Nomenclature of the garnet supergroup

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ABSTRACT

The garnet supergroup includes all minerals isostructural with garnet regardless of what elements occupy the four atomic sites, i.e., the supergroup includes several chemical classes. There are presently 32 approved species, with an additional 5 possible species needing further study to be approved. The general formula for the garnet supergroup minerals is \{X\}_\phi\{Y\}_\psi\{Z\}_

INTRODUCTION

The garnets pose somewhat different nomenclature problems than other mineral supergroups recently considered for nomenclature review, i.e., sapphireine (Grew et al. 2008), apatite (Pasero et al. 2010), pyrochlore (Atencio et al. 2010), tourmaline (Henry et al. 2011), and amphibole (Hawthorne et al. 2012), where a supergroup is defined as “consisting of two or more groups that have essentially the same structure and composed of chemically similar elements” (Mills et al. 2009). Compared to the structures of the minerals in these groups, the archetypal garnet structure, cubic space group \textit{I}a\textit{3}d (no. 230) has few sites: only three cationic and one anionic (e.g., Menzer 1928; Novak and Gibbs 1971; Merli et al. 1995; Geiger 2008), and the most common garnets have relatively simple chemical compositions.

However, the garnet structure is remarkably flexible in a chemical sense: 53 elements were reported in the Inorganic Crystal Structure Database (Allmann and Hinek 2007) and five more are reported in synthetic garnets (Geller 1967; Ronniger and Mill’ 1973; Yudintsev 2003; Yudintsev et al. 2002; Utsunomiya et al. 2005). In the period 2009–2010, 10 new species of garnet, with constituents such as Sc, Y, Sn, Sb, and U, which have not been previously reported in significant quantities in natural garnet, were approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (Voting Proposal 11-D).

Keywords: Garnet group, schorlomite group, bitikleite group, berzeliite group, henritermierite group, katoite, nomenclature, crystal chemistry
Yakovlevskaya 1972; Strunz and Nickel 2001; Back and Mandarino 2008). However, there are minerals from other classes, such as arsenates, vanadates, oxides, and even fluorides that are isostructural with the silicate garnets, and whose major constituents show chemical similarities with constituents in silicate garnets, i.e., these minerals meet the criteria for inclusion in a broader entity, the garnet supergroup (Mills et al. 2009). McConnell (1942) introduced the term “garnetoid” to “designate those substances which are not primarily silicates but have structures similar to that of true garnets,” such as “hydrogarnet,” berzeliite and the phosphate graphite (Headden 1891). It does not appear that garnetoid was discredited as a group name (Clark 1993), but our preference is to use the term garnet for the supergroup.

Rinaldi (1978) showed that garnet is not isostructural with garnet, although he found that there are some structural features in common, which were also discussed by Sokolova and Hawthorne (2002), and thus garnet is not considered to be a garnet. In addition, the silicate mineral wadalite had been thought to be related to garnet because of similarities in cell dimensions and diffraction intensities (Feng et al. 1988; Tsukimura et al. 1993; Glasser 1995). Although wadalite lacks a center of symmetry, so that the single tetrahedral site found in grossular is split in wadalite into two sites, one of which is vacant, it still can be considered a derivative of grossular, but Glasser (1995) emphasized the much closer relationship of wadalite to mayenite. Recent crystal structure refinements make no mention of a relationship of wadalite or mayenite to garnet (Boysen et al. 2007; Iwata et al. 2008; Ma et al. 2011), and the structural relationship between garnet and wadalite (or mayenite) is sufficiently distant that these minerals are not included in the garnet supergroup. The so-called “tetragonal almandine-pyrope phase” (TAPP) has the stoichiometry, but not the structure of garnet (Harris et al. 1997; Finger and Conrad 2000), i.e., TAPP has edges shared between tetrahedra and octahedra, a feature not found in garnet (see below) and thus is not considered further in this report. Similarly, although some natural and synthetic arsenates of the alluaudite group, e.g., mayenite, are approximately polymorphous with the garnet supergroup mineral manganberzeliite (Ercit 1993; Khorari et al. 1995, 1997), the structures of alluaudite-group compounds are too different from garnet to warrant further consideration of the alluaudite group in this report.

Twenty-nine of the thirty-two approved species of the garnet supergroup are divided here into five groups on the basis of the total charge of cations at the tetrahedral site, leaving three ungrouped species to emphasize that the garnet supergroup comprises not only silicates (Figs. 1a, 1c, 1d, and 1e), but also a halide (Fig. 1b), hydroxides, oxides, vanadates, and arsenates (Fig. 1g). The groups are listed in order of increasing charge of cations that occupy the Z site of the end-members. Species within each group are listed as end-members with increasing atomic number of the Z site, followed by increasing atomic number of the X site, whereas species with joint occupancies at the Y site are placed last. Table 2 lists the 32 species as end-members in the same order and compares formulas given in the 2009 list (updated in 2012) of minerals approved by the CNMNC with the end-member formulas approved with the classification presented here.

Subdivision of the groups into mineral subgroups or mineral series is not recommended, as these terms should be reserved for homologous or polysomatic series (Mills et al. 2009). This restriction constitutes another rationale for discouraging the traditional division of the garnet group into the “pyralspite” and “ugrandite” species (Winchell 1933) or series (Strunz and Nickel 2001), although there could be some fundamental structural differences that limit solid solution between the two groupings (e.g., Ungaretti et al. 1995; Boiocchi et al. 2012; cf. Geiger 2008).

Our procedure for distinguishing species relies heavily on the dominant-valency rule, which is an extension of the dominant constituent rule (Hatert and Burke 2008). The latter rule states that species designation is based on the dominant constituent at a given crystallographic site, which works well when all constituents have the same valence. However, when ions at a given crystallographic site have different valences, it is essential that the dominant valence be determined first, and then species and group designation is determined by the dominant ion having this valence. Traditionally, identifying a garnet species has

<table>
<thead>
<tr>
<th>X charge</th>
<th>GROUP or species name</th>
<th>Class</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>ψ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Katoite</td>
<td>Hydroxide</td>
<td>Ca</td>
<td>Al</td>
<td>□</td>
<td>(OH)₂</td>
</tr>
<tr>
<td>3</td>
<td>Cryolithionite</td>
<td>Halide</td>
<td>Na</td>
<td>Al</td>
<td>Li</td>
<td>F₂</td>
</tr>
<tr>
<td>6</td>
<td>Yafouaneite</td>
<td>Oxide</td>
<td>Ca</td>
<td>Te⁴⁺</td>
<td>Zn</td>
<td>O₂</td>
</tr>
<tr>
<td>8</td>
<td>HENRITERMIERITE</td>
<td>Silicate</td>
<td>Ca</td>
<td>Al</td>
<td>Si₂⁺</td>
<td>O₂O₂</td>
</tr>
<tr>
<td>9</td>
<td>Holtsstamite</td>
<td>Oxide</td>
<td>Ca</td>
<td>Al</td>
<td>Mn⁺⁺</td>
<td>O₂O₂</td>
</tr>
<tr>
<td>10</td>
<td>SCHORLIMITE</td>
<td>Silicate</td>
<td>Ca</td>
<td>Zr</td>
<td>SiAlO₂</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Menerzite-(Y)</td>
<td>Silicate</td>
<td>Y, Ca</td>
<td>Mg</td>
<td>Si</td>
<td>O₂</td>
</tr>
</tbody>
</table>

Notes: Formulas are given in the form [X][Y][Z][ω⁺]. Group names are given in capitals.
The purpose of this report is to present the essential elements of garnet nomenclature, to define concepts that are central to garnet classification, and to provide practical guidelines for application of the nomenclature in distinguishing species. The nomenclature outlined in this report has been approved by the CNMN ( Voting proposal 11-D, April 3, 2012).

**Crystallographic and crystal-chemical aspects of garnet-supergroup minerals**

In the structure of cubic garnets (e.g., Menzer 1928; Novak and Gibbs 1971; Hawthorne 1981; Merli et al. 1995; Geiger 2008), space group *Ia3d* (no. 230), there are only four symmetrically unique atomic sites (not including hydrogen): dodecahedral {X1}, octahedral [Y], and tetrahedral (Z) cation sites, as well as an anionic site designated q: to indicate O, OH, and F, giving a generalized chemical formula for the garnet supergroup, {X1} [Y] (Z)q. (modified after Geller 1967). The three cation sites are at special positions fixed by symmetry, with the Wyckoff positions 24c, 16a, and 24d, respectively, whereas the anion site is located at a general position, 96h. The structure consists of alternating Zq5 tetrahedra and Yq5 octahedra, which share corners to form a three-dimensional framework (Fig. 2). Cavities enclosed in this framework have the form of triangular dodecahedra surrounding the X site (Novak and Gibbs 1971). Each anion is coordinated by one Z, one Y, and two X cations, resulting in a high percentage of shared edges between the dodecahedra on the one hand and the octahedra and tetrahedra on the other. However, the octahedra...
and tetrahedra do not share edges with each other (cf. TAPP: Harris et al. 1997; Finger and Conrad 2000).

In hydrous garnets, the major mechanism of hydroxyl incorporation is by the coupled substitution $4\text{H}^{+}\square \rightarrow \square^{+}\text{Si}$, i.e., the hydrogen ions occupy a separate site of general symmetry (Wyckoff position 96d) coordinated to O defining the tetrahedral site, which is vacant (e.g., Ferro et al. 2003; Lager et al. 1987, 1989). The hydrogen ions lie approximately on the faces of the tetrahedron of O around a vacant center, as do the deuterium ions shown in Figure 3. The O-H and O-D distances reported for minerals or their synthetic analogues range from 0.65 Å in synthetic deuterium katoite (X-ray diffraction, Lager et al. 1987) and 0.68 Å in natural katoite (X-ray diffraction, Sacerdoti and Passaglia 1985) to 0.75 Å in henritermierite (X-ray diffraction, Armbruster et al. 2001) to 0.904–0.95 Å in synthetic katoite (neutron diffraction, Lager et al. 1987; Cohen-Addad et al. 1967). Allowing that O-H and O-D distances obtained by X-ray diffraction are shorter than those obtained by neutron diffraction, Lager et al. (1987) concluded that the reported distances are consistent with isolated OH groups (lacking H-bonding) and assumed that the residual density located near oxygen can be attributed to the displaced (bonding) electron between O and H and not to the hydrogen itself.

However, compositional data, nuclear magnetic resonance (NMR) spectra, and infrared (IR) spectra have been cited as evidence for multiple H occupancy in grossular and garnets in the hydrotrogressive series. Cation vacancies at the X and Y sites calculated from electron microprobe analyses without direct determination of H$_2$O have been cited as evidence for the presence of H in these polyhedra, either without crystallographic data (Birkett and Trzcinski 1984), or in conjunction with single-crystal refinements of Ca, Al, Fe, and Si, whereas H could be located only in a few of the crystals studied and not quantified (Basso et al. 1984a, 1984b; Basso and Cabella 1990). Kalininchenko et al. (1987) interpreted NMR spectra obtained on a grossular to indicate 2H in the octahedra and 1H in the tetrahedra. In a comprehensive IR study of the hydrotrogressive series, Rossman and Aines (1991) reported that samples containing substantial H (>11.7 wt% H$_2$O equivalent to >5.43 OH per formula unit) gave spectra consistent with the substitution $4\text{H}^{+}\square \rightarrow \square^{+}\text{Si}$, whereas samples with much less H (<3.6 wt% H$_2$O, mostly <0.5 wt%) gave 7 different types of IR spectra, suggesting OH groups were present in multiple site environments, an inference supported by NMR spectra on three grossular samples (Cho and Rossman 1993). On the basis of Fourier-transform IR spectra, Eckhout et al. (2002) concluded that there is no evidence for a multisite OH substitution in spessartine-almandine garnets from Brazilian pegmatites, leaving the hydrogarnet substitution as the only proposed mechanism for the incorporation of H. In summary, garnet samples in which concentrations of H are too low to be studied by conventional X-ray and neutron diffraction techniques give conflicting and equivocal results, whereas H-rich samples in which H can be determined by these techniques give data consistent with $4\text{H}^{+}\square \rightarrow \square^{+}\text{Si}$. Consequently, for nomenclature purposes, we have assumed that H is incorporated exclusively by $4\text{H}^{+}\square \rightarrow \square^{+}\text{Si}$.

The symmetry of garnet is predominantly isometric, space group $Ia\overline{3}d$ (no. 230) but the two species in the henritermierite group have tetragonal symmetry $I4_1/acd$ (no. 142), and the X, Z, and $\varphi$ sites are split into more symmetrically unique sites, without altering the topology such that the idealized formula becomes $\text{Ca}_1\text{Z}_1\{\text{Ca}_2\}[[\text{Si}_1,\text{Y}_1](\square_1,\square_2)\text{O}_1,\text{Y}_2,(\text{O}_3\text{H})_4$, where $\text{R}^{3+} = \text{Mn}$ or Al. Armbruster et al. (2001) concluded that Jahn-Teller distortion resulting from Mn$^{3+}$ occupancy of Y and the arrangement of the hydroxyl tetrahedra are coupled, and together are responsible for the lowering to tetragonal symmetry in henritermierite. Moreover, stabilization of the Al-dominant analog holtstamite has been thought to require a minimum Mn$^{3+}$ content, which is estimated to be at least 0.2 Mn$^{3+}$ per formula unit (pfu). The amount reported in an isometric andradite (Armbruster 1995) and no more than 0.64 Mn$^{3+}$ pfu, the lowest amount found in holtstamite, i.e., between 10 and 32% of the henritermierite end-member must be present to stabilize the tetragonal form (Hålenius 2004; Hålenius et al. 2005). However, these arguments are not supported by a Si-deficient spessartine containing no Mn$^{3+}$, but showing $I4_1/acd$ symmetry attributed to (OH,F)$_4$ groups (Boiocchi et al. 2012).
implying symmetry lowering could have more than one cause.

