

RHODIZITE-LONDONITE FROM THE ANTSONGOMBATO PEGMATITE, CENTRAL MADAGASCAR

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Londonite was approved as a new mineral species in 1999. This rare aluminum-beryllium borate is the cesium-rich analogue of rhodizite; the two end members can be separated only through quantitative chemical analysis. The only known source of gem-quality londonite is the Antsongombato pegmatite in central Madagascar, from which at least 300 carats of rhodizite-londonite have been faceted. The gemstones are colorless to greenish yellow, with an R.I. range of 1.689–1.691, S.G. of 3.34–3.42, and yellowish green fluorescence to short-wave UV. Internal features include partially healed fractures and conspicuous growth zoning that typically correlates to areas of anomalous birefringence. Some near-colorless rhodizite-londonite from Antsongombato has been irradiated to greenish yellow or yellow using X-rays. Both natural-color and irradiated rhodizite-londonite will fade on prolonged exposure to sunlight.

Rhodizite is a rare aluminum-beryllium borate— $(\text{K,Cs})\text{Al}_4\text{Be}_4(\text{B,Be})_{12}\text{O}_{28}$ —that is known only from three countries: Russia (Rose, 1834, 1836), Madagascar (Lacroix, 1910, 1922; Duparc et al., 1911), and the U.S. (Falster and Simmons, 1989). Recently a cesium (Cs)-rich analogue of rhodizite was recognized and named londonite after Dr. David London at the University of Oklahoma, in honor of his contributions to the study of granitic pegmatites. Londonite was approved by the International Mineralogical Association's Commission on New Minerals and Mineral Names in 1999, and described in the literature two years later (Simmons et al., 2001). So far, londonite has been identified only at three pegmatite mines in Madagascar, but gem-quality rhodizite-londonite is known from just one deposit: the Antsongombato pegmatite in the Betafo region. Approximately 300 carats of near-colorless to greenish yellow rhodizite-londonite gemstones (see figures 1 and 2) have been faceted since mining began in October 1998. The attractive appearance and significant hardness (8 on the Mohs scale; Simmons et al., 2001) of the gemstones make them appropriate for jewelry use (again, see figure 1).

This article reports on the history, geology, and mining—as well as the gemological characteristics—of rhodizite-londonite from Antsongombato. One of the authors (FP), who has had extensive first-hand experience with the deposit since 1998, is responsible for much of the unattributed information on the history, mining, and production of the gem material. Since gems with a saturated yellow color are more desirable for jewelry use than pale-colored material, two of the authors (WBS and FP) collaborated on a simple irradiation procedure that is also reported in this article. Note that quantitative chemical analysis is required to differentiate between rhodizite and londonite (as with, for example, elbaite and liddicoatite tourmaline): When cesium (Cs) is the dominant alkali element present, the mineral is londonite; when potassium (K) is more abundant, the species is rhodizite. Therefore, we will refer to the material as *rhodizite-londonite* where the species has not been determined chemically.

See end of article for About the Authors and Acknowledgments.
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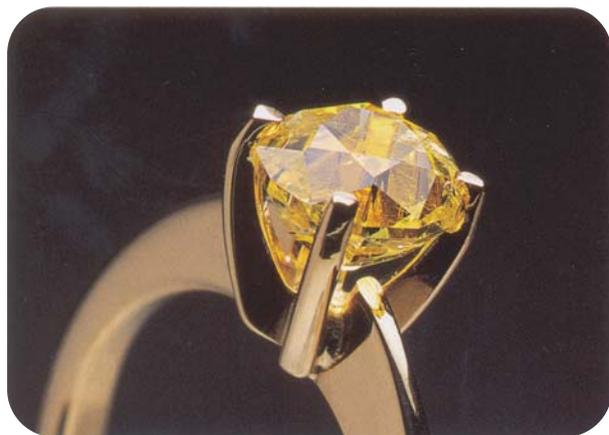


Figure 1. Although rare in gem quality, a significant amount of facet-grade rhodizite-londonite was recently recovered from Antsongombato, Madagascar. This ring by Massimo Novaga features a natural-color rhodizite-londonite that weighs 1.18 ct. Photo by R. Appiani; Pyramide Co. collection.

HISTORY

Although rhodizite has been known as a mineral species for almost 170 years (Rose, 1834), it was not described from Madagascar until much later (Duparc et al., 1910). Today, Madagascar is the only known source of gem-quality rhodizite and londonite. Lacroix (1922) reported colorless to yellow or pale green crystals of rhodizite up to 2 mm wide from the Sahatany Valley (about 35 km east of Antsongombato; figure 3). Mining at the Manjaka pegmatite in the Sahatany Valley during the 1920s is believed to have resulted in some small yellow rhodizites from which stones up to half a carat were faceted. According to local gem dealers, in the 1960s a small quantity of rhodizites up to 2 ct were faceted from colorless to yellow rough obtained from Antsongombato.

The Antsongombato pegmatites have been known since the early 20th century. Duparc et al. (1910) made the first description of the locality, one of 12 tourmaline mines in a series of pegmatites that were worked by French colonists. Attractive gem-quality red tourmaline was mined from massive quartz in the core of the pegmatites or, rarely, from miarolitic cavities. According to local gem traders, these mines and the village of Antsongombato were abandoned, probably in the early 1930s, for unknown reasons; therefore, they do not appear on the geologic map of the area published in 1954 by French geologist A. Emberger.

Behier (1960) specifically mentioned rhodizite from Antsongombato, as well as from two additional localities: Ambalalehifotsy (central Madagascar) and



Figure 2. At 2.02 ct, this is one of the finest examples of faceted natural color rhodizite-londonite seen by the authors. Such material is known only from the Antsongombato pegmatite in central Madagascar. Photo by R. Appiani; Riccardo Caprilli collection.

Anjahamiary (southern Madagascar). In 1964–65, a French colonist organized mining for rhodizite mineral specimens at Antsongombato. Some good specimens were recovered, including a particularly fine, large (about 7 cm across), and vitreous pale yellow crystal of rhodizite-londonite that is in the collection of the Museum of the School of Mines in Paris. According to local dealers, Antsongombato was worked for red tourmaline for a short period in 1978, until the mine was abandoned due to flooding.

During recent field studies (1995–present) of pegmatites in central Madagascar, one of the authors (FP) visited the rhodizite locations mentioned in the literature (i.e., Lacroix, 1910, 1922; Boulanger, 1958; Behier, 1960; Lefevre and Thomas, 1998) and helped discover several new occurrences (Pezzotta et al., 1998; Falster et al., 1999; Pezzotta, 2001). Antsongombato was recognized as having the best potential. In October 1998, investigations by FP revealed a new system of pegmatitic dikes at Antsongombato that were locally mineralized with red tourmaline and yellow Cs-rich rhodizite (later identified as londonite). Mining of one of these pegmatites, referred to as the Antsongombato Gem mine, was quickly organized by the Malagasy company “Pyramide” of Antananarivo. The recovered specimens included a number of well-formed, gem-quality yellow crystals of rhodizite-londonite associated with red tourmaline and blue apatite.

