GEM-QUALITY GROSSULAR-ANDRADITE: A NEW GARNET FROM MALI

By Mary L. Johnson, Edward Boehm, Horst Krupp, Joachim W. Zang, and Robert C. Kammerling

A find of new gem garnets has been made in contact metamorphic deposits in the Republic of Mali, western Africa. These garnets, primarily yellow-green to brown but also (rarely) intense green, have compositions between grossular and andradite. Although garnets of similar composition are relatively well known, this is the first documented occurrence of gem-quality material in commercial quantities. Because this gem variety is not represented by any of the gem garnet terms previously in use, it is described as grossular-andradite by the GIA Gem Trade Laboratory. It can be distinguished from grossular by its absorption spectrum and (usually) higher refractive index; it can be distinguished from andradite by its lower R.I. The stacked parallel planes of growth zoning, always visible between crossed polarizers, are diagnostic of grossular-andradite.

ABOUT THE AUTHORS

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Garnets have been prized as gems since at least 3200 B.C. (Andrews, 1991). Today, gem garnets are found in almost any color. They exhibit broad chemical variability between the known end-members, the most common of which are pyrope, almandine, spessartine, grossular, and andradite. (A useful overview of gem garnets was given by Stockton and Manson, 1985; see also Manson and Stockton, 1982, and Stockton and Manson, 1982, 1983, for specific color ranges). Garnets are also used as ornamental gem materials in their massive forms: Examples include hydrogrossular and grossular.

In spring 1994, a new type of gem-quality garnet (figure 1) first appeared on the market in Idar-Oberstein (one of the authors—Dr. Krupp—was first offered rough material at this time; see also Frazier and Frazier, 1995a and b). This was a transparent, facetable material in the yellow-to-green-to-brown range, with properties close, but not identical, to those of grossular. One version of the discovery was that the material was found by a West African who had once lived in Idar-Oberstein (Frazier and Frazier, 1995b). In the gem trade, the material is typically called "Mali garnet" or "grandite garnet."

Among discussions of Mali garnet in the trade press are reports on their appearance at Intergem in Munich in September of 1994 (Frazier and Frazier, 1995a and b; "Impressions of Intergem '94," 1994), and mention in the 1995 International Colored Gemstone Association (ICA) world gemstone mining report (Eliezri and Kremkow, 1994). Four technical reports have been published in German (Zang, 1994; Henn et al., 1994; Lind and Bank, 1994; Lind et al., 1995). One stone reportedly from this locality was examined in the GIA Gem Trade Laboratory in September of 1994 (Hurwit et al., 1994). Since we began work on this report in September 1994, a short article in English appeared in the *Australian Gemmologist* (Brightman, 1995).

Figure 1. One of the most recent additions to the gem marketplace are gem garnets from Mali. These grossular-andradites, from the first-known commercial gem occurrence of this material, range in color from yellow to green to brown. Although most of the stones faceted to date are smaller than 5 ct, some are quite large, as indicated by this loose 33.29-ct stone. The stones in the rings are 4.03, 4.57, and 5.53 ct. Courtesy of M. Fabrikant & Sons, New York City; photo © Harold & Erica Van Pelt.

LOCATION AND ACCESS

The garnets are being recovered from various localities in the "Zone of Sangafé," near the village of Diakon (about 100 km northeast of Bafoulabé, 110 km southwest of Nioro, and 130 km east of Kayes; air miles in all cases), in the Kayes Region of Mali (figure 2). The Zone of Sangafé is in the Sahel region (a semiarid area between the Sahara Desert to the north and the savannas to the south). William Dameron, former U.S. Ambassador to Mali, stated that many garnets come from Sibinndi, "about 20–30 km south of Sandaré" (pers. comm., 1995), in the vicinity of Diakon. One of our contacts in Mali states that the intense green Mali garnets come from the village of Duvalé.

Access to the mining area is difficult. The closest major town, Kayes, can be reached by train from either Bamako, the capital of Mali, which is about 400 km to the southeast, or Dakar, the capital of Senegal, which is about 620 km due west, on the Atlantic Coast. From Kayes, one must travel by jeep, or *bashé* (the local term for bush wagon or taxi), to cover the remaining 170 km of partially paved roads to the town of Sandaré. From there, another 20–30 km of unpaved roads lead to the mining areas around the villages of Sibinndi and Diakon.

It is possible that some material has been transported out of Mali via Dakar because of its coastal access. Despite the difficulty in reaching the mining areas, there has been such a rush to the region that extra railroad cars were added to the trains going to Kayes. The rough is carried in flour or rice sacks and transported by any available vehicle to the train station at Sandaré.

GEOLOGY AND OCCURRENCE

Western Mali is underlain by the Precambrian West African Craton. The craton has been warped into a broad bowl—the Taoudeni Basin—with edges at the Western Sahara/Mauritania border and from Sierra Leone and Guinea to southeast Mali. Cambrian sediments fill the western part of the basin and are overlain by Mesozoic deposits to the east. In the region of interest, the sediments include magnesian limestones and dolomitic limestones (Furon, 1963). These sediments have been intruded in various places by dikes primarily of diabase (that is, fine-grained gabbroic rocks mainly consisting of plagioclase and pyroxene), which extend from the border with Guinea to Mauritania (figure 3); these dikes vary from basalt to albite-quartz pegmatites (Furon, 1963; Bessoles, 1977). Southwest of the town of Nioro, these diabases are Jurassic in age (Cahen et al., 1984) and form a massif known as the Kaarta, a zone of rugged relief ranging up to 300 m in altitude (Furon, 1963).

According to reports on the regional geology of Mali, garnets formed in contact metamorphic zones along the boundaries where the widely scattered diabase dikes intruded into limestones (among other rocks). Besides garnet, the minerals that formed in the contact zone between diabase and limestone include epidote, (titaniferous) magnetite, prehnite, fluorite, and occasionally chrysoberyl (Hubert, 1914, as reported in Bessoles, 1977; Furon, 1963; Ministère des Mines [no date]). This information is consistent with statements that have been made elsewhere concerning the geologic occurrence of gem garnets in Mali. Both Lind and Bank (1994) and Henn et al. (1994) state that the garnets come from contact metamorphosed deposits, which, according to Henn et al. (1994), consist of clay and feldspar-bearing sandstones and marbles that have been intruded by a diabase. Garnet, epi-