In addition, there are numerous reports of natural garnets having orthorhombic, monoclinic, or triclinic symmetry, which have been attributed to crystal growth phenomena, multiple diffraction, strain, and/or cation ordering (e.g., Grifffen et al. 1992; McAlony and Hofmeister 1993; Armbruster and Geiger 1993; Rossmanith and Armbruster 1995; Hofmeister et al. 1998; Wildner and Andrut 2001; Shtukenberg et al. 2005; Frank-Kamenetskaya et al. 2007). As these structures have essentially the same topology, they are not regarded as separate species (Nickel and Grice 1998).

Table 3 gives the relative abundance of the generalized cations ($R^m$ with $n = 1–6$) and anions ($q^i$, $q^i$) at each of the sites reported in the $Fau$ structure, and presents the major cation and anion substitutions in natural garnets for each of the valence states of the ions. Table 4 summarizes significant heterovalent substitutions in natural garnet, as well as some chemical relations among species.

### Specific Nomenclature Issues in the Garnet Supergroup

Historical information on the 32 approved species of the garnet supergroup is summarized in Appendix 1. A more complete list of 715 synonyms, varietal, obsolete, and discredited names applied to minerals in the garnet supergroup since antiquity has been compiled in Appendix 2. This list includes the synonyms of current names that have been used in the mineralogical and gemological literature. In the following section, we discuss only those species in which there were problems or difficulties in their original characterization or where the name or formula has had to be significantly modified since the original description.

### Suffixes

With the exception of manganberzeliite (see below), up until 2009, garnets have been given new root names, without prefixes or suffixes. However, since 2009 five new names with suffixes have been approved by the CNMNC. For one of these, menzerte-Y, the suffix is a Levinson modifier for the rare earth elements (Levinson 1966), whereas the suffixes for the other four garnets identified the dominant tetravalent cation at the Y site, i.e., Sn vs. Zr in two bitikleite species [formerly bitikleite-(SnFe) and bitikleite-(ZrFe)] and elbrusite [formerly elbrusite-(Zr)], and the dominant trivalent cation at the Z site, i.e., Al vs. Fe [formerly bitikleite-(SnAl) and bitikleite-(ZrFe), Table 5]. In the present report we restrict the term “rare earth elements” to the elements from La to Lu (atomic numbers 57–71) and Y (atomic number 39) as defined by Levinson (1966), rather than calling La-Lu “lanthanoids” and including Sc as well as Y in the rare earth elements as recommended by the International Union of Pure and Applied Chemistry. With the exception of the Levinson modifiers for the rare earth elements, e.g., menzerte-Y, the application of suffixes results in unnecessary complexity in the nomenclature and could lead to confusion as further new species.

### Table 3. Relative site abundances of cations and anions in garnet-supergroup minerals

<table>
<thead>
<tr>
<th>Site</th>
<th>Relative abundance of ions</th>
<th>Cations and anions at each site in order of relative abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>$R^{m+} &gt;&gt; R^{n+} &gt; R^{n+} &gt; R^{n+}$</td>
<td>$R^{m+}$: Fe $-$ Mn $-$ Ca $-$ Mg $&gt;$ Pb $&gt;$ Na $&gt;$ Th $&gt;$ F</td>
</tr>
<tr>
<td>Y</td>
<td>$R^{m+} &gt; R^{m+} &gt; R^{n+} &gt; R^{n+}$</td>
<td>$R^{m+}$: Al $-$ Fe $&gt;$ V $-$ Cr $-$ Mn $&gt;$ Sc $&gt;$ Ga $&gt;$ Fe $&gt;$ Mn $&gt;$ Zr $&gt;$ Ti $&gt;$ Si $&gt;$ Sn</td>
</tr>
<tr>
<td>Z</td>
<td>$R^{m+} &gt; R^{n+} &gt; R^{n+} &gt; R^{1+}$</td>
<td>$R^{n+}$: Si $&gt;$ Ti $&gt;$ Ge $&gt;$ Sn $&gt;$ Pb $&gt;$ Fe $&gt;$ Mn</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>q$^i$</th>
<th>$q^i$ $&gt;$ $q^i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q^i$</td>
<td>$O$</td>
</tr>
<tr>
<td>$q^i$</td>
<td>OH $&gt;$ F</td>
</tr>
</tbody>
</table>

Notes: The cations and anions shown in bold type represent the most common ions at these sites. HREE and LREE are heavy and light rare-earth elements, respectively, excluding Y.

### Table 4. Significant garnet coupled heterovalent substitutions

<table>
<thead>
<tr>
<th>Generalized coupled substitution</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Box + 4q^i \rightarrow 5Si + 4O^+$</td>
<td>relates katoite, henritmerite and holstamite to OH-free minerals in the garnet group</td>
</tr>
<tr>
<td>$R^{m+} + R^{n+} \rightarrow 2R^{n+}$</td>
<td>relates morimotoite ($\text{Ti}^{IV}$) and majorite ($\text{Si}^{IV}$) to other garnet-group minerals</td>
</tr>
<tr>
<td>$\text{Y}$(REE)$^3+ + 3R^{n+} \rightarrow R^{n+} + 3R^{n+}$</td>
<td>relates the schorlomite group to the garnet group</td>
</tr>
</tbody>
</table>
| $\text{i}(Y, 
REE)^{3+} + 3R^{n+} \rightarrow 2R^{n+} + 3R^{n+}$ | introduces Y + REE as a YAG, [Y$(Y,\text{Al})_2$]$\text{O}_3$-type component |
| $\text{i}(Y, 
REE)^{3+} + 3Na^+ \rightarrow 2R^{n+}$ | introduces Y + REE into garnet-group minerals |
| $\text{i}(Y, 
REE)^{3+} + 3R^{n+} \rightarrow 2R^{n+} + 3R^{n+}$ | relates menzerte-Y to other garnet-group minerals |
| $R^{m+} + R^{n+} \rightarrow R^{n+} + 3R^{n+}$ | relates bitikleite, dzhuluite and usturite with schorlomite-group minerals |
| $0.5R^{m+} + R^{n+} \rightarrow 0.5R^{n+} + 2R^{n+}$ | relates elbrusite with schorlomite-group minerals |
| $0.5R^{m+} + R^{n+} \rightarrow 0.5R^{n+} + 2R^{n+}$ | observed relationship between elbrusite and schorlomite group minerals (Fig. 4) |
| $0.5Th^{IV} + R^{n+} \rightarrow 0.5R^{n+} + 2R^{n+}$ | introduces Th into minerals of the bitikleite and schorlomite groups |
| $R^{m+} + 0.5V^{IV} \rightarrow 0.5R^{n+} + 0.5Sb^{IV}$ | introduces V into bitikleite |
| $R^{m+} + 0.5V^{IV} \rightarrow 0.5U^{IV} + 0.5R^{n+}$ | introduces V into elbrusite |
| $Na^+ + 3R^{n+} \rightarrow 3R^{n+} + R^{n+}$ | introduces Na and Si or Ti into the garnet group |
| $Na^+ + 3R^{n+} \rightarrow 3R^{n+} + R^{n+}$ | relates the berzeliite group to the garnet group |

Note: $R$ represents generalized cations (see Table 3).
cies are discovered. Consequently, we recommend that suffixes (except Levinson modifiers for the REE) not be used for names of minerals in the garnet supergroup. Moreover, as the four garnets with suffixes, which are not Levinson modifiers, have only recently been described and are not entrenched in the literature, we have given these garnets new names without suffixes. This renaming has been approved by the CNMNC as part of the overall nomenclature (Table 5). The etymology of the new names can also be found in Appendix 1.

**“Hydrogarnets”**

The nomenclature of naturally occurring garnet containing substantial amounts of the hydroxyl ion has had a complex history (e.g., Pertlik 2003). Many of these garnets have compositions intermediate between grossular (x = 0) and katoite (x = 3), i.e., \( \{\text{Ca}_6\}[\text{Al}_3\text{Si}_3\text{O}_{12}\cdot3\text{OH}_6\}\), where \( 0 < x < 3 \) and \( \square \) is vacancy. For the majority of these garnets, \( x < 1.5 \) (e.g., Passaglia and Rinaldi 1984). “Hibschite” was approved by the then Commission on New Minerals and Mineral Names (CNMMN, the predecessor of the CNMNC) as a name for OH-bearing grossular with \( x < 1.5 \) (Dunn et al. 1985) because “hibschite” had priority (Cornu 1905, 1906) over “plazolite” (Foshag 1920) and “hydrogrossular” (Hutton 1943). However, “hibschite” is not distinct from grossular according to the dominant-constituent rule, i.e., Si > \( \square \) at the Z site, therefore “hibschite” is discredited in favor of grossular (Table 5). Dunn et al. (1985) allowed that “the name hydrogrossular may still be applied to members of the series with appreciable OH content but undetermined SiO\text{\textsubscript{4}}/(OH)\text{\textsubscript{4}} ratio.”

Several names have also been used describe the OH-bearing garnets considered together, including the “gossularoid group” (Belyankin and Petrov 1941) and the “hydrogarnet series” (Flint et al. 1941). Dunn et al. (1985) implied that the term “hydrogros- sular group” and “hydrogrossular series” would be acceptable for compositions along the grossular katoite join, but in our classification the binary would no longer qualify as a group, whereas the term “series” has a more restrictive meaning than a simple binary solid solution (Mills et al. 2009; see above).

The tetragonal hydroxy-bearing garnets henritermierite and holtstamite (Fig. 1a) are considered to constitute a distinct group because of their lower symmetry and because one tetra- hedral site is largely vacant, i.e., \( \square > \text{Si} \) at one of the two sites corresponding to Z in the archetypal garnet structure (Aubry et al. 1969; Arnbruster et al. 2001; Hälenius et al. 2005). Optical determinations are sufficient to distinguish this group from members of the garnet group, and crystal structure determina- tions are not necessary. Holtstamite is uniaxial and shows a high (0.030) birefringence. In contrast birefringent grossular garnets are normally biaxial (as a consequence of symmetry lowering to orthorhombic, monoclinic, or triclinic symmetries) and show low to moderate (0.001 – 0.010) birefringence (Shtukenberg et al. 2001, 2005), although birefringence as high as 0.015 has been observed for compositions with considerable andradite component. In addition, the powder XRD pattern for holtstamite and grossular are distinct because they show different d-spacings for their respective 5 strongest reflections. Henritermierite and holtstamite are distinguished from each other on the basis of the dominant cation at the Y site, respectively Mn\textsuperscript{3+} and Al.

**Elbrusite**

Elbrusite was originally described as “elbrusite-(Zr)” with the formula \( \{\text{Ca}_6\}[\text{U}^\text{VI}\text{Zr}][\text{Fe}^\text{3+}\text{Fe}^\text{2+}]\text{O}_{12}\) (Table 2 from Galuskina et al. 2010a). Determination of the site occupancies and valence states was hampered by its metamict state, which was nearly complete in elbrusite containing 24 wt% UO\text{2} (0.62 U per formula unit) and well advanced in U-rich kerimasite (Fe-dominant analog of kimzeyite in the original description) (15–17 wt% UO\text{2}, 0.37–0.42 U pfu); single-crystal X-ray diffraction was only practical for kerimasite containing 9 wt% UO\text{2} (0.21 U pfu) (Galuskina et al. 2010a). The authors noted that a Raman band below 700 cm\textsuperscript{-1} could indicate the presence of some Fe\textsuperscript{3+} in elbrusite, but the only evidence for U being hexavalent is the association with vorlanite, CaU\textsuperscript{VI}O\text{6}, for which the hexavalent state of U could be determined (Galuskina et al. 2011a).

The composition \( \{\text{Ca}_6\}[\text{U}^\text{VI}\text{Zr}][\text{Fe}^\text{3+}\text{Fe}^\text{2+}]\text{O}_{12}\) is not a valid end-member because more than one site has two occupants (Hawthorne 2002). Instead, it can be considered as the sum of two valid end-members, \( \frac{2}{3}\{\text{Ca}_6\} [\text{U}^\text{VI}\text{Zr}_3] [\text{Fe}^\text{3+}] [\text{Fe}^\text{2+}] \text{O}_{12} + \frac{1}{3}\{\text{Ca}_6\} [\text{U}^\text{VI}] [\text{Fe}^\text{2+}] \text{O}_{12} \) (Fig. 4). Compositions of elbrusite and U-rich kerimasite plot in a linear trend in terms of U and the sum of tetravalent cations between the composition representing kerimasite, \( \{\text{Ca}_6\} [\text{Zr}_2] [\text{Fe}^\text{3+}\text{Fe}^\text{2+}] \text{O}_{12} \) and \( \{\text{Ca}_6\} [\text{U}^\text{VI}] [\text{Fe}^\text{2+}] \text{O}_{12} \) (Fig. 4). The trend is very close to the substitution mechanism \( U^\text{VI} + \text{Fe}^\text{2+} = 2\text{R}^\text{III} \), and thus is consistent with the interpretation by Galuskina et al. (2010a) that U is hexavalent and Fe\textsuperscript{2+} is present. Moreover, the compositions that Galuskina et al. (2010a) identified as elbrusite and kerimasite plot in the fields for \( \{\text{Ca}_6\} [\text{U}^\text{VI}] [\text{Fe}^\text{2+}] \text{O}_{12} \) and \( \{\text{Ca}_6\} [\text{U}^\text{VI}] [\text{Fe}^\text{2+}] \text{O}_{12} \), respectively, requiring no revision of their species identifications if \( \{\text{Ca}_6\} [\text{U}^\text{VI}\text{Zr}_3] [\text{Fe}^\text{2+}] \text{O}_{12} \) is considered to be the end-member of elbrusite. Therefore \( \{\text{Ca}_6\} [\text{U}^\text{VI}\text{Zr}_3] [\text{Fe}^\text{2+}] \text{O}_{12} \) should now be used as the elbrusite end-member formula.