Mining activities stopped in October 2000 after approximately 40 m of the main pegmatite had been penetrated. In January 2001, Pyramide Co. ceased all activities in the area. At the same time, in

collaboration with local Malagasy people, one of the authors (FP) assumed ownership of a series of claims in the Antsetsindrano-Andrembesoa area, including the one containing the Antsongombato Gem mine. Under this ownership arrangement, several local miners (including many former Pyramide Co. workers) currently are prospecting and undertaking small-scale mining of a series of pegmatites that contain rare minerals.

Figure 3. Rhodizite-londonite is known from just three localities (in red), all in central Madagascar. Gem-quality material is known only from Antsongombato. Other pegmatites at Ampanivana and Antandrokombay yield pale-colored crystals that are not transparent enough for faceting. Gem-quality rhodizite (but no londonite) was recently found at a pegmatite near Tetezantsio. Modified from Simmons et al. (2001).



Londonite has also been documented from pegmatites at Ampanivana (15 km to the south) and Antandrokombay (40 km southeast), but no gem-quality material has been found at either locality thus far (Nizamoff et al., 2000; Simmons et al., 2001). Facetable rhodizite was discovered at Tetezantsio (12 km east of Antsongombato) in October 2000, but no londonite has been documented from this locality either (Levinson et al., 2001; Superchi et al., 2001).

LOCATION AND ACCESS

The Antsongombato area is located in the Betafo region in Madagascar's central highlands (again, see figure 3), 4 km east-southeast of the village of Antsetsindrano. The Antsongombato pegmatite is situated on the north side of Manentoakoho Mountain, at an elevation of 1,500–1,600 m (figure 4). Access is via a rough, unpaved road that requires a four-wheel-drive vehicle and takes about 8–10 hours from Antsirabe. The road is not passable during the rainy season (from late November to early May). The rest of the year the area is typically dry. Security is a problem because bandits operate throughout the region.

GEOLOGY

Central Madagascar is characterized by a tectonic unit known as the Itremo thrust sheet (see, e.g., Collins, 2000). Formed by rocks of the Itremo Group, it has a lower unit of gneiss and an upper unit of quartzites, schists, and marbles (Fernandez et al., 2001). Both units are locally intruded by the pegmatites, which probably formed via fractional crystallization of granitic plutons emplaced at relatively shallow depths (Pezzotta and Franchi, 1997).

The Antsongombato region is underlain by crystalline basement rocks of the upper unit of the Itremo Group. The mining area consists of white-to-gray dolomitic marbles and a system of pegmatite dikes that are exposed over a distance of about 1 km. Individual pegmatites can exceed 500 m in length; typically a few tenths of a meter thick, locally they can reach over 6 m. Large, gem-quality crystals of rhodizite-londonite have been produced from only one dike (figure 5), which measures 10–60 cm thick and is about 400 m long (Demartin et al., 2001). Rhodizite-londonite occurs in other pegmatites in the area, but in smaller, lower-quality crystals.



Figure 4. The Antsongombato Gem mine consists of a series of small cuts on the north side of Manentoakoho Mountain, at an elevation of 1,500–1,600 m. Photo by Federico Pezzotta, April 1999.

The pegmatites consist of gray K-feldspar, white to smoky quartz, white albite, polychrome tourmaline, colorless to pink or green spodumene, and a variety of accessory minerals (see Simmons et al., 2001). Micas are absent except in rare areas. The rhodizite-londonite crystals are concentrated in the more chemically evolved portions of the dikes (with green and red tourmaline). Mirolitic cavities are scarce, and rarely exceed a few centimeters in diameter. Although some well-formed

crystals of rhodizite-londonite are found with red tourmaline in these pockets, most are “frozen” within other minerals near the center of the pegmatites. Mining activities have shown that the mineralization is concentrated in coarse-grained “columns” along the dip of the pegmatite. Within these zones, some of the best gem-quality rhodizite-londonite crystals have been found in masses (up to 10+ cm across) composed of fine-grained pollucite and spodumene.

Figure 5. At Antsongombato, gem-quality rhodizite-londonite was mined from a rather narrow (up to 60 cm thick) pegmatite dike by simple hand-digging. A portion of the pegmatite is visible as the steeply dipping dike in the right foreground. Photo by Federico Pezzotta, April 1999.



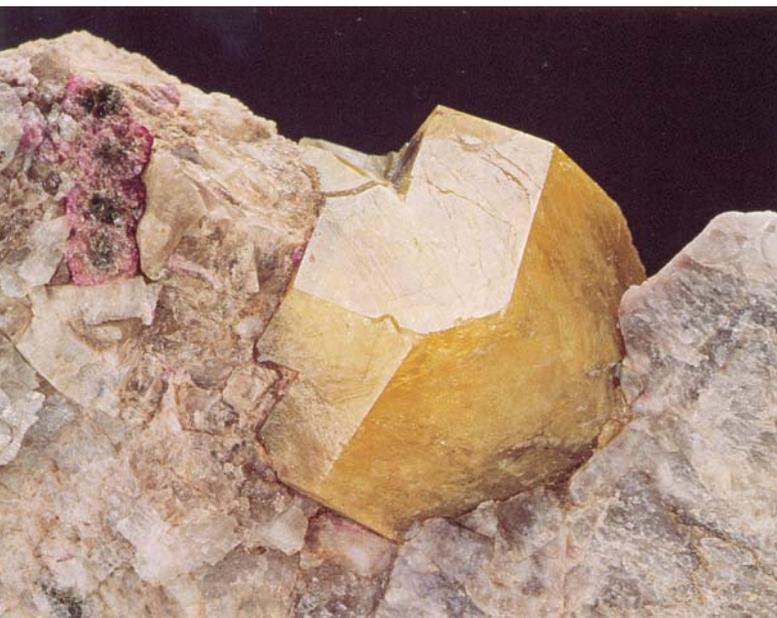


Figure 6. Well-formed crystals of rhodizite-londonite have been recovered from Antsongombato in relatively large sizes. This exceptional 6.5-cm-wide crystal is shown on a matrix consisting of K-feldspar, albite, and bicolored tourmaline. Photo by Luciano Spezia; Pyramide Co. collection.

