

TSAVORITE AND OTHER GROSSULARS FROM ITRAFO, MADAGASCAR

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Since 2002, tsavorite and other grossular varieties have been recovered from a primary deposit at Itrafo, a village in the Andrembesoa area of central Madagascar. Twenty-two samples from this locality were investigated by classical gemological methods, chemical analysis, and UV-Vis-NIR and mid-IR spectroscopy. The garnets' chemical composition was nearly pure grossular (>92 mol.%), with iron and vanadium as the main chromophores. Their iron content and $\text{Fe}_2\text{O}_3:\text{V}_2\text{O}_3$ ratio were higher than those generally found in tsavorite from well-known deposits. Although the Itrafo deposit is relatively large, and new veins could be discovered, future production will be limited by access difficulties and security concerns.

Grossular, with the chemical formula $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$, is a species of the garnet group that exhibits colors ranging from colorless to pink, brown, yellow, orange, and green. The latter is known by the varietal name *tsavorite* when the color is a saturated green (O'Donoghue, 2006), whereas less-saturated material is often referred to as *green grossular* or *mint green grossular* in the trade. Although *tsavorite* is not approved as a mineral name by the International Mineralogical Association (Nickel and Mandarino, 1987; O'Donoghue, 2006), we will use the term in this article for the sake of brevity and consistency with gemological convention.

The most important deposits of gem-quality tsavorite occur in Tanzania and Kenya (Bridges, 1974).

Other notable sources include Pakistan's Swat Valley (Jackson, 1992) and the Gogogogo area in southwestern Madagascar (Mercier et al., 1997; Johnson et al., 1999). A new source of fine gem-quality grossular (figure 1), including some tsavorite, was discovered in 2002 at the village of Itrafo in central Madagascar. This article presents a detailed characterization of this material.

LOCATION AND PRODUCTION

The garnet deposit is located a few hundred meters southeast of the village of Itrafo, in the Andrembesoa area of Madagascar's central highlands (figure 2). It is accessible from the village of Mahaiza by a two-day hike through mountainous, arid, and sparsely inhabited terrain. The deposit's coordinates are $20^\circ 12' 21.9''\text{S}$, $46^\circ 39' 38.7''\text{E}$, at an elevation of ~1,180 m. Local miners have worked the garnet-bearing vein along a trench that is ~200 m long, 5–8 m deep, and ~3 m wide, and they have also dug a series of small pits further down-dip over a distance of 15+ m. As is typical for small-scale mining in Madagascar, the work occurs seasonally, during periods when local people are not busy cultivating crops.

According to the miners' reports, grossular was discovered at this locality in 2002 by local prospectors looking for spinel and tourmaline. That same year, a few kilograms of gem-quality "green garnet" rough were sold in the markets of Antsirabe and Antananarivo. The individual pieces averaged <1 g, and only rarely exceeded 2–3 g. However, some lots contained mineral specimens with crystals exceeding 3 cm in diameter. Most of the production occurred in the first few years after the discovery, and the total quantity of gem rough is estimated at <20 kg. Production has been largely intermittent because of the rugged, remote location, and ongoing security concerns due to bandits (mostly cattle rustlers) in the area.

Only a small amount of this garnet has been cut in Madagascar, as most of it has been exported as gem

See end of article for About the Authors and Acknowledgments.

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Figure 1. The Itrafo deposit in central Madagascar is a source of gem-quality grossular, such as the crystal on the left (~10 mm in diameter, on a matrix of calcite, grossular, and phlogopite) and the 0.70 ct faceted gem on the right. Photos by Matteo Chinellato.

rough to the Asian market. Eye-clean faceted stones of green color rarely exceed 5 ct, and only a small percentage is saturated enough to be considered tsavorite.

GEOLOGIC SETTING

The Itrafo garnet deposit is hosted by a subvertical brecciated vein composed of a fine-grained, massive, graphite-rich rock. The vein is crosscut by calcite veinlets rich in yellow to green grossular crystals, locally associated with phlogopite and rarely pyrite. The grossular crystals are mostly brecciated into the calcite veinlets, and the phlogopite blades are frequently distorted and show significant brittle deformation. The graphite-rich vein trends east-southeast and is exposed over a distance of about 200 m. The vein developed along the foliation of the metamorphic host rock, which is composed of a sequence of amphibolite and marble, essentially transformed into skarn. This mass of metamorphic rocks probably represents a large roof pendant inside the southern limit of a gabbro pluton constituting the northern portion of a large granitoid intrusion (Bertucat, 1963). Such intrusions probably belong to the first magmatic cycle (early Neoproterozoic in age, about 800–790 million years ago; Nédélec et al., 1995; Handke et al., 1999) affecting the crystalline basement of this region of central Madagascar, also known as the Itremo Thrust Sheet (Collins, 2000; Fernandez et al., 2001).