Yudintsev (2001) and Yudintsev et al. (2002) reported a U-rich garnet, one of three compounds synthesized in corundum crucibles from a \( \{\text{Ca}_3\} [\text{UO}_2\text{Zr}_2] \text{Fe}_2\text{O}_6 \) bulk composition at 1400°C in air: \( \{\text{Ca}_3\} [\text{Zr}_2\text{Fe}_2\text{O}_6\text{Al}_2\text{O}_3] [\text{Fe}^\text{3+}\text{Al}_2\text{O}_3] \text{O}_{12} \), whereas Utsonomiya et al. (2002) reported synthesis of a U-rich garnet with a slightly different composition, \( \{\text{Ca}_3\} [\text{UO}_2\text{Zr}_2] \text{Fe}_2\text{O}_6 \) (Fe\textsuperscript{3+}Al\textsubscript{2}O\textsubscript{5})O\textsubscript{12}, under unspecified conditions, but presumably similar. Uranium is largely tetravalent in the starting material, and despite having been heated in a relatively oxidizing environment, was assumed by Yudintsev (2001) to have remained mostly tetravalent in the garnet because of its association with cubic oxide with the fluorite structure typical of U\textsuperscript{4+}. However, charge balance requires that 72–81% of the U be hexavalent in the two synthetic garnets. If U is assumed to be tetravalent at the X site and hexavalent at the Y site, a distribution consistent with the relative sizes of the two U ions, the two formulas give 11.754 and 12.030 positive charges, respectively. The formula of the garnet synthesized by Utsonomiya et al. (2002) is very close to the proposed elbrusite end-member (Fig. 4), and thus provides support for use of this end-member for elbrusite.

**Ti-rich garnets: Schorlomite and morimotoite**

The site occupancies of Ti-rich garnets have been the subject of considerable controversy despite being extensively studied using a diverse arsenal of spectroscopic techniques as well
as X-ray diffraction (e.g., Chakhmouradian and McCammon 2005). The two species currently accepted by the CNMNC are schorlomite, Ca$_2$(Ti,Fe$^{2+}$)$_3$(Si,Fe$^{3+}$)$_2$O$_{12}$, and morimotoite, Ca$_6$(Ti,Fe$^{2+}$,Fe$^{3+}$)$_2$(Si,Fe$^{3+}$)$_2$O$_{12}$ (Table 2). These formulas, which are listed as approved by the CNMNC, are too generalized to indicate what the distinction is between the two species, and clearly new formulas based on end-members are needed.

Schorlomite (Fig. 1f) was first described and named by Shepard (1846), who reported it to be a hydrous silicate containing Y, Fe, and possibly Th from Magnet Cove, Arkansas, U.S.A. However, Whitney (1849) and Rammelsberg (1850a, 1850b) showed schorlomite to be a silicate of Ca, Fe, and Ti, reporting compositions approaching those obtained by modern techniques. Chemical data obtained subsequently of Ti-bearing andradite, often called by the varietal name “melanite,” showed that TiO$_2$ content ranged continuously from 0 to 19 wt%, whereas Labotka (1995) reported immiscibility at one locality. Grapes et al. (1979) and Laverne et al. (2006) reported up to 30 wt% TiO$_2$ in garnets having anomalous compositions, which will be discussed separately below. Chakhmouradian and McCammon (2005) summarized the criteria proposed by various authors for distinguishing schorlomite from Ti-bearing andradite; among the most frequently used have been Ti > Fe$^{3+}$ (Ito and Frondel 1967a; Deer et al. 1982), approximately the same as TiO$_2$ > 15 wt% (Zedlitz 1933) and about twice the minimum Ti content suggested by Howie and Woolley (1968). Chakhmouradian and McCammon (2005) recommended that the proportion of schorlomite be determined as the amount of Ti, balanced by substitutions at the Z site, relative to the total occupancy in the Y site, (Ti–Fe$^{2+}$–Mg–Na)/2, i.e., deducting a morimotoite component (see below) together with a contribution from a hypothetical [Na$_2$Ca$_2$][Ti$_2$][Si$_2$]O$_{12}$ component. Several end-member formulas have been proposed for schorlomite, e.g., [Ca$_2$][Ti$_2$](Fe$^{3+}$Si)O$_{12}$ (Ito and Frondel 1967a) and [Ca$_2$][Ti$_2$](Fe$^{2+}$)TiO$_{12}$ (Rickwood 1968), whereas Chakhmouradian and McCammon (2005) argued that the crystal chemistry was too complex to be represented by a single end-member, and proposed a generalized formula instead, \{Ca$_3$\}[Ti$_2$][Si$_3$]Fe$^{2+}$,Al,Fe$^{3+}$]O$_{12}$.

MORIMOTOITE was introduced by Henmi et al. (1995) with an end-member formula Ca$_3$TiFe$^{2+}$Si$_2$O$_{12}$, based entirely on electron-microprobe data of garnet containing nearly 20 wt% TiO$_2$ from Fuka, Okayama Prefecture, Japan. Formulas that we recalculated assuming 8 cations and 12 O anions from three analyses in Henmi et al. (1995), including the one designated as type, gave 1–8% andradite, \{Ca$_3$[Fe$^{2+}]$Si$_2$O$_{12}$, 27–34% \{Ca$_3$[Ti$_2$]Fe$^{2+}$Si$_2$O$_{12}$, and 58–71% \{Ca$_3$[TiFe$^{3+}$]Si$_2$O$_{12}$ with minor Zr, Mg, Mn, and Al included with Ti, Fe$^{2+}$, Ca, and Fe$^{3+}$ according to valence. Garnets synthesized by Henmi et al. (1995) under reducing conditions (iron-wüstite buffer) have compositions very similar to the natural material; end-member morimotoite could not be synthesized. However, no structural or spectroscopic data were obtained to confirm the assumed site occupancies and calculated Fe valence, and thus the report raised objections. Fehr and Amthauer (1996) and Rass (1997) questioned the assumption that Ti was all Ti$^{4+}$. The latter authors also dismissed the infrared evidence that Henmi et al. (1995) used to justify their conclusion that OH was absent, and cited experiments by Kühlberger et al. (1989) that OH is likely to be present in morimotoite. Their conclusion is supported by the report by Armbruster et al. (1998) that the morimotoite substitution, Fe$^{2+}$+Ti$^{4+}$ → 2Fe$^{3+}$ at the Y site is coupled with 4OH → SiO$_4^{2-}$ at the tetrahedral site in Ti-bearing andradite.

Despite the variety of methods deployed to locate cations in the structure of Ti-rich garnets, authors have yet to reach a consensus, which reflects not only differing interpretations of the spectroscopic and structural data, but probably also variation between samples. Nonetheless, the question confronting us is whether we can still propose a meaningful classification based on formulas calculated from a full electron microprobe analysis assuming 8 cations and 12 oxygen anions. There is little disagreement on the occupancy of the X site, which with rare exception contains at least 2.7 (Ca+Na) atoms per formula unit (apfu), to which are added sufficient Mn and Mg to bring total X site occupancy to 3, but fewer authors (e.g., Chakhmou-
sition that Ti$^{4+}$ plays a negligible role in natural terrestrial garnet, although it could be significant constituent in some meteoritic garnet (e.g., Ma 2012).

As regards the location of Ti, Armbruster et al. (1998) located Ti at Z as well as Y, but most authors place Ti only at Y, which seems reasonable in the relatively Si-rich and Ti-rich garnets (Si > 2 apfu) because of the rarity of Si = Ti substitution at tetrahedral sites (Hartman 1969). Nonetheless, combined low pressure and high temperature could favor Ti substitution for Si at a tetrahedral site as it does in lamproitic richterite (Oberti et al. 1992). The most robust element-specific technique, XANES, yields results consistent with the bulk of Ti occupying the octahedral sites in most natural garnets (Waychunas 1987; Locock et al. 1995). Significant Ti may occupy the Z site in Si-poor garnets such as elbrusite and bitlitkeite (e.g., Galuska et al. 2010a, 2010b), and its presence has been demonstrated in Si-free synthetic garnets (Pavernykh and Shabalin 1983; Cartie et al. 1992; Yamane and Kawano 2011). Another question is the possible presence of tetrahedrally coordinated Fe$^{2+}$. Some studies reported Mössbauer spectroscopic evidence for significant Fe$^{2+}$ at the Z site (e.g., Locock et al. 1995; Koritnig et al. 1978), but the spectroscopic data do not always give unequivocal site assignments (Chakhmouradian and McCammon 2005). Last, there is the role of the hydroxyl ion; ignoring hydroxyl results in an underestimate of Fe$^{2+}$ in the formulas calculated by the method of Droop (1987). However, the effect would be serious only if >0.4 wt% H$_2$O were present, in which case at least 0.1 Fe$^{2+}$ per formula unit would not show up in the calculated formula unless OH were included in the formula calculation, i.e., (OH)+O = 12 and \( \Sigma \{X\} + \Sigma \{Y\} + \Sigma (Z) + \sum_{0(014)} + \sum_{0(014)} + \sum_{1(04)} = 8 \), or if Fe present, O+(OH)+Fe = 12 and \( \Sigma \{X\} + \Sigma \{Y\} + \Sigma (Z) + \sum_{0(014)} + \sum_{0(014)} + \sum_{1(04)} = 8 \). The few analyses available in the recent comprehensive studies give 0.02–0.21 wt% H$_2$O for natural Ti-rich garnets with >12 wt% TiO$_2$ (Kühberger et al. 1989; Locock et al. 1995; Amthauer and Rossman 1998; Chakhmouradian and McCammon 2005). An exception is “hydroschorlomite” with 5 wt% H$_2$O (Galuskin 2005); such H$_2$O-rich garnets cannot be treated in the approach discussed below.

To identify end-member formulas for the two Ti-rich garnet species schorlomite and morimotoite, we should compare the results from as many studies as possible, which necessitate our relying on chemical data. Few authors have supplemented chemical data with structure refinements using X-ray diffraction and with spectroscopic methods to determine site occupancy, and thus we think that reliance on chemical data is the most consistent approach for treating compositional data from different studies. In addition, we have made the following assumptions in treating the chemical data.

1. Ti is Ti$^{4+}$ and preferentially occupies the Y site, which rules out the end-member \( \{Ca_3\} [Ti_2] (TiFe^{2+}) O_{12} \) proposed by Rickwood (1968).

2. H$_2$O content is ≤0.2 wt%.

3. Site occupancies are estimated using formulas calculated for 8 cations and 12 oxygen anions and the procedure outlined in the next section (see below).

Figure 5 is a plot of Y-site compositions for garnets containing >12 wt% TiO$_2$ and Ti > Zr apfu in terms of the following generalized end-members \( \{Ca_3\} [R^{4+}] (SiAl) O_{12} \), \( \{Ca_3\} [R^{4+}] (SiFe^{2+}) O_{12} \), and \( \{Ca_3\} [R^{4+}] (SiFe^{2+}) O_{12} \). For R$^{4+}$ = Ti, R$^{4+}$ = Fe$^{3+}$, and R$^{4+}$ = Fe$^{2+}$, these generalized end-members correspond, respectively, to andradite, the schorlomite end-member of Ito and Frondel (1967a), and the morimotoite end-member of Henmi et al. (1995), i.e., the same components plotted by Henmi et al. (1995, their Fig. 1). It turns out that 15 wt% TiO$_2$, which Zedlitz (1933) suggested as a cutoff for schorlomite, is a good estimate of the minimum TiO$_2$ content of compositions plotting in the morimotoite and schorlomite fields unless significant Zr is present.