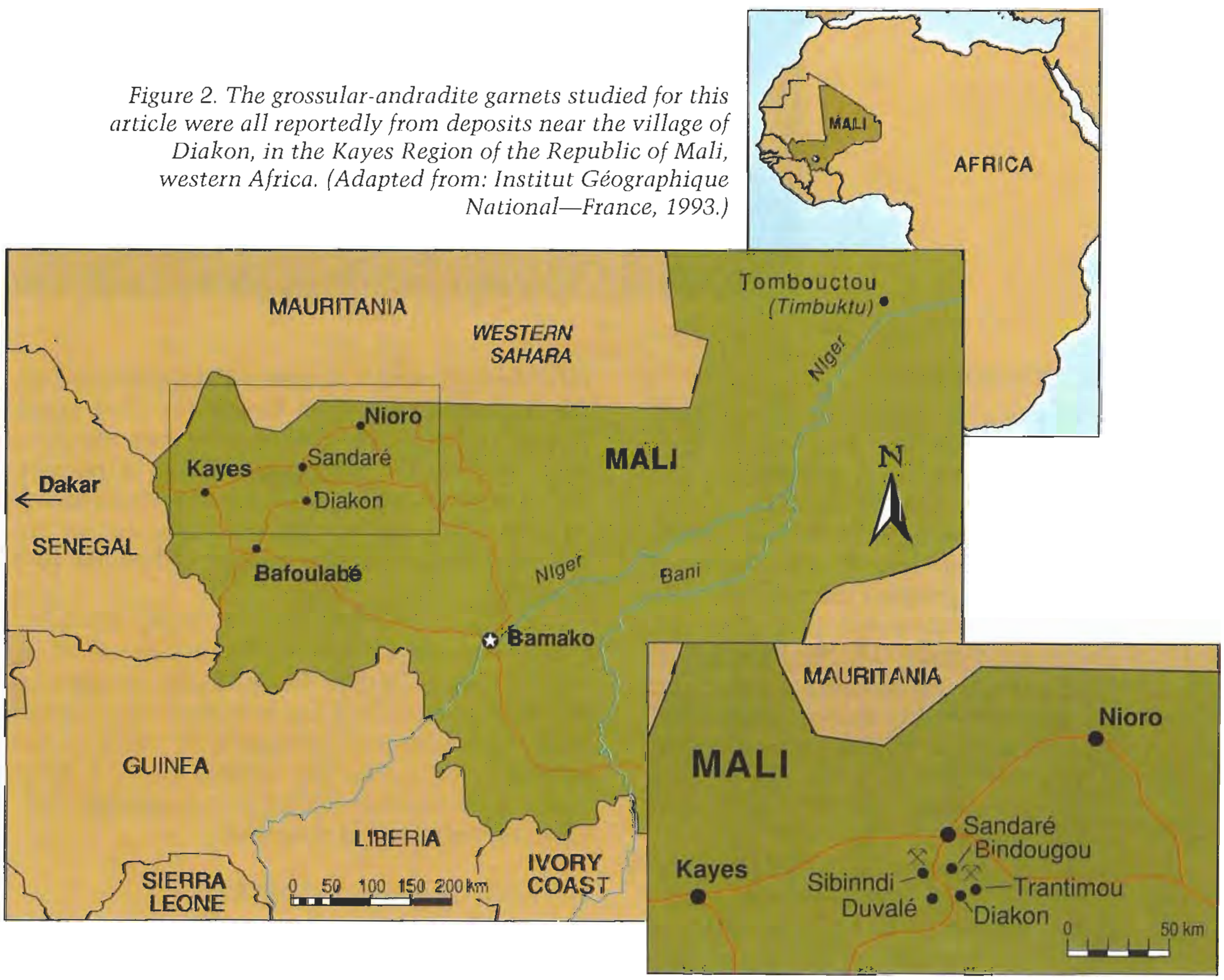


Figure 2. The grossular-andradite garnets studied for this article were all reportedly from deposits near the village of Diakon, in the Kayes Region of the Republic of Mali, western Africa. (Adapted from: Institut Géographique National—France, 1993.)

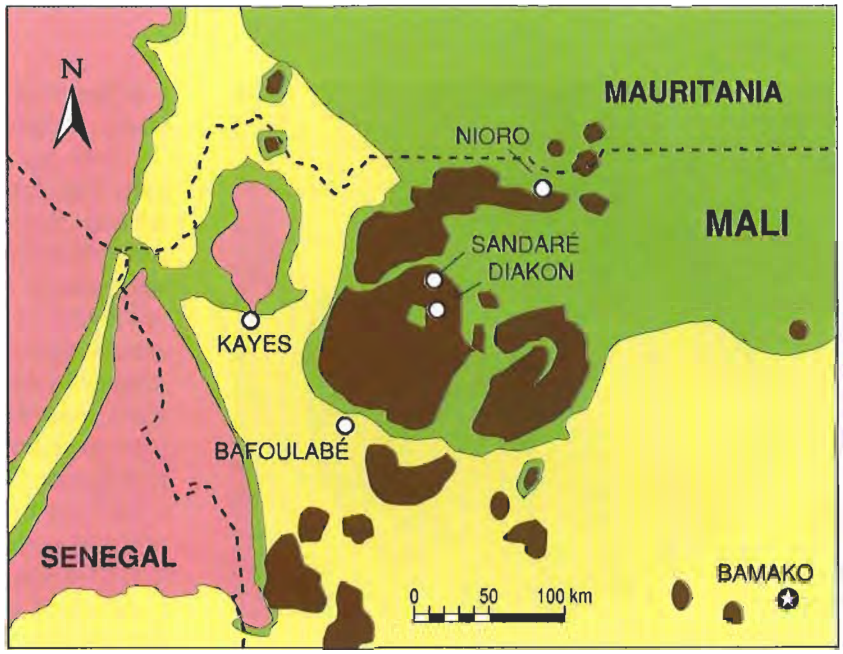


Figure 3. This geologic sketch map of western Mali, as well as parts of Senegal and Mauritania, shows the large diabase intrusions. Contact metamorphic bodies, including some that contain gem-quality garnets, are found along the boundaries of the diabase intrusives. Figure adapted from Furon, 1963.

dote, prehnite, and vesuvianite mineral specimens from Mali were marketed in Tucson, Arizona, in spring 1995 by Dave Bunk Minerals of Wheat Ridge, Colorado (with the locality given as "Sandare, Nioro du Sahel, Mali"); also, "bright green" garnets as large as 4 cm—some with chalcedony overgrowths—have been found growing on some vesuvianites mined in Mali (W. Dameron, pers. comm., 1995).

In addition to the garnets mined near Sibinndi and Diakon, well-formed opaque brownish red crystals have been found in the village of Bindougou, a few kilometers north of Diakon. Black garnets have been found a few kilometers east of Diakon, in the village of Trantimou (W. Dameron, pers. comm., 1995). Thus far, only a few intense green stones have been found, including two in this study and a recently discovered crystal that produced a 2.9-ct cut stone.

The garnets also occur as waterworn nodules, reportedly from alluvial sources near the contact metamorphic deposits (Eliezri and Kremkow, 1994; Hurwit et al., 1994).

MINING AND PRODUCTION

Although garnets from this region have been known since 1914, the recent discoveries represent the first gem-quality stones found in any significant quantities. We have seen crystals larger than 5.5 kg (Zang, 1994); for the most part, however, the facetable areas in each stone are relatively small. The largest faceted stone seen to date is a brown 57.5-ct round brilliant (figure 4). Only gemmy cores—generally, nodules—are suitable for faceting (figure 5), although cabochons are being cut from other parts of the rough. Considerable manual labor is required to break up these crystals, and most dealers now insist on purchasing only nodules, so relatively few euhedral crystals are available for mineral collectors and crystallographic study.

The authors calculate, from personal experience, that a parcel of 400–500 crystals, weighing about 200 kg, yields 160 grams of nodules, from which only 60 grams would be facet grade. Of these 60 grams (300 ct) of facet-grade rough, perhaps 150 ct of faceted gems result: a total yield of 0.015%.

Some dealers are believed to have large stockpiles of rough Mali garnets in Idar-Oberstein, with substantial quantities also in North America and Australia. We estimate that, as of September 1995, these stockpiles totaled several dozen kilos of facet-grade material and several hundred kilos of cabochon-quality rough. According to Joe Freilich of M. Fabrikant & Sons in New York, their stock of faceted Mali garnets exceeds 5,000 ct, primarily in sizes up to 5 ct, but with a few larger "collector pieces" (again, see figure 1).

