

DETERMINING GARNET COMPOSITION FROM MAGNETIC SUSCEPTIBILITY AND OTHER PROPERTIES

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Quantitative measurements of magnetic susceptibility combined with RI or SG data can provide an easy and inexpensive way of inferring garnet composition. At the time this technique was first applied to faceted garnets (Hoover et al., 2008), a reference set of samples with well-characterized compositions was not available. GIA subsequently provided 28 garnets and their chemical data determined by electron microprobe for a comparison with end-member compositions calculated from magnetic susceptibility measurements and other properties. The results show that end-member compositions based on microprobe data have error margins similar to most of those derived from directly measured properties.

Garnet is a diverse gem material showing an attractive palette of colors (e.g., figure 1) and incorporating a variety of chemical components that are responsible for widely ranging values of physical properties. The several end-member species may occur as nearly pure compositions or, more commonly, complex assemblages. The principal species (table 1) are pyrope, almandine, and spessartine (pyral-spite garnets), and grossular, andradite and minor uvarovite (ugrandite garnets). Other end-member species, including goldmanite (vanadium rich), knorringite (chromium rich), and schorlomite (titanium rich) also may be present in small amounts, and these are mainly important for their effect on garnet coloration.

In the past, gemologists have been limited in their ability to determine garnet composition by only having RI and possibly SG data as quantitative

measures, in combination with color and spectroscopic data, to infer a garnet composition that is most probable. These compositions were limited to one or two end members; for garnets in which three or more end members were important, gemologists had no effective recourse.

In recent years, with the availability of very strong rare-earth magnets, gemologists have started to apply magnetic attraction as a tool for gem identification (see, e.g., <http://gemstonemagnetism.com>). Although all materials respond to an applied magnetic field in some way (box A), it is the transition elements in garnet that give rise to a measureable magnetic attraction (reported here as the volume magnetic susceptibility) if they are present as principal components. Recently, Hoover and Williams (2007) developed a simple, inexpensive apparatus to measure volume susceptibility on cut gems (box B). Hoover et al. (2008) derived garnet composition from plots of RI versus susceptibility, and followed the conventional characterization of Stockton and Manson (1985) in defining garnet varieties (pyrope, pyrope-almandine, almandine, almandine-spessar-

See end of article for About the Author and Acknowledgments.

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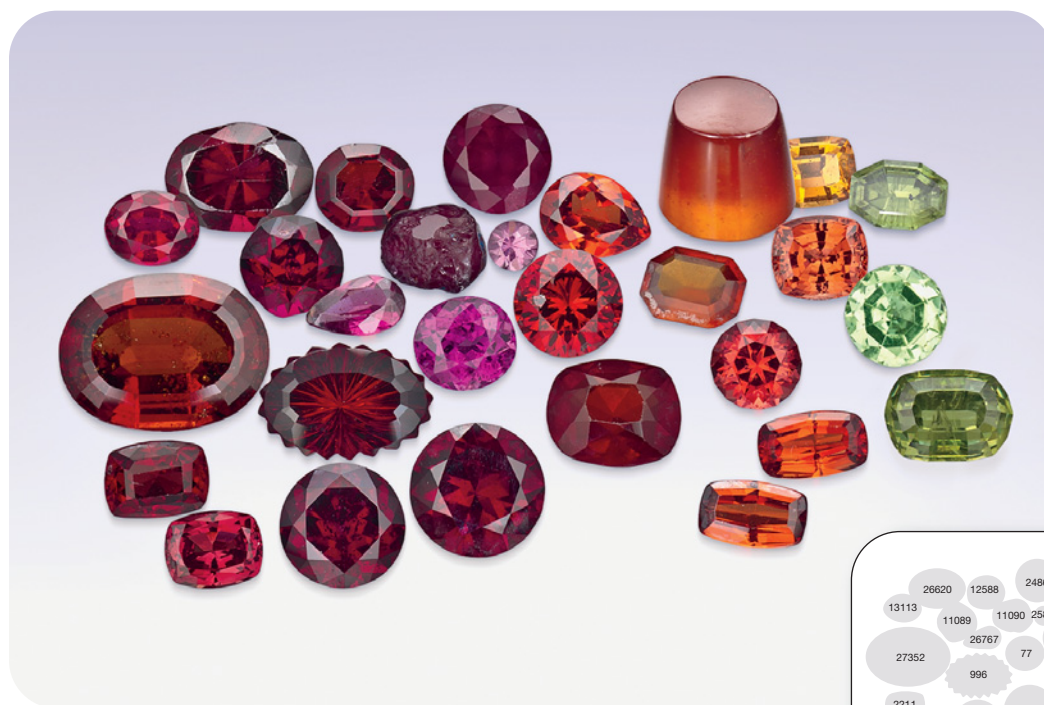


Figure 1. This photo shows the 28 GIA garnet samples used in this study (0.18–9.82 ct). Photo by Robert Weldon.

tine, etc.). Furthermore, the magnetic susceptibility technique permitted a quantitative measure of garnet composition consisting of three end members, not two, when RI was the only other data available. Unfortunately, Hoover et al. (2008) did not have garnet samples of known composition to test how well the technique agreed with quantitative chemical analysis. Using selected samples from the large group studied by Manson and Stockton, this article compares garnet compositions from GIA's electron microprobe data to those inferred from the GIA-measured properties that were combined with the author's measured magnetic susceptibilities. The

accuracy of garnet compositions derived from the various properties is assessed.

MATERIALS AND METHODS

Materials. GIA initially supplied data for 539 garnets that included color, carat weight, RI, SG, cell constant, and variety, although the data set was incomplete for a number of the stones. The author then borrowed 28 of the samples for magnetic susceptibility measurements (see figure 1 table 2) that were selected to cover the full range of compositions and RI values. An additional constraint was that each stone be large enough for good susceptibility mea-

TABLE 1. Silicate garnet end-member species and their properties.^a

End member	Symbol	Formula	RI	SG	Cell constant (Å)	Volume susceptibility (×10 ⁻⁴ SI)
Pyrope	Prp	Mg ₃ Al ₂ Si ₃ O ₁₂	1.714	3.58	11.459	-0.2
Almandine	Alm	Fe ₃ Al ₂ Si ₃ O ₁₂	1.829	4.32	11.528	40.7
Spessartine	Sps	Mn ₃ Al ₂ Si ₃ O ₁₂	1.799	4.20	11.614	47.5
Grossular	Grs	Ca ₃ Al ₂ Si ₃ O ₁₂	1.734	3.59	11.851	-0.2
Andradite	Adr	Ca ₃ Fe ₂ Si ₃ O ₁₂	1.887	3.86	12.048	30.8
Uvarovite	Uv	Ca ₃ Cr ₂ Si ₃ O ₁₂	1.865	3.85	11.996	12.9
Goldmanite	Go	Ca ₃ V ₂ Si ₃ O ₁₂	1.834	3.77	12.070	6.9
Knorringite	Kn	Mg ₃ Cr ₂ Si ₃ O ₁₂	1.875	3.84	11.622	13.7

^a See text for sources of data.