Three reports of garnets reported to contain over 20 wt% TiO$_2$ have not been plotted in Figure 5 either because of their high-H$_2$O content or because of their questionable identity as garnet. Galuska and Galuskin (unpublished data) were able to confirm the identity of an OH-bearing schorlomite in a xenolith from the upper Chegem caldera, northern Caucasus by Raman spectroscopy. Analyses of the cores of two honey-colored crystals about 30 µm across enclosed in grossular-katoite give 12.61–13.75 wt% SiO$_2$, 25.42–25.86 wt% TiO$_2$, 0.41–0.49 wt% SmO$_2$, 2.20–2.28 wt% Al$_2$O$_3$, 24.86–26.09 wt% Fe as FeO$^{2+}$, 31.03–31.71 wt% CaO, ≤ 0.03 wt% MgO, and 0.27 to 1.2 wt% H$_2$O (calculated); Mn, Cr, Zr, Nb, V, Ce, La, Na, F, and Cl were below the detection limit. These data correspond approximately to 73–76% \( \{Ca_3\} [Ti^{4+}] (SiFe^{2+}) O_{12} \), the highest proportion of the schorlomite end-member reported in a natural garnet, 12–13% \( \{Ca_3\} [Ti^{4+}] (SiAl) O_{12} \) and 12–14% andradite plus its OH analog. Grapes et al. (1979) reported an electron microprobe analysis of a garnet from Morotou, Sakhalin Island, Russia, containing 27.38 wt% TiO$_2$ and 33.50 wt% Fe as FeO, but deficient in Si and Ca with the formula: \( \{Ca_{51}Fe_{14}Mn_{01}Mg_{06}\} [Ti_{12}Fe^{3+}_{07}Mg_{08}] O_{12} \). (Si$_{14}Al_{06}Fe^{3+}_{03}Al_{08}) O_{12} \), i.e., a morimotoite from site occupancies, but anomalous because so much Ti (or Fe$^{2+}$) is forced by the formula calculation onto the Z site. A possible explanation for the high-Fe and Ti contents is X-ray fluorescence from contiguous phases (Chakhmouradian and McCammon 2005). In a study of altered basalt from the equatorial east Pacific, Laverne et al. (2006) described a “hydroschorlomite” with 22.0–28.6 wt% TiO$_2$, 6.2–12.9 wt% Fe as FeO and 22.5–26.5% wt% CaO. Laverne et al. (2006) tried to correct for celadonite impurities, which were manifested by the presence of ≤1 wt% K$_2$O in the analyses. The study included SEM and TEM, as well as micro-Raman spectra, but none provided corroborative evidence that the mineral was indeed a garnet; the reported compositions suggest the mineral could be titanite.

Three analyses, including the holotype, from the type locality of morimotoite in Fuka, Japan, plot in the morimotoite field and show that Ti and Fe$^{2+}$ are the dominant R$^{4+}$ and R$^{2+}$ cations at Y if we assume that Ti and Fe$^{2+}$ do not occupy the Z site, whereas four of the five analyses of garnet from the type locality of schorlomite at Magnet Cove, U.S.A., plot in the schorlomite field and show that Ti is the dominant R$^{4+}$ cation, and Fe$^{3+}$ is the dominant R$^{3+}$ cation. The latter situation holds even if Al is assumed to preferentially occupy the Z site (e.g., Chakhmouradian and McCammon 2005), which is not supported by all studies (e.g., Locock et al. 1995; Armbruster et al. 1998). Thus, we recommend that \( \{Ca_3\} [Ti^{4+}Fe^{3+}] (SiAl) O_{12} \) and \( \{Ca_3\} [Ti^{4+}SiFe^{2+}] O_{12} \) be the end-member formulas for morimotoite and schorlomite, respectively. Despite the assumptions and simplifications discussed above,
we believe that Figure 5 can be used to distinguish schorlomite and morimotoite in the absence of structural and spectroscopic studies if allowance is made for the uncertainties in attempting to identify borderline cases.

Figure 5 shows that many garnets reported as schorlomite plot in the morimotoite and andradite fields; garnets plotting in the schorlomite field other than those from Magnet Cove are from Ardnamurchan, Scotland (Huggins et al. 1977), the Tamazeght complex, Morocco (Marks et al. 2008), the Polino carbonatite, Italy (Lupini et al. 1992), and Alnö Island, Sweden (von Eckermann 1974). The dominant $R^{3+}$ cation in these garnets is Fe$^{3+}$, even if Al is assumed to preferentially occupy the Z site. Using the above assumptions, garnets plotting in the morimotoite field (with Fe$^{3+}$ > Mg at the Y site) are from Iivaara, Finland (Zedlitz 1935), Afrikanda, Russia (Chakhmouradian and McCammon 2005), Ice River, Canada (Locock et al. 1995; Peterson et al. 1995), Sung Valley, India (Melluso et al. 2010), and Rusing Island, Kenya (Howie and Woolley 1968). However, Mössbauer spectroscopy of the Ice River garnet indicates that a significant proportion of the Fe$^{3+}$ is located at the Z site and dominance of [(Ti,Zr)$_2$] over [(Ti,Zr)R$^{3+}$] at Y, so Locock et al. (1995) and Peterson et al. (1995) had reason to call this garnet schorlomite. Two relatively Zr-rich garnets from the Marathon Dikes, Ontario, Canada (Platt and Mitchell 1979), also plot in the morimotoite field, but are unique in that total Mg > Fe$^{3+}_{\text{total}}$ (circled in Fig. 5) suggesting the possibility of a Mg-dominant analog of morimotoite (see the section on Possible new species and compositional variations in natural garnet).

All the analyses plotted in Figure 5 have Si $> 2$ and total charge at Z $> 11$, i.e., all the garnets would be classed as garnet group, including compositions of schorlomite from the type locality (e.g., Appendix 3). This contradiction arises because the compositions include more garnet-group components, largely andradite, [Ca$_3$](R$^{3+}$) (Si$_{10-n}$)O$_{2n+2}$, and morimotoite, [Ca$_3$]$(R^{3+})_{2}$ (Si$_{10-n}$)O$_{2n+2}$, than schorlomite-group components, largely, [Ca$_3$] $(R^{3+})_{2}$ (Si$_{10-n}$)O$_{2n+2}$.

Menzerite-(Y)

The validity of menzerite-(Y) has been questioned because the end-member formula proposed for menzerite-(Y), [Y$_2$Ca$_4$]$\text{[Mg}_3$]$(\text{SiO})$O$_{12}$, is quite far from the measured compositions of the type and only known material, which averages much closer to [Y$_2$(Ca,Fe$^{3+}$)$_2$]$_{}$[(Mg,Fe$^{3+}$)Fe$^{2+}$,Al]$_{(\text{SiO})}O_{12}$, an empirical formula that can be simplified to [Y$_2$Ca$_4$]$_{}$[(Mg,Fe$^{3+}$)$(\text{SiO})$O$_{12}$]. This simplified formula is not a valid end-member because it has two sites with two occupants (Hawthorne 2002). Instead, it can be resolved into an equal mixture of [Y$_2$Ca$_4$]$_{}$[(Mg,Fe$^{3+}$)SiO$_{12}$]$_{}$[menzerite-(Y)] and [Ca$_3$]$_{}$[Fe$^{2+}$]$^{(\text{SiO})}O_{12}$$_{}$ (andradite). Type menzerite-(Y) compositions are close to the midpoint between these two end-members, but in two grains divalent cations are dominant at the Y site and Mg is the dominant divalent cation at this site (e.g., Appendices 3 and 4), confirming that menzerite-(Y) is a valid species (Grew et al. 2010). Of course, this approach depends on the accuracy of the electron microprobe analyses and calculation of Fe$^{3+}$/Fe$^{2+}$.
A second argument forwarded to challenge the validity of menzerite-(Y) is that trivalent cations, i.e., Y+REE, are not dominant at the X site in any of the analyzed menzerite-(Y) grains, the maximum being 1.1 Y+REE per formula unit. Simple application of the dominant-valency rule gives [{Ca}1]{Mg3}{Si12}O12, which is not balanced in charge. Charge balance allows only 2 (Y+REE) per formula unit, i.e., the menzerite end-member should be {Y3Ca}{Mg3}{Si12}O12. The presence of >1 (Y+REE) means that [{Y3REE}Ca] exceeds 50% of the maximum possible consistent with valency-imposed double site-occupancy.

Rates of diffusion of Y and REE in garnet provide evidence for the importance of the menzerite component in garnet, i.e., mobility of Y and REE at the X site is closely linked to mobility of Al at the Y site (Carlson 2012).

Majorite

The current list of CNMNC approved minerals (http://pub- sites.uws.edu.au/ima-cnmnc/) gives the formula for majorite as Mg3{Fe2+Si}3{Si12}O12 (Table 2), equivalent to [{Mg}3{SiFe2+}3]{Si12}O12, which indeed is a good approximation of the empirical formula of the type material reported by Smith and Mason (1970), (MgNa)3{Fe3SiAlCr}3{Si12}O12. It was assumed that Fe occupied the Y site, but the valence and distribution of the Fe were not determined. Recalculating a formula for 8 cations and 12 oxygen anions from the published analysis and listing cations at a given site in order of decreasing abundance gives: {Mg5.9{Na0.09}}[{Si10.5Fe0.07Fe0.54Al0.22Cr0.04Mg0.02}]{Si12}O12

However, the assumption regarding Fe2+ occupancy is not supported by Mössbauer spectroscopic data on synthetic majorite (Geiger et al. 1991a, 1991b; O’Neill et al. 1993a, 1993b; McCammon and Ross 2003). In a study that included samples that Geiger et al. (1991a, 1991b) and O’Neill et al. (1993a, 1993b) had investigated, McCammon and Ross (2003) reported that Fe2+/2Fe2+ = 0.89–0.95, and Fe2+/Fe3+ + Mg at X (0.05–0.22) is three to seven times Fe2+/Fe3+ + Mg at Y (0.01–0.08) in 15 synthetic tetragonal majorite samples, and Fe2+/2Fe2+ = 1.0 in one isomorphous synthetic sample, demonstrating that Fe2+ is strongly fractionated onto the X site. Because the compositions of the type specimen and these synthetic samples are similar, we think it is reasonable to assume that Fe distribution is the same in synthetic and natural majorite, and the partial ordering at the X and Y sites in tetragonal samples does not significantly affect the Fe distribution. Assuming that Fe2+ occupies only the X site, the formula of the type material becomes {Mg5.9{Fe0.07Na0.09}}[{Si10.5Fe0.07Fe0.54Al0.22Cr0.04}]{Si12}O12, i.e., the dominant component is [{Mg}3{SiMg}]{Si12}O12. Consequently, we recommend that [{Mg}3{SiMg}]{Si12}O12 be used as the end-member formula for majorite. A natural Fe2+ analog has not been reported, and as far as we are aware, it has not been synthesized (e.g., Kato 1986).

Although synthetic majorite has tetragonal symmetry (space group I41/a, n. 88) resulting from a high degree of ordering of Mg and Si at the two symmetrically unique octahedral sites (e.g., Angel et al. 1989), no naturally occurring tetragonal majorite has been reported. Apparently, majorite in shocked meteorites was quenched with sufficient rapidity to preserve cubic symmetry (Tomoka et al. 2002). The problem of preserving cubic symmetry on cooling would probably not arise in terrestrial majorite, which contains substantial Al, because incorporation of Al at the Y site is thought to stabilize the cubic structure (Hatch and Ghose 1989). Moore and Gurney (1985) confirmed isometric symmetry for garnet from the Monastery Mine kimberlite pipe, South Africa, one of which we calculated to contain 36% of a generalized majorite component, {R3+3}{MgSi}3{Si12}O12.

The term “majoritic” has found wide use in the literature on garnets included in diamond (e.g., Harte 2010; Collerson et al. 2010), i.e., garnet is described as “majoritic” if Si is incorporated at the Y site through the “majorite” substitution {R3+3}Si → 2Al (Table 4). Collerson et al. (2010) also include the contribution from the generalized component {R3+3Na}3{Si12}O12 in their majorite substitution parameter, X(Mg).

Manganberzeliite

Manganberzeliite, {Ca3Na}3[Mn4+3]{As5+}O12 (Fig. 1g) has a complicated history revolving around the use of its name, which is briefly described below. Over 40 yr after the original description of berzeliite from Långban, Filipstad district, Sweden (Kühn 1840), Igelström (1886) described a Sb-bearing, Mn-rich berzeliite-like mineral from the nearby Sjögren mine, and named it “pyroharsoenite.” On the basis of a new chemical analysis giving 28.38 wt% MnO, Igelström (1894) concluded that “pyroharsoenite” is a manganese-dominant variety of berzeliite and could also be referred to as “Mangan-Berzeliit.”

In summarizing his discussion of the mineral, Hintze (1922) wrote that Igelström (1894) had found no antimony and had concluded from his studies that “pyroharsoenite” is just a Mn-rich variety of berzeliite. Hintze (1922) cited Igelström’s (1894) conclusion that the mineral containing 28% MnO can be referred to as “Manganberzeliit,” but Hintze (1922) wrote the name in bold type and unhyphenated.

Landergren (1930) used the terms “Mg-berzeliitt” and “Mn-berzeliitt” for the end-members of the series. These names were later used by other mineralogists studying this series, e.g., Blix and Wickman (1959).

Moore (1972) reported powder XRD data for the type specimen of “pyyrohsarenite” studied by Igelström (specimen NRM18870324 at the Swedish Museum of Natural History)
from Sjögren. He concluded that “pyrrhoarsenite” = berzelite. However, recent energy-dispersive spectroscopic analyses (Hålenius, unpublished data) of fragments of the mineral from this specimen, as well as cell parameter refinement (Locock, unpublished data) of Moore’s powder X-ray diffraction data, show that it is in fact Mn-dominant berzelite, i.e., manganberzelite (or “pyrrhoarsenite”). Prior to publication, Moore in 1971 submitted to the CNMMN a proposal to discredit several of the minerals outlined in his 1972 paper. After Moore published his paper, it was subsequently abstracted by Fleischer (1973), who noted that these minerals were discredited by the CNMMN and that “pyrrhoarsenite” was equivalent to berzelite. However, the discreditation of pyrrhoarsenite was actually not included in Moore’s proposal to the CNMMN. Therefore, the report by Fleischer (1973), which was then carried forward by Nickel and Mandarino (1987), was in error.