MATERIALS AND METHODS

For our gemological investigation, we examined 23 faceted stones (some are shown in figure 6), 20

Figure 4. This 57.5-ct round brilliant-cut stone is the largest faceted grossular-andradite garnet from Mali seen by the authors to date. Courtesy of Gustav Zang, Lapidary, Idar-Oberstein; photo © Harold and Erica Van Pelt.

rough crystals and crystal sections, and eight rough nodules (see, e.g., figure 7). The faceted stones ranged from 0.34 to 15.67 ct, and the rough crystals weighed from 8 grams to greater than 2.1 kg. The gem nodules weighed from 3.11 to 9.32 ct; the nodule examined by Hurwit et al. (1994), which will sometimes be mentioned for comparison purposes, weighed 25.35 ct.

Figure 5. Although most of the Mali garnet crystals seen to date appear to be opaque (right, 61.02 ct), many have large areas of transparent material (left, 106.29 ct). Courtesy of Firegems; photo © GIA and Tino Hammid.

Face-up colors were viewed using both fluorescent and incandescent light sources. Refractive indices were measured with a Duplex II refractometer and a near-monochromatic, Na-equivalent light source. We determined specific gravity hydrostatically as an average of three sets of measurements. Fluorescence to ultraviolet radiation was observed in a darkened room using a short-wave/long-wave ultraviolet lamp. We noted polarization behavior using a GIA GEM Illuminator polariscope, and observed absorption spectra using a Beck prism-type spectroscope. The Chelsea filter reaction was determined with illumination from a spectroscope base unit. We examined internal features using a standard gemological microscope in conjunction with brightfield, darkfield, and oblique fiber-optic illumination, as well as polarizing filters.

Chemical compositions for five stones (a mix of faceted and rough) were determined quantitatively using a CAMEBAX electron microprobe at the University of Mainz, in Mainz, Germany. Three additional faceted stones were studied with a Camscan Series II analytical scanning electron microscope (SEM) at the California Institute of Technology, in Pasadena, California. Back-scattered electron imaging was also perfomed to look for fine compositional details in these garnets. Eleven stones of various colors were also examined with energy-dispersive X-ray fluorescence (EDXRF) spectroscopy, using a Tracor Xray Spectrace 5000 with a rhodium-target X-ray tube.

We obtained visible spectra on two stones, one yellowish green and one intense green, using a Perkin-Elmer Lambda 3 UV/VIS spectrophotometer, with a 0.2-nm step width and 15 nm/min. scanning speed. The two faceted stones were embedded in $BaSO_4$ and measured in reflection mode using an integration sphere. A few additional stones were run in absorption mode using a Hitachi UV/VIS spectrophotometer.

X-ray powder diffraction images were taken from minute amounts of powder scraped from nine stones (representing both faceted and rough), with a Debye-Scherrer camera mounted on a Siemens Kristalloflex diffractometer. The unit-cell edge of an additional stone was measured with the more precise Guinier technique (see, for example, Taylor, 1961).

We calculated garnet end-member components as follows: All magnesium was apportioned

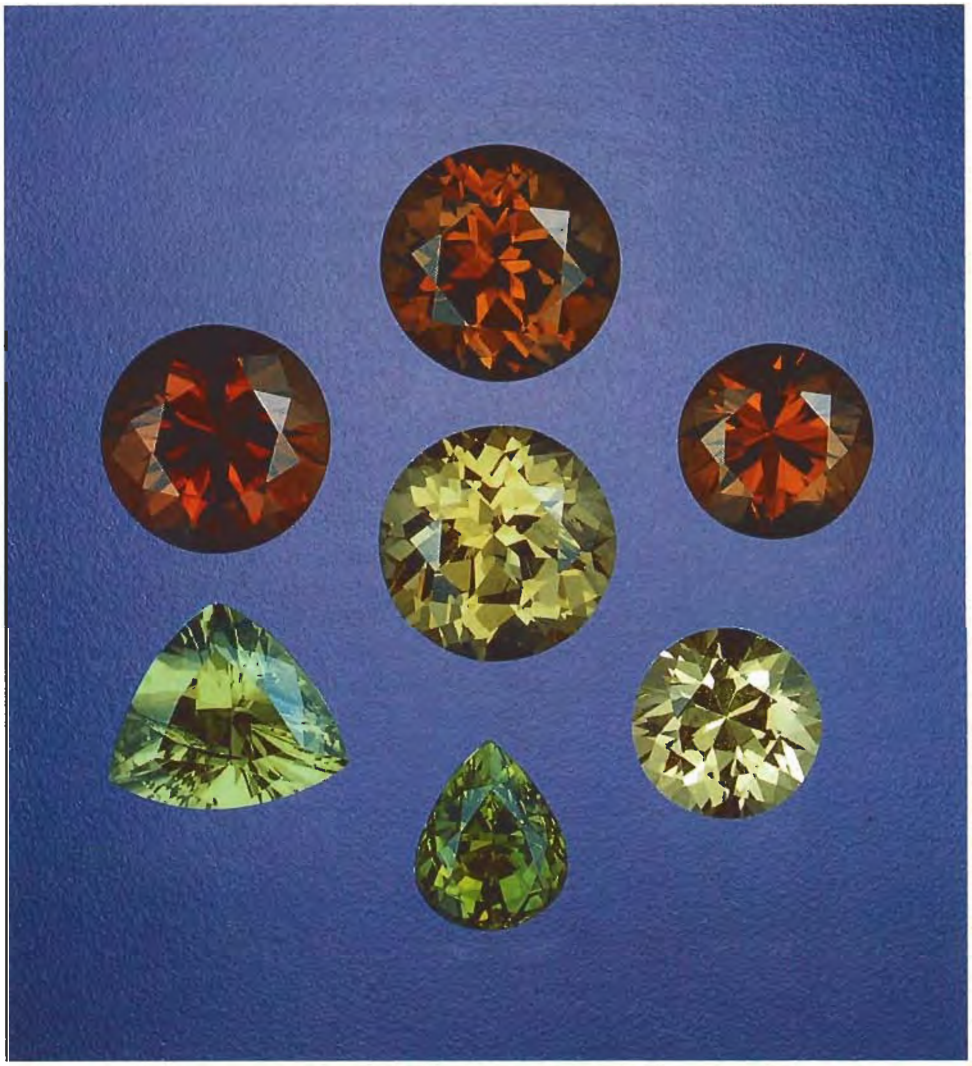


Figure 6. These seven faceted brown, yellow-green, and green grossular-andradite garnets from Mali (ranging from 0.85 to 2.39 ct) are part of the study sample. Stones courtesy of Pala Properties International and Thomas M. Schneider; photo © GIA and Tino Hammid.

to the pyrope component, *Py*; all manganese to the spessartine component, *Sp*; all chromium to the uvarovite component, *Uv*; and all iron (Fe^{3+}) to the andradite component, *And*. Assignment of all iron as Fe^{3+} is supported by our spectra, which revealed no evidence of Fe^{2+} (as in almandine). Calcium, aluminum, and silicon were distributed according to stoichiometry; remaining aluminum was apportioned to the grossular component, *Gr*. Because none of the stones revealed a significant titanium content, Ti was ignored in calculating end members. Components were normalized to 100% (e.g., $Gr_{78}And_{20}Py_1Sp_1$).

CRYSTAL MORPHOLOGY

The rough samples we examined (again, see figure 7) occurred in two forms: as crystals, often nearly complete, and as rounded nodules. Most of the crystals showed dodecahedral *d* {110} faces; some also showed minor trapezohedral *n* {211} faces; and, in at least one case, the trapezohedron was the major form shown. Most crystals showed regular shapes, but a few were distorted; distorted crystals are flattened in a variety of directions.