TABLE 2. Garnet samples used in this study, their measured and calculated properties, and their compositions.^a

Sample no. ^b	Variety	Weight (ct)	Measured					Calculated (Locock)				
			RI	SG	Cell constant (Å)	Volume susceptibility (×10 ⁻⁴ SI)	Composition	RI	SG	Cell constant (Å)	Volume susceptibility (×10 ⁻⁴ SI)	Composition ^c
77	Rhodolite	2.42	1.752	3.83	11.493	16.0	Prp ₆₃ Alm ₂₂ Sps ₁₅	1.752	3.83	11.494	13.5	Prp ₆₃ Alm ₃₂ Grs ₃ Sps ₁
79	Color-change (pyralispite)	1.88	1.751	3.85	11.583	16.4	Prp ₆₃ Sps ₂₀ Alm ₁₇	1.752	3.82	11.571	15.9	Prp ₄₈ Sps ₂₃ Grs ₁₅ Alm ₁₂ Uv ₁
198	Mint green grossular	2.73	1.735	3.61	11.850	0.4	Grs ₉₉ Adr ₁	1.736	3.60	11.850	0	Grs ₉₄ Prp ₁ Adr ₁ Go ₁
234	Malaya	2.27	1.765	3.91	11.549	24.6	Prp ₄₇ Sps ₃₂ Alm ₂₁	1.766	3.93	11.545	23.7	Prp ₄₃ Sps ₃₄ Alm ₁₈ Grs ₄ Adr ₁
491	Malaya	1.53	1.762	3.90	11.555	24.7	Prp ₄₇ Sps ₃₄ Alm ₇	1.759	3.88	11.558	21.8	Prp ₄₅ Sps ₃₈ Alm ₈ Grs ₇ Adr ₁
996	Almandine-spessartine	6.78	1.810	4.22	11.580	44.9	Sps ₆₃ Alm ₃₇	1.811	4.24	11.580	44.4	Sps ₅₇ Alm ₄₀ Grs ₁
2211	Pyrope-almandine	2.14	1.762	3.87	11.530	16.2	Prp ₆₂ Alm ₄₀ Grs ₈	1.763	3.88	11.529	16.5	Prp ₅₀ Alm ₃₉ Grs ₉ Adr ₁ Sps ₁
2486	Rhodolite	2.20	1.762	3.85	11.509	15.7	Prp ₆₂ Alm ₃₆ Grs ₁₂	1.759	3.86	11.508	15.3	Prp ₅₇ Alm ₃₆ Grs ₄ Sps ₁ Adr ₁
2489	Hessonite	1.25	1.755	3.65	11.889	5.8	Grs ₈₃ Adr ₉ Alm ₁ or Grs ₄₁ Prp ₄₀ Adr ₁₉	1.760	3.64	11.882	5.0	Grs ₈₀ Adr ₁₆ Prp ₁
2491	Demantoid	1.45	1.881	3.84	—	29.7	Adr ₉₆ Grs ₄	1.887	3.86	12.048	30.8	Adr ₉₆
3429	Pyrope-almandine	3.55	1.784	4.02	11.508	22.9	Alm ₅₇ Grs ₃₃ Prp ₁₀	1.781	4.00	11.510	23.6	Alm ₅₅ Prp ₄₀ Sps ₂ Grs ₂
4967	Pyrope-almandine	3.18	1.750	3.82	11.534	12.1	Prp ₆₆ Alm ₃₀ Grs ₄	1.751	3.80	11.529	11.8	Prp ₅₉ Alm ₂₈ Grs ₁₁ Adr ₁
5821	Almandine-spessartine	2.52	1.810	4.19	—	46.6	(Outside the ternaries)	1.804	4.22	11.601	46.3	Sps ₈₃ Alm ₁₆
11089	Chromopyrope	1.96	1.744	3.70	11.537	6.2	Grs ₆₇ Prp ₂₇ Alm ₁₆	1.740	3.70	11.521	6.8	Prp ₇₂ Alm ₁₄ Grs ₇ Uv ₆ Adr ₁ Sps ₁
11090	Chromopyrope	5.37	1.742	3.72	—	8.0	Prp ₆₈ Grs ₂₂ Alm ₂₀	1.742	3.71	11.533	6.9	Prp ₇₁ Alm ₁₄ Grs ₇ Uv ₆ Adr ₁ Sps ₁
11568	Pyrope-almandine	3.39	1.807	4.15	—	31.3	Alm ₇₇ Grs ₁₉ Prp ₄	1.804	4.16	11.525	32.4	Alm ₇₄ Prp ₁₉ Sps ₄ Grs ₂
12487	Spessartine	1.41	1.800 ^d	4.23	—	47.0	Sps ₉₇ Alm ₃	1.805	4.22	11.580	45.6	Sps ₇₂ Alm ₂₆
12588	Almandine-spessartine	1.62	1.812	4.26	—	44.3	Sps ₅₃ Alm ₄₇	1.812	4.25	11.560	43.3	Alm ₅₂ Sps ₄₇ Grs ₁
13047	Spessartine	1.91	1.800 ^d	4.20	—	52.3	(Outside the ternaries)	1.805	4.22	11.581	45.4	Sps ₇₂ Alm ₂₆
13113	Chromopyrope	1.08	1.732 ^e	3.74	11.535	8.0	Prp ₆₈ Grs ₂₂ Alm ₂₀	1.744	3.73	11.530	7.9	Pyp ₆₈ Alm ₁₇ Grs ₇ Uv ₆ Adr ₁ Sps ₁
13234	Demantoid	1.79	1.882	3.87	—	28.8	Adr ₉₀ Uv ₇ Grs ₃	1.887	3.86	12.048	30.8	Adr ₉₈
25000 (35A)	Pyrope	1.27	1.744	3.77	11.492	10.9	Prp ₇₄ Alm ₂₃ Sps ₁	1.745	3.77	11.495	10.2	Prp ₆₈ Alm ₂₄ Grs ₃ Adr ₁
25867 (4097D)	Pyrope	0.18	1.730	—	—	4.5	Prp ₇₉ Alm ₁₂ Grs ₉	1.733	3.68	11.512	5.3	Prp ₇₇ Alm ₁₂ Grs ₈ Adr ₁ Uv ₁
26620 (5544A)	Almandine	3.06	1.791	4.13	11.534	27.8	Alm ₆₄ Prp ₃₂ Sps ₄	1.795	4.10	11.531	28.8	Alm ₆₇ Prp ₂₄ Grs ₅ Sps ₃
26767 (6673F)	Almandine	0.52	1.793	4.10	11.513	25.3	Alm ₆₂ Grs ₃₅ Prp ₃	1.798	4.13	11.513	30.4	Alm ₇₃ Prp ₂₄
27257 (12822A)	Spessartine	1.42	1.800 ^d	4.25	—	46.6	Sps ₉₇ Alm ₃	1.805	4.22	11.580	45.4	Sps ₈₉ Alm ₂₆
27352 (13122A)	Hessonite	9.82	1.754	3.64	—	4.3	Grs ₉₇ Adr ₁₃	1.757	3.64	11.875	4.8	Grs ₈₄ Adr ₁₂ Alm ₁ Sps ₁
27423 (13167A)	Hessonite	9.10	1.755	3.65	—	3.9	Grs ₉₆ Adr ₁₄	1.752	3.63	11.872	3.4	Grs ₈₆ Adr ₁₂

^a Data that was not available from GIA is indicated by "—".^b Numbers in parentheses are the former catalog numbers.^c Note that calculations from the oxide chemistry seldom give end-member compositions that add to 100%.^d These RI values are problematic; see text.^e This RI was rechecked by the author and determined to be 1.742.

surements (e.g., >1 ct was preferred). When available, samples with measured SG and cell constant data were used; color was not part of the selection process.

