

# PINK TO PINKISH ORANGE MALAYA GARNETS FROM BEKILY, MADAGASCAR

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Malaya garnets from Bekily, Madagascar, are predominantly pink to pinkish orange, with some stones orange to red. Discovered only in the late 1990s, the majority are intermediate members of the pyrope-spessartine series with variable contents of almandine and subordinate grossular. The refractive index, specific gravity, and color of these garnets are related to their iron and manganese contents. Inclusions identified by Raman analysis are rutile needles and platelets, graphite, quartz, apatite, zircon, and sillimanite. Negative crystals were also seen. Important differences in predominant color and chemistry were noted when the Bekily garnets, only the second commercial source of malaya garnet, were compared to malaya garnets from East Africa, which have been available since the late 1970s.

**T**he Bekily area of southern Madagascar, which produces attractive color-change (blue-green to purple) garnets (Schmetzer and Bernhardt, 1999), also has produced garnets that are mainly pink to pinkish orange (figure 1), and less commonly orange to red. These garnets first appeared in the local market about 1997.

Pyrope-spessartines that contain only minor amounts or traces of vanadium and chromium have been reported to occur in colors ranging from pink to red to orange and even yellow-orange (see, e.g., Rouse, 1986; Arem, 1987; and Dirlam et al., 1992). Until recently, the only commercial source for this type of garnet was the large mining area in East Africa that covers various localities in northern Tanzania and southern Kenya, which is commonly referred to as the Umba mining region. Gemological and chemical data for the Umba garnets were published by Saul et al. (1978), Jobbins et al. (1978), Schmetzer and Bank (1981a,b), and Stockton and Manson (1982); a detailed examination of inclusions appeared in Gübelin (1981). Various trade names such as "malaya" (malaia), "umbalite," and "pyral-

spite" have been applied to intermediate pyrope-spessartine garnets in this color range, but only "malaya" has found international acceptance in the trade and the literature (see, e.g., references above and Curtis, 1980; Stockton and Manson, 1985; Keller, 1992; and Hänni, 1999). Limited amounts of rough are still mined in northern Tanzania and marketed as malaya garnet (Karl Egon Wild, pers. comm., 2001). In this article, the term *malaya* is used for garnets that are pink to pinkish orange, as well as orange to red, that are composed primarily of pyrope-spessartine. Note, however, that there is no established definition of this term based on a precise compositional range.

*[Editor's note: Although a trade name, because of its long acceptance in the trade, for the balance of the article malaya will not be enclosed in quotation marks or capitalized.]*

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Figure 1. Malaya garnets from Bekily, Madagascar, are predominantly pyrope-spessartine. The color of these six pink to pinkish orange samples (2.94–4.06 ct) is representative of more than 97% of the commercially available malaya garnets from this locality. Photo by Maha Tannous; incandescent light.



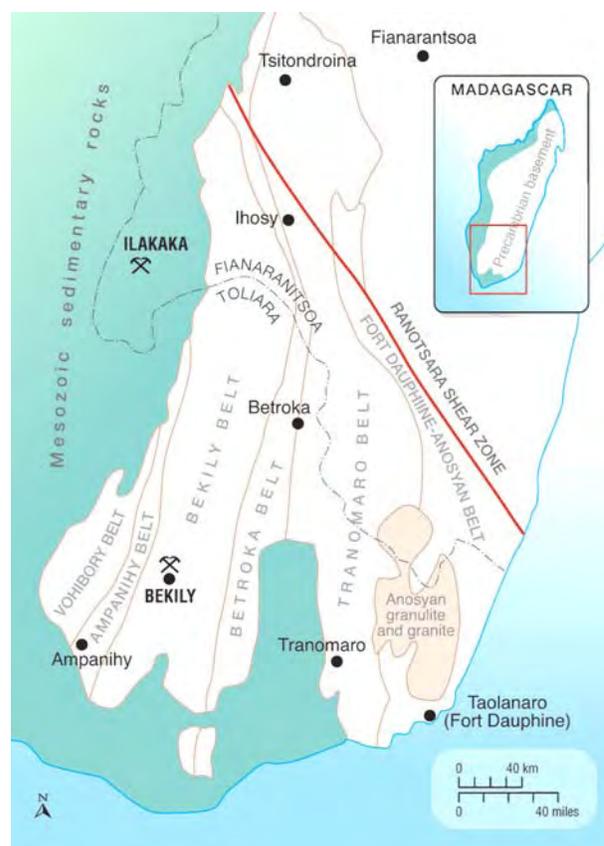
A brownish pinkish orange pyrope-spessartine from an unknown locality reportedly in central Madagascar was documented by Johnson and Koivula (1998). Zylberman (1999) described a parcel of predominantly pink to pinkish orange pyrope-spessartine garnets from an unknown primary source in Madagascar. He included gemological properties and chemical data, and noted a distinct shift of color between daylight and incandescent light. A new occurrence of malaya garnets in Madagascar also was reported by Hänni (1999), but the exact locality was not provided.

The present study was undertaken to characterize the predominantly pink to pinkish orange garnets from the mining region near Bekily in Madagascar. The large number of intermediate pyrope-spessartines in this group make this locality, to the best of our knowledge, the second commercial source of malaya garnets in the world today. Samples of pink-to-red Bekily garnets in their host rock also were examined, as were faceted samples representing other colors of pyrope-almandine-spessartine. Last, the Madagascar samples are compared to malaya garnet from Umba in East Africa.

## LOCATION AND GEOLOGY

The village of Bekily is located about 200 km northwest of Taolanaro (formerly Fort-Dauphin) in southern Toliara Province (figure 2). The mining area for the color-change garnets described by Schmetzer and Bernhardt (1999) is located about 15 km north of Bekily; the malaya garnets documented in the present article were excavated in

Figure 2. Malaya garnets are mined from an area north of Bekily in southern Madagascar's Toliara Province. This area consists of high-grade metamorphic rocks that have been subdivided into six tectonic zones. The Bekily belt is composed mainly of sillimanite-cordierite-garnet gneisses. Modified from Windley et al. (1994).



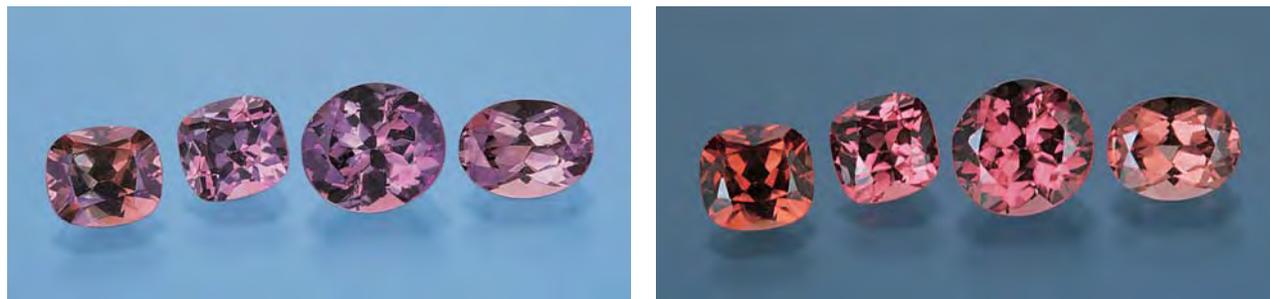


Figure 3. Malaya garnets from Madagascar (here, 0.74–1.59 ct) reveal a distinct shift of color from pink or pinkish orange in daylight (left) to a more reddish pink or reddish orange in incandescent light (right). Microprobe analyses of the four samples pictured gave FeO contents from 6.65 to 9.89 wt.%, and MnO contents from 10.39 to 15.95 wt.%. Photos by Maha Tannous.

garnet crystals as large as 3 mm. To determine the mineral assemblages of these specimens, we prepared petrographic thin sections of each for examination with a petrographic microscope. Several garnet crystals (i.e., 5–20) in each of four of the thin sections were analyzed by the Cameca electron microprobe mentioned above; a total of 77 point analyses were obtained. In addition, a garnet crystal was carefully removed from one rock sample and analyzed with the Adamas Advantage SAS 2000 spectrophotometer.