MINING

Because of the difficult access to the locality, the shape of the deposit, and its limited production, mining activities have been restricted to hand excavation (again, see figure 5). Organized mining for gem and mineral specimens of rhodizite-londonite began in late 1998, when about 40 miners (orga-

nized in groups of eight) dug several pits into mineralized areas of the pegmatite. The work proceeded carefully to remove the valuable mineral specimens with as little damage as possible. Using pry bars along natural cracks in the rock, the marble host rock was removed first, and then the pegmatites were excavated; no explosives were used. Barren portions of the dike were left in place to provide stability for the excavation. Mining was discontinued during the rainy season.

At the time activities ceased in January 2001, a total of nine mineralized areas had been worked to depths of 35–40 m. In some areas, the mineralization ended at this point; in others, flooding and collapse of some of the pits made continued mining very dangerous. Furthermore, the very hard nature of the unweathered rock at depth would make continued mining difficult. There has been no further mining activity since the deposit was closed, although small amounts of material are periodically released into the market from stock owned by Pyramide Co.

PRODUCTION AND DISTRIBUTION

Most of the gem material and fine mineral specimens were mined from February 1999 to September 2000. Specimens from this production debuted at the 2000 Tucson gem shows, where their high quality and rumored identity as a new mineral created excitement (Moore, 2000). Up to January 2001, the mine yielded several hundred grams of rough gem-quality rhodizite-londonite, from which more than

Figure 7. Twenty-two faceted samples of natural-color rhodizite-londonite (0.09–0.54 ct) were gemologically characterized for this study. They show the range of color that is typically exhibited by the Antsongombato material. Photo by Maha Tannous.



300 carats of faceted gems were obtained. Some were cut in Madagascar, while higher-quality material was sent to Italy for faceting. Most of the gemstones range from 0.5 to 1 ct, although approximately one dozen 1–2 ct stones were faceted. Gemstones exceeding 2 ct are extremely rare, and typically contain abundant inclusions. The majority of the gemstones are moderate to pale greenish yellow; approximately 20% are very pale to near colorless, and less than 15% are saturated greenish yellow. At present, faceted material is sold to gem dealers and collectors by the French venture Polychrome France. Mineral specimens are distributed by the Italian dealer Lino Caserini. Several fine mineral specimens (see, e.g., figure 6) have been sold to major European and U.S. museums.

DESCRIPTION OF THE ROUGH

The rhodizite-londonite crystals from Antsongombato form equant modified dodecahedra that typically measure up to 1 cm, with exceptional specimens up to 6–7 cm. The dominant dodecahedral {110} faces are modified by deltoïd dodecahedral {221}, tristetrahedral {211}, and tetrahedral {111} faces and rare cubic {100} faces (Simmons et al., 2001). A few crystals display only tetrahedral faces and some are perfect octahedra due to combined positive and negative tetrahedral faces. Such pseudo-octahedral crystals display deep striations along the edges.

Based on the experience of FP, the crystals range from colorless to deep yellow; larger ones are commonly color zoned with increasing saturation from core to rim. Facetable portions are present mainly near the rim of the largest crystals, although the best gems have been cut from smaller crystals (up to 1 cm).

MATERIALS AND METHODS

We examined 22 faceted samples (0.09–0.54 ct; figure 7) and nine crystal fragments (0.24–2.86 ct; see, e.g., figure 8) of natural-color rhodizite-londonite, as well as 24 faceted stones (0.06–2.42 ct) that were irradiated by WS (see, e.g., figure 9). These originally near-colorless samples were irradiated to greenish yellow or yellow in a Scintag XDS 2000 X-ray diffraction unit for 24 hours, at 35kV/15mA using $\text{CuK}\alpha$ radiation.

With the exception of specific gravity, standard gemological properties were obtained on all samples.



Figure 8. These four crystal fragments (up to 2.86 ct) of natural-color rhodizite-londonite were part of the sample base for this study. Photo by Maha Tannous.

A Duplex II refractometer with a near-sodium equivalent light source was used for refractive index readings. Specific gravity was determined by the hydrostatic method (for the 43 samples that weighed >0.20 ct), and a desk-model spectroscope was used to observe absorption spectra. Reaction to ultraviolet radiation was viewed with four-watt long- and short-wave UV lamps. Internal features were studied with a standard gemological microscope. Anomalous birefringence was observed with the microscope, and also with a polariscope.

Advanced testing was performed on selected faceted samples that were representative of the full color range shown by natural- and treated-color rhodizite-londonite. The three natural-color samples ranged from near colorless to a moderately saturated greenish yellow (0.27, 0.10, and 0.30 ct, respectively), and the two of treated color were a

Figure 9. The two stones on the left (0.28 and 0.30 ct) show the range of color seen in natural-color rhodizite-londonite, whereas the two stones on the right (0.28 and 0.39 ct) are representative of material that has been irradiated. Photo by Maha Tannous.



moderately saturated greenish yellow (0.28 ct) and yellow (0.39 ct). At GIA in Carlsbad, qualitative chemical analysis of four of these samples was performed with a KeveX Omicron energy-dispersive X-ray fluorescence (EDXRF) spectrometer, using a 200 second live time and two sets of analytical conditions to maximize detection of the elements Na through Fe. For two samples (0.30 and 0.39 ct), conditions were also optimized for the detection of rare-earth elements. The other two samples (0.10 and 0.28 ct) also were analyzed with a Tracor Xray Spectrace 5000 EDXRF spectrometer, using a 200 second live time with instrument parameters optimized for light elements and rare-earth elements.

UV-Vis-NIR absorption spectra of these four samples were obtained in the region 250–1000 nm with a Hitachi U4001 spectrophotometer. Fourier-transform infrared (FTIR) transmission spectrometry was performed on all five samples using a

Nicolet Magna 760 instrument. Spectra were collected from 6000 to 400 cm^{-1} at a resolution of 4 cm^{-1} . Raman spectra were obtained in the range of 2000–100 cm^{-1} with a Renishaw 2000 Ramascope laser Raman microspectrometer on the dodecahedral and tetrahedral faces of a natural-color crystal fragment, and on specific spots of the 0.10, 0.28, and 0.39 faceted samples that were known to be londonite or rhodizite from chemical analyses (see below). Mineral inclusions in selected samples (both faceted and rough) also were analyzed by Raman microspectrometry.