This raises the question whether “pyrrhoarsenite” has priority over manganberzelite and should be reinstated, although manganberzelite has been the preferred name since 1894 (e.g., Hintze 1922; Palache et al. 1951). Given that Igelström’s original description of the mineral was poor even by the standards of the late 19th century, e.g., he did not detect the appreciable sodium content, in contrast to his contemporary Sjögren (1894), we conclude that priority does not justify reviving “pyrrhoarsenite” at the present time and manganberzelite should remain the name for the Mn analog of berzelite.

**APPLYING THE NOMENCLATURE OF THE GARNET SUPERGROUP**

**Assumed cation occupancies**

A major objective of the classification is to provide a basis for identifying the species of an analyzed garnet from its chemical composition. As is the case for the tourmaline supergroup (Henry et al. 2011), chemical analyses of garnet establish which elements are present, but provide no information on which site(s) they occupy in the structure. Proper site allocation requires single-crystal or Rietveld structure refinement using X-ray or neutron diffraction methods, and spectroscopic data are often also needed for unambiguous site assignment, particularly when constituents could be present in more than one valence state, which is not rare in garnet. However, most investigators have only electron microprobe analyses, which provide no direct evidence of valence state. An added difficulty is that as a result of charge balance requirements, several garnet end-members have one site with mixed occupancy, the so-called valency-imposed double site-occupancy of Hatert and Burke (2008).

For all garnet-supergroup minerals we recommend that cations be allocated from a chemical analysis with the procedure given in the next section. This procedure is analogous to that proposed in connection with the nomenclature recommended for the tourmaline supergroup of Henry et al. (2011). It includes only constituents found in known end-members (Table 1) or some potential end-members (Tables 6–7). Examples illustrating our recommended procedure are given in Appendix 3, and a spreadsheet is given in Appendix 4.

As in the case of many mineral groups, some reasonable assumptions can be made concerning site assignments of specific cations on the basis of relative abundance (Table 3). Lithium and hydrogen are the only light elements (atomic number < 8) that have been reported in major amounts in garnet supergroup minerals, e.g., cryolithionite and katoite, respectively. When common silicate garnet species are checked for light elements, generally very little is found, i.e., Li contents are reported to not exceed 121 ppm, and Be and B contents, not to exceed 20 ppm (e.g., Grew et al. 1990; Grew 2002a, 2002b; Steppan 2003; Marschall 2005). An exception are the 259–1113 ppm Li in almandine from leucocratic granulite at Horni Bory, Czech Republic, corresponding to 0.019–0.079 Li pfu, determined by laser ablation-inductively coupled plasma-mass spectroscopy (Cempírek et al. 2010 and unpublished data). According to Cempírek et al. (2010), Li could occupy either the X site as it does in synthetic {Li2Mg(Al(Si)3O12 (Yang et al. 2009) or sites occupied by Li in synthetic garnets. The majority of synthetic Li garnets are compounds of Li with REE, Ta, Nb, Te, Zr, and Ba that are valued for their high-ionic conductivity (e.g., Cussen 2006, 2010; O’Callaghan and Cussen 2007; Wang and Lai 2012). Lithium occupies not only the Z site, but also octahedral sites that are vacant in natural garnet, resulting in Li contents up to 6.8 apfu and cation totals up 11.8 apfu. Other exceptions involving light elements are the reports of 4.40 wt% B2O3 determined by electron microprobe analysis (EMPA) in andradite (Galuskin et al. 1995) and 0.45–2.09 wt% B2O3 by EMPA in OH-bearing grossular (Galuskin et al. 1998, 2001) from the Wiluy River, Yakutia, Russia. Pending studies of Li and B in silicate and hydroxyl garnet, it would be best to assume Li and B, as well as S6+ (up to 2.27 wt% SO4), equivalent to 0.11 S pfu, Passaglia and Rinaldi 1984; Galuskin et al. 2001), are located at the Z site.

Calcium has been assumed to occupy only the X site in natural garnet; even in synthetic garnets there are very few reports of Ca at the Y site and none can be considered unequivocal (Geller 1967; Lobanov et al. 1989). Nonetheless, it should be noted that Huggins et al. (1977) and Pieper et al. (1983) concluded that a small excess of cations at X and a correspondingly small deficit at Y could be explained in some cases by small amounts of Ca at Y, 0.024–0.055 apfu in andradite and 0.04 apfu in grossular, respectively. Gadás et al. (2012) reported up to 3.15 Ca pfu in grossular from pegmatite at Ruda nad Moravou, Czech Republic.

Scandium is assumed to occupy only the Y site as in enargite, although its role could depend on the occupancy of X if synthetic garnets are any guide, where Sc preferentially occupies Y only in andradite, whereas in pyrope, X is favored and in grossular, a more even distribution (Oberti et al. 2006; Quartieri et al. 2006). Titanium is assumed to be tetravalent, and V, either pentavalent or trivalent. The last assumption received validation from Bordage et al. (2010), who reported that V was entirely V3+ in a grossular (variety “tsavorite” containing 0.14 V pfu) based on the K-edge X-ray absorption near-edge structure (XANES) spectra obtained with high-energy resolution fluorescence-detected X-ray absorption spectroscopy. In contrast, Righter et al. (2011) reported mixed valences also based on the K-edge X-ray absorption near-edge structure in other garnets, viz. 2.46–2.55 ±0.15 in pyrope of mantle origin and 2.56–2.67 (±0.15) for V valence in a goldmanite from the Czech Republic, i.e., 40% of the V in the goldmanite is V3+, the remainder V5+. However, this conclusion is in contrast to the structural and chemical data reported by these authors.
Site allocation of cations

The assumed occupancies, most importantly, \(^2\)Li, \(^3\)Ca, \(^3\)Sc, Ti\(^{4+}\), \(^7\)V\(^{3+}\), and \(^7\)V\(^{5+}\) in conjunction with Table 3, lead to the following procedure for recasting the chemical data into idealized site occupancies for purposes of classification.

1. Calculate formulas from the chemical analysis assuming 8 cations and 12 anions and apportion Fe\(^{3+}\) and Fe\(^{2+}\) or Mn\(^{2+}\) and Mn\(^{3+}\) if calculations give negative values for Fe\(^{2+}\) (method of Droop 1987). If quantitative F or H data are available, assume \(z = \frac{1}{4}F + \frac{1}{4}H\). In this case, the basis for formula calculation becomes \(O + (OH) + F = 12\) and \(\Sigma \{X\} + \Sigma \{Z\} + \Sigma (Z)\)\(^{2+}\) = 8.

2. Li, Zn, P, As\(^{5+}\), and V\(^{5+}\) to Z. If Li < \(\frac{1}{4}F\), assume sufficient vacancies to make up the deficit (see step 1).

3. Si and Ge: First to Z to a maximum of 3 apfu, including Si, Ge, and overflow to Y.

4. Al: First to Z to bring total to 3 apfu, then Y.

5. Fe\(^{3+}\): First to Z to bring total to 3 apfu, then Y.

6. Ca, Na, K, Y, REE, Th, Pb to X.

7. Al (remainder after deducting Al at Z), Sc\(^{3+}\), Ti\(^{4+}\), V\(^{3+}\), Cr\(^{3+}\), Mn\(^{2+}\), Fe\(^{3+}\) (remainder after deducting Fe\(^{2+}\) at Z), Ga, Zr\(^{4+}\), Hf\(^{4+}\), Nb\(^{5+}\), Sn\(^{4+}\), Sb\(^{5+}\), Te\(^{4+}\); and U\(^{4+}\); and U\(^{4+}\) to Y. If Z is still <3 apfu, then add Fe\(^{2+}\) to bring Z total to 3 apfu. If the content of Y exceeds 2 apfu, and Z is <3 apfu, then move Ti to Z to bring Z total to 3 apfu.

8. Mg: First to Y to bring total to 2 apfu, then to X.

9. Fe\(^{2+}\) (remainder after deducting Fe\(^{3+}\) at Z): First to Y to bring total to 2 apfu, then to X.

10. Mn\(^{2+}\): First to Y to bring total to 2 apfu, then to X. This should bring total X to 3 apfu, if calculations were done correctly.

If H is suspected, but no quantitative data are available, as is the case with electron microprobe analyses, then either its content must be assumed so that Fe\(^{2+}\)/Fe\(^{3+}\) ratio can be calculated, or the Fe\(^{2+}\)/Fe\(^{3+}\) ratio must be assumed so that H content can be calculated. In garnets containing significant Si, it is reasonable to assume that H is incorporated at the expense of Si, that is, H = 4\(^{2+}\) (O).

The site allocation procedure above, based solely on chemical data, fails to differentiate holtstamite from grossular, which would require additional information such as optical properties or crystallographic data, although henritermierite is uniquely determined because there is no report as yet of an isometric garnet having the composition \{Ca\(_3\)\}[Mn\(^{2+}\)]\{(Si\(^{2+}\)\[Mn\(^{2+}\]\])O\(_4\)(OH)\(_x\).\}

We have also prepared an Excel spreadsheet (Appendix 4) to perform the above cation allocation, species and group determination, but have omitted several elements that rarely exceed 1 wt% in natural garnets: B, S, K, Ni, Sr; or which occur in significant amounts but whose occurrence is rare: Ga, Ge, and Pb (Tables 6 and 8).

Identifying a garnet species

Once the cations have been allocated, then the dominant valence is determined for each site by summing the ions for each valence, e.g., Ca\(^{2+}\)+Mg\(^{2+}\)+Mn\(^{2+}\) at the X site, and then the dominant...
cation identified. As species are defined in terms charge-balanced end-members (Hawthorne 2002), the possibility of valency-imposed double site-occupancy (Hatert and Burke 2008) must be considered. The dominant ion for each valence determines the species (e.g., bitikleite group, Fig. 6). Six examples are given in Appendix 3, and a calculation procedure for species and group determination in Appendix 4. Our discussion below is limited to the schorlomite and garnet groups because these are most likely to cause difficulties in identifying species.

**Applying the nomenclature to the schorlomite group**

Characteristic of the end-member formulas in this group is Si = 1 apfu; there are no divalent and trivalent cations at the Y site and no divalent or pentavalent cations at the Z site. However, in most analyses of Ti-, Zr-, or Sn-rich garnets containing minor Sb\(^{5+}\), Nb\(^{5+}\), or U\(^{4+}\), Si commonly exceeds 1 apfu, e.g., all the analyses plotting in the schorlomite field in Figure 5 have Si > 2 apfu and total charge at the Z site > 11, because all contain substantial proportions of garnet group components (see above).

The primary criterion for a composition to belong to the schorlomite group is that the generalized schorlomite component \( [R^{3+}_2] [R^{3+}_2] (R^{2+}_2) \) be the most abundant (Fig. 7); i.e., the spreadsheet gives this as the most abundant component possible.

**Table 7. Summary of specific components potentially significant in natural garnets**

<table>
<thead>
<tr>
<th>Name</th>
<th>Synthesis Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbrusite</td>
<td>((Y_i)[Fe^{3+}][Al]_2(OH)_3)</td>
</tr>
<tr>
<td>Uman (Fe(^{3+}) at Z)</td>
<td>0.67-0.70</td>
</tr>
<tr>
<td>Uman (Fe(^{3+}) at Z)</td>
<td>0.67-0.70</td>
</tr>
<tr>
<td>Bitikleite</td>
<td>((Y_i)[Al]_4[Ca]_4)</td>
</tr>
<tr>
<td>Dzhuluite</td>
<td>((Y_i)[Al]_4[Ca]_4)</td>
</tr>
<tr>
<td>Sb(^{5+})Zr(^{4+}) Sn(^{4+})</td>
<td>0.93-0.95</td>
</tr>
</tbody>
</table>

**Table 8. Possible new species in the garnet supergroup**

<table>
<thead>
<tr>
<th>Relationship to known species</th>
<th>UM no.</th>
<th>End-member formula</th>
<th>Criteria</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn analog of elbrusite</td>
<td>Sn/((Sn + Zr) = 0.93) 0.33 Zr; 0.05 Ti; 0.48 Nb apfu at Y site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NB analog of usturite</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al analog of schorlomite</td>
<td>Al/(Al + Fe(^{3+})) = 0.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ti analog of kimzevite)</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg analog of morimotoite</td>
<td>Mg/(Mg + Fe(^{3+})) = 0.63-0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ga–Ge analog of grossular</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge analog of grossular</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6.** \( Y \)-site occupancy in species of the bitikleite group, including the possible unnamed Sn-dominant analog of elbrusite. Placement of the divisions is indicated.
and $R^{2+} = Mg, Fe^{2+}$, and differs from Figure 7a of Grew et al. (2010) in that the Ti corner is now Ti$^{3+}$, representing a component in garnet, morimotoite. However, menzerite-(Y) is a four component system because of the substitution of R$^{3+}$ for Si at the Z site, and compositions must be projected from four-component space onto the three-component plane shown in Figure 10. Appendix 3 (Example 3) gives the five possible generalized components in menzerite-(Y), of which only four are independent. We have selected the $\{Y_3\}[Al_3]Al_3O_{12}$-type component to project menzerite-(Y) compositions. The $\{Y_3\}[Al_3]Al_3O_{12}$-type component comprises 4–8% of the analyzed menzerite-(Y) grains. Despite the differences between Figure 10 and Figure 7a of Grew et al. (2010), the disposition of the points is very similar.