## RESULTS

**Characterization of the Garnet-Bearing Rock Samples.** The rock samples were deeply weathered, partly decomposed gneisses consisting of the following mineral assemblage: garnet, quartz, plagioclase, sillimanite, rutile, graphite, zircon, and symplectite of unknown composition. Thus, the garnets are hosted by sillimanite gneisses. This is consistent with previous work on rocks from southern Madagascar, including the Bekily belt (Windley et al., 1994).

**Visual Appearance and Gemological Properties of the Gem Garnets.** Prior to cutting, the gem rough obtained by TH was visually examined to document its morphology and surface characteristics. These samples consisted mostly of irregular fragments that lacked external crystal faces. A minor fraction of the rough garnets, however, revealed a somewhat rounded surface, similar to that typically seen on rolled pebbles from alluvial deposits.

The faceted samples were predominantly pink to pinkish orange with a homogeneous color distribution. They showed distinctly variable saturation, ranging from almost colorless, very light pink or very light pinkish orange, to intense pink, pinkish orange, brownish pink, orange-red, to red in daylight. The lighter colored garnets in particular exhibited a distinct color shift from pink or pinkish

orange in daylight to a more reddish pink or reddish orange in incandescent light (figure 3). One sample revealed an unusual orange coloration.

The refractive indices and specific gravities of 15 of the 31 malaya garnets are presented in table 1 (M1–M15). The other 16 samples more or less duplicate the physical and chemical properties of the 15 samples selected for the table. The garnets revealed a distinct variation in refractive indices from 1.739 to 1.782 and in specific gravity between 3.77 and 4.04 (figure 4A). Twenty-seven garnets revealed a narrower range of both refractive indices (i.e., between 1.747 and 1.766) and specific gravities (between 3.80 and 3.96) than the full group of 31, and this color group represented 97% of the 1,000 faceted stones studied.

**Chemical Properties. Faceted Malaya Garnets.** The 31 faceted garnets analyzed were relatively homogeneous; they did not show any distinct chemical zoning. The analyses of the 15 representative samples (M1–M15) are given in table 1. The samples consisted of 24 to 70 mol.% pyrope and 13 to 59 mol.% spessartine. Almandine varied from 4 to 25 mol.%, and there were smaller percentages of grossular (3–5 mol.%). Calculating the garnet composition for 12 oxygens and for both Fe<sup>2+</sup> and Fe<sup>3+</sup>, we found that iron in the trivalent state either was not present or was present in very small amounts (mostly <0.01 Fe<sup>3+</sup> atoms per formula unit). This indicates a very small andradite component if present at all (cf. Spectroscopic Properties). Traces of vanadium and chromium were always present and are calculated as the goldmanite and uvarovite molecules, respectively, in table 1.

A plot of refractive index versus the sum of FeO + MnO (figure 4B) shows the variation of this optical property with chemical composition. A similar diagram (not shown) is obtained when specific gravity is plotted against the sum of FeO + MnO. These

**TABLE 1.** Physical and chemical properties of representative garnets from Madagascar.

Bekily <sup>a</sup>											
Pyrope-almandine-spessartine (malaya), faceted gems											
Property	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
Color	Light pink	Light pink	Orange	Pinkish orange	Pink	Pink	Pink	Pink	Intense pink	Pink	Pink
Refractive index	1.747	1.740	1.782	1.753	1.748	1.748	1.749	1.750	1.754	1.758	1.755
Specific gravity	3.80	3.78	4.04	3.89	3.81	3.85	3.85	3.85	3.86	3.88	3.89
Microprobe analyses (wt.%) <sup>b</sup>											
SiO <sub>2</sub>	40.96	41.24	38.68	40.97	40.69	39.94	41.91	41.33	39.93	41.29	40.34
TiO <sub>2</sub>	0.01	0.01	0.09	0.06	0.05	0.04	0.05	0.06	0.04	0.04	0.03
Al <sub>2</sub> O <sub>3</sub>	23.59	23.94	22.10	23.27	23.14	22.85	23.84	23.61	23.01	23.83	23.34
Cr <sub>2</sub> O <sub>3</sub>	0.09	0.05	0.07	0.04	0.06	0.10	0.07	0.09	0.16	0.05	0.05
V <sub>2</sub> O <sub>3</sub>	0.11	0.08	0.08	0.04	0.05	0.07	0.08	0.09	0.16	0.03	0.05
FeO <sup>c</sup>	2.13	2.00	5.65	3.61	3.60	4.11	4.45	5.75	6.99	9.73	10.07
MnO	14.81	12.44	26.63	16.72	13.50	13.53	13.04	12.70	12.82	11.57	10.42
MgO	16.94	19.07	6.17	14.89	16.46	15.96	16.65	15.81	14.69	14.93	15.31
CaO	1.81	1.26	1.77	1.23	1.70	1.68	1.81	1.98	2.03	1.05	1.07
Total	100.45	100.09	101.24	100.83	99.25	98.28	101.90	101.42	99.83	102.52	100.68
FeO:MnO	0.14	0.16	0.21	0.22	0.27	0.30	0.34	0.45	0.54	0.84	0.97
Cations <sup>d</sup>											
Si	2.973	2.965	2.993	3.000	2.991	2.977	2.999	2.989	2.963	2.982	2.965
Ti	0.001	0.001	0.005	0.003	0.003	0.002	0.003	0.003	0.002	0.002	0.002
Al	2.018	2.028	2.016	2.008	2.005	2.007	2.010	2.012	2.012	2.029	2.022
Cr	0.005	0.003	0.004	0.002	0.004	0.006	0.004	0.005	0.009	0.003	0.003
V	0.006	0.005	0.005	0.002	0.003	0.004	0.005	0.005	0.010	0.002	0.004
Fe	0.129	0.121	0.366	0.221	0.221	0.256	0.266	0.348	0.434	0.588	0.619
Mn	0.910	0.757	1.746	1.036	0.841	0.854	0.790	0.778	0.806	0.708	0.649
Mg	1.832	2.043	0.711	1.625	1.804	1.773	1.775	1.704	1.625	1.607	1.676
Ca	0.141	0.097	0.147	0.096	0.134	0.134	0.139	0.154	0.161	0.081	0.085
Mol. % end members <sup>e</sup>											
Pyrope	60.8	67.7	23.9	54.6	60.1	58.8	59.8	57.1	53.7	53.9	55.3
Spessartine	30.2	25.1	58.8	34.8	28.0	28.3	26.6	26.1	26.6	23.7	21.4
Almandine	4.3	4.0	12.3	7.4	7.4	8.5	9.0	11.7	14.3	19.7	20.4
Grossular	4.2	2.9	4.5	3.0	4.2	3.9	4.3	4.8	4.4	2.5	2.5
Goldmanite	0.3	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.5	0.1	0.2
Uvarovite	0.2	0.1	0.2	0.1	0.2	0.3	0.2	0.2	0.4	0.1	0.1

<sup>a</sup> Samples from Bekily are arranged according to increasing FeO:MnO ratio. All samples are faceted except for A–D, each of which consists of several grains in petrographic thin sections; nd = not determined.