Determination of End-Member Compositions. Silicate garnets have the general formula $X_3^2+Y_2^3+Si_3O_{12}$,

where X is commonly Ca^{2+} , Mn^{2+} , Fe^{2+} , and/or Mg^{2+} , and Y is commonly Al^{3+} , Fe^{3+} , Cr^{3+} , and/or V^{3+} . Because garnets form an isomorphous series, the X and Y positions can hold any combination of the respective ions listed; substitutions may also occur for Si.

There are two basic ways to determine the end-member composition of garnets: calculation from chemical data and derivation from measured properties. Chemical data (such as from an electron microprobe or wet chemical analysis) are typically expressed as wt.% oxides, and there are numerous (nonequivalent) ways to calculate end-member compositions from such data. A commonly used procedure from Rickwood (1968) was slightly modified by Manson and Stockton (1981). Rickwood (1968) discussed the variations that can arise from the different calculation methods, using a common metamorphic garnet composition of $\text{Prp}_{44}\text{Alm}_{42}\text{Grs}_{17}$ as an example, in which the pyrope content can vary by 3.4%, the almandine by 3.4%, and the grossular by 5.2%, depending on how the calculations are done. A more recent procedure by Locock (2008) incorporated advances in the understanding of the crystal chemistry of natural garnets through a

NEED TO KNOW

- Combined with RI or SG data, magnetic susceptibility is one more measureable property that is useful toward inferring garnet composition.
- Magnetic susceptibility of faceted gemstones can be measured nondestructively with a relatively simple apparatus.
- Susceptibility measurements are plotted against other properties on modified Winchell diagrams to derive garnet composition.
- A comparison of garnet compositions derived from measured properties versus chemical data showed a fairly good correlation.

measure of the quality of the analysis. For this paper, the author used the Locock procedure to

BOX A: MAGNETIC MATERIALS

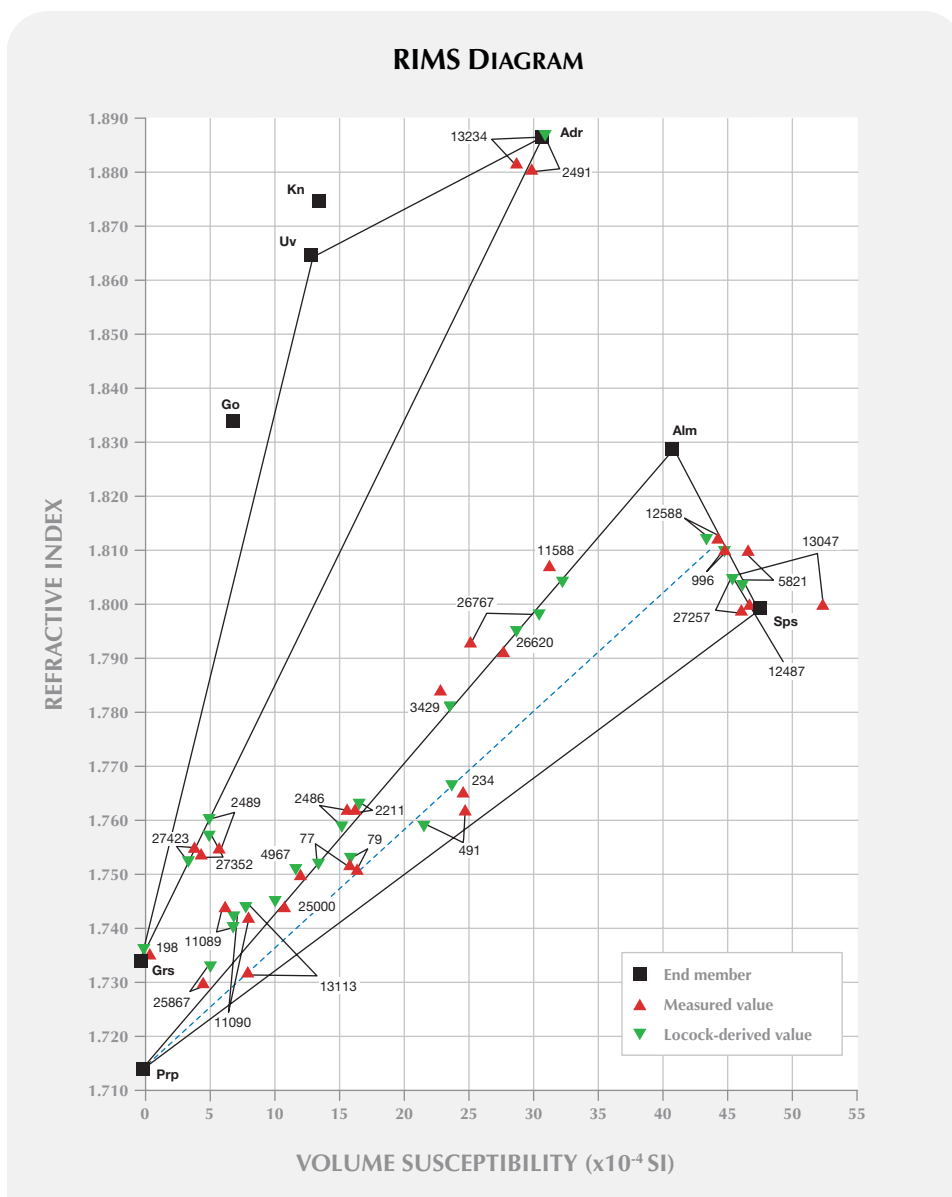
All material substances react to the presence of a magnetic field: They develop an induced magnetic field in response to the applied field. The ratio of the induced field to the applied field is called the *volume susceptibility* (k) of the substance. It is a simple dimensionless ratio.

Materials react to a magnetic field in three different ways. Most materials are very weakly repelled, or *diamagnetic*. In this case, k is negative. A material with a sufficient number of atoms of the transition elements (Fe, Mn, Cu, Cr, etc.) or the rare-earth elements—depending on their valence state—may overcome the diamagnetic effects of the other atoms and be attracted to a magnet. For these materials, k is positive. If the value of k is independent of the strength of the applied field, the material is called *paramagnetic*. Here, k will be positive and of small to intermediate magnitude. If k changes with the strength of the applied magnetic field, the material is *ferromagnetic*, and k can be very large. Ferromagnetic materials are further divided into *true ferromagnetic*, *ferrimagnetic*, *antiferromagnetic*, and *canted antiferromagnetic*. These variations in behavior are due to interactions between the electrons in the material and the formation of what are called magnetic domains.

Of greatest interest to gemology are the paramagnetic materials and their susceptibilities, which can have some diagnostic value. By contrast, diamagnetic susceptibilities have little diagnostic value. Ferromagnetic materials, when present as inclusions in gems, can give anomalously high values of magnetic susceptibility for the host material.

Physicists have defined several different kinds of magnetic susceptibility. Although volume magnetic susceptibility is dimensionless, the numeric value will differ with the system of units being used, changing by a factor of 4π , or 12.57. Thus the system of units needs to be stated, even for this dimensionless number. This article uses the International System of Units (SI), which may be a possible source for confusion if one is not familiar with this peculiarity in some electromagnetic measurements. Another commonly used property is mass magnetic susceptibility, also called specific susceptibility. This measure has dimensions of inverse density (e.g., cubic centimeters per gram), and again one needs to be aware of a multiplier of 4π when other units of measurement are used. Molar magnetic susceptibility may also be expressed in units of cubic centimeters per mol, or their equivalent.