The most widespread garnet-group minerals are related by homovalent substitutions at the $X$ and $Y$ sites, i.e., $[R^3_2][R^2_3]$ (Si$^{4+}$)O$_{12}$. Since only four constituents occupy the $X$ site, the compositions can be plotted in a tetrahedron with Ca, Mg, Mn$^{2+}$, and Fe$^{2+}$ as vertices (Fig. 11a). Garnets with one of these cations dominant at the $X$ site fill a volume whose edges inside the Ca-Mg-Mn$^{2+}$-Fe$^{2+}$ tetrahedron are shown as lines inside this tetrahedron. Figures 11b and 11c show compositions projected from the Mn and Ca vertices of the tetrahedron, respectively. These two faces of the tetrahedron suffice to illustrate the dispositions of the species. Final characterization will depend on the dominant occupancy of the $Y$ site.

**Figure 7.** Diagram for discriminating the five species of the schorlomite group from Ca species in the garnet group.

**Figure 8.** $Y$-site occupancy in species of the schorlomite group.

**Figure 9.** Diagram distinguishing menzerite-(Y) from species within the garnet group.

**Figure 10.** Plot of menzerite-(Y) compositions at the $Y$ site projected from $\{Y_3\}[R^3_2][R^2_3]$O$_{12}$ onto the plane defined by the components $\{Ca_3\}[Ti^{3+}R^{2+}]$Si$^{4+}$O$_{12}$, $\{Ca_3\}[R^3_2]$Si$^{4+}$O$_{12}$, and $\{(REE)Ca_3\}[R^2_3]$ (Si$^{4+}$)O$_{12}$ (cf. Fig. 7a, Grew et al. 2010). $R^{3+}$ = Fe in morimotoite, Mg in menzerite-(Y); $R^{3+}$ = Fe in andradite. Numbers refer to grains used for the crystal-structure refinement (SREF), optical measurements, and menzerite-(Y) sensu stricto (Mzr), including grain no. 5 used as the holotype to characterize the mineral. The points for SREF and Optic are superimposed. Open diamonds indicate the other nine grains analyzed (data from Grew et al. 2010).
Possible new species and compositional variations in natural garnet

The compositional variations found in the 32 approved species by no means exhaust the compositional variations observed in natural garnet, which is greatly exceeded by the very extensive variations in synthetic garnet. In the present section we will consider these variations, note compositions containing components that could be new species if they were present in larger amounts (Tables 6 and 7), and briefly describe possible new species (Table 8). Synthetic garnets will be considered only in so far that they relate to natural garnets. The components are discussed under the group to which they would belong.

Vacancy-dominant garnets—A “kenogarnet” group?

Vacancy-dominant garnets are distinguished by $\phi$ being a monovalent anion such as OH or F, as well as low content of cations at the Z site. Katoite is the only known garnet that is vacancy-dominant. However, there is considerable potential to discover more species, and thus a group could be recognized following the procedures outlined in Mills et al. (2009). In anticipation, we suggest the name “kenogarnet” from the Greek kenos, meaning “empty,” a term introduced as a prefix in pyrochlore supergroup nomenclature (Atencio et al. 2010).

The most abundant vacancy-dominant garnets are the so-called “hydrogarnets,” an informal term (Appendix 2) introduced by Flint et al. (1941) and generally used for any garnet containing OH incorporated by the substitution of (O$_4$H$_4$) tetrahedra for (SiO$_4$) tetrahedra (Fig. 3). Significant incorporation of OH by this substitution is largely limited to garnet in which the X site is occupied by Ca, e.g., katoite, henritermierite, and holistamite. Up to 10 wt% H$_2$O has also been reported in andradite (Peters 1965; Lager et al. 1989; Armbruster 1995; Anthauer and Rossman 1998), leading to compositions with up to 35% of the Fe$^{3+}$ analog of katoite (Table 6) and 4.5% of its Mn$^{3+}$ analog (H content calculated by difference from Si occupancy determined by single-crystal refinement, Armbruster 1995). Galuskina and Galuskin (2003) and Galuskin (2005) calculated OH contents of 2.6–2.9 apfu (equivalent to 4.8–5.1 wt% H$_2$O) from charge balance in “hydroschorlomite” containing 13.5–14.5 wt% TiO$_2$ from the Wiluy River, Yakutia, Russia, the highest reported in Ti-rich garnets (cf. Chegem caldera schorlomite discussed above). In contrast, H$_2$O contents in pyrope, almandine, and uvarovite are reported not to exceed 0.3 wt%, and, in spessartine, not above 0.64 wt% (e.g., Aines and Rossman 1984; Rossman et al. 1988; Smyth et al. 1990; Andrut and Wildner 2001; Maldener et al. 2003; Beran and Libowitzky 2006; Johnson 2006). Wilkins and Sabine (1973) reported 2.5 wt% H$_2$O in spessartine,
but this high content is anomalous and needs confirmation.

Only “hydrogarnets” with the large cations Ca and Sr (Ito and Frondel 1967b; Ivanov-Emin et al. 1982a, 1982b) at the X site have been synthesized, including katoite (Flint et al. 1941; Cohen-Addad et al. 1967). Syntheses of the hydroxyl-dominant analogues of uvarovite (Morán-Miguélez et al. 1986) and enstatite (Ivanov-Emin et al. 1982a); as well as of {Ca}1[Mn]3+[□O]2(OH)12 (Ivanov-Emin et al. 1982b), {Ca}1[TiFe]3+[Fe4□O]2(OH)12 (Ito and Frondel 1967b), and {Ca}1[ZrFe]3+[Fe4□O]2(OH)12 (Ito and Frondel 1967b) have been reported. However, attempts to synthesize the end-member {Ca3[Fe3+]□O}2(OH)12 failed, although a garnet with about 90% {Ca3[Fe3+]□O}2(OH)12 and 10% andradite could be synthesized (Flint et al. 1941; Ito and Frondel 1967b). The reported compositions are based on starting materials; only the compositions of katoite and a hydroxyl-dominant analog of andradite, {Ca}1[Fe3+]3+[Si3□O]2(OH)12, have been confirmed independently (e.g., by structure refinement, Cohen-Addad 1970; Cohen-Addad et al. 1967). In summary, the H2O contents of natural and synthetic garnets are consistent with the conclusion reached by Lager et al. (1989) that the extent of OH substitution in garnets appears to be structurally controlled, i.e., it is greater, when the effective ionic radius (Shannon 1976) of the X-site cation exceeds 1.0 Å and the shared octahedral edge is longer than the unshared edge, which is the case for natural and synthetic garnets with Ca dominant at the X site (Novak and Gibbs 1971; Quartieri et al. 2006).

Fluorine contents up to 6 wt% F, equivalent to about 11 mol% of a {R3□}4/R12, have been reported in grossular, spessartine, and andradite (Valley et al. 1983; Flroh and Ross 1989; Manning and Bird 1990; Smyth et al. 1990; Barbansson and Bastos Neto 1992; Visser 1993; Włodyka and Karwowski 2006; Chakhmouradian et al. 2006). Only Smyth et al. (1990) measured H2O content, reporting 0.64 wt% in the F-bearing spessartine (Table 6), equivalent to 3% {R3□}4/R12(OH)12, but Flroh and Ross (1989) and Chakhmouradian et al. (2008) reported evidence for H2O in the infrared and Raman spectra. Attempts to synthesize an F-dominant analog of katoite have not been successful (Tokamori et al. 1987).

Chlorine was sought in four of the studies of F-bearing garnet cited above, but no more than 0.01 wt% Cl was reported. Up to 0.2 wt% Cl was reported in OH-bearing grossular from the Wiluy River, Yakutia, Russia (Galuskina et al. 2001). Chesnokov (1996), Chesnokov and Bushmakhin (1995), and Chesnokov et al. (1994, 2008) described “igumnovite,” ideally {Ca}1[Al]3+[Si3□O]2Cl4, and “chlorhibschite,” ideally, {Ca}1[Al]3+[Si3□O]2Cl4, from burned material in the Chelyabinsk coal basin, Urals, Russia, but these compounds are not considered to be naturally formed, and thus do not qualify as minerals (e.g., “igumnovite,” Jambor et al. 1997). The reported cell parameter of 12.008 Å for “igumnovite” is smaller than expected for a Cl-rich garnet from the relationship of Langley and Sturgeon (1979). Although the measured composition for “igumnovite,” Ca9.0λAl9.72Fe0.11Mg0.01Si3.2Sb1.94O10.59Cl1.07 approaches ideal garnet stoichiometry, it is doubtful that either “igumnovite” or “chlorhibschite” are garnets. More likely, “igumnovite” is related to mayenite, wadalite, and the new mineral eltyubyuite (Galuskin et al. 2011b), whereas “chlorhibschite” could be a mixture of grossular, wadalite, and, perhaps, chlorides.

Yafsoanite
The 9% proportion of the component {Pb3□}[Fe3□]ZnO12 listed in Tables 6 and 7 is based on the single-crystal structure refinement of material from the type locality (Mills et al. 2010; cf. Jarosch and Zemann 1989). Electron microprobe analyses reported in the original description gave 11–16% of the Pb analog (Kim et al. 1982), but the formulas deviate from ideal stoichiometry, possibly as a result of using sulfides, a silicate and a native element for standards. Ronniger and Mill’ (1973) reported synthesis of several Pb3□-bearing vanadate garnets (berzellite group) with Pb at the X site, and Mill’ (1970) reported synthesis of yafsoanite and other Te-bearing garnets, but neither reported attempts to synthesize the Pb3□ analog of yafsoanite.

The unnamed end-member {Ca3□[U3□]□}2(OH)3+O12 is calculated to be major constituent of elbrusite (Fig. 4; Table 6) and dzholuite (Appendix 3), but has not yet been synthesized.

Henritermite group
Boiocchi et al. (2012) reported nearly end-member spessartine containing 0.09 Fe and 0.04 Ca pfu, but only 2.52 Si pfu, the deficiency being made up by OH and F in nearly equal proportions (Table 6). The I4/accd symmetry indicates that the mineral is more closely analogous to holstamite rather than katoite. The spessartine is the first example of a garnet showing I4/accd symmetry but containing no Mn2+, and thus Boiocchi et al. (2012) attribute the lower symmetry to (OH, F)3 groups. Si is partially ordered, preferentially occupying the Z1 site (93.0%) vs. the Z2 site (73.8%).

Bitikleite group
Given the large number of elements found in analyses of garnets of the bitikleite group, the potential for new species is great. For example, analysis 10 of elbrusite in Table 2 of Galuskina et al. (2010a) corresponds to the Sn-dominant analog of elbrusite (Fig. 4), and is possibly a new species (Table 8). Zaitsev et al. (2010) reported a zone with up to 10.1 wt% Nb2O5 in a keramisite crystal, this amount corresponds to 0.48 Nb per formula unit, or nearly 50% of a {Ca}1[NbZr]R12□O12 component, which implies the possibility of new species for R12□ = Fe and Al, the Nb analog of usterite (Table 8).

Up to 4 wt% ThO2 (0.1 Th pfu) has been reported in bitikleite and schorlomite-group minerals (Lupini et al. 1992; Galuskina et al. 2010a, 2010e), which would correspond to 20 mol% of a {Th3□Ca2□}R12□O12 component. The end-member with Zr and Fe, i.e., {Th3□Ca2□[Zr□]□}O12, has been synthesized (Ito and Frondel 1967a; Yudintsev 2003; Utsunomiya et al. 2005).

Yttrium-aluminum (YAG) and yttrium-iron (YIG) garnets
The rare earth elements can form a large number of synthetic compounds having general formulas of the type {R12□}4/R12□(R12□)12 and isostructural with garnet (e.g., Yoder and Keith 1951; Geller 1967), of which {Y1□[Al]□}O12 (yttrium aluminum garnet or YAG) and {Y1□[Fe]□}O12 (yttrium iron garnet or YIG) are the most relevant to minerals (Tables 6 and 7). Although the total charge at Z is 9, the garnet end-members YAG and YIG have not been placed in the bitikleite group because of the very different occupancies at Y and X. Up to 5 mol% of the YAG component has been reported in spessartine and almandine (e.g.,
Jaffe 1951; Röhr et al. 2007), and 5 mol% of the YIG component has been reported in andradite (Kasowski and Hogarth 1968), but the maximum proportion of a generalized [(Y,REE)₂][(Fe³⁺,Al₂)₃((Al₄)O₁₂ component in a natural garnet is 8% in menznerite-(Y)-andradite solid solution (Grew et al. 2010).

Schorlomite group

Koritnig et al. (1978) reported Zr-rich schorlomite from calc-silicate inclusions in gabбро of Radualtal, Harz Mountains, Germany. Analyses of three samples gave 6.2–6.8 wt% Al₂O₃ and 23.1–25.5 wt% SiO₂ contents; the sample giving the highest ZrO₂ content (Zr = 0.55 apfu) is plotted in Figure 5. Our calculations for this sample give 48.9–49.0% {Ca₃[(R³⁺)₂]SiO₃}×₂ with Ti > Zr at Y and Al > Fe³⁺ at Z, i.e., a possible Al analog of schorlomite or Ti analog of kimzeyite. Using Mössbauer spectroscopic data, Koritnig et al. (1978) gave the Z site composition as (Si₁₀₆Al₉₆Fe₂₄₂₂₄ Tₐ₆₁Fe₀₅₀)×. Ito and Frondel (1967a) synthesized end-member schorlomite and kimzeyite, but we are not aware of a successful synthesis of the end-member {Ca₃[Ti₂]SiO₃}×.