MATERIALS AND METHODS

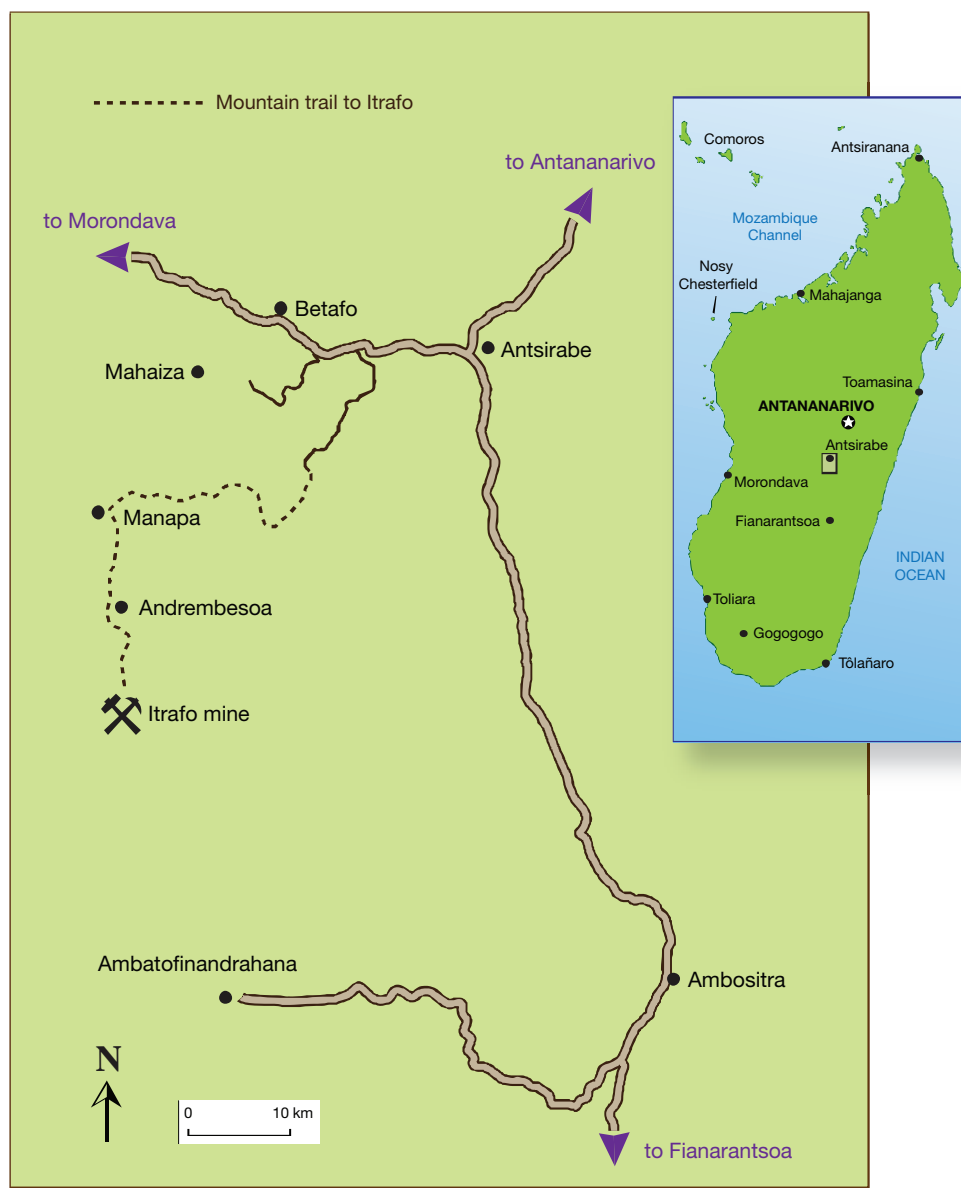
We examined 22 grossular samples from the Itrafo deposit, consisting of 13 faceted stones (0.34–3.16 ct; e.g., figure 3) and nine rough specimens (0.07–0.50 g). They ranged from greenish brown to green, and included two samples that were green enough to be

In Brief

- Itrafo, in central Madagascar, has been a source of tsavorite and other grossular varieties since 2002.
- Production has been limited by the mountainous, remote location combined with security concerns.
- The material ranges from greenish brown to brownish/yellowish green to pure green; the rough rarely exceeds 2–3 g.
- Itrafo tsavorite is colored mainly by vanadium and contains more iron than tsavorite from other localities.

considered tsavorite in the authors' opinion. For comparison, we also investigated six tsavorites from other localities: three faceted samples from Tanzania (0.40–2.10 ct), plus two faceted gems (0.25 and 0.98 ct) and one rough stone (0.10 g) from Gogogogo in southwestern Madagascar.