At the University of New Orleans, an Amray 1820 SEM, operated at 25 kV accelerating voltage, was used to generate backscattered electron images of eight faceted samples (including the five described above); these images were subsequently colorized to enhance visibility of the differences in atomic weight (and thus Cs content) across the table of each

TABLE 1. Properties of rhodizite-londonite from Antsongombato, Madagascar.^a

| | |
|--------------------------|--|
| Composition | (K,Cs)Al ₄ Be ₄ (B,Be) ₁₂ O ₂₈ ; rhodizite is K-dominant and londonite is Cs-dominant |
| Color | Natural color: Near colorless to greenish yellow with moderate saturation Treated color (irradiated): Greenish yellow to yellow with moderate to strong saturation |
| Morphology | Isometric (cubic) system; crystals are equant with dominant dodecahedral {110} faces modified by deltoid dodecahedral {221}, tristetrahedral {211}, and tetrahedral {111} faces and rare cubic {100} faces ^b |
| Weight of faceted stones | 0.5–1 ct are typical, 1–2 ct are rare, and >2 ct are extremely rare |
| Refractive index | 1.689–1.691; most were 1.690 1.693±0.001 (measured with Cargille oils) ^b |
| Specific gravity | 3.34–3.42 3.34 (measured with a Berman balance) or 3.42 (calculated) ^b |
| Hardness | 8 ^b |
| Luster | Vitreous ^b |
| Cleavage/fracture | No cleavage or parting; fracture is conchoidal ^b |
| UV fluorescence | |
| Short-wave (253.7 nm) | Very weak to moderate yellowish green |
| Long-wave (365 nm) | Inert to weak yellowish green |
| Internal features | Partially healed fractures with “fingerprint,” stringer-like, and “spiderweb” arrays of one- and two-phase inclusions; growth zoning (with a parallel planar, swirled, or roiled appearance) and associated anomalous birefringence; conchoidal fractures; feathers; needles and/or tubes; rare mineral inclusions (albite, columbite, pollucite, and chambersite; apatite, tourmaline, and quartz have been seen in rough gem material) |
| Optic character | Isotropic, commonly with anomalous birefringence in parallel planar, cross-hatched, patchy, and irregular, complex zones, or showing a subtle cloud-like appearance |
| Raman spectra | Main peaks at 470 and 430 cm^{-1} ; smaller peaks at 857, 803, 651, 544, and 294 cm^{-1} |
| UV-Vis-NIR spectra | Gradually increasing absorption below approximately 550 nm (greenish yellow and yellow samples) or 470 nm (near colorless sample), and cutoff below 300 nm; no features seen with the desk-model spectroscopy |
| FTIR spectra | Complete absorption between approximately 3600 and 3150 cm^{-1} and below ~2400 cm^{-1} . Peaks at 5235 (with a shoulder at 5145), 4740, 4555, 4410, and 4130 cm^{-1} were present in all samples, and minor peaks at 4025 and 3910 cm^{-1} were recorded in some stones. |
| Fade testing in sunlight | Natural color: Slight fading after two weeks, noticeable fading after three weeks, and near colorless after one month Treated color (irradiated): Slight fading after one week, noticeable fading after nine days, and near colorless after three weeks |

^a Arem (1987) reported that the dispersion of rhodizite is 0.018; this property was not determined for samples in this study.

^b Reported by Simmons et al. (2001).

stone. Quantitative chemical analyses of these samples were obtained using an ARL-SEMQ electron microprobe with 15 kV (for sodium) and 25 kV accelerating voltages, 15 nA beam current, and 3 µm beam diameter. Analyses were calibrated with natural mineral and synthetic compound standards, and a ZAF correction procedure was applied to the data. Generally five spots were analyzed on each sample. For samples showing discrete variations in Cs (as revealed in the backscattered electron images), analyses were obtained in areas representative of the highest and lowest Cs content. Where possible, surface-reaching inclusions were identified by electron microprobe analysis.

Fade-testing experiments were performed by placing one natural- and one treated-color sample (moderately saturated greenish yellow and yellow,

respectively) in a south-facing window in Carlsbad, California in November-December 2002. Samples of the same starting colors were kept in a darkened drawer for daily comparison to the test samples.

RESULTS

The results for general gemological properties, including internal features and spectra, are provided in table 1. The chemical and physical properties of selected samples are reported in table 2.

Visual Appearance. The natural-color samples (both rough and faceted) ranged from near colorless (one sample) to a slightly greenish yellow of moderate saturation, and the irradiated samples ranged from greenish yellow to yellow of moderate to strong saturation; both showed light tone (again, see figure 9).

TABLE 2. Chemical and physical properties of eight faceted rhodizite-londonite samples (natural and treated color) from Antsongombato, Madagascar.^a

| Property | 0.27 ct | 0.18 ct | 0.10 ct | 0.30 ct | | 0.28 ct | 0.32 ct | 0.07 ct | 0.39 ct | |
|------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Color | Near cls | Pale gY | Mod gY | Mod gY | | Mod Y | Mod gY | Mod gY | Mod-str Y | |
| Color origin | Natural | Natural | Natural | Natural | | Treated | Treated | Treated | Treated | |
| R.I. | 1.690 | 1.690 | 1.69 | 1.691 | | 1.690 | 1.690 | 1.69 | 1.690 | |
| S.G. | 3.36 | nd | nd | 3.39 | | 3.39 | 3.34 | nd | 3.41 | |
| Mineral | Rhodizite | Rhodizite | Londonite | Rhodizite | Londonite | Rhodizite | Londonite | Rhodizite | Rhodizite | Londonite |
| Oxides (wt.%) | | | | | | | | | | |
| SiO ₂ | bdl | 0.04 | bdl |
| B ₂ O ₃ calc | 48.18 | 49.53 | 47.89 | 48.22 | 48.51 | 48.31 | 48.17 | 48.16 | 47.86 | 46.76 |
| Al ₂ O ₃ | 25.93 | 26.92 | 25.73 | 25.87 | 25.99 | 26.00 | 25.97 | 25.88 | 25.70 | 25.25 |
| BeO calc | 15.73 | 16.17 | 15.64 | 15.75 | 15.84 | 15.78 | 15.73 | 15.73 | 15.64 | 15.27 |
| Na ₂ O | 0.08 | 0.14 | 0.10 | 0.16 | 0.23 | 0.04 | 0.02 | 0.17 | 0.09 | bdl |
| K ₂ O | 2.63 | 2.28 | 1.57 | 2.34 | 2.02 | 2.51 | 1.89 | 2.31 | 2.56 | 1.46 |
| Rb ₂ O | 1.27 | 1.14 | 1.63 | 2.00 | 2.20 | 1.27 | 1.78 | 1.24 | 1.71 | 1.59 |
| Cs ₂ O | 5.35 | 4.59 | 8.15 | 5.43 | 6.21 | 5.97 | 6.64 | 6.23 | 5.12 | 7.56 |
| Total | 99.17 | 100.77 | 100.71 | 99.77 | 101.00 | 99.88 | 100.20 | 99.72 | 98.72 | 97.89 |
| Cations per 28 oxygens | | | | | | | | | | |
| Si | bdl | 0.006 | bdl |
| B | 11.000 | 11.000 | 11.000 | 11.000 | 11.000 | 11.000 | 11.000 | 11.000 | 10.994 | 11.000 |
| Be | 5.000 | 5.000 | 5.000 | 5.000 | 5.000 | 5.000 | 5.000 | 5.000 | 5.000 | 5.000 |
| Al | 4.042 | 4.082 | 4.035 | 4.030 | 4.024 | 4.042 | 4.050 | 4.037 | 4.033 | 4.056 |
| Na | 0.021 | 0.035 | 0.026 | 0.041 | 0.059 | 0.010 | 0.005 | 0.044 | 0.022 | bdl |
| K | 0.444 | 0.374 | 0.267 | 0.395 | 0.339 | 0.422 | 0.319 | 0.390 | 0.435 | 0.254 |
| Rb | 0.108 | 0.094 | 0.139 | 0.170 | 0.186 | 0.108 | 0.151 | 0.105 | 0.146 | 0.139 |
| Cs | 0.302 | 0.252 | 0.462 | 0.306 | 0.348 | 0.336 | 0.375 | 0.352 | 0.290 | 0.439 |
| Sum of alkalis ^b | 0.875 | 0.755 | 0.894 | 0.912 | 0.932 | 0.876 | 0.850 | 0.891 | 0.893 | 0.832 |

