

GEMMOLOGY

GARNETS – A COLOURFUL GEMSTONE FAMILY

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Garnets continually surprise us with their large range of colours and the wide variation in their diagnostic features of refractive index and density. This article introduces the main gem types, and explains their main similarities and differences.

Idealized pure garnets

Each mineral is defined both by its crystal structure (atomic structure) and by its chemical composition (atomic composition). The individual building blocks of the crystal structure are **ions**, which are positively or negatively charged atoms of a variety of elements which occupy the crystal structure. During crystallisation, the ions order themselves into the garnet structure with cubic symmetry. Although all garnets possess the same crystal structure, this can be made up of different, although similar, atoms. Because of this, a large number of garnet types occur. Studies have been carried out on naturally occurring garnets to determine which chemical elements participate in the structure and in what amounts. The results are best presented in the form of a chemical formula. A formula, like a recipe, shows which elements (as single ions) are present and in what relative quantities. These quantities are indicated by the small number (index), after and just below the abbreviated name (symbol) of the element. Crystals of visible dimensions contain many billions of the smallest unit of mineral formula. The smallest possible amount of garnet is formed by one formula unit, termed a **molecule**.

The following idealized and chemically pure end-members are of significance for the description of the gem garnets:

The main garnet-types

PYROPE	$\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	(colourless)
ALMANDINE	$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	(dark red)
SPESSARTINE	$\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	(yellow-orange)
GROSSULAR	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	(colourless)
ANDRADITE	$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12}$	(yellow-green)
UVAROVITE	$\text{Ca}_3\text{Cr}_2\text{Si}_3\text{O}_{12}$	(green-black)

These chemically pure types occur solely as synthetic crystals, and in nature only crystals representing a chemical "mixture" of the above types are generally found.

The garnets can be classified into two chemical groups. These are named using the first letters of the members of the participating garnets. The PYRALSPITE group is composed of the aluminium-containing (minus grossular) garnets pyrope, almandine and spessartine. The UGRANDITE group is composed of the calcium-containing garnets uvarovite, grossular and andradite. As a Ca-Al garnet, grossular possesses characteristics of both groups.

Apart from the uniform crystal structure, the garnets show distinct chemical similarities. All chemical formulae contain:

- 3 divalent ions (e.g. Mg^{2+} , Fe^{2+} , Mn^{2+} , Ca^{2+})
- 2 trivalent ions (e.g. Al^{3+} , Fe^{3+} , Cr^{3+} , V^{3+})
- 3 SiO_4 groups (can also be written as Si_3O_{12})

Apart from the garnet types mentioned above, additional types can be visualized with constituent ions fitting the general garnet formula. For example, the minerals **knorringite** ($\text{Mg}_3\text{Cr}_2\text{Si}_3\text{O}_{12}$) and **goldmanite** ($\text{Ca}_3\text{V}_2\text{Si}_3\text{O}_{12}$) have been synthetically produced. Furthermore, silicate-free garnets such as YAG ($\text{Y}_3\text{Al}_2\text{Al}_3\text{O}_{12}$) and CGG ($\text{Gd}_3\text{Ga}_2\text{Ga}_3\text{O}_{12}$) can be synthetically prepared and these are used in part as diamond substitutes.

On the basis of their typical chemical composition, each idealised pure garnet type possesses characteristic physical properties:

Physical properties of idealized garnet types (chemical end-members)

	Hardness	Density	Refractive Index
Pyrope	7 $\frac{1}{4}$	3.58 g/cm ³	1.714
Almandine	7 $\frac{1}{2}$	4.32	1.830
Spessartine	7 $\frac{1}{4}$	4.19	1.800
Grossular	7 $\frac{1}{2}$	3.59	1.734
Andradite	7 $\frac{1}{2}$	3.86	1.887
Uvavovite	7 $\frac{1}{2}$	3.85	1.865

Formation of mixed crystals

The chemically pure end-members previously described correspond to a theoretically idealized composition which is very rarely found in nature. Natural garnets are virtually always composed of "mixtures" of the end-members. When garnet crystals are formed in nature, there are usually several different types of divalent and trivalent ions available. For example, a natural garnet will form simultaneously making use of Mg^{2+} and Fe^{2+} . Pyrope molecules and almandine molecules are thus formed simultaneously and a so-called **mixed crystal** is formed whose composition will lie somewhere between that for pyrope and almandine, depending on the proportion of the Fe^{2+} and Mg^{2+} ions used in the formation of the crystal. Pyrope and almandine can form a complete series of "mixed crystals", or a solid solution series.