Figure 2. The Itrafo deposit is located near the village of Andrembesoa, in the Antananarivo Province of central Madagascar.



All 13 faceted samples from Itrafo were examined by standard gemological methods at the Italian Gemological Institute in Milan to determine their optical properties, hydrostatic specific gravity, UV fluorescence, and microscopic features.

Quantitative chemical analysis was performed on a total of 15 samples—nine from Itrafo and all six of the stones from Gogogogo and Tanzania—at the Earth Science Department of the Università degli Studi di Milano. We used a JEOL JXA-8200 electron microprobe in wavelength-dispersive mode under the following conditions: 15 kV accelerating voltage, 15 nA beam current, and count times of 60 seconds on peaks and 30 seconds on the background. The following

standards were used: natural grossular (for Si and Ca), anorthite (Al), fayalite (Fe), olivine (Mg), rhodonite (Mn), omphacite (Na), ilmenite (Ti), K-feldspar (K), and pure V and Cr for those elements. The raw data were corrected for matrix effects using a conventional $\Phi\rho Z$ routine in the JEOL software package.

The trace-element composition of seven samples from Itrafo and one specimen from Gogogogo, all previously analyzed by electron microprobe, were determined by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the CNR Geosciences and Georesources Institute in Pavia. The instrument consisted of a Quantel Brilliant 266 nm Nd:YAG laser coupled with a PerkinElmer Elan



Figure 3. These faceted grossular samples from Itrafo (0.70–3.16 ct) represent some of the cut specimens studied for this report. Photo by Matteo Chinellato.

DRC-e quadrupole ICP-MS. The spot size was 40 μm , the external standard was NIST SRM 610 glass, and the internal standard was Ca, as analyzed by microprobe. Precision and accuracy estimated on the basaltic glass standard BCR2 standard were better than 10%.

Ultraviolet/visible/near-infrared (UV-Vis-NIR) spectroscopic measurements in the 250–1800 nm range were performed with a PerkinElmer Lambda 950 spectrophotometer in the Material Sciences Department at the Università degli Studi di Milano-Bicocca. The instrument was operated with spectral resolutions of 0.05 and 0.30 nm/minute for the UV-Vis and NIR intervals, respectively, at a 1 nm/minute scan rate. Spectra were collected on three selected rough samples (through parallel faces of the crystals) from Itrafo.

Mid-IR spectroscopy (4000–400 cm^{-1}) of all the Itrafo faceted samples was performed at the Earth Sci-

ences Department of the Università degli Studi di Milano with a Nicolet Nexus FTIR spectrometer, equipped with a diffuse reflectance (DRIFT) accessory, at a resolution of 4 cm^{-1} and 200 scans per sample.

RESULTS

Gemological Properties and Internal Features. The standard gemological properties of the 13 faceted samples from Itrafo are listed in table 1. The color of the rough and faceted samples ranged from greenish brown, brown-green, and brownish and yellowish green to pure green, including two stones (one faceted and one rough) with an intense green color.

Microscopic observations revealed that the samples were rather clean. The most common internal features were fluid inclusions, including two-, three-, and multiphase varieties (e.g., figure 4). We also observed several negative crystals and some crystalline



Figure 4. Multiphase inclusions, consisting of a single bubble and three crystals in a watery solution, were observed in grossular from Itrafo. Photomicrographs by I. Adamo; magnified 60 \times (left) and 65 \times (right).

TABLE 1. Gemological properties of grossular from Itrafo, Madagascar.

Color	Greenish brown, brown-green, brownish and yellowish green, and green
Diaphaneity	Transparent
Optic character	Singly refractive with moderate to strong anomalous double refraction
Refractive indices	1.740–1.742
Specific gravity	3.58–3.62
UV fluorescence	Inert to both long- and short-wave UV
Internal features	Fluid inclusions (two-, three-, and multi-phase varieties), fractures (some partially healed), crystalline inclusions, negative crystals, straight growth lines or planes, and growth tubes

inclusions. Black aggregates, as seen in figure 5 (left), appeared to consist of an assemblage of graphite (black) and another mineral (yellowish white). Prismatic colorless birefringent crystals were also observed (figure 5, right). A few samples also contained fractures, some partially healed with liquid or solid remnants (figure 6). Straight growth lines or planes were observed in four samples, and fine growth tubes were seen in one stone (figure 7).