^aAbbreviations: bdl=below detection limits, cls=colorless, gY=greenish yellow, mod=moderate, nd=not determined, sl=slightly, str=strong, Y=yellow. Samples with two analyses showed areas with high and low Cs content in backscattered electron images, whereas those with only one analysis appeared to be more uniform in composition. All data by electron microprobe (average of five analyses, in general), with B and Be calculated by stoichiometry: B + Si = 11.000 apfu (atoms per formula unit) and Be = 5.000. Note that some columns may not add up exactly as shown, due to rounding. Detection limits (wt.%, calculated at 99% confidence levels) for Na₂O and SiO₂ were 0.018; not detected were CaO (0.008), Fe₂O₃ (0.006), MgO (0.011), MnO (0.018), and TiO₂ (0.015).

^bAlkalis are Na, K, Rb, and Cs. The apparent shortfall in this site, which should add up to 1.000, may be due to vacancies. However there is some uncertainty about this, since ZAF corrections for boron and beryllium could not be applied in the data reduction program.

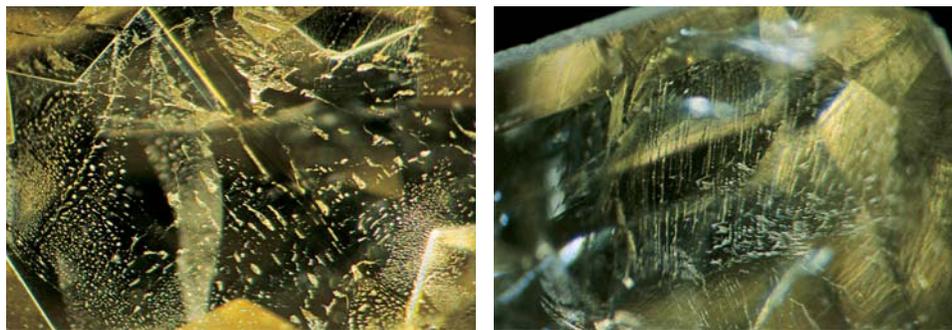


Figure 10. "Fingerprints" (left; magnified 25 \times) were the most common inclusion seen in the rhodizite-londonite. Partially healed fractures also took the form of subparallel stringers (right, magnified 15 \times) that resemble the step-like conchoidal fractures seen in some samples. Photomicrographs by John I. Koivula.

No color zoning was evident in any of the faceted or rough samples. The faceted stones were eye-clean to moderately included, and the rough ranged from semitransparent to transparent. Smooth crystal faces were present on all of the rough samples, which permitted the measurement of R.I. readings. The dominant dodecahedral {110} faces showed subtle striations, whereas smaller tetrahedral {111} modifying faces were smooth.

Physical Properties. R.I. values ranged from 1.689 to 1.691, but most samples (both natural- and treated-color) yielded 1.690. A few of the samples (particularly those of small size) showed nebulous R.I.'s that could only be determined as 1.69. Only three samples (all treated) yielded the 1.689 value, and the 1.691 value was obtained for seven of the treated and one of the natural-color stones. The eight samples that were chemically analyzed showed no relation between R.I. value and composition (all were 1.690 [or 1.69], except for one sample with zones of both rhodizite and londonite that yielded 1.691).

S.G. ranged from 3.34–3.42, although most values clustered around 3.37. There was no systematic

correlation between the S.G. values and composition (table 2), color, color origin, or size of the samples, or between rough and cut stones. All samples fluoresced yellowish green (very weak to moderate intensity) to short-wave UV radiation. Most were inert to long-wave UV, although a few (of both natural- and treated-color) fluoresced very weak to weak yellowish green. No features were seen with the desk-model spectroscope. The irradiated samples showed the same properties as the natural-color stones.

Internal Features. There were no differences in the internal features of the natural- and treated-color samples. When viewed with the microscope, the most common inclusions were partially healed fractures composed of one- and two-phase fluid-gas inclusions. They commonly resembled "fingerprints" (both wavy and flat planar), although planes of stringer-like fluid inclusions in subparallel or "spiderweb" arrangements were also seen in many of the samples (see, e.g., figure 10). The subparallel arrangement of these stringers mimicked the step-like conchoidal fractures noted in several of the samples. Small feathers were present in a few samples.

In two faceted stones, minute needles were seen along partially healed fractures, and another two samples contained tubes with flat cross-sections. Long, very thin needles (probably tubes) were also seen in a few of the stones (figure 11). Some appeared locally discontinuous, as if intermittently filled with fluid. In one crystal, these needles were abundant and oriented perpendicular to some crystal faces. Abundant needle-like inclusions with a similar appearance are locally present in other minerals from Antsongombato (i.e., quartz and tourmaline) from the same cavities in which the rhodizite-londonite occurs. In some cases, these microscopic tubes are filled with a fibrous white to pale brown mineral. Powder X-ray diffraction analysis of this mineral, as well as of the "needles" hosted in quartz, showed the presence of montmorillonite (unpublished data of FP).

Figure 11. Long, very thin needles (probably tubes) were seen in a few of the rhodizite-londonite samples. Photomicrograph by John I. Koivula; magnified 20 \times .