All the crystals appeared to have dodecahedral core zones, and some very large crystals showed only the dodecahedral habit (that is, not all crystals have trapezohedral faces). In some cases, gemmy yellowish green or green cores were found in crystals with dull, nearly opaque, brown surface "skins" (again, see figure 5). The surface regions were less transparent than the cores. At least one crystal was so dark brown as to appear nearly black, and one showed a bright green surface region (figure 8).

Most crystal faces on the predominantly dodecahedral crystals were sharply reflective, although

Figure 7. Also in the study sample were these seven rough crystals and eight nodules of Mali garnet. From top left down: approximately 126-gram dodecahedron, 24-gram trapezohedron/dodecahedron, 16-and 8-gram dodecahedra. From top right down: approximately 780 gram (94 × 71 × 66 cm) dodecahedron, and 22- and 13-gram distorted dodecahedra/trapezohedra. The eight nodules in the center weigh from 3.11 to 9.32 ct. Courtesy of Pala Properties International, Firegems, and the authors; photo by Shane F. McClure.

some had rough surfaces (figure 9), which may be due to intergrowth with other minerals. Some dodecahedral internal surfaces (and all faces on those crystals that were predominantly trapezohedral) had a rough or stepped appearance. This appearance may be due to the dissolution of intergrown minerals, especially calcite, during either weathering or processing of the mined material.

In contrast to these crystals, the "nodules" we examined—actually cobbed rough material, rather than alluvial nodules—had rounded surfaces and no crystal faces. The curved surfaces were probably caused by fracturing along curved fluid-filled inclusions (see "Appearance with Magnification and in Polarized Light," below).

PHYSICAL APPEARANCE AND GEMOLOGICAL PROPERTIES

Gemological properties of the 23 faceted stones examined are given in table 1 and described below, with additional reference to the results for the eight gem nodules examined, as appropriate.

Color. The 23 faceted stones ranged from slightly greenish yellow to dark orangy brown and from greenish yellow to yellowish green and intense green (again, see figure 6). The most common colors appear to be greenish yellow to yellow-green (figure 10). The brownish colors include brownish greenish yellow, brown-orange, and dark orangy brown. The colors of two green samples resembled those typically associated with tsavorite garnet.

Yellow-green Mali garnets typically are of medium tone, with a stronger yellow component than tsavorites from East Africa and transparent green chromium-bearing grossulars from Quebec (see, for

Figure 8. The bright green surface on the top of this 28.0 × 26.3 × 25.4 mm bicolored crystal from Mali was found to have a composition slightly different from the yellowish green regions. Courtesy of William Dameron; photo by Maha DeMaggio.

TABLE 1. Gemological properties of yellowish green, green, and orange-to-brown grossular-andradite garnet from Mali.

Property	Yellowish green (18)[a]	Green (2)	Orange to brown (3)
Color	Slightly greenish yellow to light yellowish green	Green	Brown-orange to dark orangy brown
Color distribution	Even	Even	Even to uneven
Refractive index	1.752–1.769	1.762–1.764	1.773–1.779
Optic character[b]	SR, often ADR	Moderate ADR	Moderate to strong ADR
Color filter reaction	Negative (appears green)	Red (1), negative (1)	Negative (appears green)
Absorption spectrum	Weak 415, 440 band, sometimes faint 465, 495 lines	Weak 415 band or 440 cutoff, moderate 445 band, and 600 line	440 cutoff and/or 445 band
Fluorescence to long- and short-wave UV	Inert	Inert	Inert
Specific gravity	3.64–3.68	3.65–3.67	3.67–3.68
Growth zoning	Dodecahedral	Dodecahedral	Dodecahedral or trapezohedral
Inclusions	Fingerprints, sometimes small crystals	Fingerprints, sometimes small crystals	Fingerprints, sometimes small crystals

[a] Numbers in parentheses represent number of samples studied. All data are from this study.
[b] SR = Singly refractive; ADR = anomolously doubly refractive.

instance, Anderson, 1966; Dunn, 1978; Schmetzer and Bank, 1982). Intense green and orangy brown stones from Mali cannot be distinguished from other types of garnets on the basis of color.

Refractive Indices. We recorded R.I. ranges of 1.752–1.769 for the yellowish green and green stones we examined; and 1.773–1.779 for the orangy brown stones. These are consistent with R.I. values of 1.755–1.782 reported in the literature for Mali garnets (Zang, 1994; Henn et al., 1994; Lind and Bank, 1994; Brightman, 1995). Grossular is usually reported as having a refractive index between 1.73 and 1.76, and the R.I. of andradite is in the 1.880– 1.895 range (Stockton and Manson, 1985).

Polariscope Reaction. Seventeen of the 23 faceted stones showed moderate-to-strong anomalous double refraction (ADR) when viewed in a polariscope. All showed anomalous birefringent colors when examined microscopically between crossed polarizing filters. Strong ADR was also observed in all of the rough nodules that were sufficiently transparent to be so examined.

Optical Absorption Spectroscopy. All 31 nodules and faceted stones that we examined with the handheld spectroscope showed a band centered about 440 nm (with the center ranging from 435 to 450 nm). We also noted a 415-nm line in the 17 faceted stones and nodules with the lightest colors. We saw two faint lines in the 460–470 nm and 495–500 nm regions in six of these 17 stones. In the stone with the most intense green color, we also saw a line at 600 nm (which we tentatively attributed to chromium). The spectra for the darkest toned (orangy brown and green) stones had a cutoff at about 440 nm. In general, the strongest feature—the cutoff or 440-nm band—was consistent with the typical spectrum for andradite (figure 11; see also Payne, 1981).

Figure 9. This surface on a 13-gram garnet crystal from Mali shows evidence that additional minerals, possibly blades of epidote, had grown adjacent to it. Courtesy of Firegems. Photomicrograph by John I. Koivula; magnified 2×.

Figure 10. Most of the Mali garnets seen to date have been in the greenish yellow to yellow-green range. These six faceted yellow-green grossular-andradite garnets (1.76 to 2.55 ct) from Mali are part of the test sample. Most stones courtesy of Pala Properties International; photo © GIA and Tino Hammid.

Specific Gravity. Values determined for our samples are consistent with ranges reported by Zang (1994), Lind and Bank (1994), and Brightman (1995): 3.63 to 3.70. Henn et al. (1994) report the much larger range of 3.58 to 4.19; the highest value is anomalous. Our faceted stones showed a general increase in specific gravity with increase in refractive index, although there was considerable variability from one stone to the next.

Appearance with Magnification and in Polarized Light. For the cleanest stones we examined, inclusions were very rare or nonexistent. However, all stones showed pronounced dodecahedral growth zoning (sometimes only visible as parallel layers). Although these layers were frequently visible (as color zoning) with standard illumination (figure 12, left), they were especially distinct when the stones were examined between crossed polarizers, showing up as dull-to-bright-gray birefringent layers (anomalous birefringence; figure 12, right). Such growth zoning took on an unusual appearance in the darkest brown stone: It consisted of darker orange trapezoids, which we suspect are trapezohedral {211} growth zones (figure 13).

The most common inclusions were curved, partially healed fractures, or "fingerprint" inclusions (figure 14), seen in nine faceted stones and near the surfaces of all the nodules (figure 15). In fact, the rounded surfaces of the (cobbed) nodules could be seen to be made up of material etched or broken along the curved fingerprints. Two-phase fluid inclusions were seen in a healed fracture in one stone.

Five of the faceted stones contained tiny included crystals, which were too small and too far from the surface to identify. Although the stone described by Hurwit et al. (1994) showed a very fine, wispy, "horsetail" (visible at 50× magnification), we did not detect this feature in any of the sample nodules or faceted stones.