Chemical Composition. Chemical analyses by electron microprobe and LA-ICP-MS are reported in tables 2 and 3, respectively.

Electron microprobe analyses showed that all the Itrafo samples were essentially unzoned, with a composition dominated by grossular (92–94 mol.%; Deer et al., 1997). Among the minor and trace elements (see table 2), iron was the most abundant (1.08–1.85 wt. %

Fe₂O₃), followed by vanadium (0.19–0.83 wt. % V₂O₅), titanium (0.17–0.42 wt. % TiO₂), magnesium (0.06–0.34 wt. % MgO), and manganese (0.10–0.16 wt. % MnO). Chromium was nearly absent, with contents measured by LA-ICP-MS never greater than 72 ppm (table 3).

Tsavorite samples A and B from Gogogogo contained 86 and 91 mol% grossular, respectively (table 2). Both contained significant vanadium (2.17 and 0.97 wt. % V₂O₅), with small amounts of chromium (0.40 and 0.16 wt. % Cr₂O₃). However, tsavorite specimen C from Gogogogo (95 mol% grossular) showed a higher content of chromium than vanadium (0.30 wt. % Cr₂O₃ and 0.03 wt. % V₂O₅).

The three samples from Tanzania had high vanadium (1.11–1.47 wt. % V₂O₅) and low chromium (0.18–0.34 wt. % Cr₂O₃) values, with Fe₂O₃ always less than 0.10 wt. %. The Tanzanian tsavorites also showed slightly higher manganese (0.75–1.19 wt. % MnO) and magnesium (0.49–0.58 wt. % MgO) than the Itrafo samples.

Spectroscopy. *UV-Vis-NIR.* The UV-Vis-NIR spectra of two representative samples (brown-green and green) are shown in figure 8. The spectra displayed similar features: total absorption below ~360 nm, two well-defined peaks at 370 and 425–427 nm, an absorption band centered at 606–608 nm, and a broad absorption feature at ~1220 nm. Taking into account each specimen's inferred path length (i.e., sample thickness), we observed less absorption in the 350–550 nm range of the green sample, in agreement with its purer green color.

Mid-Infrared. The samples' mid-IR spectra in diffuse reflectance mode were characterized by two domi-

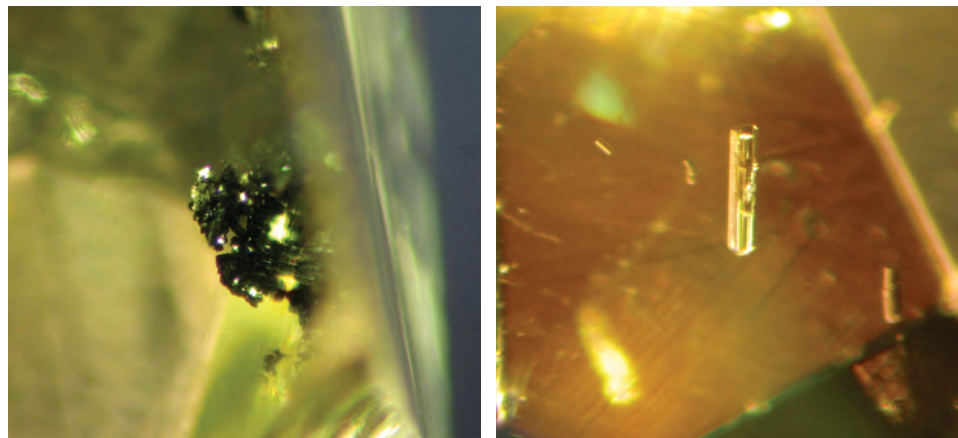


Figure 5. Opaque black crystalline aggregates, consisting mainly of what appear to be graphite, were observed in our grossular samples (left). Prismatic, colorless, birefringent crystals were also seen in some stones (right). Photomicrographs by I. Adamo; magnified 50 \times .

