these extremely unusual pegmatites. More work needs to be

done to understand the origin of the pegmatite-forming melts and the genesis of members of the londonite–rhodizite series.
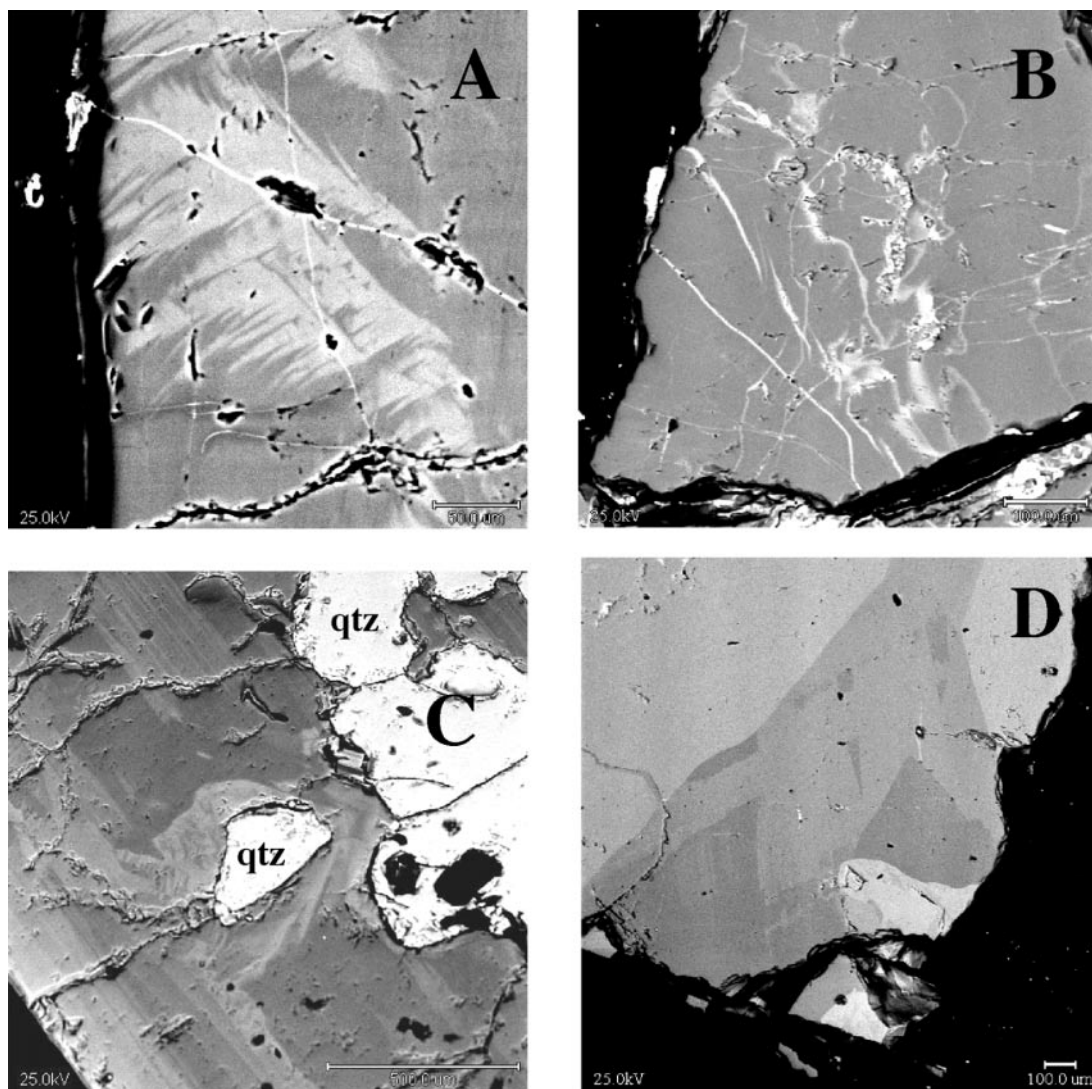
FIG. 3.   Back-scattered electron images of heterogeneities in londonite–rhodizite from samples collected in pegmatites in central Madagascar. Brightness correlates with increasing Cs content. Scale bar represents 50 μm in A, 100 μm in B and D, and 500 μm in C. A. Feathery exsolution-induced (?) domains of londonite (brighter areas) in rhodizite (darker areas) from Antandrokomby. B. Stringers and patches of Cs-rich areas in a londonite–rhodizite crystal from Ampanivana. C. Oscillatory and patchy zoning in a londonite–rhodizite crystal with a londonite rim from Ifasina. The bright white areas are quartz grains. D. Broad irregular patches of varying Cs content in a londonite–rhodizite crystal from Antandrokomby.
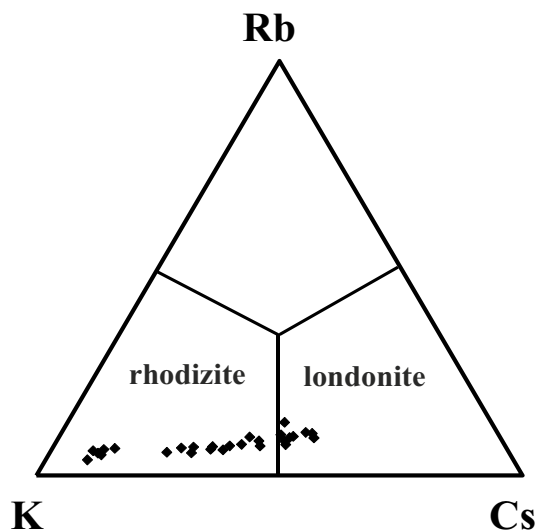
FIG. 4.   Plot of representative compositions of Madagascar rhodizite and londonite in terms of K, Cs, and Rb.

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