<sup>b</sup> Average composition of 10 analyses each, except for samples A (19), B (15), C (6), and D (37).

<sup>c</sup> Total iron as FeO.

<sup>d</sup> Calculated on the basis of 12 oxygens.

<sup>e</sup> Pyrope=Mg<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub>, Spessartine=Mn<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub>, Almandine=Fe<sub>3</sub><sup>2+</sup>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub>, Grossular=Ca<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub>, Goldmanite=Ca<sub>3</sub>V<sub>2</sub><sup>3+</sup>Si<sub>3</sub>O<sub>12</sub>, Uvarovite=Ca<sub>3</sub>Cr<sub>2</sub>Si<sub>3</sub>O<sub>12</sub>.

results explain the variability of some optical and physical properties with chemical composition in individual samples.

The chemical variability of the Bekily garnets is revealed in figure 5. Most (27 samples) plot in a relatively small area of the pyrope-almandine-spessartine ternary diagram. These samples represent more than 97% of the 1,000 faceted malaya garnets from Bekily that we examined, that is, those with a predominantly pink or pinkish orange—but sometimes orange red or red—coloration.

Although most samples are members of the pyrope-spessartine series with smaller percentages of almandine than spessartine, six of the 31 ana-

lyzed samples have almost equal spessartine and almandine contents (samples M11, M12, and M13 in table 1, plus three samples not listed in the table). Two garnets (samples M14 and M15 in table 1) have distinctly higher percentages of almandine than spessartine. The samples in table 1 illustrate the broad range of compositions within pyrope-almandine-spessartine for the pink, pinkish orange, orange-red, or red garnets from Bekily.

**Garnets from Rock Specimens.** Chemical data for the garnet grains analyzed in four petrographic thin sections are also presented in table 1 (samples A–D); all were homogeneous except for small chemical

Bekily <sup>a</sup>				Madagascar (unspecified), faceted gems							
Garnets from rock samples				Spessartine				Pyrope-almandine			
M12	M13	M14	M15	A	B	C	D	S	PA1	PA2	R
Light pink	Orange-red	Pink	Red	Pink to red	Pink to red	Pink to red	Pink to red	Orange	Red	Red	Purplish pink (rhodolite)
1.739	1.754	1.760	1.756	nd	nd	nd	nd	1.802	1.753	1.760	1.750
3.77	3.86	3.93	3.87	nd	nd	nd	nd	4.19	3.83	3.88	3.84
41.44	39.99	39.41	40.86	38.90	39.11	39.40	39.58	35.83	40.30	40.20	42.30
0.04	0.06	0.02	0.05	0.02	0.01	0.02	0.02	0.04	0.05	0.05	0.01
23.32	23.31	22.88	23.00	22.48	22.60	22.74	22.91	20.71	23.10	23.28	24.14
0.08	0.12	0.05	0.19	0.15	0.09	0.08	0.09	0.01	0.11	0.04	0.03
0.09	0.17	0.04	0.08	0.06	0.06	0.07	0.06	0.01	0.13	0.05	0.01
6.11	9.65	12.12	11.75	17.20	16.56	16.32	16.79	3.51	14.41	19.24	16.79
6.25	9.18	10.09	7.83	8.74	8.34	8.07	5.78	38.32	3.39	1.29	0.20
19.41	15.62	14.03	15.07	10.49	11.39	11.96	13.37	0.01	16.18	15.18	18.27
2.05	1.60	1.07	1.90	1.63	1.38	1.36	1.19	0.46	1.68	1.56	1.02
98.79	99.70	99.71	100.73	99.67	99.54	100.02	99.79	98.90	99.35	100.89	102.77
0.98	1.05	1.20	1.50	1.97	1.99	2.02	2.90	0.09	4.25	14.90	84.90
2.998	2.954	2.954	2.995	2.974	2.976	2.975	2.969	2.981	2.975	2.956	2.986
0.002	0.003	0.001	0.003	0.001	0.001	0.001	0.001	0.003	0.003	0.003	0.001
1.989	2.029	2.020	1.987	2.026	2.027	2.024	2.025	2.031	2.009	2.018	2.009
0.004	0.007	0.003	0.011	0.009	0.005	0.005	0.005	—	0.007	0.003	0.002
0.005	0.010	0.003	0.005	0.004	0.004	0.004	0.004	—	0.008	0.003	—
0.370	0.596	0.760	0.720	1.100	1.054	1.030	1.054	0.245	0.889	1.183	0.991
0.383	0.575	0.640	0.486	0.567	0.538	0.516	0.367	2.700	0.212	0.080	0.012
2.093	1.720	1.568	1.647	1.194	1.292	1.346	1.494	0.002	1.780	1.664	1.932
0.159	0.127	0.086	0.149	0.134	0.113	0.110	0.096	0.041	0.133	0.123	0.077
69.7	57.0	51.3	54.9	39.9	43.1	44.8	49.6	0.1	59.1	54.6	64.1
12.7	19.1	21.0	16.2	18.9	18.0	17.2	12.2	90.4	7.0	2.6	0.4
12.3	19.7	24.9	24.0	36.7	35.2	34.3	35.0	8.2	29.5	38.8	32.9
4.8	3.4	2.6	4.3	3.9	3.4	3.3	2.8	1.4	3.7	3.8	2.5
0.3	0.5	0.1	0.2	0.2	0.2	0.2	0.2	—	0.4	0.1	—
0.2	0.3	0.1	0.5	0.4	0.2	0.2	0.2	—	0.3	0.1	0.1

variations (about 2 wt.% for FeO, MgO, or MnO). The color of the larger garnet crystals seen macroscopically in the hand specimens was almost identical to that of the malaya garnets with the highest iron contents, such as samples M14 and M15, but the crystals had distinctly higher iron contents (and, therefore, higher almandine percentages—34 to 37 mol.%) than those measured for the 31 faceted samples, as also seen in figure 5.

**Spectroscopic Properties.** The absorption spectra of our sample Bekily garnets revealed a series of absorption bands of variable intensity (figure 6). The intensities of some of the absorption bands directly correlated to the iron and manganese contents of the garnets determined by electron microprobe. Six typical absorption spectra are shown in figure 6A, arranged according to FeO:MnO ratio.

One rough garnet removed from sample A revealed an absorption spectrum similar to that of the

faceted garnet sample M15, which showed one of the highest iron contents of our 31 samples (figure 6B).

**Features Observed with the Microscope.** When examined with crossed polarizers, all samples revealed strong anomalous double refraction, occasionally parallel to growth planes that form angles of 150° to one another (figure 7). This angle occurs in garnet between faces of the most common forms, namely, the dodecahedron {110} and the trapezohedron {211}. Anomalous double refraction caused by internal strain is characteristic of pyrope-almandine-spessartine-grossular garnets (Hofmeister et al., 1998).

Most samples contained a three-dimensional network of oriented rutile needles (figure 8). Occasionally we also observed oriented platelets or elongated tabular crystals that were identified as rutile by Raman analysis (figure 9).

A variety of other mineral inclusions were identified in the 17 samples selected for Raman analysis.