Fig. 1 shows the relationship between refractive index and density, and the mixing ratio of pyrope and almandine. The values for the mixed crystals lie between the extreme values of the end-members.

The illustration above is an example of a mixed crystal comprising of only two components, viz. the pyrope and almandine molecules. Most naturally occurring garnets are mixed crystals composed of two or more garnet end-members in varying quantities. Usually, mixed crystals are optically homogeneous, and can be

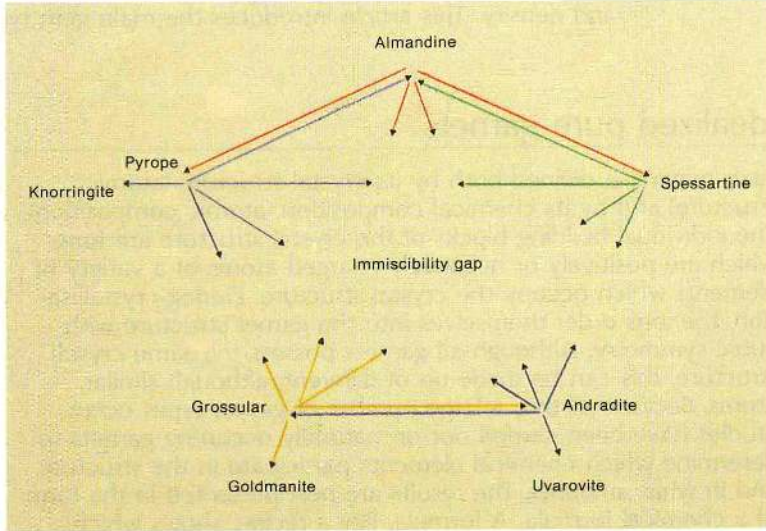
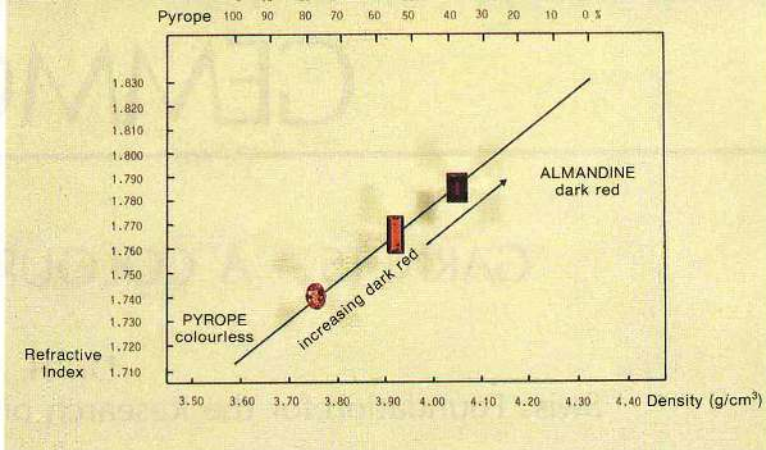
considered to be solidified solutions: in the central gemstone in Fig. 1, 40% almandine molecule is “dissolved” in 60% pyrope. Some garnet types possess only limited miscibility with other types. It has been found that the garnets within the pyrospite group exhibit a large amount of miscibility; similarly, the garnets within the ugrandite group. On the other hand, miscibility between the pyrospite and the ugrandite groups themselves is very limited. Areas of mixed proportions which do not occur in nature are termed “miscibility gaps”. Fig. 2 shows a graphical attempt to define the miscibility possibilities between the main garnet types. The length of each arrow towards an other end-member indicates the extent of miscibility. In this kind of graphical representation, “mixtures” of three or more end-members (as occur in nature) cannot be shown.

True gem garnets

The following are some examples of garnets which will be examined in some more detail. The principle of miscibility of two chemical compounds possessing the same crystal structure can result in the formation of a large number of different mixed crystals. Their colour, refractive indices and densities can be regarded as functions influenced by the values of the participating end-members. The type of garnet formed during crystallisation depends on the available material, local geological factors and physico-chemical factors. Naming of individual garnet types often preceded the technique of non-destructive chemical analysis but the results of analysis later permitted quantitative data on the various end-members to be made known.