TABLE 2. Average chemical composition obtained by electron microprobe of grossular from Itrafo (Madagascar), Gogogogo (Madagascar), and Tanzania.^a

Location	Itrafo, Madagascar									Gogogogo, Madagascar			Tanzania		
Sample	1	2	3	4	5	6	7	8	9	A	B	C	A	B	C
Color	Brown-green	Yellowish green	Yellowish green	Green	Green	Green	Green	Green	Intense green	Intense green	Intense green	Intense green	Intense green	Intense green	Intense green
Oxide (wt.%)															
SiO ₂	39.47	39.81	39.73	39.69	39.61	39.64	39.71	39.33	39.76	39.21	40.12	39.39	39.59	39.18	40.01
TiO ₂	0.34	0.18	0.23	0.23	0.19	0.17	0.42	0.18	0.29	0.35	0.36	0.56	0.40	0.43	0.35
Al ₂ O ₃	21.14	21.89	22.09	21.94	21.35	21.11	21.56	20.96	21.45	20.67	21.00	21.84	19.93	20.36	21.29
Cr ₂ O ₃	bdl	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.40	0.16	0.30	0.34	0.20	0.18
V ₂ O ₃	0.19	0.30	0.30	0.41	0.44	0.51	0.52	0.54	0.83	2.17	0.97	0.03	1.15	1.47	1.11
Fe ₂ O ₃	1.85	1.58	1.54	1.50	1.45	1.08	1.08	1.36	1.26	bdl	bdl	0.24	0.03	bdl	0.10
FeO	0.12	0.15	0.29	0.28	0.22	0.21	0.24	0.17	0.11	0.07	0.61	bdl	bdl	bdl	bdl
MnO	0.10	0.16	0.13	0.13	0.14	0.13	0.12	0.14	0.13	1.03	0.57	0.15	0.75	1.19	1.14
MgO	0.27	0.17	0.31	0.34	0.29	0.10	0.06	0.11	0.08	0.65	0.61	0.40	0.58	0.51	0.49
CaO	36.49	36.77	36.45	36.41	36.38	37.03	36.99	36.44	37.01	34.98	35.67	36.81	36.70	35.10	36.13
Na ₂ O	0.01	0.01	0.01	bdl	0.01	0.01	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.02
K ₂ O	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.01
Total	99.98	101.03	101.09	100.95	100.10	100.01	100.71	99.24	100.93	99.53	100.07	99.72	99.47	98.44	100.83
Ions per 12 oxygens															
Si	5.964	5.948	5.928	5.931	5.973	5.990	5.955	5.988	5.954	5.958	6.042	5.944	6.028	6.013	5.992
Ti	0.039	0.020	0.026	0.026	0.022	0.019	0.047	0.021	0.033	0.040	0.041	0.064	0.045	0.050	0.039
Al	3.674	3.854	3.884	3.865	3.794	3.759	3.810	3.761	3.785	3.702	3.727	3.883	3.576	3.683	3.757
Cr	bdl	0.001	0.001	0.002	0.002	0.002	0.001	0.001	0.001	0.048	0.019	0.036	0.041	0.024	0.022
V	0.023	0.036	0.036	0.049	0.053	0.062	0.063	0.066	0.100	0.264	0.117	0.004	0.140	0.181	0.134
Fe ³⁺	0.210	0.178	0.173	0.169	0.165	0.123	0.122	1.156	0.142	bdl	bdl	0.027	0.003	bdl	0.011
Fe ²⁺	0.015	0.019	0.036	0.035	0.028	0.027	0.030	0.022	0.014	0.009	0.077	bdl	bdl	bdl	bdl
Mn	0.013	0.020	0.017	0.017	0.017	0.017	0.015	0.018	0.016	0.133	0.073	0.019	0.096	0.154	0.144
Mg	0.061	0.037	0.068	0.077	0.066	0.023	0.013	0.025	0.018	0.147	0.137	0.090	0.132	0.117	0.109
Ca	5.907	5.885	5.828	5.829	5.877	5.995	5.943	5.944	5.937	5.695	5.755	5.950	5.987	5.771	5.798
Na	0.002	0.002	0.002	bdl	0.002	0.003	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.005
K	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.002
Mol% end members															
Grossular	91.69	92.91	92.13	91.75	92.11	93.70	93.20	92.82	92.33	86.39	90.77	94.89	90.35	89.06	90.62
Pyrope	1.03	0.62	1.15	1.29	1.11	0.37	0.22	0.42	0.30	2.46	2.27	1.48	2.12	1.93	1.79
Almandine	0.25	0.31	0.61	0.59	0.46	0.44	0.50	0.36	0.23	0.15	1.27	bdl	bdl	bdl	bdl
Spessartine	0.22	0.34	0.28	0.29	0.29	0.27	0.25	0.30	0.28	2.22	1.20	0.32	1.55	2.55	2.38
Andradite	5.26	4.40	4.27	4.17	4.10	3.10	3.05	3.90	3.54	bdl	bdl	0.69	0.07	bdl	0.28
Uvarovite	bdl	0.03	0.03	0.06	0.06	0.06	0.03	0.03	0.03	1.20	0.48	0.91	1.07	0.62	0.55
Goldmanite	0.58	0.89	0.90	1.21	1.32	1.56	1.56	1.65	2.48	6.59	2.97	0.10	3.66	4.58	3.38
Schorlomite	0.97	0.51	0.63	0.65	0.54	0.49	1.18	0.52	0.81	1.00	1.03	1.61	1.18	1.27	0.99

^a Ten points per sample were analyzed, except for Tanzanian samples A and B, which were analyzed in two and four points, respectively. Abbreviation: bdl = below detection limit (0.01 wt. %).