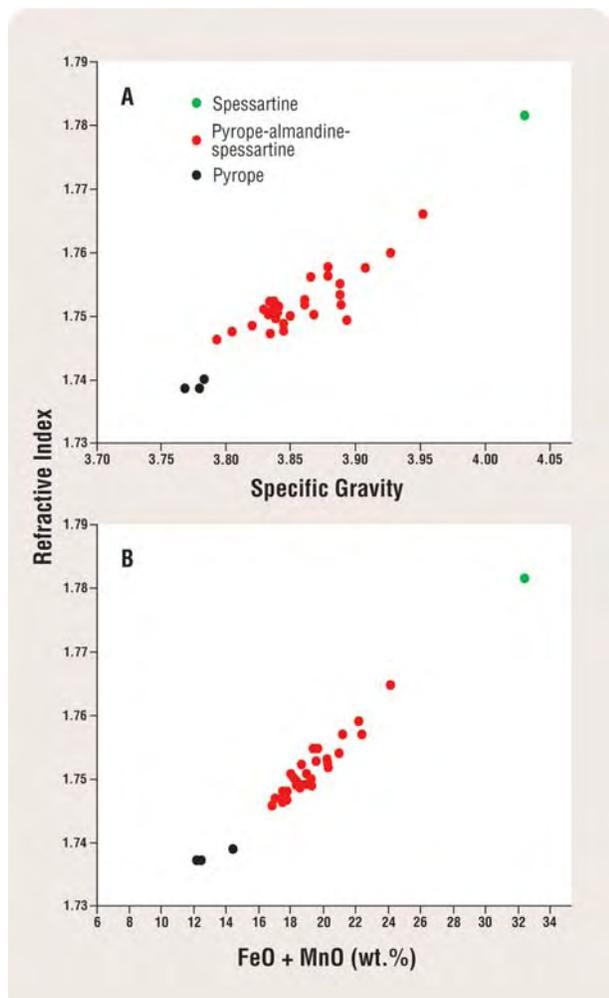
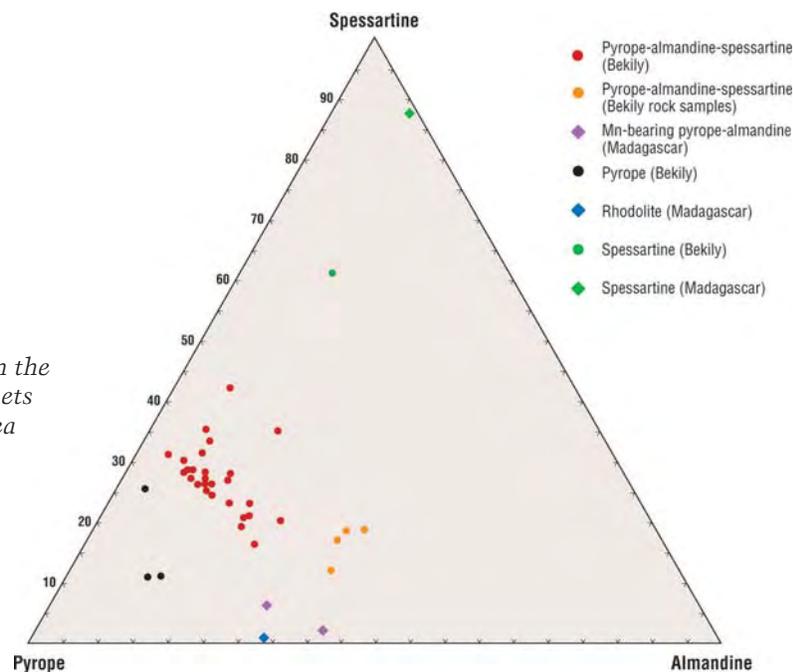


Figure 4. The 31 faceted garnet samples from Bekily showed a positive correlation between refractive index and specific gravity (A). The low Fe, Mn-bearing pyropes (e.g., M2 and M12 in table 1) showed the lowest values, and the Mg-rich spessartine sample (M3) had the highest values. A positive correlation between refractive index and FeO + MnO content was also evident (B).

Figure 5. Garnet samples from Bekily (circles), in the color range typically associated with malaya garnets from this locality, plotted in a relatively small area on this diagram that corresponded to pyrope-spessartine, with a few exceptions. The Bekily garnets from the rock samples showed significantly more almandine component. Four garnet samples from unspecified localities in Madagascar also were analyzed for comparison (diamonds).



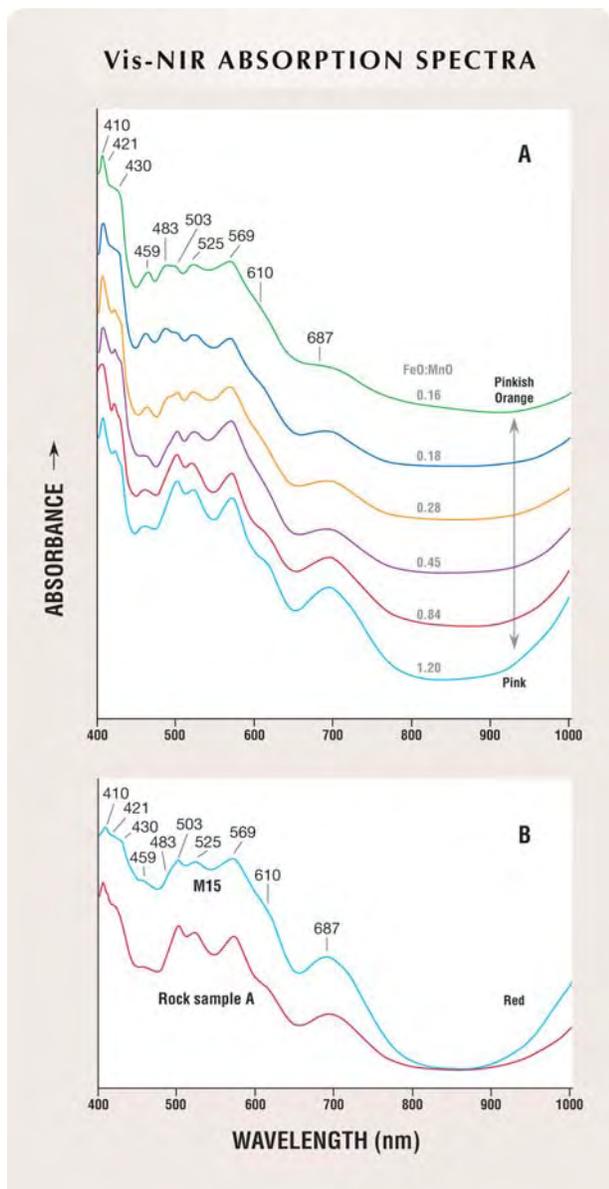
Six samples contained unoriented, irregularly shaped platelets of graphite, some surrounded by tension cracks (figure 10). Five garnets had irregularly shaped quartz inclusions (figure 11). Prismatic apatite crystals, sometimes with slightly rounded edges, were identified in six samples (figure 12). Negative crystals resembling typical garnet morphology were seen in six samples (figure 13); in transmitted light, these cavities appeared opaque (again, see figure 9). Three of the samples contained zircon inclusions with tension cracks (figure 14). Occasionally, mineral inclusions were seen at the center or at the tip of a rutile needle (figure 15); these inclusions were identified as quartz. In one garnet, oriented tabular rutile crystals were surrounded by small quartz crystals. In another sample, we identified minute needle-like to fibrous inclusions as sillimanite.

In general, the mineral inclusions reflect the mineral assemblages that were identified in the thin sections of the garnet-bearing rock specimens (i.e., graphite, quartz, rutile, zircon, and sillimanite).