Figure 2. This plot of RI vs. magnetic susceptibility (RIMS diagram) compares measured properties (indicated by red triangles) against properties calculated from end-member compositions (green triangles, according to Locock [2008]) for the 28 GIA garnet samples. The black squares represent pure end-member properties (see table 1 for key to abbreviations). The pyrospite and ugrandite ternary triangles are shown by black lines connecting the corresponding end members.



obtain the end-member compositions from the GIA oxide chemical data.

The second way to determine garnet end-member composition is to use quantitative measured properties and solve a series of equations that are based on Vegard's law, which showed that garnet properties are additive functions of the molar proportions of end-member compositions (Hutchison, 1974). The equations are:

1. $RI_m = ARI_{EM1} + BRI_{EM2} + CRI_{EM3}$
2. $S_m = AS_{EM1} + BS_{EM2} + CS_{EM3}$
3. $A + B + C = 1$

where RI = refractive index, S = magnetic susceptibility, m = measured, EM = end-member values, and A, B, and C = percentages of end members. With two measured properties, one can solve for three possible end members. With three measured properties, the end members increase to four, and so on. As with compositions based on chemical analyses, the result is not unique; there will be several (similar) possibilities. Winchell (1958) showed how these equations can be solved graphically in a rather simple way, and his diagram of RI vs. unit cell dimensions (or cell constant) demonstrated the interrelation between the pure end members and a particular garnet. However, the cell constant of an unknown garnet is

not easily obtained by the gemologist because X-ray diffraction data is required, so Hoover et al. (2008) modified the Winchell diagram so that the composition of an unknown garnet can be determined—according to three or four end members—from quantitative measurements of properties such as magnetic susceptibility, RI, and SG. Box B describes how magnetic susceptibility was measured, both in this study and by Hoover et al. (2008).

Figure 2 is the modified Winchell diagram plotting RI vs. magnetic susceptibility (RIMS). Eight garnet end members of gemological importance (black squares) are shown on the diagram. The garnet ternaries pyrospite (pyrope, almandine, and spessartine) and ugrandite (uvarovite, grossular, and andradite) are shown as triangles outlined in black that connect each of the three corresponding end members. Other end members shown are goldmanite and

BOX B: MEASUREMENT OF MAGNETIC SUSCEPTIBILITY

While there are several ways to quantitatively measure magnetic susceptibility, volume susceptibility is routinely measured with a Gouy balance or the similar Evans balance (see www.geneq.com/catalog/en/msbalance.html). Susceptibility is measured by placing a sample on one arm of a laboratory balance and subjecting it to a strong magnetic field gradient. The weight loss or gain is measured and converted to susceptibility. Unfortunately, the sample must be in the form of a cylinder. In practice, the sample is often ground to a powder and placed in a cylindrical sample holder. This obviously is not practical for gem materials.

Hoover and Williams (2007) showed that if a very strong permanent magnet is used, and its pole face is smaller than the table (or other flat facet) of the gem to be measured, then the force of attraction between the magnet's pole face and the facet will be proportional to the gem's volume susceptibility. To calculate the gem's susceptibility, the magnet only needs to be calibrated with a material of known susceptibility. The apparatus used by Hoover and Williams (2007), Hoover et al. (2008), and in this study consisted of a biological microscope with the optics removed (figure B-1). In place of the optics, a small iron rod was fixed vertically to hold a variety of small ($\frac{1}{16}$ in. to $\frac{1}{4}$ in. diameter) cylindrical rare-earth magnets. The important components are the fine focus mechanism (for precise control of the magnet's vertical position) and the moveable X-Y stage that is used to align the gem's table with the magnet's pole face. A small digital scale was placed on the microscope stage, and a gem was placed on a pedestal in the weighing dish. The magnet's pole face was brought just into contact and parallel

with the gem's table. The gem was then slightly separated from the magnet to obtain a maximum change in weight (i.e., weight loss for a paramagnetic gem).

The procedure is no more complex than measuring specific gravity—and takes about as much time. The apparatus can be constructed at low cost using a surplus microscope.

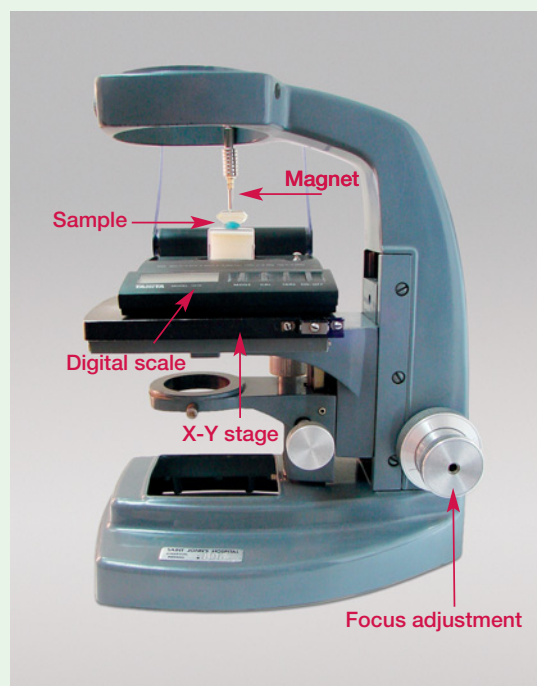


Figure B-1. This instrument was designed by Hoover and Williams (2007) for taking magnetic susceptibility measurements, and was used in the current study. Photo by Bear Williams.

knorringite. (Schorlomite is not shown because end-member property values are not available in the mineralogical literature, and in gem garnets this component may be present in only very small quantities.) The positions of all the garnets obtained for this study are also plotted: the green triangles represent the compositions calculated from microprobe analyses (using the Locock procedure), and the red triangles plot the RI and susceptibility data. The various garnet compositions can be recognized by their position with respect to the end members.

The process to determine the composition of the three garnet end members from any data point is simple. For example, for the green triangle representing the Locock five end-member composition of sample no. 234, which is plotted with an RI of 1.766 and a susceptibility of 23.7×10^{-4} SI:

- From the pyrope apex of the pyralspite ternary, draw a line through the center of the data point to intercept the opposite base of the triangle, shown by the blue dashed line.
- Next, measure the total length of the line, and then the length from the data point to the base of the triangle.
- Divide the line length from the data point to the base by the total length, which will give the percentage of pyrope end member.

For sample no. 234, the result is 47%. The process can be repeated for the other two apices, but it is simpler to measure the relative proportions of almandine and spessartine on the almandine-spessartine join where the blue line crosses it, and proportion them to the remaining percentage (53% for this example). Here it is at 60% spessartine, which yields 32% for spessartine and 21% for almandine, or $\text{Prp}_{47}\text{Sps}_{32}\text{Alm}_{21}$. By comparison, the Locock technique characterizes this stone, rounding to the nearest 1%, as $\text{Prp}_{43}\text{Sps}_{34}\text{Alm}_{18}\text{Grs}_4\text{Adr}_1$.

End-Member Properties. The properties of each garnet end member (table 1) are required to plot their positions in the various modified Winchell diagrams. For every end member but knorringite, the RI, SG, and cell constant used were reported by Meagher (1982). For knorringite, the calculated data from McConnell (table 50 in Deer et al., 1982) were used by Hoover et al. (2008), but the data do not agree well with the RI and cell dimension data measured

on synthetic samples by Ringwood (1977), or with the data presented by Nixon and Hornung (1968), who first defined knorringite. The McConnell data will continue to be used in this article, with the understanding that knorringite end-member values are subject to change.