TABLE 3. Trace-element composition obtained by LA-ICP-MS of grossular from Itrafo and Gogogogo, Madagascar.^a

Location	Itrafo							Gogogogo
Sample	2	3	4	6	7	8	9	C
Color	Yellowish green	Yellowish green	Green	Green	Green	Green	Intense green	Intense green
No. analyses	7	5	5	3	6	3	5	5
Element (ppmw)								
Li	0.89	1.01	0.95	0.31	0.65	0.87	0.24	0.19
Be	0.64	bdl	bdl	0.38	0.81	bdl	bdl	0.18
B	5.42	1.46	1.74	0.49	4.40	0.24	1.60	1.28
Na	29.2	41.7	106	na	32.1	na	21.3	137
Mg	884	1408	1530	na	380	na	427	2390
Sc	5.46	7.60	9.41	14.2	5.03	5.86	9.48	18.6
Ti	947	1327	1162	1217	1973	1033	1526	3165
V	1872	1561	2359	3689	3088	3179	5470	233
Cr	8.61	40.5	71.1	53.4	4.91	12.1	11.0	1934
Mn	1184	1050	986	na	876	na	958	1128
Co	0.08	0.12	0.17	0.02	0.05	0.03	0.04	0.06
Ni	0.35	0.00	0.27	2.07	0.31	0.25	0.22	0.12
Zn	2.36	6.89	11.3	1.07	0.82	2.26	0.81	4.55
Rb	bdl	0.05	0.27	0.02	0.04	bdl	0.06	0.01
Sr	0.03	0.08	0.22	0.01	0.04	0.03	0.02	0.34
Y	84.3	115	169	151	51.8	96.8	55.9	28.2
Zr	3.15	9.95	9.28	2.92	1.96	2.24	1.63	68.5
Nb	0.03	0.07	0.03	0.05	0.05	0.10	0.07	0.09
Cs	0.01	bdl	0.12	bdl	0.02	bdl	bdl	bdl
Ba	0.03	0.02	0.01	0.01	0.03	bdl	0.03	0.02

^a Abbreviations: bdl = below detection limit; na = not analyzed.

nant areas of absorption saturating the detector in the 3700–3500 and 2000–400 cm⁻¹ regions. The first area of total absorption is intrinsic to garnet, whereas the latter is related to incorporation of hydroxyl groups into the structure (Rossman and Aines, 1991).

DISCUSSION

The various samples from Itrafo exhibited typical gemological properties for grossular (e.g., O'Donoghue, 2006). In particular, the saturated green samples (tsavorite) showed RI and SG values comparable to those of tsavorite from the other notable sources (Tanzania, Kenya, Pakistan, and Gogogogo, Madagascar; see O'Donoghue, 2006).

Crystalline inclusions (probably graphite together

with other minerals) are typical in grossular and tsavorite from all sources, whereas the multiphase fluid inclusions we observed in many Itrafo samples are rather unusual in tsavorite. Nevertheless, similar multiphase inclusions have been reported in a few samples from Tanzania (Seifert and Hyršl, 1999; Gübelin and Koivula, 2005).

The grossulars from Itrafo were characterized by their high iron content. Each showed >1 wt.% Fe₂O₃, corresponding to a small but significant percentage of andradite (>3 mol%; see table 2 and figure 9), which is the predominant substitutional molecule in grossular (Deer et al., 1997). In particular, the maximum value of iron (1.85 wt.% Fe₂O₃) measured in the brown-green sample (no. 1) demonstrated the strong