## DISCUSSION

**Nomenclature.** All samples analyzed were pyrope-spessartines or pyrope-almandine-spessartines.

Using the nomenclature proposed by Stockton and Manson (1985), most of the samples we analyzed were pyrope-spessartines (again, see figure 5). Three light pink garnets (see, e.g., M2 and M12 in table 1)



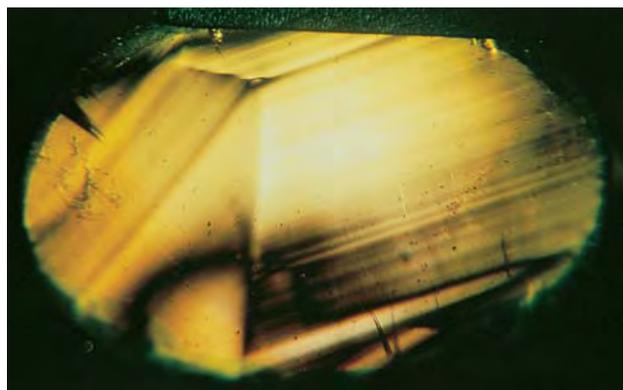
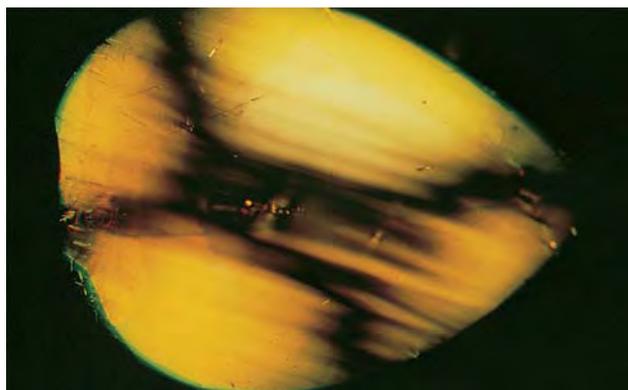
are low manganese- and iron-bearing pyropes. One orange sample (M3) was spessartine with a high magnesium (pyrope) content; in both color and chemistry, it appears to be unusual for stones from the Bekily area. Using the classification proposed by Hanneman (1997), only a few of our samples would be considered pyrope-spessartines; most would be described as pyrope-almandine-spessartines. In contrast, Lind et al. (1998) designated intermediate garnets of various colors with up to 20 mol.% spessartine as rhodolite. This nomenclature is inconsistent with both of the systems mentioned above, as well as with the purplish pink or purplish red color from which rhodolite garnet derives its name.

**Interpretation of Absorption Spectra.** The absorption features recorded in the Bekily garnets are due mostly to Fe<sup>2+</sup> and Mn<sup>2+</sup>. Assignment of the bands at 503, 610, and 687 nm to Fe<sup>2+</sup> and at 483 nm to Mn<sup>2+</sup> (table 2) is consistent with data from the literature (see, e.g., Moore and White, 1972).

A general problem with the assignment of garnet absorption bands is an overlap of several bands from different elements in the visible range. Iron-rich gar-

Figure 6. Absorption spectra of six faceted malaya garnets from Bekily (A) show systematic variations according to their iron and manganese contents. The color of the samples varies from pink (at higher FeO:MnO ratios) to pinkish orange (at low FeO:MnO ratios). The top and bottom spectra are for samples M2 and M14, respectively (see table 1); analyses for the other spectra are not shown in table 1. One faceted sample and one garnet from a rock specimen, both with relatively high iron contents (B), show similar absorption features and color.

Figure 7. Anomalous double refraction was observed in all the Bekily garnet samples when examined between crossed polarizers (left; magnified 20×). Occasionally, internal strain parallel to growth planes was also observed. The growth planes are the most common forms for garnet: the dodecahedron {110} and the trapezohedron {211} (right; magnified 30×). Both taken in immersion with crossed polarizers.



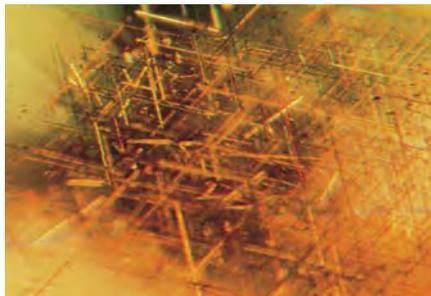
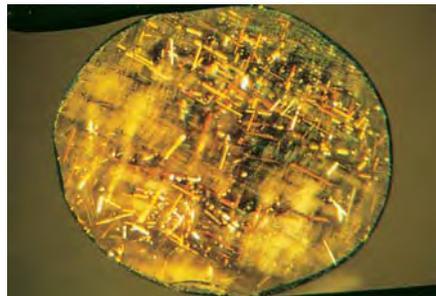


Figure 8. Anomalous double refraction is frequently observed together with rutile needles in Bekily garnet samples (left; magnified 30×). The image on the right shows the three-dimensional network of oriented rutile needles (magnified 40×). Both taken in immersion with crossed polarizers.

nets without significant manganese contents were available to researchers studying this problem in the late 1960s and early 1970s, but samples of pure spessartine were not. Consequently, in pyrope-almandine spectra those bands not previously assigned to iron were assigned to manganese.

Spectroscopic examination of synthetic iron-free spessartines and synthetic manganese-free almandines, however, revealed manganese absorption bands at approximately the same positions as some iron absorption maxima (Langer and Frentrup, 1979; Smith and Langer, 1983). These observations were later confirmed for iron-poor spessartines from Namibia and Nigeria (Lind et al., 1993, 1994; Milisenda and Zang, 1999; Lind and Henn, 2000). On the basis of these references and our own results, the bands at 459 and 525 nm can be assigned to both  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$ . The intensities of these two bands vary only slightly in our samples with variable Fe:Mn ratios (again, see figure 6).

Another overlap may be present at 569 nm. An iron band at this wavelength is commonly observed in iron-bearing rhodolites without significant manganese, vanadium, or chromium, but this band also has been attributed to  $\text{V}^{3+}$  and/or  $\text{Cr}^{3+}$  in garnets

(Amthauer, 1976; Schmetzer and Ottemann, 1979; Schmetzer et al., 1980; Schmetzer and Bernhardt, 1999). Small amounts of  $\text{V}_2\text{O}_3$  and  $\text{Cr}_2\text{O}_3$  were recorded in our samples (table 1), so the absorption at 569 nm is partially due to these trace elements.

A final overlap is also possible between  $\text{Mn}^{2+}$  and  $\text{Fe}^{3+}$  at 430 nm. This band is seen in the spectra of  $\text{Fe}^{3+}$ -bearing garnet without manganese (i.e., hessonite, which is iron-bearing grossular). However, due to the intense  $\text{Mn}^{2+}$  absorption in the 410–430 nm range, it is impossible to determine if a weak  $\text{Fe}^{3+}$  band is also present.

**Color and Color Causes.** The intensities of the absorption maxima are related to the iron and manganese contents, and to the FeO:MnO ratio.  $\text{Mn}^{2+}$  and  $\text{Fe}^{2+}$  both replace the  $\text{Mg}^{2+}$  of “pure” pyrope garnet, which is colorless. With increasing iron (i.e., with increasing almandine content), the color intensifies from very light pink or very light pinkish orange to an intense pink, or almost red (figure 16). Traces of vanadium and/or chromium also may contribute to pink coloration. With increasing manganese, the samples appear more orange, and may attain the color of near-end-member spessartines

Figure 9. Occasionally, the network of rutile needles was associated with birefringent rutile platelets; a negative crystal in the center appears opaque in transmitted light. Immersion, crossed polarizers, magnified 30×.

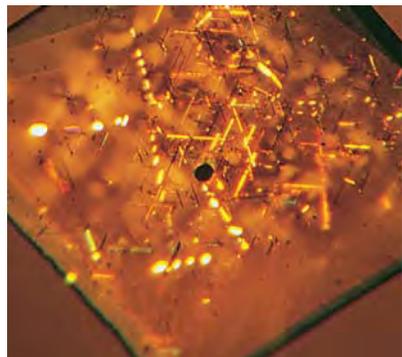


Figure 10. Tabular graphite crystals were identified in a few Bekily garnets, some surrounded by tension cracks. Magnified 50×.