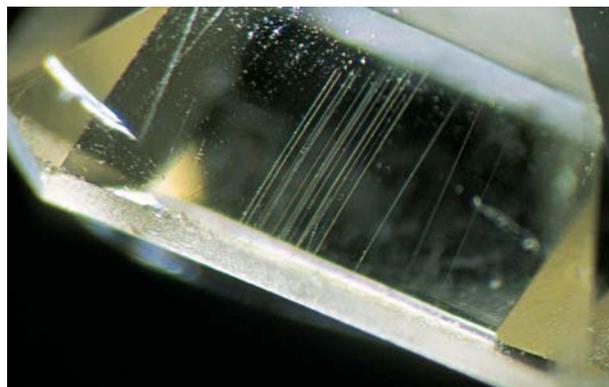


Figure 12. Mineral inclusions were seen in only two of the faceted rhodizite-londonites. One sample contained several colorless chambersite and tiny brownish red columbite inclusions (left). The chambersite inclusions were highly birefringent (right). Photomicrographs by John I. Koivula; magnified 25 \times .

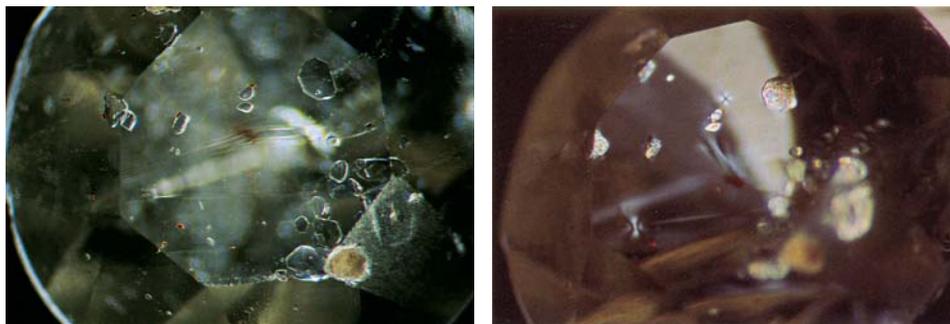


Figure 13. Strong planar growth patterns were visible with plane-polarized light in some of the rhodizite-londonites (left). When viewed with cross-polarized light, the growth patterns displayed anomalous birefringence (right). Photomicrographs by John I. Koivula; magnified 15 \times .

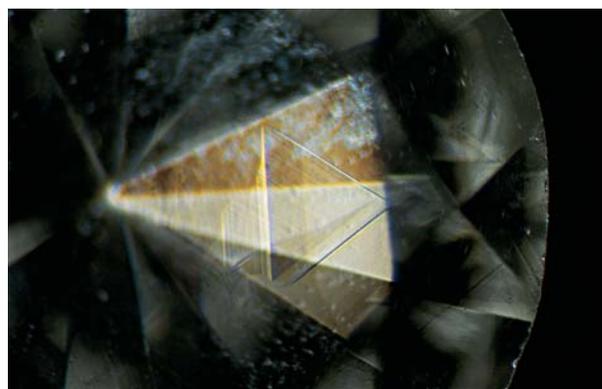


Mineral inclusions were rare. One faceted sample contained stout, euhedral, brownish red prisms identified as columbite by both Raman and electron-microprobe analyses (figure 12). Several colorless, subhedral birefringent inclusions (some surface-reaching) in this sample were identified as chambersite ($\text{Mn}_3\text{B}_7\text{O}_{13}\text{Cl}$) by a combination of Raman and electron-microprobe analyses. Three minute colorless inclusions just under the surface of a crystal fragment were identified as albite with Raman analysis. A minute, colorless inclusion that reached the surface of one faceted sample was confirmed as polucite by the electron microprobe. Other inclusions observed could not be identified due to their position and/or small size. These included a minute, colorless crystal with high relief and tiny colorless inclusions along a partially healed fracture. Blue apatite, pale pink tourmaline, and quartz have been noted in rough rhodizite-londonite from Antsongombato by some of the authors (FP, WBS, and AUF), but so far these inclusions have not been confirmed in faceted stones.

Growth patterns were seen in most samples, and ranged from subtle to very prominent. Isolated or multiple parallel planar features were most common (figure 13), although roiled, swirled, and angular patterns were seen in a few samples. One sample contained a series of triangular growth zones (figure 14). The growth zoning typically correlated to similar patterns of anomalous birefrin-

gence when viewed with cross-polarized light (again, see figure 13). This birefringence was obvious in all but four samples, and commonly formed striking patterns—parallel planar, cross-hatched, patchy, and irregular, complex zones—or more subtle clouds. The anomalous birefringence was directional in some samples, where it was visible only in specific orientations. With the polariscope, patchy, cloud-like, and planar patterns of anomalous birefringence were observed in most samples, but these appeared much less obvious than when viewed with the microscope.

Figure 14. Viewed through the table of this 0.28 ct rhodizite, a series of triangular growth zones are illuminated by light reflected from the pavilion facets. Photomicrograph by John I. Koivula; magnified 20 \times .



Chemical Composition. All eight of the Antsongombato samples analyzed by electron microprobe were remarkably similar in composition (see table 2), except for significant variations in cesium (4.59–8.15 wt.% Cs_2O) and minor differences in potassium (1.46–2.63 wt.% K_2O), rubidium (1.14–2.20 wt.% Rb_2O), and sodium (<0.02–0.23 wt.% Na_2O). Most samples consisted only of rhodizite or rhodizite + londonite (figure 15). To determine the particular species present, the cations for Cs, K, and Rb that were calculated from the electron microprobe data must be normalized to show their relative abundance in the alkali site. These data are conveniently evaluated by plotting the normalized values on a ternary diagram.

To evaluate the compositional heterogeneity of the samples before analysis, we viewed the table facet of each sample in backscattered electron (BSE) mode using the SEM. This imaging technique contrasts differences in average atomic number; since Cs is considerably heavier than K (and Rb), compositions corresponding to londonite show slightly lighter tones than those of rhodizite in standard

black-and-white BSE images. To improve contrast, the BSE images in figure 16 have been colorized. Striking heterogeneity was revealed in some samples, as elongate or patchy zones that are separated by sharp boundaries. One sample displayed a subtle, gradual chemical zonation within each zone (again, see figure 16). There was no correlation between color and composition in the samples analyzed.

None of the electron microprobe analyses revealed any Ca, Fe, Mg, Mn, or Ti. EDXRF spectrometry showed major Al, K, and Cs, as well as a small amount of Rb, as expected. Traces of Mn and Zn were detected by EDXRF in a 0.10 ct greenish yellow sample. No rare-earth elements were detected.

Raman Analysis. A Raman spectrum of a rhodizite-londonite crystal showed principal Raman peaks at 470 and 430 cm^{-1} , and smaller peaks at 857, 803, 651, 544, and 294 cm^{-1} . There were no Raman spectral features seen above 857 cm^{-1} . Analyses taken on dodecahedral and tetrahedral faces yielded identical spectra. The Raman spectra of three faceted samples of known composition also displayed the peaks at 470, 430, and 294 cm^{-1} ; however, the other peaks were often not present. No consistent differences in the Raman spectra were evident between the rhodizite and londonite areas in these samples.