CHEMICAL COMPOSITION

Electron Microprobe Analysis. Results of quantitative chemical analyses for five stones are given in table 2. Two yellowish green faceted stones, analyses MA01 and MA02 (previously described by one of the authors: Zang, 1994), are typical in color and gemological properties of most grossular-andradites coming from Mali, with compositions of approximately $Gr_{80}And_{18}Py_2$. An 11-point traverse (figure 16) was made across a portion of sample MA19, which had a green core (average composi-

Figure 11. The absorption spectrum seen with a handheld spectroscope in most grossular-andradite garnets from Mali resembles this spectrum for typical yellowish green demantoid andradite garnet. Figure © GIA.

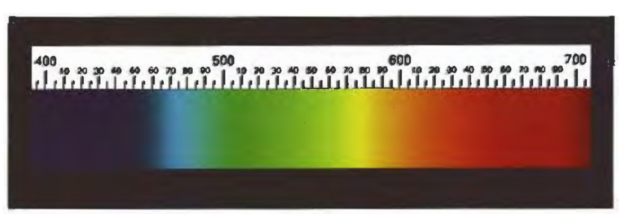


Figure 12. Straight growth zoning parallel to two dodecahedral faces was commonly seen in the test sample of grossular-andradite garnet from Mali (left). This feature appears particularly sharp when viewed between crossed polarizers (right). Photomicrographs by John I. Koivula; magnified 20×.

tion $Gr_{73}And_{25}Py_2$) and a 0.5-mm-thick brown rim (average composition $Gr_{33.5}And_{65}Py_{1.5}$). Sample MA93, an intense green stone, contained chromium (0.63 wt.% Cr_2O_3), but no vanadium was detected (approximate composition $Gr_{79}And_{16}Py_3Uv_2$). Sample MA23, a brown rhombohedral crystal about 1.5 cm in diameter, was found to have a relatively homogeneous composition (about $Gr_{30}And_{68}Py_2$) that included 0.04 wt.% V_2O_3.

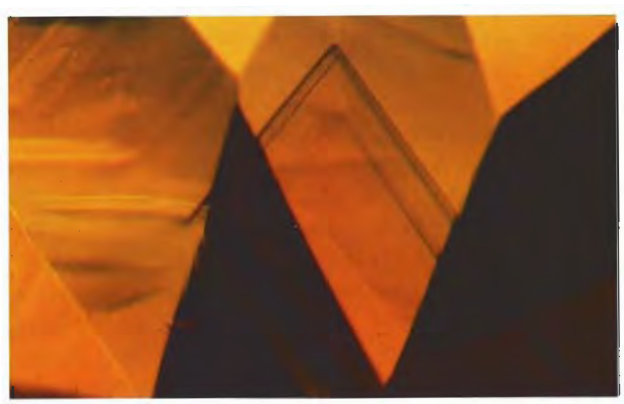
Scanning Electron Microscopy. With the scanning electron microscope, analyses can be made of individual submicron spots, and of rectangular areas up to the size of the (magnified) field of view. Both techniques were used in this study. The results are also given in table 2; two faceted stones had compositions similar to those seen in the microprobe analyses of Mali garnets. (Unfortunately, we were not able to run both electron microprobe and SEM analyses on the same stones.) A third faceted greenish yellow stone, R-2596, contained significantly more magnesium (about 1 wt.% MgO; pyrope content about 4 mole %). This stone also had a significantly lower R.I. (1.752) than the other greenish yellow stones in our sample.

These faceted samples were imaged in backscattered electron (BSE) mode. In two stones, no compositional detail was seen using BSE imaging. However, R-2596 showed brighter stripes against an evenly toned background (figure 17). A bright region in BSE imaging corresponds to a higher average atomic weight (see, e.g., Newbury, 1975), and these stripes represent linear regions of lower magnesium content. For this stone, we successfully obtained analyses from one point on a BSE-bright stripe and two spots (plus a regional average) in BSE-darker regions. There was no appreciable difference in iron (calculated as andradite) content between light and dark regions, but there was significantly more magnesium (pyrope component) in the darker regions than in the bright stripe.

EDXRF analyses of 11 additional samples gave results that were consistent with those reported above.

Composition Determined by Indirect Methods. Properties such as refractive index, specific gravity, and unit-cell-edge length vary linearly between end-member compositions in the garnet mineral group (Deer et al., 1982). For some garnets in our study with measured compositions, we checked whether these properties can be used to predict garnet compositions. Our samples fit chemically

Figure 13. The growth zoning seen here in a 15.67-ct dark orangy brown garnet from Mali appears to parallel trapezohedral growth faces. Photomicrograph by John I. Koivula; magnified 20×.



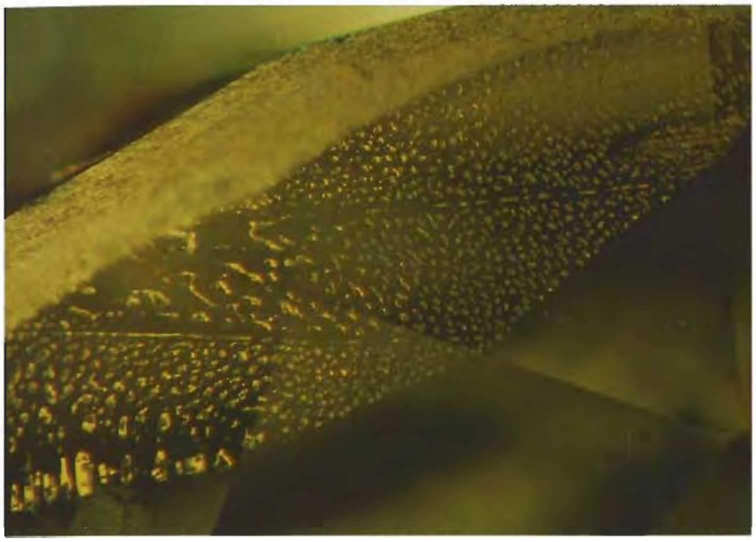


Figure 14. Partially healed fractures were among the most common internal features seen in the Mali garnets examined. Photomicrograph by John I. Koivula; magnified 30×.

between the end members grossular and andradite, with minor deviations caused by small amounts of other end members such as pyrope, spessartine, uvarovite and, possibly, hydrogrossular. A good estimate of a given stone's composition can be made by measuring its refractive index and interpolating between 1.734 (pure grossular) and 1.887 (pure andradite); the other indirect measurements, especially specific gravity, have lower certainties and are less useful for this determination.

Spectrophotometry and Causes of Color. The two faceted stones for which optical absorption spectra were studied in detail—yellowish green sample MA02 and intense green sample MA93—were very similar in chemical composition (as determined by electron microprobe analysis), about $Gr_{81}And_{15.5}$. Intense green sample MA93 contained 0.63 wt.% Cr_2O_3, but no chromium was detected in sample MA02.

The spectrum of yellowish green sample MA02 shows a small peak at 408 nm, a broad band centered at 432 nm, and a weaker, still broader band centered at 585 nm (figure 18). The color-inducing element in this sample is trivalent (ferric) iron, which has absorption bands with maxima at about 432 and 585 nm (see Moore and White, 1972; Amthauer, 1976; Rossman, 1988; Burns, 1993). The weak manganese peak at 408 nm has no appreciable influence on the color (Moore and White, 1972; Duffy, 1990).