Garnet group

Formulas calculated from the two analyses richest in Ti from garnets of the Marathon dikes, Ontario (Platt and Mitchell 1979), plot in the morcitolite field (Fig. 5) and have total Mg/ (Mg+Fe²⁺) = 0.63–0.64, i.e., the end-member {Ca₃[TiMg] (Si₀₂)×₁₂, the Mg analog of morcitolite, is dominant (Table 8). However, the Marathon dikes compositions plot close to the boundary with schorlomite and calculation of Fe³⁺/Fe²⁺ ratio from stoichiometry has a large uncertainty (Giaramita and Day 1990); thus a clear dominance of {Ca₃[TiMg](Si₃)O₁₂ in a natural garnet remains to be demonstrated.

Gallium and germanium can form a large number of synthetic compounds isosstructurial with garnet (Geller 1967), but only {Ca₃[Ga₃]GeO₁₂ might have a natural analog. Johan and Oudin (1986) reported from the Pyrenees of France equant, six-sided crystals up to 10 µm across of a Ca-Ga-Ge mineral having compositions consistent with garnet stoichiometry (abstract in Jambor et al. 1988b). Cores of the highly zoned grains are close to {Ca₃[Ga₃]GeO₁₂ in composition, whereas the rims have compositions approximately intermediate between this composition and grossular. The list of valid unnamed minerals (Smith and Nickel 2007) also gave {Ca₃[Al₃]Ge₃O₁₂ as a possible new species (Table 8), but our recalculation of formulas from the two compositions closest to this end-member (Johan and Oudin 1986) gave Si > Ge at the Z site and minor Ge at the Y site assuming Si is preferentially incorporated at the Z site. The crystals were too small to confirm the identification as a garnet by the technologies available at the time.

Fennor (1926, 1938) introduced three hypothetical garnet end-members (Tables 6–7; Appendix 2): “blythite,” [{Mn³⁺}][Mn³⁺]Si₃O₁₂, as a subordinate component in a garnet from Cargoan, Nagpur, India; “khoharite,” [{Mg²⁺}][Fe³⁺]Si₃O₁₂, as the precursor to enstatitic chondrules in the Khohar meteorite and as a subordinate component in a pyrope from a “garnet-diopside” xenolith (eclogite)? in kimberlite from South Africa; and “skiagite,” [Fe³⁺][Fe³⁺]Si₃O₁₂, as a component in almandine from Glen Skiag, Scotland. Although later studies have reported up to nearly 9 mol% “blythite” based on measurement or stoichiometric calculation of Mn³⁺ in andradite from manganese formations, Otjosondu, Namibia (Anthaver et al. 1989; Bühn et al. 1995), “khoharite” and “skiagite” have been elusive, e.g., Virgo and Yoder (1974) failed to find “skiagite” in spessartine-almandine from the type locality at Glen Skiag, Scotland. The main problem in identifying these components in complex natural garnets is that the calculation depends on the sequence of calculation (Rickwood 1968; Locock 2008), i.e., Fe³⁺ is first assumed to be present as the andradite component; only leftover Fe³⁺ would be combined with Mg in the “skiagite” or “khoharite” components, respectively, and Mn³⁺ could be present as {Ca₃} [Mn³⁺]Si₃O₁₂ as well as {Mn³⁺}[Mn³⁺]Si₃O₁₂ in the Otjosondu garnet (Table 6). Garnets containing a significant proportion of {Ca₃}[Mn³⁺]Si₃O₁₂, “blythite,” “khoharite,” and “skiagite” end-members have been synthesized at relatively high pressures, i.e., above 30 kbar (Coes 1955; Nishizawa and Koizumi 1975; Karpinskaya et al. 1982; Fersen 1983; woodland and O’Neill 1993, 1995; Arlt et al. 1998), and could become more abundant under mantle pressures.

Rudashevskii and Mochalov (1984) reported a Mn-Cr-Si mineral thought be a garnet in heavy concentrates from eluvium of Pt-bearing serpentinite in the Far East of Russia (summary in Jambor et al. 1988a). The mineral forms highly zoned grains 1–30 µm across enclosed in Cr-Ni-bearing γ-Fe. The formula (with cations grouped by valence) for the analysis with the highest Cr content is [Mn₃₂⁵₉₉][Cr₂⁰₁₇Mn₂₃₃][Si₂₂₂₃₈₁₆Al₂₈Fe⁵₀ₙ]O₁₂×, i.e., a {Mn³⁺}[Cr³⁺]Si₃O₁₂ component can be considered dominant, whereas that for the lowest Cr content is [Mn₃₂⁵₉₉Cr₂⁰₁₇Al₂₈Fe⁵₀ₙ]Ti₂₂₃₈₁₆O₁₂×, i.e., with “blythite” dominant. The presence of significant Mn³⁺ in association with Fe³⁺ is unexpected, as is the preservation of metallic Fe in eluvium. In the absence of X-ray or electron diffraction patterns and clearer evidence for the natural origin of the concentrates, the natural occurrence of a {Mn³⁺}[Cr³⁺]Si₃O₁₂-dominant or {Mn³⁺}[Mn³⁺]Si₃O₁₂-dominant garnet remains to be demonstrated.

Three components have been proposed for incorporation of Na in garnet-group minerals (Tables 4 and 6), all of which have been inferred to be favored by increasing pressure, ⁵Na⁺(Y, Yb) = 2R⁺ (Enami et al. 1995; Röhr et al. 2007) and ⁵Na⁺Si = ⁴R⁺Al or ⁶Na⁺Ti = ⁴R⁺Al (Ringwood and Major 1971; Sobolev and Lavrent’ev 1971; Bobrov et al. 2008; Harte 2010; Collerson et al. 2010).

Bergelitie group

Phosphorus contents generally do not exceed 1 wt% P₂O₅ in pyrope, almandine, and spessartine, both in wet chemical (e.g., Koritnig 1965; Deer et al. 1982) and in electron microprobe analyses (e.g., Bishop et al. 1978; Hiroi et al. 1997; Breiter et al. 2005; Kawakami and Hokada 2010). Mason and Berggren (1942) reported 4.1 wt% P₂O₅ in spessartine from Wodgina, Australia (sample no. NRM 884695, Swedish Museum of Natural History), but Breiter et al. (2005) found only 0.24–0.27 wt% with the electron microprobe. An energy-dispersive spectroscopic analysis of the spessartine in this specimen (normalized to 100%) with an SEM gave P contents closer to the amounts reported by Breiter et al. (2005): SiO₂ 35.78, Al₂O₃ 20.52 Fe₂O₃ 3.91, MnO 39.15, CaO 0.20, P₂O₅ 0.42 (±0.12) (Hålenius, unpublished data). The spessartine grains are cut by microfissures ranging
from <1 μm to ca. 10 μm thick filled with Ca-Mn-phosphates. In some grains, the microfissures are sufficiently abundant to form networks, whereas in other grains they occurred singly up to 100 μm apart. It would have been nearly impossible to obtain a pure spessartine concentrate suitable for wet chemical analyses from this specimen.

Thompson (1975) reported experimental evidence for increased incorporation of P and Na with increasing pressure, a relationship consistent with the presence of up to 0.25 wt% P2O5 in pyrope associated with coesite at Dora Maira, Italy (Brunet and Lecoq 1999), exsolvedapatite in garnet from mantle eclogite (Haggerty et al. 1994) and with the synthesis of \{Na1\}([Al2\(\text{P}_5\text{O}_{12}\) at 150–170 kbar by Brunet et al. (2006). Thilo (1941) reported synthesis of \{Na1\}([Al2\(\text{P}_5\text{O}_{12}\) at atmospheric pressure, but subsequent attempts to reproduce such syntheses failed (Schwarz and Schmidt 1971). On the basis of a large number of analyses yielding up to 1.21 wt% P2O5 (equivalent to 0.086 P pfu) in almandine and spessartine from granitic rocks, Breiter et al. (2005) showed that: (1) P content varies inversely with Si; (2) Na/P ratio to be approximately 1.5; and (3) Al is relatively constant, consistent with the substitutions \(\Delta\text{O}+2\text{P} = \Delta\text{R}^2+2\text{Si}\). There was no evidence in their data for the substitution \(\text{Al}^3\text{Fe}^{2+}+\text{P} = \text{Si}^2\) reported in an almandine-spessartine containing up to 2.1 wt% P2O5 from rhyolite, Tanzawa Mountainland, Japan (Arima and Yamashita 1994). Breiter et al. (2005) also concluded that the main control on incorporation of P seems to be the P contents in melt or postmagmatic fluid instead of pressure.

The maximum FeO content reported in a berzeliite-group mineral is 1.52 wt% in berzeliite from Montaldo mine, Italy, equivalent to 6% of the \{Ca,Na\}([Fe3+\text{Al}3\text{Si}\text{O}_3\text{O}_4\} end-member (Nagashima and Armbuster 2012). Attempts to synthesize the \text{Fe}^{2+} analog of berzeliite have not been successful (Ito 1968; Schwarz and Schmidt 1971).

**SUMMARY OF CONCLUSIONS, ACTIONS, AND RECOMMENDATIONS**

- The garnet supergroup comprises 32 approved species, with an additional 5 possible species needing further study to be approved.
- The supergroup includes all minerals isostructural with garnet regardless of what elements occupy specific cation or anion sites.
- We have subdivided the supergroup into groups based on symmetry and total charge at the tetrahedral Z site. Twenty-nine species belong to one of five groups, one tetragonal (henritermierite), and four isometric—bitikleite, schorlomite, garnet, and berzeliite, in which the total Z charge is 8, 9, 10, 12, and 15, respectively. Three species are single representatives of potential groups in which total charge at Z is 0 (katoite), 3 (cylolithionite), and 6 (yafsoanite).
- Species are identified on the basis of the dominant-constituent and dominant-valency rules, and in some cases, by valency-imposed double site-occupancy.
- We recommend that suffixes (other than Levinson modifiers) not be used in naming minerals in the garnet supergroup. We have discarded existing names that have suffixes and replaced them with new root names where necessary, specifically, bitikleite-(SnAl) with bitikleite, bitikleite-(SnFe) with dhzuluite, bitikleite-(ZrFe) with usturite, and elbrusite-(Zr) with elbrusite.
- We have discarded the name hibschite in favor of grossular, as Si is the dominant cation at the Z site.
- Twenty-one end-members have been reported as subordinate components in minerals of the garnet supergroup of which six have been reported in amounts up to 20 mol% or more, whereas several others have been synthesized, which implies the potential for more species in the garnet supergroup.

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**REFERENCES CITED**


Armbruster, T. (1995) Structure refinement of hydrous andradite, Ca\textsubscript{Fe}1\textsubscript{2}Al4Mn\textsubscript{30}O\textsubscript{39}(SO\textsubscript{4})\textsubscript{12}(H\textsubscript{2}O)\textsubscript{17}, from the Wessels mine, Kalahari manganese field, South Africa. European Journal of Mineralogy, 7, 1221–1225.


(1984b) Crystal chemical and petrological study of hydrogarnets from a Fe-gabbro metaroodingite (Gruppo di Voltri, Western Liguria, Italy). Neues Jahrbuch für Mineralogie Abhandlungen, 150, 247–258.


Nagashima, M. and Armbruster, T. (2012) Palenzoizitate, berzelizite, and managan-
berzelite: (As<sup>5+</sup>:V<sup>4+</sup>Si<sup>3+</sup>) tetrahedra in garnet structures. Mineralogical Magazine, 76, 1081–1097.

Mineral Names: procedures and guidelines on mineral nomenclature. Canadian
Mineralogist, 36, 913–926.

Nickel, E.H. and Mandarino, J.A. (1987) Procedures involving the IMA Com-
mission on New Minerals and Mineral Names and guidelines on miner-
nomenclature. American Mineralogist, 72, 1031–1042.

Nishizawa, H. and Koizumi, M. (1975) Synthesis and infrared spectra of Ca,
Mn<sub>2</sub>SiO<sub>4</sub> and Cd<sub>2</sub>SiO<sub>4</sub> (B: Al, Ga, C, V, Fe, Mn) garnets. American
Mineralogist, 60, 84–87.

Nixon, P.H. and Hornung, G. (1968) A new chromium garnet end member, knor-

American Mineralogist, 56, 791–825.

of Ti in amphiboles: I. Four- and six-coordinate Ti in richterite. European

Oberti, R., Quarziere, S., Dalcino, C.M., Boscherini, F., Iezzi, G., Boicocci, M.,
and Eeckout, S.G. (2006) Site preference and local geometry of Sc in garnets: Part
I. Multifularrious mechanisms in the pyrope-grossular join. American Mineralo-
gist, 91, 1230–1239.