Magnetic susceptibility values are not well known, either. Pure grossular and pyrope have no transition elements in their composition and are thus diamagnetic. Their susceptibilities are very small and slightly negative; they were assigned by Hoover et al. (2008) values of -0.2×10^{-4} SI, typical of diamagnetic materials. The other six end members are less easy to define. Frost (1960) measured the mass, or specific, susceptibilities of andradite, almandine, and spessartine, which (when converted to volume susceptibility) are 23.8, 36.9, and 42.7×10^{-4} SI, respectively. But the data are not robust. The four almandine-spessartine garnets Frost measured, ranging from $\text{Alm}_{65}\text{Sps}_{35}$ to $\text{Alm}_{10}\text{Sps}_{87}$, all had the same mass susceptibility. Nathan et al. (1965) measured spessartine's volume susceptibility as 44.3×10^{-4} SI, but the author's own measurements on spessartine suggested that this was slightly low. Hoover et al. (2008) were unable to find measured susceptibilities for the other three garnet end members. Approximate values, however, were calculated based on the magneton numbers of the constituent transition element ions present (Kittel, 1956), using the Langevin equation. This is how Hoover et al. (2008) obtained the values shown in the figures—30.8, 40.7, 47.5, 12.9, 6.9, and 13.7×10^{-4} SI, respectively—for andradite, almandine, spessartine, uvarovite, goldmanite, and knorringite.

Measured Properties. Except for the magnetic susceptibility measurements, all properties for the 28 study samples were supplied by GIA from the Manson-Stockton research. The volume susceptibility measurements were taken by the author, using the apparatus described in box B, with cobalt chloride as a susceptibility standard (described by Hoover et al., 2008).

RESULTS

RI vs. Magnetic Susceptibility Diagram. In the RIMS diagram (figure 2), the gem ugrandites plot on or very near the line joining grossular and andradite. The single mint green grossular (sample no. 198) is very close to the grossular end member. The three hessonites (2489, 27352, and 27423) are about 14% toward andradite. The two demantoids (2491 and 13234) are close to the andradite end member. For

the pyrospite garnets, a mixed almandine-spessartine group (996, 5821, and 12588) plots along the almandine-spessartine join, quite distinct from the rest. Spessartine samples (12487, 13047, and 27257) plot near their end-member composition. Three stones, consisting of two malaya (234 and 491) and one color-change garnet (79), are positioned within the pyrospite ternary. The rest of the garnets are arrayed near the pyrope-almandine join, or within the grossular-pyrope-almandine ternary; three chrome-pyropes (11089, 11090, and 13113) are included in the latter group.

Comparing the measured and calculated end-member data for most samples shows fair agreement (figure 2 and table 2). The variations between the two techniques are about what one would expect due to measurement error and some uncertainty in end-member properties. Not including sample 13113, for which the originally measured RI was incorrect, the average difference between measured and calculated RI values is 0.003. For volume susceptibility, there is a difference of 0.5×10^{-4} SI, if one disregards samples 13047 and 26767, which are anomalous. For specific gravity (figure 3), the average difference is 0.01.

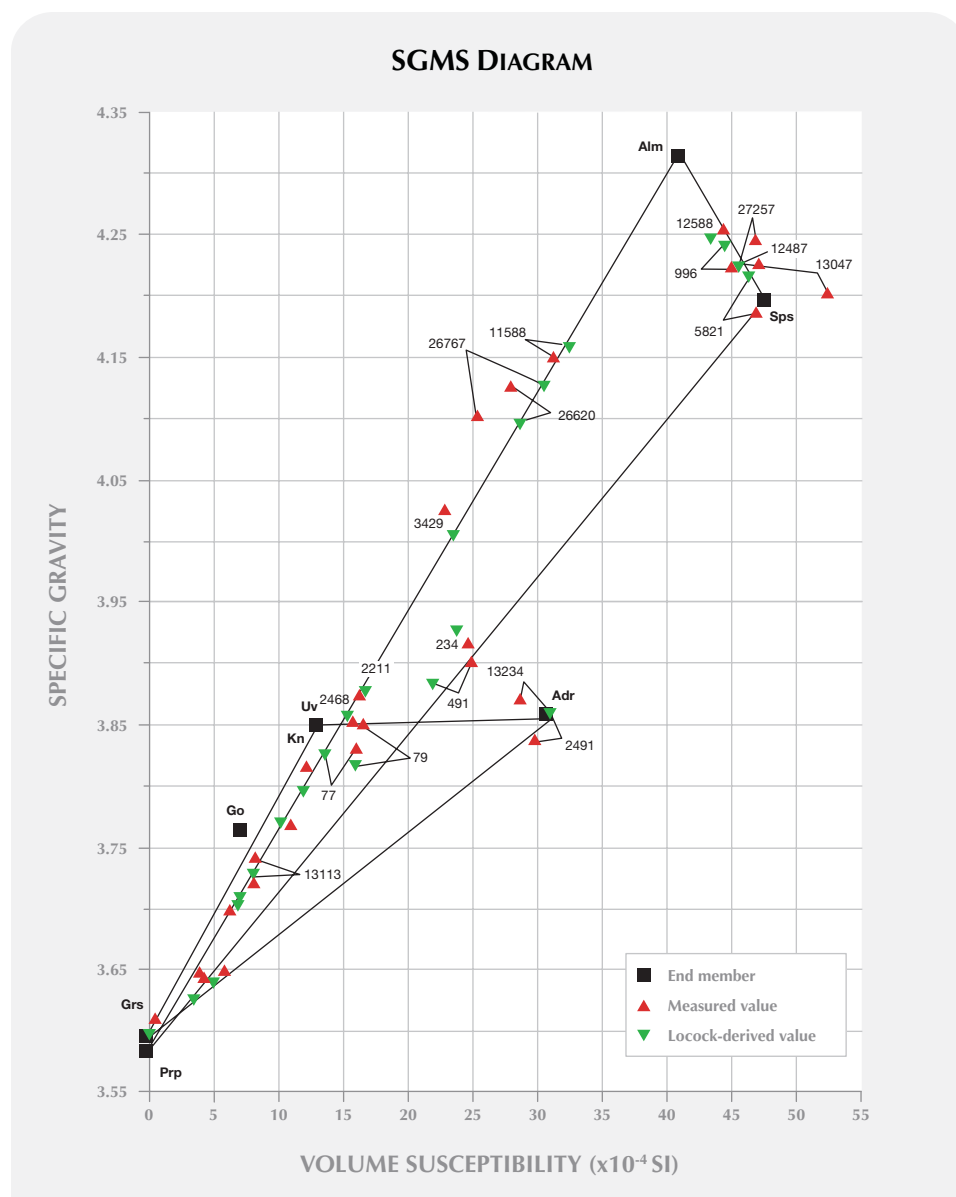


Figure 3. This plot shows SG vs. magnetic susceptibility (SGMS diagram) for the 27 GIA garnets for which the data were available. However, sample numbers are not shown for those samples that plot toward the pyrope and grossular end members, which overlap on this diagram.

To give a sense of how these variations are reflected in terms of garnet composition, let us assume a 3% difference in end-member composition of a $\text{Pyr}_{50}\text{Alm}_{50}$ garnet. This would produce a change of 0.004 in RI, 1.22×10^{-4} SI in volume susceptibility, and 0.02 in SG. Thus the average difference between these three measured properties and those calculated from the Locock procedure represents less than 3% compositional change in a mid-range pyrope-almandine. It is important to remember that such a derived composition will not be unique, and that any additional information, such as absorption spectra, may further reduce uncertainties in determining garnet composition.