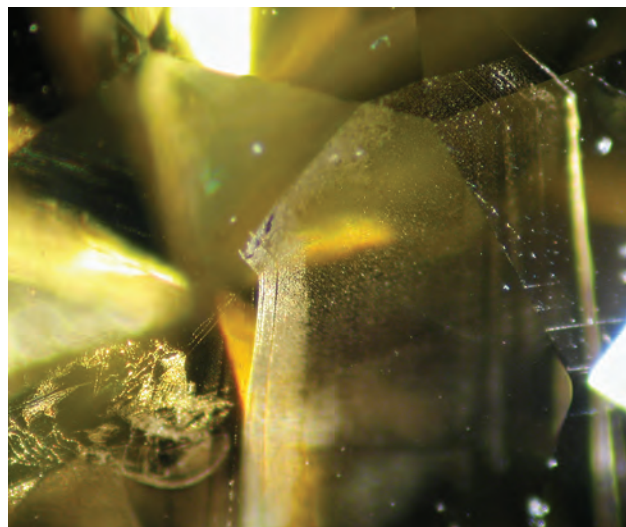


Figure 6. A few of the grossular samples contained partially healed fractures. Photomicrograph by I. Adamo; magnified 45 \times .

influence of this chromophore. Vanadium had a positive correlation with green coloration, as the brown-green and yellowish green samples (nos. 1–3) contained lower V_2O_3 (0.19–0.30 wt.%) than the green specimens (>0.40 wt.%). In all nine samples analyzed here, the $Fe_2O_3:V_2O_3$ ratio was greater than 1 and increased directly with the strength of the brown and yellow color components, reaching a maximum

Figure 7. One grossular sample displayed fine parallel growth tubes. Photomicrograph by I. Adamo; magnified 45 \times .

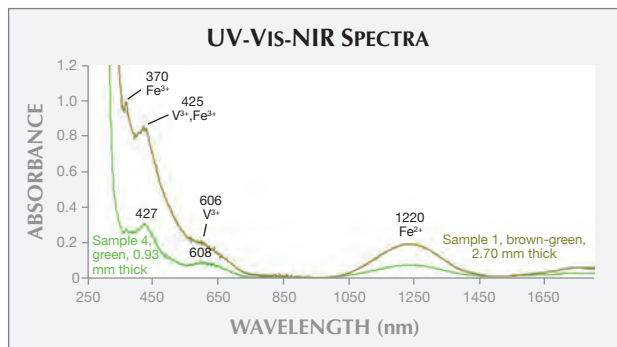
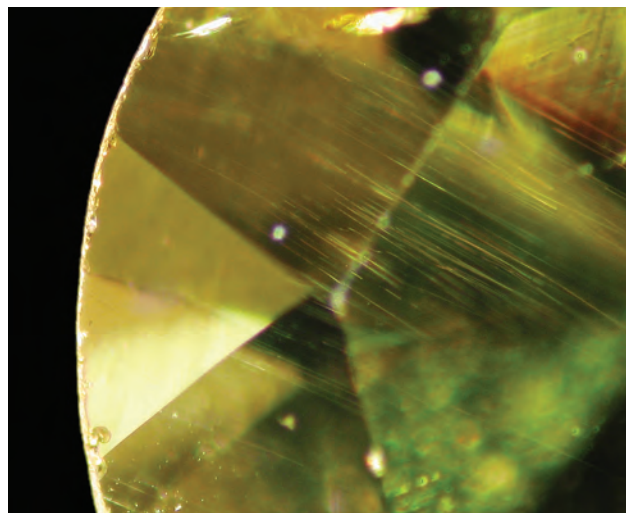


Figure 8. The UV-Vis-NIR spectra of two representative samples from Itrafo show features related to Fe^{3+} , Fe^{2+} , and V^{3+} .

value of nearly 10:1 in the brown-green specimen (figure 10). The very low Cr contents (5–71 ppm; table 3) suggest that this element does not have a significant effect on the green coloration in our Itrafo grossulars, confirming the predominance of V as the green chromophore.

Comparing the chemical composition of our Itrafo samples with specimens from other localities (data from Gübelin and Weibel, 1975; Muije et al., 1979; Manson and Stockton, 1982; Key and Hill, 1989; Kane et al., 1990; Jackson, 1992; Mercier et al., 1997), the most important difference is the iron content (see table 2 and figure 9). In fact, Fe_2O_3 is always very low in tsavorite from Tanzania, Kenya, Pakistan, and Gogogogo—generally not exceeding 0.3 wt.%. The Itrafo tsavorites had lower V contents than those from other localities, with the latter usually containing >1 wt.% V_2O_3 (see table 2, figure 9, and references above). The $Fe_2O_3:V_2O_3$ ratio in tsavorite from Itrafo (figure 10) was always greater than 1, whereas samples from the other sources generally show a ratio less than 1. The average Cr content of Itrafo tsavorite was lower than that of Tanzanian and Kenyan samples but similar to that of some Pakistani specimens (Jackson, 1992). Our samples' Mg and Mn contents also corresponded to the levels found in tsavorite from Pakistan (Jackson, 1992).