The absorption spectrum of intense green sample MA93 shows a maximum at 478 nm, followed by a minimum near 526 nm (i.e., maximum transmission in the green part of the spectrum) and a strong band in the 550–650 nm range that has a maximum intensity at about 608 nm. Two sharp lines are evident at at about 696 nm and 700 nm (again, see figure 18). In this spectrum, chromium is the most important color-inducing element, as indicated by the two wide bands with maxima at about 478 and 608 nm; the sharp lines are also due to chromium (Moore and White, 1972; Amthauer, 1972; Burns, 1993). The color is intensified by the influence of ferric iron, similar to those bands seen in sample MA02: The 435-nm band can be easily seen in the spectrum, and the Fe^{3+} peak around 585 nm—although less prominent—is also observed.

For some orangy brown stones on which spectra were also run, the 435-nm band was visible as a shoulder on a strong background absorption that increased toward the blue and violet region of the spectrum. In lighter-toned orangy brown stones, the 585-nm band could also be seen; however, in general the strong absorption edge dominated the spectrum.

DISCUSSION

Classification of Garnet Type. For the yellow-green, intense green, and orangy brown garnets from

Figure 15. The curved surfaces of the nodules appear to be broken along healed fractures. This fracture is barely under the surface of a 3.11-ct yellowish green garnet nodule from Mali. Photomicrograph by John I. Koivula; magnified 15×.

TABLE 2. Quantitative chemical analyses of eight Mali garnets.[a]

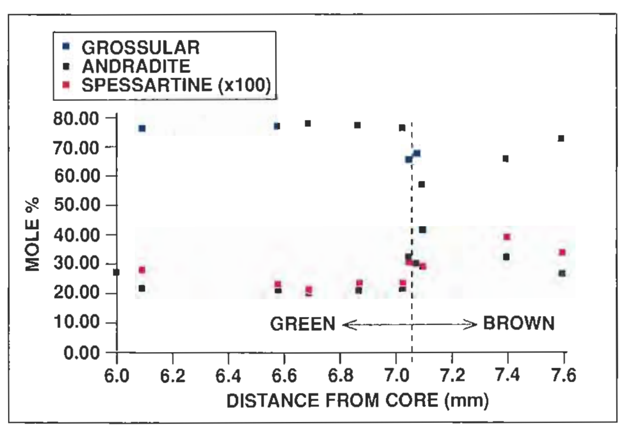
Results	Microprobe analyses, by sample number						Analytic SEM analyses, by sample number			
	MA01	MA02	MA93	MA23	MA19		R-2597	R-2594	R-2596	
	Yellowish green	Yellowish green	Intense green	Brown	Green core	Brown rim (3)	Greenish yellow	Yellow-green	Greenish yellow BSE dark (3)[b]	Greenish yellow BSE light (1)[b]
Wt. % oxides										
MgO	0.49	0.47	0.67	0.34	0.48	0.33	0.78	0.70	1.06	0.80
Al_2O_3	17.26	18.09	17.55	6.29	15.67	6.97	17.70	17.51	18.25	18.47
SiO_2	38.80	38.97	39.11	36.43	39.02	36.67	40.23	40.01	38.58	39.15
CaO	36.29	36.63	36.49	34.42	35.94	34.57	34.05	34.59	36.95	36.94
TiO_2	0.19	0.18	0.65	1.15	0.68	0.87	0.10	0.09	0.13	nd
Cr_2O_3	nd	nd	0.63	nd	nd	nd	0.09	0.07	0.12	nd
V_2O_3	nd	nd	nd	0.04	nd	nd	—	—	—	—
MnO	0.11	0.10	0.13	0.10	0.11	0.14	0.09	0.11	0.10	nd
Fe_2O_3	6.88	5.23	5.20	20.91	7.99	20.25	6.96	6.92	4.80	4.64
Sum	100.02	99.67	100.43	99.68	99.89	99.81	(100)	(100)	(100)	(100)
Mole % garnet end-members										
Py	1.91	1.85	2.65	1.46	1.96	1.40	2.93	2.73	4.17	3.1
Sp	0.24	0.22	0.29	0.24	0.26	0.34	0.18	0.23	0.23	nd
Uv	nd	nd	1.98	nd	nd	nd	0.25	0.20	0.37	nd
And	20.29	15.58	15.59	67.97	24.58	64.95	20.00	20.07	14.37	13.9
Gr	77.56	82.34	79.48	30.32	73.20	33.31	76.60	76.77	80.87	83.0
Unit-cell edge	11.8937						11.87	11.88	11.88	
R.I.							1.765	1.765	1.752	
S.G.							3.67	3.66	3.64	

[a] *Microprobe analyses were run on a CAMEBAX electron microprobe, and analytical SEM analyses were run on a Camscan Series II SEM. Elemental concentrations below the detection limits of the microprobe are listed as "nd;" vanadium was not looked for with the SEM (as indicated by a dash). Consult the authors for further experimental details.*
[b] *BSE = Backscattered electron imaging.*

Mali, which have more than 50% grossular component, the proper *mineralogic* name is *grossular garnet* or, since the iron is in the Fe^{3+} (ferric) oxidation state, *ferrian grossular garnet*. As a gem variety, we are referring to this material as grossular-andradite garnet, since it lies between the two pure end-members. This is analogous to Stockton and Manson's (1985) use of the terms *pyrope-almandine*, *pyrope-spessartine*, and *almandine-spessartine* to describe intermediate garnets in the pyralspite subgroup. For any (probably orange-to-brown) garnets with compositions of 50% (or more) andradite, we propose also using the grossular-andradite designation, although the mineralogic name for such garnets would be (aluminian) andradite. Some gem garnet names currently in use by the GIA Gem Trade Laboratory are given in table 3.

Intermediate grossular-andradite garnets, sometimes called grandite garnets in the petrologic and mineralogic literature, are common as

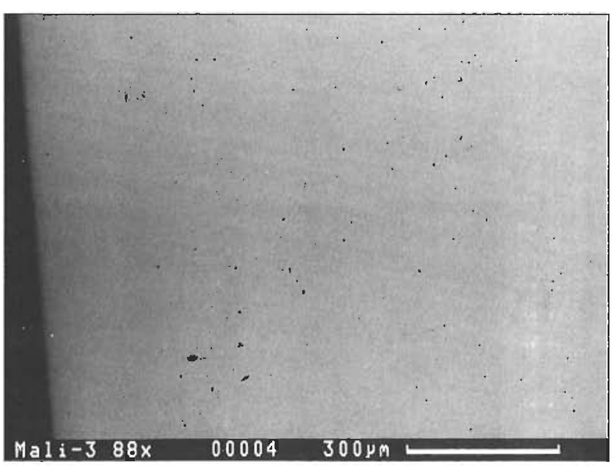
Figure 16. These calculated garnet end-member components were derived from a microprobe traverse across part of a Mali garnet section (specimen MA19; see table 2) that had a green core and a brown rim. Manganese (spessartine) values are exaggerated by 100× for clarity. Pyrope contents do not vary significantly in this stone.



semi-translucent to opaque dull-colored garnets in contact-metamorphic (skarn) deposits, but they have not been previously documented as facetable gem materials. However, another gem-quality intermediate garnet in the uvarovite-grossular-andradite series was described by Burns (1973): "lime" green crystals from a drill core at Marvel Loch, Western Australia, that were found to have a composition of $Gr_{55}And_{13}Uv_{32}$. The largest was reportedly about 5 mm in diameter. The Mali grossular-andradites are extraordinary among the contact-metamorphic ugrandite garnets for their combination of size and transparency.