The RIMS diagram shows the advantage of such plots in evaluating how accurate our property measurements need to be. Consider the various joins in the illustration. Those between pyrope or grossular and the other end members are relatively long, and therefore span a wide range in refractive index and susceptibility. A difference of a few percentage points in composition will have a measurable effect on these properties. By comparison, the almandine-spessartine join is quite short: a larger percentage change in composition is needed to produce a measurable change in properties.

Regarding the two samples with anomalous susceptibilities, no. 26767 had a small chip on the table below the magnet, which probably was responsible for its lower susceptibility. Sample 13047, a spessartine, had a high susceptibility. In the author's collection, a Brazilian spessartine shows a similarly high susceptibility. Neither shows evidence of ferromagnetic inclusions, such as magnetite, that could explain their anomalous susceptibilities. The author suspects that these are yttrium-bearing spessartines, with relatively enriched rare-earth contents that are responsible for their high susceptibilities. Note that sample 13047, in this property space, falls well beyond the expected measurement error from any ternary triangle using the eight more-common garnet end members.

Chrome-pyrope 13113 originally had an anomalously low measured RI, 1.732, compared to a calculated value of 1.744. Yet the other measured values of SG, cell constant, and susceptibility agreed well with calculated values. The refractive index is clearly questionable, which illustrates the utility of Winchell diagrams in checking the consistency between measured properties and chemical data. The sample's RI was rechecked by the author and found to be 1.742. The RIs of the three spessartines

(13047, 12487, and 27257) may also have been measured incorrectly. Each had a reported RI of 1.800 from the Manson-Stockton data set, and each had a very similar end-member composition. The calculated RIs are all 1.805. GIA, however, remeasured the RI of sample 13047 as >1.810 , or above the index of the refractometer liquid. The author checked these values with an experimental deviation angle refractometer and found all three to be 1.809, but the error range of the instrument is no better than 0.004. These stones remain problematic.

SG vs. Magnetic Susceptibility Diagram. Another modified Winchell diagram, plotting specific gravity vs. magnetic susceptibility (SGMS), holds some promise. This diagram (figure 3) shows the 27 garnets for which SG data were available. Stockton and Manson (1985) did not consider specific gravity in their characterization of garnet, though they measured it for many of the samples:

There is so much overlap in specific gravity ranges for the various types of garnets that the usefulness of this property is questionable. Moreover the difficulty of accurately measuring density as well as the considerable variability introduced by the presence of inclusions suggests that this is not a reliable characteristic for the identification and classification of gems. (Stockton and Manson, 1985, p. 212)

However, figure 3 suggests otherwise. Note the positions of samples 996, 11588, 26767, 26620, 3429, 234, 491, 2211, and 2486 with respect to the pyral-spilite ternary in this figure, compared to their positions in figure 1. They indicate very similar chemical composition, whether RI or specific gravity is used with magnetic susceptibility. Of particular importance for the practicing gemologist is that RI values that cannot be obtained on a conventional refractometer can now be measured by substituting SG for RI to infer composition in a manner similar to using a RIMS plot. This possibility was suggested by Hoover et al. (2008), assuming SG values were accurate enough. The Manson-Stockton data clearly demonstrate the usefulness of SG data for stones that are not too included. For example, metamorphic garnets of high almandine content can be easily distinguished from typical pegmatitic almandine-spessartine compositions.

Unfortunately, the SGMS plot also shows that the specific gravity and magnetic susceptibility of pyrope and grossular are almost identical, and that the pyrope and grossular ends of the pyral-spilite and

ugrandite ternaries overlap. Clearly there are problems in distinguishing a pyrope-almandine-spessartine from a grossular-almandine-spessartine. It should be no surprise, then, that using SG to add a fourth end member to inferred compositions from RI and susceptibility is questionable.

RI vs. SG Diagram. Figure 4 is the modified Winchell plot of RI vs. SG (RISG), using the 27 stones shown previously. Jackson (2006) used such a diagram for characterization, but noted the lack of robustness for garnets of multiple end-member compositions. Stockton and Manson (1985) also plotted

an RISG diagram for 202 stones used in their studies, but did not show the end-member positions. Notice that chrome pyrope no. 13113 is again anomalous in this diagram, but not in the SGMS plot of figure 3.

There is a significant problem with using the RISG diagram: The pyralspite and ugrandite ternaries are very narrow, indicating that within either, the relationship between the two properties is nearly linear. This is a consequence of the Gladstone-Dale relationship between the two properties (Larsen and Berman, 1934). Thus we are unable to distinguish—in the case of a pyralspite, for example—the proportions of each of the three components based only on these

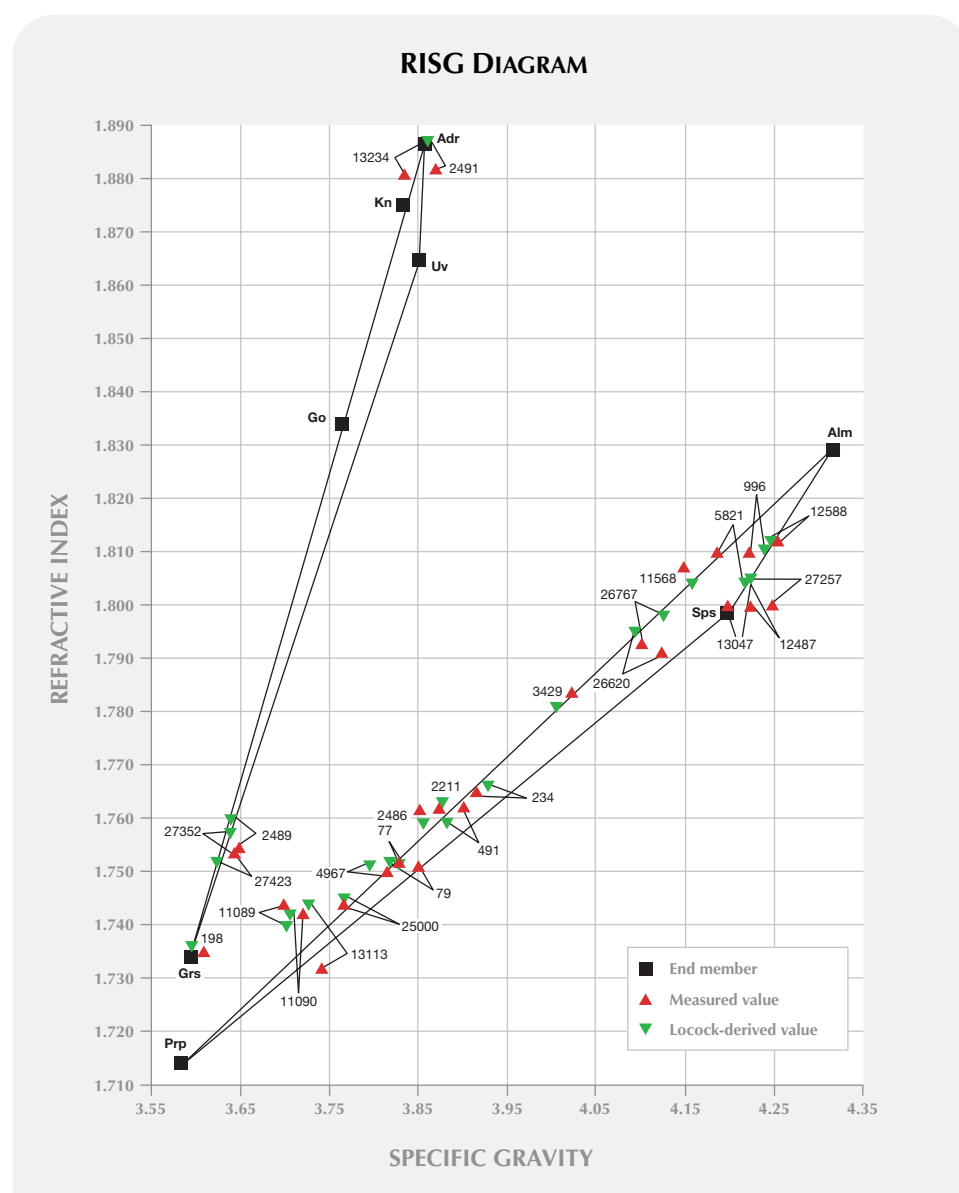


Figure 4. This plot shows RI vs. SG (RISG diagram) for the 27 GIA garnets with data available.