The UV-Vis-NIR spectra of grossulars from Itrafo are characterized by vanadium and iron features, the latter in both divalent and trivalent states. In particular, the absorption features at 425–427 and 606–608 nm are related to V^{3+} (Schmetzer and Ottemann, 1979; Schmetzer, 1982). The chromophore Fe^{3+} is responsible for the 370 nm peak, though it can also

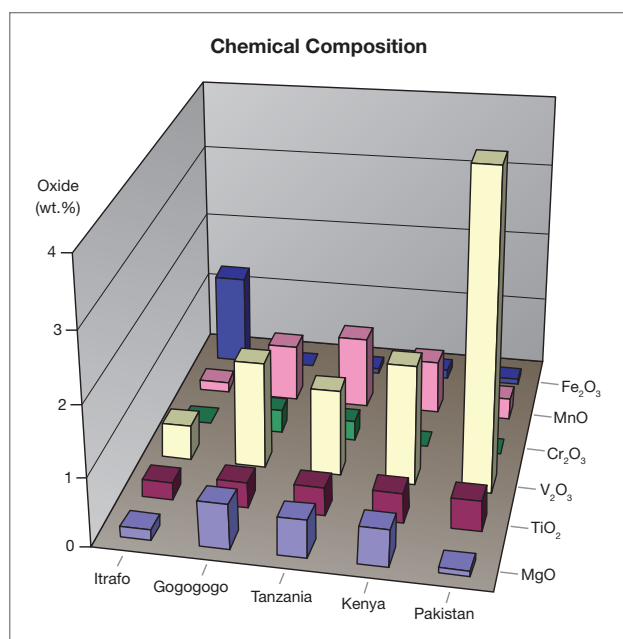


Figure 9. The average contents of MgO, TiO₂, V₂O₃, Cr₂O₃, MnO, and Fe₂O₃ are shown for tsavorite from various localities. The chemical data for samples from Kenya and Pakistan are those reported in Key and Hill (1989) and Jackson et al. (1992), respectively.

contribute to the 425–427 nm absorption (Manning, 1969, 1972; Moore and White, 1972; Amthauer, 1976; Rossman, 1988). Iron, as Fe²⁺, causes the 1220 nm broad band in the near-infrared region (Manning, 1972; Rossman, 1988). Although the absorption bands due to V³⁺ are very close to those of Cr³⁺ (Amthauer, 1976; Rossman, 1988), we consider vanadium the predominant chromophore due to its higher concentration in the chemical data.

Mid-IR spectroscopy allowed us to easily detect the presence of hydroxyl groups, which are known to occur in variable amounts in grossular (Rossman and Aines, 1991).

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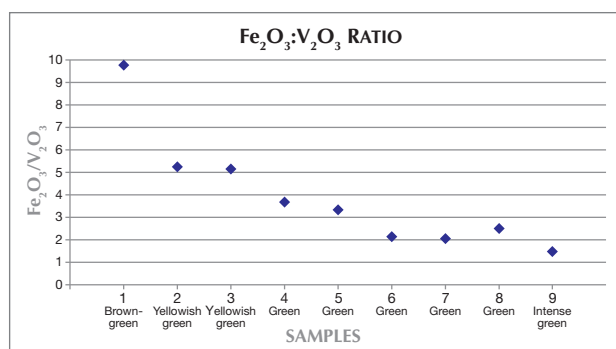


Figure 10. The Fe₂O₃:V₂O₃ ratio of our nine samples from Itrafo was always greater than 1, with higher values in samples showing brown or yellow color components (nos. 1, 2, and 3).

CONCLUSIONS

Since the 2002 discovery of brown and green (tsavorite) grossular at Itrafo, Madagascar, the locality has probably produced <20 kg of gem-quality rough, typically as fragments weighing <1 g. This study of rough and faceted samples, representative of the gem material from this deposit, showed a grossular composition (91–94 mol%) consistent with the material's gemological properties (RI = 1.740–1.742, SG = 3.58–3.62). Our chemical and spectroscopic data showed that Fe and V, in variable ratios but always higher than 1:1, are responsible for the various colors. Iron is responsible for brown or yellow color components, while V³⁺ causes a green hue. The samples' low Cr content (<71 ppm) suggests that its contribution to the color is negligible. Comparing the gemological, chemical, and spectroscopic features of these garnets with those from other localities (Tanzania, Kenya, Pakistan, and Gogogogo, Madagascar), the main difference concerns the Itrafo samples' higher iron content (Fe₂O₃ >1 wt.% and Adr >3 mol%), which is consistent with the brown or yellow components of their coloration.

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