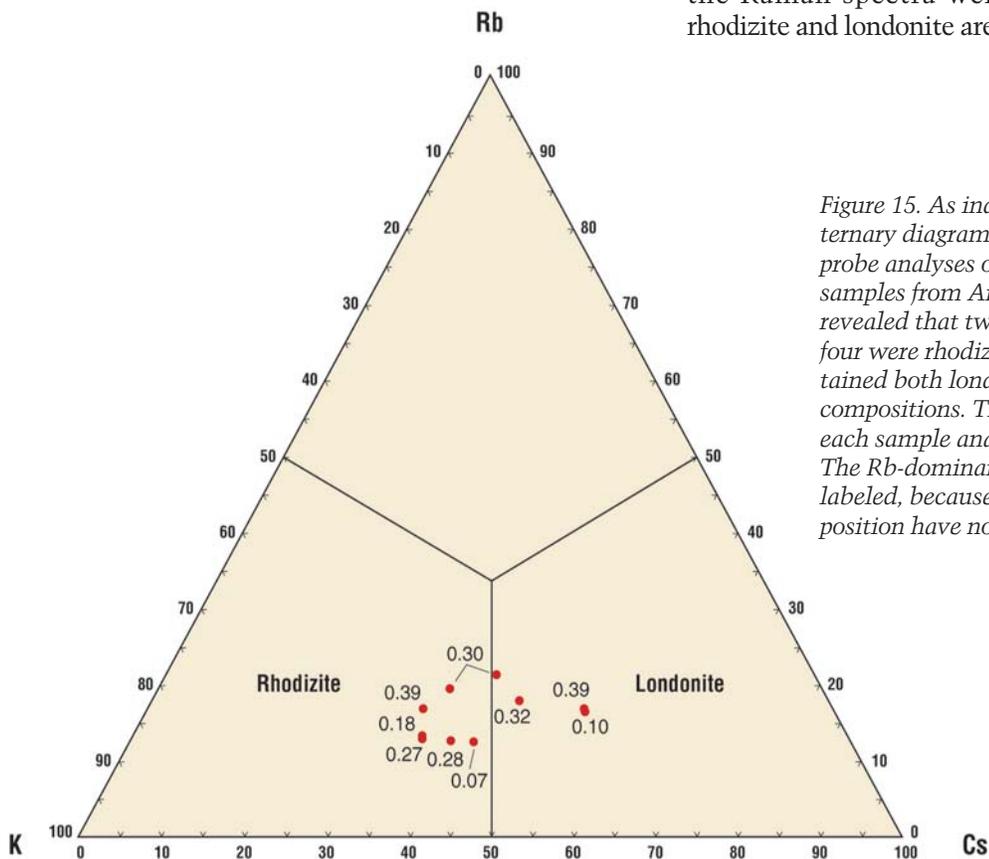


Figure 15. As indicated in this ternary diagram, electron-microprobe analyses of eight faceted samples from Antsongombato revealed that two were londonite, four were rhodizite, and two contained both londonite and rhodizite compositions. The carat weights for each sample analyzed are shown. The Rb-dominant field is not labeled, because stones of this composition have not been recorded.

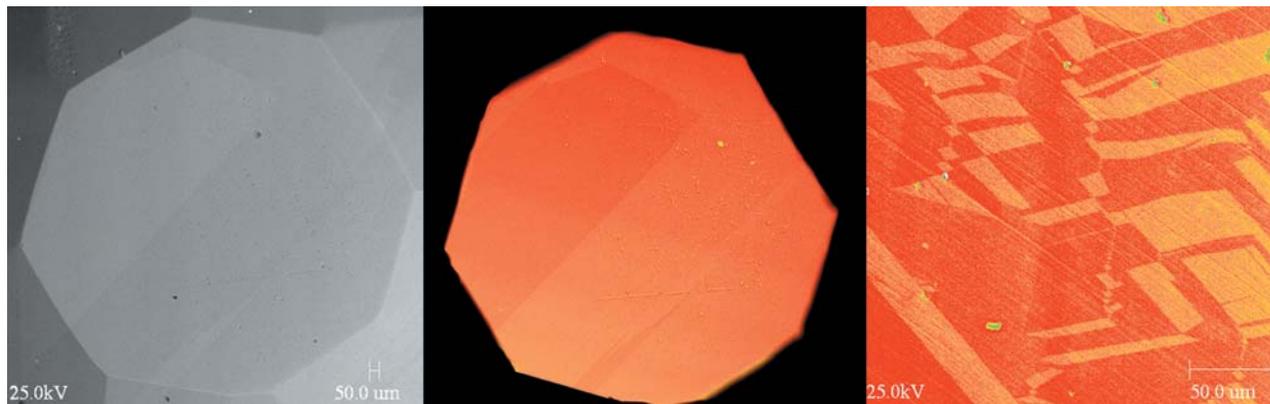


Figure 16. These backscattered electron (BSE) images of two rhodizite-londonite samples were generated with the electron microprobe to reveal compositional zoning (i.e., differences in overall atomic number). The standard BSE image on the left shows the table of a 0.07 ct round brilliant; lighter tones indicate heavier overall atomic weight (i.e., more Cs). Note the subtle tonal differences in diagonal zones, which are seen more easily in the colorized image in the center. The image in the center also shows subtle gradual zonation within each zone. The colorized BSE image on the right reveals the complex patchy compositional zoning on the table of a 0.30 ct sample. In both colorized images, yellow = rhodizite and orange = londonite. The minute yellow or green-blue spots correspond to pits on the surface of the samples.

UV-Vis-NIR Spectrometry. No sharp absorption features were recorded in any of the four samples analyzed. The near-colorless sample exhibited a slight, gradually increasing absorption below approximately 470 nm, and a cutoff below 300 nm. The absorption spectra for the natural- and treated-color greenish yellow and yellow stones were indistinguishable from one another, and showed a strong absorption band starting below about 550 nm, with a local maximum at approximately 355 nm. A cutoff below 300 nm was also present in the greenish yellow and yellow stones.

FTIR Spectrometry. All five samples showed complete absorption between approximately 3600 and 3150 cm^{-1} and below approximately 2400 cm^{-1} . Peaks at 5235 (with a shoulder at 5145), 4740, 4555, 4410, 4130, and 4025 cm^{-1} were present in all the spectra. The relative strength of the peaks at 4555 and 4410 cm^{-1} and at 4130 and 4025 cm^{-1} varied from sample to sample. Although the bulk composition of these samples was not determined quantitatively, surface variations in their Cs:K ratio were known from BSE images and electron microprobe analyses. Accordingly, a londonite sample showed a slightly stronger 4410 cm^{-1} peak compared to the 4555 cm^{-1} peak, and the opposite was shown by a rhodizite sample. Except for one sample (0.30 ct) of intermediate rhodizite-londonite composition, four samples displayed a minor peak at 3910 cm^{-1} . A peak at 4025 cm^{-1} was present in two samples of intermediate composition, and in the londonite sample. However, this peak was missing in the rhodizite sample.