Possible Causes of Growth Zoning and Anomalous Birefringence. The most pronounced visual feature of the grossular-andradite garnets from Mali is linear growth zoning, which we saw when the stones were magnified, sometimes with standard darkfield illumination, but always when viewed between crossed polarizers. This feature is typically found in grandite garnets and has been extensively studied in the mineralogical literature. The possible causes include: variation and ordering between Fe^{3+} and Al (Lessing and Standish, 1973; Akizuki, 1984; Akizuki et al., 1984; Hirai and Nakazawa, 1986; Soós et al., 1991; Jamtveit, 1991); strain (Foord and Mills, 1978; McAloon and Hofmeister, 1993); orientational variation of OH groups (Rossman and Aines, 1986; Allen and Buseck, 1988); and twinning within individual layers (Hirai and Nakazawa, 1982). Another possible cause for the zoning may be immiscibility unmixing between components in the grandite and pyralspite subgroups (Bosenick et al., 1995).

Figure 17. Compositional variation in a 1.86-ct greenish yellow grossular-andradite garnet from Mali (R-2596) can be seen as variations in brightness in this back-scattered electron image taken with a scanning electron microscope. Bright bands are lower in pyrope than the dark bands. (The dark band to the left is the edge of the table facet; the dark spots are dust particles on the stone's surface.) Electronmicrograph by Mary L. Johnson; magnified 88×.



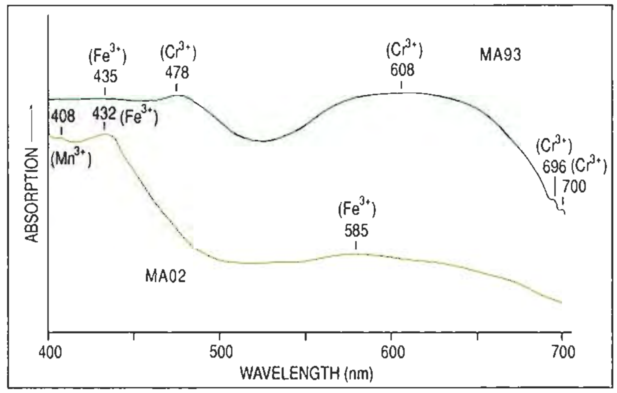


Figure 18. Ultraviolet-visible absorption spectra for yellowish green (MA02) and intense green (MA93) grossular-andradite garnets from Mali show peaks associated with trivalent iron (Fe^{3+}), the principal cause of color in sample MA02, and chromium (Cr), another important color-inducing element in sample MA93.

TABLE 3. Chemical compositions and refractive index ranges for gem garnets.[a]

Gem garnet	Chemical composition	Refractive indices
Pyrope	$Mg_3Al_2(SiO_4)_3$	1.714 – <1.742
Pyrope-almandine	$(Mg,Fe)_3Al_2(SiO_4)_3$	1.742 – <1.785
Almandine	$Fe_3Al_2(SiO_4)_3$	1.785 – 1.830
Almandine-spessartine	$(Fe,Mn)_3Al_2(SiO_4)_3$	1.810 – 1.820
Spessartine	$Mn_3Al_2(SiO_4)_3$	1.780 – <1.810
Pyrope-spessartine	$(Mg,Mn)_3Al_2(SiO_4)_3$	1.742 – <1.780
Grossular	$Ca_3Al_2(SiO_4)_3$	1.730 – 1.760
Grossular-andradite	**$(Ca,Fe)_3Al_2(SiO_4)_3$**	**1.752 – 1.782**
Andradite	$Fe_3Al_2(SiO_4)_3$	1.880 – 1.895

[a] *Derived from Stockton and Manson (1985) and present study.*

CONCLUSIONS

Gem Nomenclature and the Distinguishing Features. Mali garnets examined to date were greenish yellow to green or greenish yellow to orangy brown, with an R.I. range between 1.752 and 1.782, and S.G.'s between 3.63 and 3.70 (disregarding the single 4.19 value of Henn et al., 1994). The absorption spectra and chemistry of these garnets agreed with those of garnets colored primarily by trivalent iron (with the exception of the intense green stones, which also contained chromium and possibly vanadium). The most common internal features seen were parallel growth planes, sometimes showing dodecahedral or trapezohedral angular boundaries (again, see figures 12 and 13) that are related to the anomalous birefringence of the material. *These growth features are ubiquitous in, and may be considered diagnostic for, grossular-andradite garnets.* "Fingerprint" inclusions, small white and dark anhedral crystals, and (one) very wispy horsetail inclusion have also been seen in stones from Mali. All these properties are consistent with the material from Mali being an intermediate garnet in the grossular-andradite series of the ugrandite (*u*varovite-*gr*ossular-*and*radite) subgroup, with less than 10% pyralspite (*pyr*ope plus [possibly] *al*mandite plus *sp*essartine) components.

At the moment, the gem trade seems to be calling this material "Mali garnet," or "Mali grossular garnet." It is also being sold as "grandite garnet," a short-hand term used by petrologists but not a name accepted by the International Mineralogical Association (IMA). The GIA Gem Trade Laboratory calls this material *grossular-andradite* (as opposed to simply *grossular*) because its properties lie between the two gem species. To wit: (1) the range of refractive indices extends beyond, and barely overlaps, that which is traditionally considered to be grossular, and does not reach the andradite range; (2) the yellow-green, green, and orangy brown colors and absorption spectra are consistent with andradite (pure grossular is colorless); and (3) the absorption spectrum (440 band) is consistent with andradite (pure grossular has no absorption spectrum). The composition extends from grossular toward andradite, far beyond the most Fe-rich transparent grossulars reported by Manson and Stockton (1982). Transparent stones on both sides of the 50/50 split between grossular and andradite should have gem properties consistent with this classification.

Effect on the Gem Market. Most gem-quality grossular-andradite garnets from Mali seen thus far are reminiscent of pale greenish yellow to yellow-green grossulars from Tanzania, and are similar in appearance to faceted chrysoberyl from Sri Lanka and Brazil. Some rare stones resemble peridot. There are also numerous brown to brownish orange stones which can be quite brilliant, due to their (andradite-derived) higher R.I.'s and dispersions. These may serve as inexpensive substitutes for "cognac" diamonds. Although only a few intense green stones have been found so far, Mali is a promising source for these garnets. In light of the current low supply of tsavorite from Kenya and Tanzania, and the extreme rarity of fine demantoids, this potential new source would be a welcome alternative.

This new gem variety of garnet will undoubtedly reach mass-marketing channels soon. Stockpiles of rough, rumored to total several tons, await processing in Idar-Oberstein, Australia, and America. Also ready for cutting as of early September 1995 were several dozen kilograms of facet-grade nodules and several hundred kilos of cabochon-grade material. Already, thousands of carats of fashioned gems are poised to enter the marketplace.

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REFERENCES

Akizuki M. (1984) Origin of optical variations in grossular-andradite garnet. *American Mineralogist*, Vol. 69, No. 3/4, pp. 328–338.

Akizuki M., Nakai H., Suzuki T. (1984) Origin of iridescence in grandite garnet. *American Mineralogist*, Vol. 69, No. 9/10, pp. 896–901.

Allen F.M., Buseck P.R. (1988) XRD, FTIR, and TEM studies of optically anisotropic grossular garnets. *American Mineralogist*, Vol. 73, No. 5/6, pp. 568–584.

Amthauer G. (1976) Kristallchemie und Farbe chromhaltiger Granate: *Neues Jahrbuch für Mineralogie Abhandlungen*, Vol. 126, No. 2, pp. 158–186.

Anderson B.W. (1966) Transparent green grossular—a new gem variety; together with observations on translucent grossular and idocrase. *Journal of Gemmology*, Vol. 10, No. 4, pp. 113–119.