Figure 5. These garnets show similar color but have different compositions. From left to right: GIA sample nos. 79 (pyralspite), 37369 (hessonite), and 25000 (pyrope-almandine). Photo by Robert Weldon.

two properties, unless we have extremely accurate measurements of both properties. It is interesting to note that for these particular stones, the measured RI and SG values agree reasonably well with the calculated values. This is further evidence that Manson and Stockton were able to measure SG adequately to provide useful data for Winchell-type diagrams.

Multiple End Members and Compositional Possibilities. A few garnet varieties, such as tsavorite and demantoid, are often characterized by a single end member, but most other garnets require more. Figures 2 and 3 show that the malaya (nos. 234 and 491) and color-change (no. 79) garnets are the only pyralspites studied that plot well within the pyralspite ternary. The others are either close to the almandine-spessartine or pyrope-almandine joins, or within the grossular-pyrope-almandine ternary. The malaya and color-change garnets are best described by a combination of the pyralspite end members, plus significant grossular. Thus they are very useful for comparing the inferred three or four end members by applying Winchell diagrams to the microprobe composition.

Sample no. 79 is particularly useful because of its relatively high grossular component. The Locock procedure yields a composition of $\text{Prp}_{48}\text{Sps}_{23}\text{Grs}_{15}\text{Alm}_{12}\text{Uv}_1$, with less than 1% consisting of other components. From figure 2 the composition can be derived as (1) $\text{Prp}_{63}\text{Sps}_{20}\text{Alm}_{17}$ or (2) $\text{Sps}_{35}\text{Grs}_{34}\text{Prp}_{31}$. Either of these compositions gives an RI of 1.751 and a susceptibility of 16.4×10^{-4} SI. Note that neither PrpGrsAlm nor GrsAlmSps fits the two properties. The calculated SGs from these two composi-

tions are 3.83 and 3.80, respectively, a difference of less than 1%, which is very slight for such a large difference in composition. The measured SG for this 1.88 ct stone is 3.85. Clearly, this value does not fit, so one cannot calculate a mixed PrpSpsGrsAlm garnet from these measured data. For this stone, a rather accurate SG (of 3.817) is needed to derive a four end-member composition obtained with the Locock method. This example demonstrates the problem with adding SG to determine a fourth end member for distinguishing between some pyralspite garnets. A photo of sample no. 79 is shown in figure 5, along with no. 25000 and a hessonite that resembles the latter in color.

Garnet no. 25000 is also an interesting stone. From the Locock procedure, its composition is $\text{Prp}_{68}\text{Alm}_{24}\text{Grs}_3\text{Adr}_1$. GIA had classified it as a pyrope. Interestingly, the stone's color matches that of many hessonites. But its measured susceptibility is close to its calculated properties, and the stone is clearly not hessonite (figure 2). The measured properties indicate $\text{Pyp}_{75}\text{Alm}_{25}$, if it is assumed to have only pyrope and almandine components, and this composition would have RI and SG values of 1.743 and 3.77, respectively. However, this sample can also be fit with a composition of $\text{Grs}_{51}\text{Prp}_{26}\text{Sps}_{23}$ and RI and SG values of 1.744 and 3.77, respectively. These properties fall within the measurement error of $\text{Prp}_{75}\text{Alm}_{25}$. This example shows that very minor differences in measured properties may tip the composition to one side or the other of the pyrope-almandine join. The author suspects there are other such pyropes that could masquerade as hessonites.

RI vs. Cell Constant Diagram. While Manson and Stockton did not use cell constant in their articles, they did measure it for a number of their samples. This makes it possible to compare the modified Winchell RIMS plot against a standard Winchell plot of RI vs. cell constant (RICC), as well as four other variations, when four quantitatively measurable properties are available.

Figure 6 shows a conventional Winchell plot for 16 of the 28 GIA samples for which cell constant was measured. Note that the differences between the calculated and measured values are about the same as those shown for the RIMS plots in figure 2. Comparing these two plots shows distinct differences in the positioning of some stones within the pyralspite ternaries.

Consider the stones arrayed near the pyrope-almandine join. In figure 2 they are positioned, on