Figure 11. Irregular fragments of transparent crystals seen in some of the garnets were identified as quartz. The quartz inclusion shown here is intergrown with a rutile needle. Magnified 100×.





Figure 12. Apatite crystals, some with rounded edges, were identified by Raman analysis. Immersion, crossed polarizers, magnified 80 $\times$ .

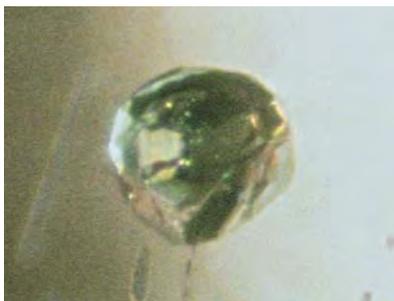


Figure 13. Negative crystals with a garnet morphology were also seen in the Bekily material. Magnified 50 $\times$ .



Figure 14. Zircon crystals with tension cracks were seen rarely in the samples examined. Magnified 100 $\times$ .

when iron contents are low (figure 17; see box A).

Garnets of the pyrope-almandine series without significant manganese usually are purplish pink to purplish red (see figure 18). The absorption spectrum of sample R consists of iron-related bands (see table 2) and two distinct minima in the visible range, namely in the blue-violet and red regions. Small amounts of manganese (i.e., 1–3 wt.% MnO, samples PA1 and PA2 in table 1) are sufficient to eliminate the purple color component, resulting in an intense red. This dramatic change (again, see figure 18) is caused by the strong manganese absorption bands in the violet region (i.e., at 410, 421, and 430 nm).

The color of the Mn-bearing pyrope-almandine garnets we analyzed (samples PA1 and PA2 in table 1) resembles that of the orange-red, pink, or red garnets from Bekily with high Fe and relatively low Mn contents (e.g., samples M13 to M15). It is clear that an increase in MnO from about 3 wt.% (in Mn-bearing pyrope-almandines) to about 7–10 wt.% (in the malaya garnets from Bekily) does not strongly influence color. This also explains the similarity in color between the faceted malaya garnets with high

Figure 15. In some samples, mineral inclusions—identified as quartz—were found at the center or tip of rutile needles. Magnified 120 $\times$ .



**TABLE 2.** Assignment of absorption maxima observed in malaya garnets from Bekily, Madagascar.

Absorption maximum (nm)	Fe <sup>2+</sup>	Mn <sup>2+</sup>	V <sup>3+</sup> and/or Cr <sup>3+</sup>	Fe <sup>3+</sup>
410		X		
421		X		
430		X		X
459	X	X		
483		X		
503	X			
525	X	X		
569	X		X	
610	X			
687	X			

iron contents and the relatively iron-rich garnet specimens in our rock samples.

At least two other mechanisms are known that can change the color of pyrope-almandines from purplish pink or purplish red (rhodolites) to red or orange-red: (1) the superimposition of a chromium spectrum over the iron-related absorption bands, as in Cr-bearing pyropes that contain some iron; and (2) the superimposition of absorption bands related to Fe<sup>3+</sup> (which are found in the same spectral range as the strongest manganese absorption bands; see table 2) over the Fe<sup>2+</sup> spectrum (see also Manson and Stockton, 1981; Stockton and Manson, 1985).

#### Comparison with Malaya Garnets from East Africa.

Based on our observations and photographs in the literature (see, e.g., Stockton and Manson, 1982, 1985; Rouse, 1986; Arem 1987; Dirlam et al. 1992), most malaya garnets from East Africa are intense orange, pinkish orange, or yellowish orange. Malaya garnet from Bekily also is pinkish orange, but the orange to yellowish orange material is uncommon.

The chemical compositions of malaya garnets from East Africa (see especially Stockton and Manson, 1982) showed a larger compositional vari-

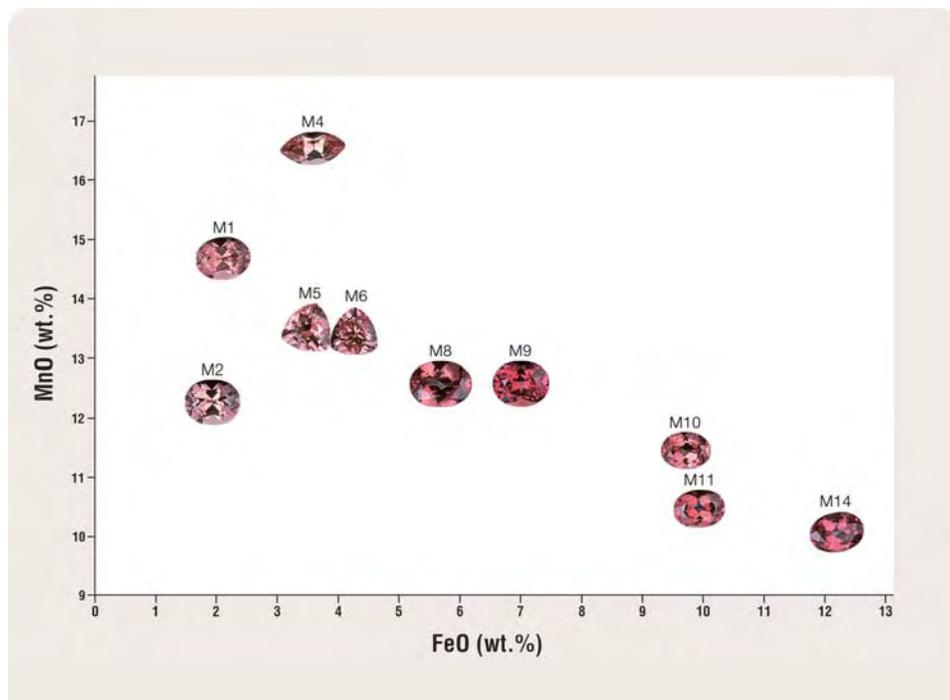


Figure 16. The color of malaya garnets is related to their chemical composition. With increasing iron, the pink component is intensified, and with increasing manganese, the orange color becomes stronger. The Bekily samples shown here weigh 0.72–1.46 ct, and were taken from a photo by Maha Tannous in incandescent light.

ation than our Bekily samples (figure 19). However, only a small fraction of the Umba samples actually fall within the compositional field of the 27 garnets that represent the color range of the majority of our samples from Bekily. Significantly, most Umba garnets contain distinctly higher amounts of manganese (i.e., a higher spessartine component). This accounts for the general differences in color seen between the two localities.

Mineral inclusions in Umba malaya garnets consist of networks of oriented rutile needles, smaller black rutile prisms, numerous tiny apatites, quartz,

brown to reddish brown zircon, yellow to yellowish brown pyrite, black pyrrhotite, and (rarely) monazite (Gübelin, 1981). The negative crystals and graphite platelets described in the Bekily garnets have not been reported in malaya garnet from Tanzania.

**Comparison with Color-Change (Blue-Green to Purple) Garnets from Bekily.** As noted above, garnets with a color change from blue-green to purple are mined in the vicinity of the malaya garnets described here (Schmetzer and Bernhardt, 1999). Both types of

Figure 17. The pink malaya garnet on the left has a lower manganese content (sample M7; 13.04 wt.% MnO) than the orange malaya garnet in the center (sample M3; 26.63 wt.% MnO). A spessartine (sample S; 38.32 wt.% MnO) is shown on the right for comparison. The samples weigh 1.16–1.47 ct. Photo by Maha Tannous; incandescent light.