Andrews C. (1991) *Ancient Egyptian Jewelry*. Harry N. Abrams, New York.

Bessoles B. (1977) *Géologie de l'Afrique: Le Craton Ouest Africain*. Bureau de Recherches Géologiques et Minières, Mémoire No. 88, Paris, France.

Bosenick A., Geiger C. A., Schaller T., Sebald A. (1995) A ^{29}Si MAS NMR and IR spectroscopic investigation of synthetic pyrope-grossular garnet solid solutions. *American Mineralogist*, Vol. 80, No. 3/4, pp. 691–704.

Brightman R. (1995) A new variety of grossular garnet with extended gemmological constants. *Australian Gemmologist*, Vol. 19, No. 1, pp. 19–22.

Burns R.G. (1993) *Mineralogical Application of Crystal Field Theory*, 2nd ed. Cambridge University Press, Cambridge, England, pp. 108–159.

Burns R.L. (1973) A member of the ugrandite garnet series found in Western Australia. *Australian Gemmologist*, Vol. 11, No. 12, pp. 19–20.

Cahen L., Snelling N.J., Delhal J., Vail J.R., Bonhomme M., Ledent D. (1984) *Geochronology and Evolution of Africa*. Clarendon Press, Oxford, England.

Deer W.A., Howie R.A., Zussman J. (1982) *Rock Forming Minerals, Volume 1A, Orthosilicates*, 2nd ed. Longman Group, London, pp. 484–497 and 617–636.

Duffy J.A. (1990) *Bonding, Energy Levels and Bands in Inorganic Solids*. Longman Group, London, pp. 44–55.

Dunn P.J. (1978) On the composition of some Canadian green garnets. *Canadian Mineralogist*, Vol. 16, pp. 205–206.

Eliezri I.Z., Kremkow C. (1994) The 1995 ICA world gemstone mining report. *ICA Gazette*, December, pp. 1, 12–19.

Foord E.E., Mills B.A. (1978) Biaxiality in "isometric" and "dimetric" crystals. *American Mineralogist*, Vol. 63, No. 3/4, pp. 316–325.

Frazier S., Frazier A. (1995a) Just in from Intergem. *Lapidary Journal*, Vol. 48, No. 10, pp. 32–36.

Frazier S., Frazier A. (1995b) New innovations reign at 10th Intergem. *Colored Stone*, Vol. 8, No. 1, pp. 473–474.

Furon R. (1963) *Geology of Africa*, 2nd ed. Transl. by A. Hallam and L. A. Stevens, Hafner Publishing Co., New York, NY.

Henn U., Bank H., Milisenda C.C. (1994) Gemmologische Kurzinformationen: Grossular-Andradit Mischkristalle aus Mali. *Zeitscrift der Deutschen Gemmologischen Gesellschaft*, Vol. 43, No. 3/4, p. 105.

Hirai H., Nakazawa H. (1982) Origin of iridescence in garnet: An optical interference study. *Physics and Chemistry of Minerals*, Vol. 8, No. 1, pp. 25–28.

Hirai H., Nakazawa H. (1986) Grandite garnet from Nevada: Confirmation of origin of iridescence by electron microscopy and interpretation of a moiré-like texture. *American Mineralogist*, Vol. 71, No. 1/2, pp. 123–126.

Hubert H. (1914) Les coulées diabasiques de l'Afrique occidental française. *Comptes Rendus de l'Academie Science Française*, Vol. 159, pp. 1007–1009.

Hurwit K., Johnson M. L., Fritsch E. (1994) Gem trade lab notes: Grossular-andradite garnet from Mali. *Gems & Gemology*, Vol. 30, No. 4, pp. 265–266.

Impressions of Intergem '94 (1994). *Bangkok Gems & Jewellery*, Vol. 8, No. 5, pp. 64–65.

Institut Géographique National—France (1993) *Mali, Carte Générale au 1:2 000 000* (map). Paris, France.

Jamtveit B. (1991) Oscillatory zoning patterns in hydrothermal grossular-andradite garnet: Nonlinear dynamics in regions of immiscibility. *American Mineralogist*, Vol. 76, No. 7/8, pp. 1319–1327.

Lessing P., Standish R.P. (1973) Zoned garnet from Crested Butte, Colorado. *American Mineralogist*, Vol. 58, No. 9/10, pp. 840–842.

Lind Th., Bank H. (1994) Neues Vorkommen von transparenten grünen, gelben und braunen Granaten (Grossularen) in Mali. *Schweitzerische Uhrmacher und Goldschmiede Zeitung*, No. 12, p. 122.

Lind Th., Bank H., Henn U. (1995) Schleifwürdige Granate (Grossulare) von einem neuen Vorkommen in Mali. *Zeitscrift der Deutschen Gemmologischen Gesellschaft*, Vol. 44, No. 1, pp. 17-24.

Manson D.V., Stockton C.M. (1982) Gem-quality grossular garnets. *Gems & Gemology*, Vol. 18, No. 4, pp. 204-213.

McAloon B.P., Hofmeister A.M. (1993) Single-crystal absorption and reflection infrared spectra of birefringent grossular-andradite garnets. *American Mineralogist*, Vol. 78, No. 9/10, pp. 957–967.

Ministère des Mines, de l'Industrie et de l'Hydraulique, Republique du Mali (no date) Preliminary note about the "pierres precieuses de Sangafe Simbiti" (precious stones of Sangafe Simbiti), 2 pp.

Moore R.K., White W.B. (1972) Electronic spectra of transition metal ions in silicate garnets. *Canadian Mineralogist*, Vol. 11, pp. 791–811.

Newbury D.E. (1975) Image formation in the scanning electron microscope. In J. Goldstein and H. Yakowitz, Eds., *Practical Scanning Electron Microscopy*, Plenum Press, New York, pp. 95–148.

Payne T. (1981) The andradites of San Benito County, California. *Gems & Gemology*, Vol. 17, No. 3, pp. 157–160.

Rossman G.R. (1988) Optical spectroscopy. *Reviews in Mineralogy*, Vol. 18, Chapter 7, pp. 207–254.

Rossman G.R., Aines R.D. (1986) Spectroscopy of a birefringent grossular from Asbestos, Quebec, Canada. *American Mineralogist*, Vol. 71, No. 5/6, pp. 779–780.

Schmetzer K., Bank H. (1982) Gelbgrüner Grossular aus Ostafrika. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 31, No. 1/2, pp. 81–84.

Soós M., Jánosi M., Dódony I., Lovas G. (1991) Anomalous grandite garnet from Recsk, Mátra Mts. (N-Hungary). Part I. Chemical composition, optical and diffraction properties. *Neues Jahrbuch für Mineralogie Monatshefte*, Vol. 1991, No. 2, pp. 76–86.

Stockton C.M., Manson D.V. (1982) Gem garnets: The orange to red-orange color range. In *Proceedings of the 1982 International Gemological Symposium*, Gemological Institute of America, Santa Monica, CA, pp. 327–338.

Stockton C.M., Manson D.V. (1983) Gem andradite garnets. *Gems & Gemology*, Vol. 19, No. 4, pp. 202–208.

Stockton C.M., Manson D.V. (1985) A proposed new classification for gem-quality garnets. *Gems & Gemology*, Vol. 21, No. 4, pp. 205–218.

Taylor A. (1961) *X-ray Metallography*, John Wiley & Sons, New York, pp. 762–763.

Zang J. (1994) Neue Grossulare aus Dionboko/Mali. *Lapis*, Vol. 19, No. 10, pp. 45–46.