Fade Testing. After one week of exposure to sunlight (on four sunny and three cloudy days), slight fading was seen in the treated-color sample; this sample was noticeably faded after nine days, and became near colorless after three weeks (figure 17). Slight fading of the natural-color sample was noticed after two weeks of exposure. This sample became noticeably faded after three weeks, and still retained some color after one month (again, see figure 17).

DISCUSSION

Our results indicate that rhodizite and londonite have overlapping gemological properties, and these mineral species cannot be separated without quantitative chemical analysis. FTIR spectroscopy may provide some clues, but further research is necessary. The physical properties obtained in this study are consistent with those of rhodizite and londonite that have been reported in the literature (e.g., Webster, 1994; Gaines et al., 1997; Simmons et al., 2001), although a slightly higher R.I. range was measured by Simmons et al. (2001). It was not possible to conclusively separate treated-color stones from those of natural color by any of the methods used in the current study. Although there were slight differences in their R.I. values (i.e., a greater variation shown by the treated-color stones), these were not distinct enough to aid in the identification of color origin.

According to our research, mineral inclusions are not common in faceted rhodizite-londonite. Those identified in this study are typical of the

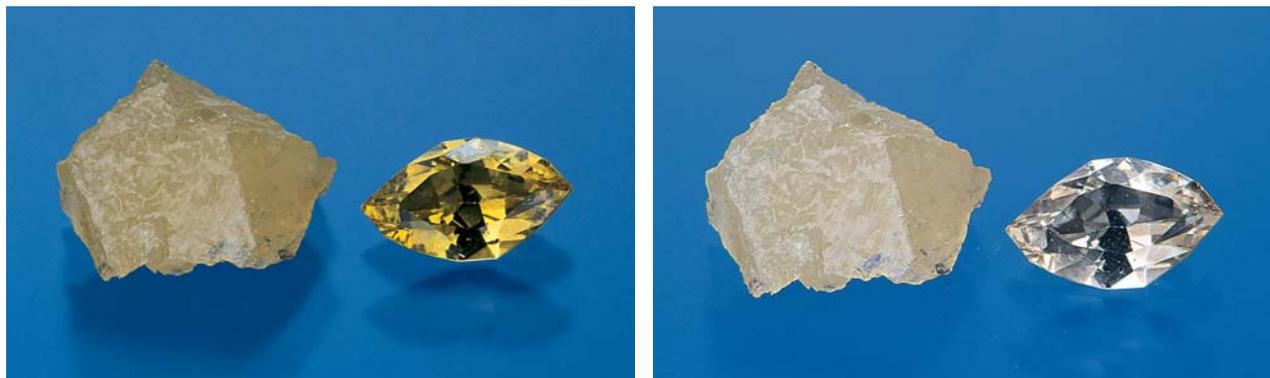


Figure 17. Before prolonged exposure to sunlight, these samples of rhodizite-londonite (a natural-color 1.44 ct rough, and an irradiated 0.29 ct faceted stone) were greenish yellow and yellow, as shown on the left. The treated-color stone became near colorless after three weeks, whereas the natural-color sample still retained some color after one month of exposure in a south-facing window (right image). Photos by Maha Tannous.

granitic pegmatite environment, with the exception of chambersite. This is the first time chambersite has been documented from any granitic pegmatite.

Early chemical analyses for Madagascar rhodizite were reported by both Lacroix (1910) and Duparc et al. (1911). For decades, there was considerable confusion over the chemical formula (see Frondel and Ito, 1965, as well as discussions by Pring et al., 1986, and Simmons et al., 2001). One reason for the confusion may be the difficulty of obtaining analyses of boron and beryllium.

The most Cs-enriched composition measured in our samples, 8.15 wt.% Cs_2O , approaches the highest value (8.37 wt.%) obtained thus far for londonite (from Antandromby, Madagascar; Simmons et al., 2001). However, the traces of Fe, Mn, and Ca in londonite from that locality were not detected in our samples from Antsongombato. As shown in figure 16, backscattered electron (BSE) images are effective for revealing chemical zoning in rhodizite-londonite from Antsongombato. Simmons et al. (2001) also documented Cs-enriched areas that showed feathery, oscillatory, and stringer-like shapes in rhodizite-londonite from other pegmatites found in central Madagascar.

The visible spectra do not yield any specific information on the origin of the yellow color. The color of rhodizite-londonite is most likely related to defects in the crystal structure, which appear to be light sensitive (Simmons et al. 2001). This was corroborated by the fade-testing experiments in this study. In addition, rhodizite-londonite collected from the mine dumps at Antsongombato was colorless on the side exposed to the sun, and a darker yellow on the unexposed bottom surfaces. Radiation-induced color centers may be responsible

for the color, as suggested by the change in hue from exposure to X-rays (Dr. G. Rossman, pers. comm., 2002). However, the fade testing performed for this study clearly showed that these color centers are somewhat less stable in the laboratory-irradiated stones.

The Raman spectra showed no consistent differences between rhodizite and londonite, regardless of whether the spectra were obtained from different portions of the same stone or from different stones.

Although the FTIR spectra showed some variations according to composition, their use for separating londonite from rhodizite remains inconclusive. This is due to the small number of samples examined, as well as to the lack of quantitative data on their bulk composition; such data would be required for comparison with the FTIR spectra since they were obtained with transmission geometry. However, our preliminary results suggest that further work on using FTIR spectroscopy for separating rhodizite and londonite could be worthwhile.

CONCLUSION

Londonite is a new gem mineral that occurs in a solid-solution series with rhodizite. The Antsongombato pegmatite in central Madagascar is the only known source of gem-quality rhodizite-londonite; more than 300 carats have been faceted since 1998. The gem rough was recovered during mining of the pegmatite for mineral specimens of yellow rhodizite-londonite and red tourmaline. Its attractive appearance and significant hardness (8 on the Mohs scale) make rhodizite-londonite a desirable gemstone for collectors who can find this scarce material in the gem trade. Note, though,

that both natural-color and irradiated rhodizite-londonite will fade on prolonged exposure to sunlight, so the stones should not be worn or displayed in lighting conditions that will promote fading.

Future production will be limited by the difficult

access and small size of the deposit. Since the pegmatite that has yielded all of the recently mined gem material appears exhausted, exploration for additional gem pegmatites in the Antsongombato area will be necessary before significant production can resume.

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