Pyrope-almandine garnets

The most common garnets are red stones of the pyrope-almandine series (Fig. 3). A pleasing red colour is shown when the colourless pyrope component contains 10–40% almandine component. Higher almandine-contents result in a too dark colour. Pure **almandine** is very dark red. **Rhodolite** is a light purple-red pyrope-almandine variety which contains 10–25% almandine component. A few percent of the almandine molecule is enough to have a strong effect on the colour. This is the reason why the absorption spectrum of light rhodolite exhibits the almandine bands at 575, 527 and 505 nm. **Pyrope**, which is colourless when pure, can be idiochromatically coloured by the presence of garnet types other than almandine.



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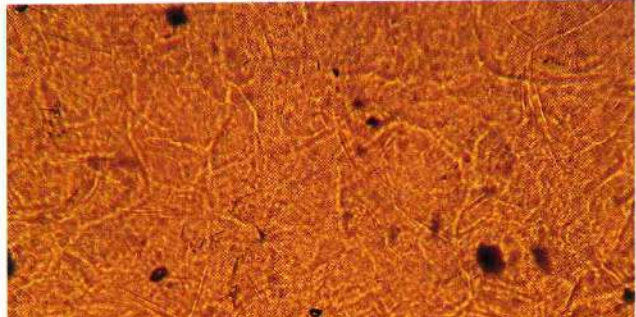
Fig. 1 Relationship between density and refractive index, and composition in the pyrope-almandine system.

Fig. 2 Miscibility within the pyrospite and ugrandite groups. Between the groups there is a large immiscibility gap.

Fig. 3 Garnets from the pyrope-almandine solid solution series. The oval stone in the centre represents the colour variety rhodolite.

Fig. 4 Grossulars (left), grossularites (rear) and hessonites (right). Their colour originates from small contents of other, coloured garnet types. The green stones are tsavolites (vanadium and/or chromium grossulars).

Fig. 5 Microscope image (transmitted light) of hessonite showing the swirly structure, stemming from the granular structure of the stone.



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Idiochromatic spessartine (yellow) and knorringite (red) are also miscible with pyrope. Blood-red **chromium pyrope** contains a small portion of knorringite molecules.

Some garnets, mainly composed of pyrope-almandine mixtures, also contain a few percent grossular, spessartine or andradite molecules. The two last-named can influence colour.

Grossulars and grossularites

Pure **grossular** is colourless, but through mixture with idiochromatic garnet types, alien-coloured (allochromatic) mixed crystals with red, yellow, green and brown colours (Fig. 4) are formed. The almandine, andradite, uvarovite and goldmanite molecules are the main donors of colour. Small portions of iron-rich types (almandine, andradite) lead to red, orange and brown colourations. **Hessonites** are representatives of these varieties of grossular. Their distinctive optical peculiarity is a granular structure, which appears under the microscope as a swirlyness. The granular structure is due to the polycrystalline structure of hessonite (Fig. 5 and 6). Hessonites are therefore not single crystals, but polycrystalline structures as sometimes seen in other grossulars, too. **Grossularite** is the correct name for this form. Green varieties of grossular can also possess polycrystalline structure. Green grossularites (or hydro-grossularites) are known as "Transvaal Jade". Many grossularites are not necessarily composed solely of single-mineral grossular grains, but can contain other minerals, such as vesuvianite or chromite. As they are an association of diverse minerals they become defined as a **rock**. Variations therefore range from the single crystal grossular to grossularite and to a grossular-rich rock, and the densities can be quite different from those of pure grossular.

At present, the most significant grossulars are the green **Tsavalites**, mainly found in the Tsavo National Park in Kenya. The green colour of the tsavalites is due to the elements vanadium and/or chromium. These elements occur in the grossular as either the goldmanite ($\text{Ca}_3\text{V}_2\text{Si}_3\text{O}_{12}$) or uvarovite ($\text{Ca}_3\text{Cr}_2\text{Si}_3\text{O}_{12}$) molecules. Both produce an emerald-green colour. The vanadium-rich molecule is usually dominant.

Spessartine and spessartine-rich garnets

Pure, yellow spessartine seldom occurs in nature in crystal size of interest to the gem cutter. An occurrence in California produces light orange-yellow stones containing over 90% spessartine

Fig. 6 Scanning electron micrograph of a breakage surface in a hessonite (length of black scale bar = 0.1 mm). The granular, polycrystalline texture is recognisable. The yellow stone originates from East Africa.

Fig. 7 Spessartines and spessartine-rich stones in artificial light. The stones in the front row possess a small amount of vanadium.