Figure 18. The pink and almost red malaya garnets on the left are relatively iron rich (samples M13 and M15), and have similar colors to the pyrope-almandine garnets with low manganese contents (samples PA1 and PA2, center and lower right). A rhodolite without significant manganese (sample R) is shown on the far right for comparison. The samples weigh 0.72–1.41 ct. Photo by Maha Tannous; incandescent light.



## BOX A: SPESSARTINE-ALMANDINE GARNETS FROM MADAGASCAR

Spessartine from Madagascar was documented by Tisdall (1962), but until recently (see Laurs and Knox, 2001) no chemical data from gem-quality samples were published. Thus, we analyzed 12 representative spessartine and spessartine-almandine garnets from various unspecified locations in Madagascar (figure A-1). These samples were selected from several parcels totaling about 200 faceted spessartine and spessartine-almandine garnets in the orange, orange-brown, and brownish red to almost red color range. Chemical and physical properties of one spessartine sample (sample S) are presented in table 1.

Microprobe analyses revealed 34.7–39.1 wt.% MnO and 2.4–8.2 wt.% FeO. Traces of calcium were present (0.2 and 0.5 wt.% CaO), and MgO was below 0.05 wt.% in all samples. The chemical data correlate to 80.4–93.2 mol.% spessartine and 5.5–18.9 mol.% almandine. Grossular varies from 0.6 to 1.5 mol.%, and pyrope contents were ~0.1 mol.%. With increasing iron (i.e., almandine content), the color varied from

bright orange to orange brown and almost red (again, see figure A-1). Also, as iron content increased, the refractive index and specific gravity values varied continuously from 1.800 to 1.808 and from 4.15 to 4.22.



Figure A-1. These samples (0.58 to 1.42 ct) show the range of color seen in spessartine-almandine garnets from Madagascar. With increasing almandine and decreasing spessartine percentages, the colors vary from bright orange to almost red. Photo by Maha Tannous.

garnets are members of the pyrope-spessartine series, with similar features. The only significant differences are the distinctly higher vanadium (about 1 wt.%  $V_2O_3$ ) and chromium (about 0.20 wt.%  $Cr_2O_3$ ) contents in the color-change garnets.

## CONCLUSIONS

Bekily, Madagascar, is a relatively new source of malaya garnets that are predominantly pink to pinkish orange members of the pyrope-spessartine series. Their colors are due to variable amounts of iron and manganese; in general, they contain lower amounts of manganese than most malaya garnets from East Africa. Some light pink garnets from Bekily are pyropes with relatively little manganese and iron. One orange sample from Bekily had an unusual composition: spessartine with high amounts of pyrope. Graphite platelets and negative crystals have not been reported in malaya garnets from East Africa.

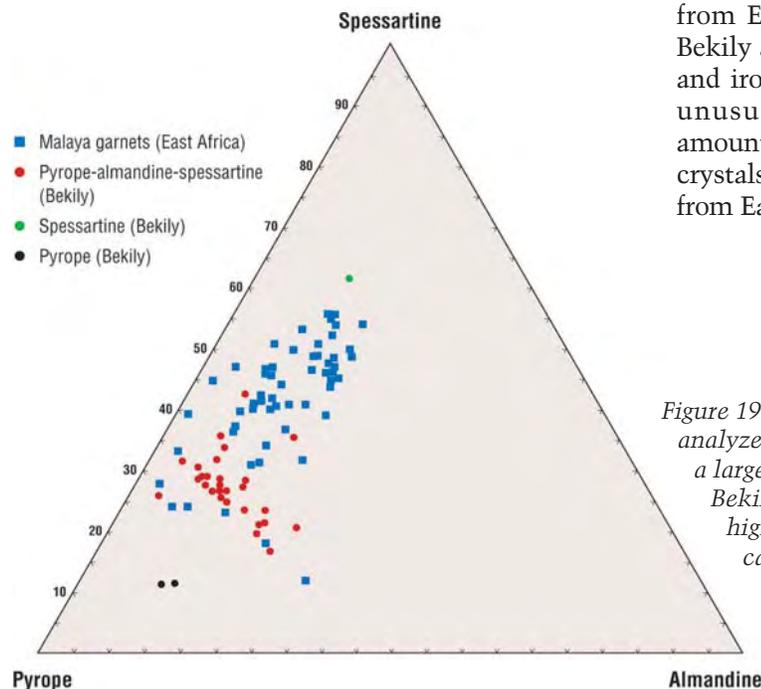


Figure 19. The malaya garnets from East Africa analyzed by Stockton and Manson (1982) showed a larger compositional variation than those from Bekily. Most of the East African samples had a higher spessartine component than the so-called malaya garnets from Madagascar.

the region between Bekily and the mines that are producing the color-change garnets.

The geology of the Bekily area is characterized by a series of Precambrian high-grade metamorphic rocks (migmatites, mica schists, and gneisses) that are locally graphite bearing (Besairie, 1964; Windley et al., 1994). Several tectonic zones are present in this region. The garnet mines are located in the Bekily belt, which consists predominantly of sillimanite-cordierite-garnet gneisses derived from metamorphosed sedimentary rocks (Windley et al., 1994).

## MINING AND PRODUCTION

From the discovery of the deposit in 1997 to mid-1999, only a limited supply of rough was available. However, mining activities and production began to increase in summer 1999 and then grew until fall 2000 (producing some tens of kilograms of facet-grade material). During this time, one of the authors (TH) purchased several parcels (weighing altogether about 1 kg) of crystal fragments for cutting. Mining activities and production have declined significantly since winter 2000. This is due to the generally small size of the garnet rough recovered, as well as to the discovery of ruby deposits at Vatomandry and Andilamena in winter 2000–2001, which enticed miners away from Bekily and other mining areas.

According to local dealers, groups of four to 10 workers mined the garnets from several pits along the mineralized “vein” where it outcropped on the surface. The pits reached depths of 10 m, at which level groundwater became a major problem.

Production of facetable material was modest; neither large stones nor large quantities of rough were usually found. TH calculated that of the approximately 1 kg of mixed lots he purchased, 60% weighed less than 0.3 grams, and fewer than 4% exceeded 1 gram. The yield from this garnet rough was about 30% for the smaller sizes and up to about 40% for the larger stones. He obtained about 1,600 carats of faceted material from this 1 kg of rough.

Because the pieces of rough are typically small, faceted stones over 2 ct are scarce and, according to local dealers, only rarely are 4–6 ct stones cut. The largest fine-quality faceted stone seen by TH weighed 10.69 ct. The Umba region has produced significantly larger stones (e.g., 20–30 ct) and greater quantities.

## MATERIALS AND METHODS

For the present study, we examined about 1,000 faceted garnets from Bekily. These were predomi-

nantly pink to pinkish orange, but included some orange to red samples; all were in the color range typically associated with malaya garnets. About 900 of these stones were purchased by TH directly from local dealers as rough crystal fragments mined in this area and then faceted outside Madagascar; the other approximately 100 samples were obtained from a European dealer who purchased several parcels of faceted garnets (stated to be from the Bekily area) in Madagascar in 1999 and 2000.

We selected 31 samples—representing the full range of colors we observed—for detailed gemological, chemical, and spectroscopic characterization. These samples were tested by standard gemological methods for refractive index, fluorescence to long- and short-wave UV radiation, and specific gravity. We also examined these 31 samples for inclusions and internal structural features by standard microscopic techniques using different microscopes and lighting conditions both with and without immersion in methylene iodide. In addition, we examined all samples that were not selected for extensive analytical testing to find solid inclusions other than the rutile needles noted in the 31 study samples. Finally, 17 garnets in which we found mineral inclusions were analyzed with a Renishaw 1000 laser Raman microspectrometry system.