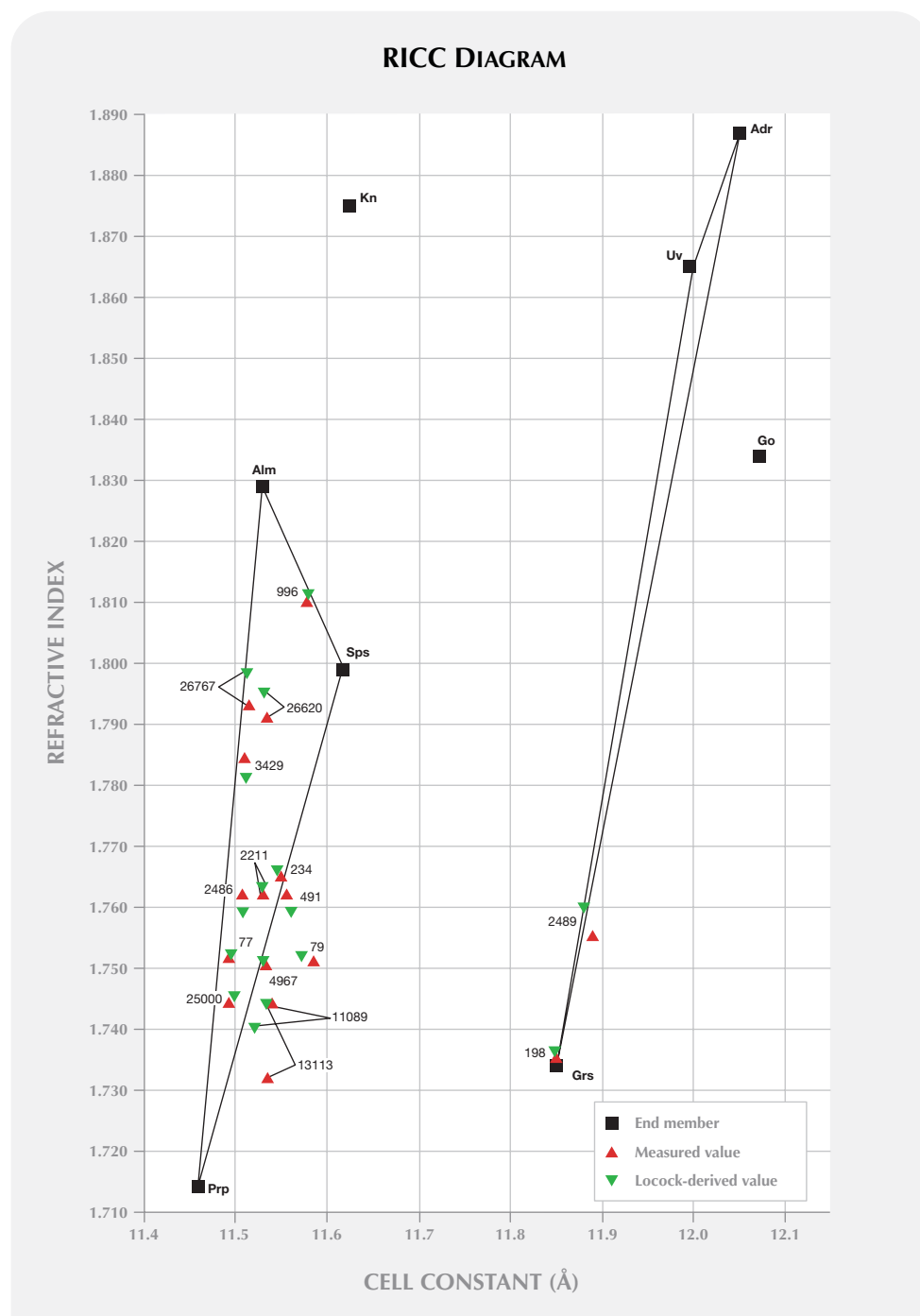


Figure 6. This conventional Winchell plot shows the RI vs. cell constant (RICC diagram) for 16 GIA garnet samples.

average, slightly to the left of the join (nos. 26767, 3429, 2211, 2486, 77, and 25000). In figure 6 they are within the pyrospite ternary. But the malaya (no. 491) and color-change (79) garnets are outside the pyrospite ternary. These differences reflect the effects of end members other than pyrospite's on the measured properties. If the composition of a garnet is purely pyrospite, its position within the ternary would not change according to the particular

Winchell diagram used. In these cases, the differences are due to grossular and/or uvarovite components. Note that in the RICC plot the ugrandite ternary is very narrow, indicating that a ugrandite with all three end members as major components cannot be well characterized by this type of diagram.

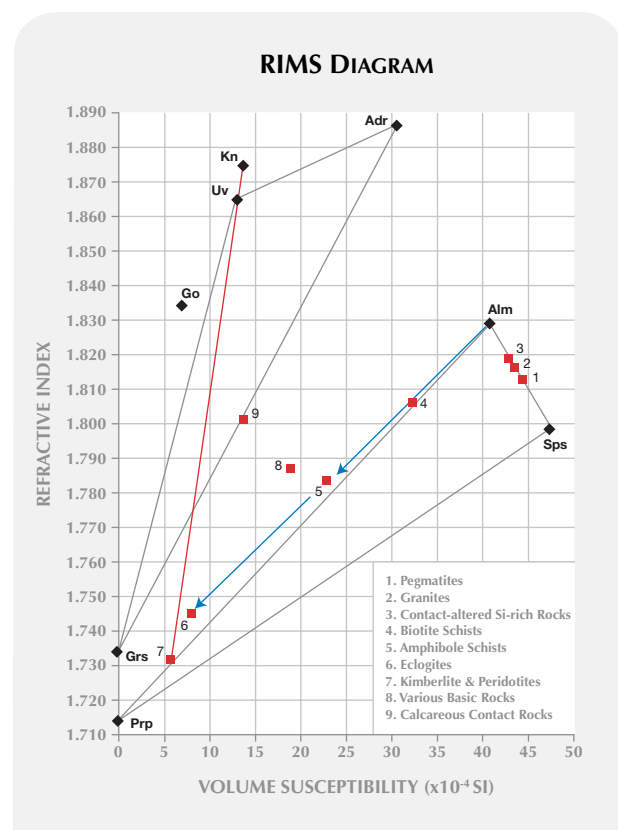
Usefulness of Modified Winchell Diagrams. These diagrams provide a simple but powerful demonstra-

tion of the relationship between garnet properties and composition. Any garnet with properties that plot near an end member will have a preponderance of that end member in its composition. A sample positioned toward the center of a given ternary will be composed of similar quantities of each end member. One can also estimate the effect that adding or subtracting any end member will have on the various properties. The effect on properties is directly related to the garnet's distance from the end member.

In addition to offering compositional information, the modified Winchell diagrams can also provide insights into garnet paragenesis. Figure 7 is a RIMS plot of data from Wright (1938) showing the average compositions of garnets from various rock

types. The RIs and susceptibilities were calculated from Wright's average compositions. The plot shows that garnets associated with felsic igneous rocks (nos. 1, 2, and 3) such as the granitic pegmatites are essentially almandine and spessartine. Metamorphic garnets (nos. 4, 5, and 6) show higher pyrope/grossular as the metamorphic grade increases (blue arrows), with the highest grade (eclogitic; no. 6) approaching the composition of peridotitic garnet (no. 7). The red line shows the change in properties of an average peridotitic pyrope toward the knorringite component as chromium is added. Comparing figure 7 with figure 2, correlations are evident between many of the garnet samples and their probable genetic origins. Malaya and color-change garnets are not represented in the Wright data, but the present author suspects they represent metamorphosed, subducted, high-Mn oceanic sediments.

Figure 7. This RIMS diagram shows the average garnet compositions from various rock associations, as given by Wright (1938). The RI and susceptibility data are plotted from compositions that include the average proportions of five major garnet end members. The blue arrows show the compositional change for metamorphic garnets as the metamorphic grade increases.



CONCLUSION

Gem garnets (e.g., figure 8) encompass a broad range of compositions and properties. Because most gemologists lack the capability to obtain quantitative chemical data, garnet composition must be inferred from measured/observed properties. In the past, RI and possibly SG were the only quantitative measures for deriving chemical composition. Yet these properties are not sufficiently independent of each other for such determinations. By measuring magnetic susceptibilities on selected garnets with well characterized compositions, the author has demonstrated a technique for inferring garnet composition from measurements of two or more quantitative properties.

Inferring chemical composition in this way should not be considered equivalent to the results obtained from a microprobe or other chemical analysis. While chemical data typically give the percentages of oxides in a sample, these data are not of prime interest to the gemologist, who seeks the proportion of ideal end members. This proportion may be obtained from either oxide chemistry or garnet properties, but neither method gives unique results. When oxide percentages are used, the number of ideal end members will vary according to the number of elements analyzed. Using garnet properties to infer end-member composition limits the number of end members to one more than the number of properties measured. Using RI and magnetic susceptibility, then, we can infer a three end-member composition.



Figure 8. Gem garnets, such as these examples from the Dr. Edward J. Gübelin Collection, show a variety of properties and compositions. Magnetic susceptibility is one more measureable property the gemologist can use to help estimate garnet composition. Shown clockwise from the top: 44.28 ct pyrope-spessartine from Madagascar (GIA Collection no. 34387a), 19.12 ct pyrope-almandine from Sri Lanka (34769), 4.24 ct demantoid (33303), 3.65 ct tsavorite from Tanzania (35569), and 19.90 ct spessartine from Brazil (33238); photo by Robert Weldon.

The various modified Winchell diagrams give the gemologist new insight into garnet chemical composition and its relation to measured properties. They can be a useful educational tool—showing the range of RIs possible where pyrope is the principal component, for example. In addition, Winchell diagrams can yield information on a garnet's probable geologic environment.

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