Fig. 8 The same stones as in Fig. 6, but in bluish artificial illumination. The stones in the front row exhibit an alexandrite-like colour change.

Fig. 9 Garnets from the Umba Valley (Tanzania). These examples are composed of varying amounts of the three main components pyrope, almandine and spessartine. Often known in the trade as Malaia Garnets or Umbalites.

Fig. 10 Demantoid from the Urals (USSR). The original colour of the andradite is masked by green stemming from the small amount of uvarovite component. The "byssolite" (asbestos) fibres which are typical for demantoid garnets are easily distinguished.

component. More commonly, almandine-rich spessartines are encountered, which are coloured dark orange to reddish-brown by virtue of the almandine-content. Almandine-spessartines cannot be distinguished from pyrope-almandine solely on the basis of refractive index and density, and studies using the spectroscope have to be undertaken to recognize the higher spessartine-content, illustrated by the appearance of absorption bands at 432, 424 and 412 nm. Stones with a very high spessartine-content will display the weaker absorption lines at 573, 520, 504 and 480 nm, also due to manganese. In Fig. 7, the back row is composed of pure spessartine: they stem from the Taita Hills (Kenya) and the one with the octagonal step cut originates from Ramona, California (USA).

Spessartine often forms mixed crystals with pyrope, almandine and grossular. A peculiar phenomenon can be seen on rare occasions when spessartine-pyrope mixed crystals contain traces of vanadium. In blue-rich daylight, they appear blue- or olive-green, and in red-rich incandescent light they are purple or brownish-red. Thus, they exhibit a colour change (similar to the chrysoberyl variety alexandrite). Some examples of the stones described are shown in Fig. 8.

Pyralspite mixed crystals

Mixed garnets from the pyralspite group with small amounts of grossular occur in the Umba Valley in Tanzania. The orange to reddish-brown mixed crystals are mainly made up of pyrope (40–70%) and yellow spessartine (15–40%). Minor amounts of almandine (5–20%) supply the red component to the colour. These pyralspite garnets are known in the trade as **Malaia** or **Umbalite** garnets (Fig. 9).

Andradite and demantoid

Pure andradite is idiochromatically yellowish-green and exhibits strong dispersion, giving the name demantoid (diamond-like) to the mineral. Demantoids of gem quality were mined until the beginning of this century at a deposit in the Urals. This deposit is now exhausted and Russian demantoids are in high demand by collectors. The dispersion in some of these gems is masked by the emerald green colour. This allochromatic colouration stems from the small chromium-content or the uvarovite component (Fig. 10). Andradites from other localities are rather more yellowish and are usually known as topazolites.

Conclusions

Garnets form a fascinating mineral group, and supply us with gemstones of widely differing appearances. Transparent single crystals of all colours with the exception of pure blue are found and faceted. Most of these colours stem from the natural mixing of different types during crystallisation. A broad spectrum of colours is formed by the various combination possibilities of two or more of the differently coloured and colourless types. Polycrystalline aggregates (massive form) and stones with potential asterism can be used as cabochon material. An andradite-almandine type from Nevada (USA) actually exhibits a magnificent opal-like play of colours. Due to the large number of varieties, obvious nomenclatural problems occur. As colour is one of the main features of many gemstones, many names designate a definitive colour variety (rhodolite, tsavolite). The chromophore chemical elements often colour different garnet types in the same way. Thus, we often encounter different mineralogical types exhibiting the same colour. Chromium grossular, vanadium grossular and chromium demantoid clearly illustrate this point.

The correct identification of garnet mixed crystals requires, in many cases, a laborious and non-destructive chemical analysis to determine the quantities of the end-member components. Garnet nomenclature based on such analysis are mineralogically correct and **in agreement with the results obtained by gemmological identification techniques** (refractive index and density). In the case of a light orange Malaia garnet (or umbalite) composed of 45% pyrope, 35% spessartine, 11% almandine and 9% grossular, the designation "pyralspite garnet", or the name "spessartine-rich pyrope" are both correct. Unfortunately, these two terms give us no idea as to the colour, and the addition of a colour description would be helpful. The simplest and obviously correct designation is "orange-coloured garnet", but this term would also include similarly-coloured spessartines and hessonites.

A classification of garnets with due consideration to the gemmological instruments used in determination has recently been recommended by STOCKTON und MANSON (1985). The system allows a rational designation system to be used in classifying garnets.

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Suggested further reading

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