For the same 31 samples mentioned above, we recorded UV-visible spectra with both a Leitz-Unicam SP 800 spectrophotometer and an Adamas Advantage SAS 2000 spectrophotometer. To determine the quantitative chemical composition of these 31 samples, we used a Cameca Camebax SX 50 electron microprobe, with a traverse of 10 point analyses measured across the table of each.

To compare the malaya garnets from Bekily to other colors of *pyrope-almandine-spessartine* (*pyral-spite* in mineralogical nomenclature) garnets, we selected three faceted purplish pink (typical of rhodolite), three intense reddish orange to red (typical of pyrope-almandine), and 12 orange to orange-brown and almost red garnets (typical of the colors seen in spessartine). All of these were also reportedly from Madagascar (specific localities unknown). For these 18 garnets, we performed the same routine and advanced testing as for the 31 pink to orange Bekily garnets.

Several months after purchasing the gem rough, we obtained six hand specimens of a garnet-bearing rock from the Bekily area from a local dealer. These samples probably did not come from the same pits that produced the facetable rough used in this study. All six rock samples contained intense pink-to-red

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#### REFERENCES

- Amthauer G. (1976) Kristallchemie und Farbe chromhaltiger Granate. *Neues Jahrbuch für Mineralogie, Abhandlungen*, Vol. 126, No. 2, pp. 158–186.
- Arem J.E. (1987) *Color Encyclopedia of Gemstones*, 2nd ed. Van Nostrand Reinhold, New York, 248 pp.
- Besairie H. (1964) Madagascar—Carte Géologique (1:1,000,000). Service Géologique de Madagascar, Antananarivo.
- Curtis C.M. (1980) “Malaya” lady of the evening. *Lapidary Journal*, Vol. 33, No. 11, pp. 2348–2349.
- Dirlam D.M., Misiowski E.B., Tozer R., Stark K.B., Bassett A.M. (1992) Gem wealth of Tanzania. *Gems & Gemology*, Vol. 28, No. 2, pp. 80–102.
- Gübelin E.J. (1981) Einschlüsse im Granat aus dem Umba-Tal. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 30, No. 3/4, pp. 182–194.
- Hanneman W.W. (1997) A unified system for classifying garnets. *Journal of Gemmology*, Vol. 25, No. 7, pp. 471–473.
- Hänni H.A. (1999) Les grenats gemmes. *Revue de Gemmologie A.F.G.*, No. 138/139, pp. 50–54.
- Hofmeister A.M., Schaal R.B., Campbell K.R., Berry S.L., Fagan T.J. (1998) Prevalence and origin of birefringence in 48 garnets from the pyrope-almandine-grossularite-spessartine quaternary. *American Mineralogist*, Vol. 83, pp. 1293–1301.
- Jobbins E.A., Saul J.M., Statham P.M., Young B.R. (1978) Studies of a gem garnet suite from the Umba River, Tanzania. *Journal of Gemmology*, Vol. 16, No. 3, pp. 161–171.
- Johnson M.L., Koivula J.I., Eds. (1998) Gem News: Pyrope-spessartine garnet from Madagascar. *Gems & Gemology*, Vol. 34, No. 3, p. 222.
- Keller P.C. (1992) *Gemstones of East Africa*. Geoscience Press, Phoenix, AZ, 144 pp.
- Langer K., Frentrup K.R. (1979) Automated microscope-absorption-spectrophotometry of rock-forming minerals in the range 40,000–5000 cm<sup>-1</sup> (250–2000 nm). *Journal of Microscopy*, Vol. 116, No. 3, pp. 311–320.
- Laurs B., Knox K. (2001) Spessartine garnet from Ramona, San Diego County, California. *Gems & Gemology*, Vol. 37, No. 4, pp. 278–295.
- Lind Th., Henn U. (2000) A new find of spessartine garnets in Nigeria. *Journal of Gemmology*, Vol. 27, No. 3, pp. 129–132.
- Lind Th., Bank H., Henn U. (1993) Spessartine aus Namibia. *Neues Jahrbuch für Mineralogie Monatshefte*, Vol. 1993, No. 12, pp. 569–576.
- Lind Th., Henn U., Bank H. (1994) Leuchtend orangefarbige Spessartine aus einem neuen Vorkommen in Namibia. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 43, No. 1/2, pp. 39–47.
- Lind Th., Henn U., Milisenda C.C. (1998) Vergleichende Untersuchungen an Rhodolithen verschiedener Provenienz. *Gemmologie—Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 47, No. 1, pp. 53–59.
- Manson D.V., Stockton C.M. (1981) Gem garnets in the red-to-violet color range. *Gems & Gemology*, Vol. 17, No. 4, pp. 191–204.
- Milisenda C.C., Zang J. (1999) Spessartine aus Nigeria. *Gemmologie—Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 48, No. 4, pp. 223–226.
- Moore R.K., White W.B. (1972) Electronic spectra of transition metal ions in silicate garnets. *Canadian Mineralogist*, Vol. 11, pp. 791–811.
- Rouse J.D. (1986) *Garnet*. Butterworths, London, 134 pp.
- Saul J.M., Jobbins E.A., Statham P.M., Young B.R. (1978) Un essai d'établissement d'une échelle de couleurs pour des grenats de la vallée de l'Umba, Tanzanie. *Revue de Gemmologie A.F.G.*, No. 59, p. 9.
- Schmetzer K., Bank H. (1981a) Garnets from Umba Valley, Tanzania—Members of the solid solution series pyrope-spessartine. *Neues Jahrbuch für Mineralogie Monatshefte*, No. 8, pp. 349–354.
- Schmetzer K., Bank H. (1981b) Garnets from Umba valley, Tanzania: Is there a necessity for a new name? *Journal of Gemmology*, Vol. 17, No. 8, pp. 522–527.
- Schmetzer K., Bernhardt H.-J. (1999) Garnets from Madagascar with a color change of blue-green to purple. *Gems & Gemology*, Vol. 35, No. 4, pp. 196–201.
- Schmetzer K., Ottemann J. (1979) Kristallchemie und Farbe Vanadium-haltiger Granate. *Neues Jahrbuch für Mineralogie Abhandlungen*, Vol. 136, No. 2, pp. 146–168.
- Schmetzer K., Bank H., Gübelin E. (1980) The alexandrite effect in minerals: Chrysoberyl, garnet, corundum, fluorite. *Neues Jahrbuch für Mineralogie Abhandlungen*, Vol. 138, No. 2, pp. 147–164.
- Smith G., Langer K. (1983) High pressure spectra up to 120 kbars of the synthetic garnet end members spessartine and almandine. *Neues Jahrbuch für Mineralogie Monatshefte*, Vol. 1983, No. 12, pp. 541–555.
- Stockton C.M., Manson D.V. (1982) Gem garnets: The orange to red-orange color range. In D.M. Eash, Ed., *International Gemological Symposium Proceedings 1982*, Gemological Institute of America, Santa Monica, CA, pp. 327–338.
- Stockton C.M., Manson D.V. (1985) A proposed new classification for gem-quality garnets. *Gems & Gemology*, Vol. 21, No. 4, pp. 205–218.
- Tisdall F.S.H. (1962) Similar constants but different colour. Spessartines from Madagascar. *The Gemmologist*, Vol. 31, No. 372, pp. 124–125.
- Windley B.F., Razafiniparany A., Razakamanana T., Ackermann D. (1994) Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: A review and reappraisal. *Geologische Rundschau*, Vol. 83, pp. 642–659.
- Zylberman, N. (1999) Un nouveau grenat pyrope-spessartine malgache à changement de couleur. *Revue de Gemmologie A.F.G.*, No. 138/139, pp. 72–73.