O’Callaghan, M.P. and Cussen, E.J. (2007) Lithium dimer formation in the Li-
Fe<sub>5+</sub>Al<sub>2</sub>O<sub>12</sub> garnet Li<sub>2</sub>Al<sub>2</sub>SiO<sub>4</sub>. Chemical Communications

O’Neill, H.S.C., McCannon, C.A., Canin, D., Rubie, D.C., Ross, C.R. II, and Seif-
ert, F. (1993a) Mössbauer spectroscopy of mantle transition zone phases.
Magnetic and petrogenetic implications. European Journal of Mineralogy,
7, 847–858.

O’Neill, H.S.C., Rubie, D.C., Canin, D., Geiger, C.A., Ross, C.R. II, and Seif-
ert, F. and Woodland, A.B. (1993b) Ferric iron in the upper mantle and in the
transition zone assemblages: Implications for relative oxygen fugacities in the
mantle. In E. Takahashi, R. Jeanloz, and D.C. Rubie, Eds., Evolution of the Earth and
Planets, Geophysical Monograph, 74, 73–88. American Geophysical Union,
Washington, D.C.

and interactions in garnets: End-member properties. American Mineralogist,
81, 429–447.

Palache, C., Berman, H., and Frondel, C. (1951) The system of mineralogy of
James Dwight Dana and Edward Salisbury Dana, Yale University, 1837–1892,

Pasero, M., Kampf, A.R., Ferraris, C., Pekov, I.V., Rakovan, J., and White, T.J.
of Mineralogy, 22, 163–179.

Passaglia, E. and Rinaldi, R. (1984) Katoite, a new member of the Ca<sub>3</sub>Al<sub>2</sub>(SiO<sub>4</sub>),
Ca<sub>2</sub>Al(OH)<sub>4</sub> series and a new nomenclature for the hydrogarnet group of
minerals. Bulletin du Société Française de Minéralogie et de Cristal-
lographie, 107, 605–618.

Union. Ocean Pictures, Moscow.


Peters, T.J. (1965) A water-bearing andradite from the Totpal serpentine (Davos,

in garnet: The crystal-structure refinement of schorlomite. Canadian Mineralo-
gist, 33, 627–631.

Piddington, H. (1850) On caliderite, an undescribed silico-iron-and-manganese
rock, from the district of Burdwan. Journal of the Asiatic Society of Bengal,
19, 145–148.

der Kationenverteilung in den natürlichen Granaten Pyrop und Hessonit
durch Neutronenbeugung. Neues Jahrbuch für Mineralogie Abhandlungen,
147, 147–159.

titanates and manganese magnesio-ulvöspinel-magnetite spines. American
Mineralogist, 64, 546–550.

Povarennykh, A.S. and Shabalin, B.G. (1983) Structural role of titanium and iron
in synthetic zirconium- and titanium-containing garnets. Geologicheskii
Zhurnal, 43, 45–50 (in Russian).

Quarziere, S., Oberti, R., Boiocchi, M., Dalcocò, M.C., Boscherini, F., Safonova,
O., and Woodland, A.B. (2006) Site preference and local geometry of Sc in garnets:
Part II. The crystal-chemistry of octahedral Sc in the andradite-Ca<sub>3</sub>Al<sub>2</sub>SiO<sub>4</sub>

crystal-electron paramagnetic resonance study. European Journal of
Mineralogy, 15, 697–698.

Rammelsberg, K.F.A. (1850a) V. Mineralogical Notes. Schorlomante
2(VO<sub>2</sub>·SO<sub>4</sub>)·3(2VO<sub>2</sub>·TiO<sub>2</sub>). Philosophical Magazine and Journal of
Science, 36, 21.
of crustal rocks from the Ries impact crater (Germany). Contributions to Mineralogy and Petrology, 161, 275–291.


Thilo, E. (1941) Über die Isotopie zwischen Phosphaten der allgemeinen Zusammensetzung (Me,$^+$,Me,$^2+$)PO$_4$, und den Silikaten der Granitgruppe. Naturwissenschaften, 29, 239.


Chemistry, 184, 965–970.
Yang, H., Konzett, J., Downs, R.T., and Frost, D.J. (2009) Crystal structure and Raman spectrum of a high-pressure Li-rich majoritic garnet, (Li,Mg)Si(SiO$_3$)$_2$, American Mineralogist, 94, 630–633.
Yoder, H.S. and Keith, M.L. (1951) Complete substitution of aluminium for silicon: The system 3MgO·Al$_2$O$_3$·3SiO$_2$ – 3Y$_2$O$_3$·SiAlO$_3$. American Mineralogist, 36, 519–533.
— (1935) über titanhaltige Kalkeisengranate. II. Zentralblatt für Mineralogie, Geologie und Paläontologie, Abteilung A: Mineralogie und Petrographie, 68–78.

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APPENDIX I. LIST OF GARNET SPECIES, END-MEMBER FORMULAS, MODIFICATIONS, ETYMOLOGY, TYPE LOCALITIES; CRYSTAL STRUCTURE REFINEMENTS

The following garnet species either have been previously accepted by the IMA-CNMNC or have been modified by the current garnet subcommittee. Modifications to the original garnet species descriptions are noted except for grandfathered species. One or two references are given for the crystal structure, either of natural material (when available) or of synthetic material, or both.

**Almandine**
- **End-member formula:** [{Fe$^{3+}$}][Al$_2$Si$_3$O$_9$]
- **Group:** Garnet
- **IMA number:** Grandfathered
- **Modifications:** None
- **Etymology:** The “Alabandic carbuncles” of Pliny were so named as they were cut and polished in Alabanda (Dana 1837, 1892), an ancient city in what is presently Aydin Province, Turkey.
- **Type locality:** Not known
- **Crystal system, space group and structure refinement:** Isometric, $Ia3d$. Novak and Gibbs (1971); synthetic material: Armbruster et al. (1992).
- **Original or oldest description:** Known in ancient times. Name first used by D.L.G. Karsten in 1800 (Dana 1892).

**Andradite**
- **End-member formula:** [Ca$_3$][Fe$^{3+}$]Si$_3$O$_9$
- **Group:** Garnet
- **IMA number:** Grandfathered
- **Modifications:** None
- **Etymology:** For José Bonifácio de Andrade e Silva (1763–1838), the Brazilian mineralogist who described a variety under the name “alchoiroze” in 1800 (Dana 1892; Clark 1993).
- **Type locality:** Not known
- **Crystal system, space group and structure refinement:** Isometric, $Ia3d$. Armbruster and Geiger (1993). Original or oldest description: “alchoiroze” of de Andrade in 1800 and “melanite” of Werner in 1800 (Dana 1892).

**Berzelite**
- **End-member formula:** [Ca$_2$Na$_3$][Mg$_2$Al$_2$O$_9$]$_2$
- **Group:** Berzelite
- **IMA number:** Grandfathered
- **Modifications:** None
- **Etymology:** For Jacob Berzelius (1799–1848), a Swedish chemist.
- **Type locality:** Längban, Filipstad district, Värmland, Sweden.
- **Crystal system and structure refinement:** Isometric, $Ia3d$. Hawthorne (1976); Nagashima and Armbruster (2012).
- **Original or oldest description:** Kühn (1840)

**Bitikleite**
- **End-member formula:** [Ca$_3$][Sn$^{4+}$][Al$_2$O$_9$]
- **Group:** Bitikleite
- **IMA number:** 2009-052
- **Modifications:** Originally described as bitikleite-(SnAl) with the same formula.
- **Etymology:** From Bitikle, the name of an old fortification near the type locality.
- **Type locality:** Upper Chegem caldera, Kabardino-Balkaria, North Caucasus, Russia.
- **Crystal system, space group and structure refinement:** Isometric, $Ia3d$. Galushkina et al. (2010b)
- **Original or oldest description:** Galushkina et al. (2010b)

**Calderite**
- **End-member formula:** [Mn$^2+$_1][Fe$^{3+}_2$]Si$_3$O$_9$
- **Group:** Garnet
- **IMA number:** Grandfathered
- **Modifications:** None
- **Etymology:** From James Calder, a member of the Asiatic Society of Bengal, originally applied to the rock containing the mineral (Piddington 1850).
- **Type locality:** Either in Burdwan (Bardhaman) district, West Bengal State, or near Hazaribagh, Jharkhand State, India.
- **Crystal system, space group and structure report:** Isometric, $Ia3d$. No structure refinement; structure optimization by distance least-squares refinement (Ottonello et al. 1996).
- **Original or oldest description:** Fermor (1909, 1926)

**Crysdationite**
- **End-member formula:** [Na$_3$_1][Al$_2$Li$_2$F$_2$]
- **Group:** ungrouped
- **IMA number:** Grandfathered
- **Modifications:** None
- **Etymology:** From the presence of Li and its relation to cryolite
- **Type locality:** The Ivigtut cryolite deposit, Ivigtut (Ivigtat), Assuk, Kitas Province, Greenland.
- **Crystal system, space group and structure refinement:** Isometric, $Ia3d$. Geller (1971).
- **Original or oldest description:** Ussing (1904)

**Dzhuluite**
- **End-member formula:** [Ca$_3$][Sn$^{4+}$][Fe$^{3+}$]O$_9$
- **Group:** Bitikleite
- **IMA number:** 2010-64
- **Modifications:** Originally described as bitikleite-(SnFe) with the same formula.
- **Etymology:** After Dzhulu Mountain near the type locality.
- **Type locality:** Upper Chegem caldera, Kabardino-Balkaria, North Caucasus, Russia.
- **Crystal system and space group:** Isometric, $Ia3d$. Structure not yet refined.
- **Original or oldest description:** Galushkina et al. (2011a)

**Elbrusite**
- **End-member formula:** [Ca$_3$][U$^{4+}_n$][Zr$_3$_2][Fe$^{3+}_2$]O$_9$
- **Group:** Bitikleite
- **IMA number:** 2009-051
- **Modifications:** Originally described as elbrusite-(Zr) with a formula [Ca$_3$][U$^{4+}_n$][Zr$^{4+}_3$][Fe$^{3+}_2$]O$_9$.
- **Etymology:** From the highest peak in Europe - Mount Elbrus (5642 m).
- **Type locality:** Upper Chegem caldera, Kabardino-Balkaria, North Caucasus, Russia.
- **Crystal system, space group and structure refinement:** Isometric, $Ia3d$. Structure of elbrusite has not yet been refined, but that of U-rich kerimasite has been refined [under the name “Fe-dominant analog of khinzesite”, Galushkina et al. (2010a)].
- **Original or oldest description:** Galushkina et al. (2010a)

**Eringaite**
- **End-member formula:** [Ca$_3$][Se$_2$][Si$_3$O$_9$]
- **Group:** Garnet
- **IMA number:** 2009-054
- **Modifications:** None
- **Etymology:** From the Eringa River, a tributary of the Wiluy River.
- **Type locality:** Wiluy River, Sakha-Yakutia Republic, Russia (63.0°N, 112.3°E).
- **Crystal system, space group and structure refinement:** Isometric, $Ia3d$.
- **Synthetic material:** Mill’ et al. (1977), Quarterni et al. (2006)
- **Original or oldest description:** Galushkina et al. (2010d)

**Goldmanite**
- **End-member formula:** [Ca$_3$][V$^{5+}_2$][Si$_3$O$_9$]}
Group: Garnet
IMA number: 1963-003
Modifications: None
Type locality: Sandy (or South Laguna) mine area, Laguna, New Mexico, U.S.A.
Crystal system, space group and structure refinement: Isometric, Ia3d. Novak and Gibbs (1971); Righter et al. (2011).
Original or oldest description: Moench and Meyrowitz (1964)

**Grossular**
End-member formula: [Ca3](Al3)[Si5]O12
Group: Garnet
IMA number: Grandfathered
Modifications: None
Etymology: From the color resembling gooseberry. Bibes grossularia (Dana 1892; Clark 1993).
Type locality: Wiluy River, Sakha-Yakutia Republic, Russia.
Synthetic material: Geiger and Armbruster (1997).
Original or oldest description: A.G. Werner in 1808–1809. However, grossular was described earlier under other names, viz. as “Cinnamon Stone” (Kanelstein) from Sri Lanka by Werner in 1803–1804 and as “Granat” by Pallas in 1793 (Dana 1892).

**Kimzeyite**
End-member formula: [Ca3](Mg2)[Zr3]Si10O12
Group: Schorlomite
IMA number: Not recorded
Modifications: None
Etymology: For members of the Kimzey family, who were instrumental in obtaining and preserving mineral specimens from Magnet Cove.
Type locality: Kimzey quarry, Magnet Cove, Arkansas, U.S.A.
Crystal system, space group and structure refinement: Isometric, Ia3d. Munno et al. (1980)
Original or oldest description: Milton and Blade (1958), Milton et al. (1961)

**Knoerringite**
End-member formula: [Mg3]([Cr3]4)[Si18]O46
Group: Garnet
IMA number: 1968-010
Modifications: None
Etymology: For Oleg von Knoerring (1915–1994), a Russian mineralogist who worked in Finland and the United Kingdom.
Type locality: Kao kimberlite pipe, Butha-Buthe, Lesotho.
Crystal system, space group and structure refinement: Isometric, Ia3d. Synthetic material: Jušini et al. (2010).
Original or oldest description: Nixon and Homung (1968)

**Majorite**
End-member formula: [Mg3][Si16]O48
Group: Garnet
IMA number: 1969-018. Modifications: Formula originally given as [(Mg,Na)3][Fe3Si12Al2O48].
Etymology: For Alan Major, who assisted A.E. Ringwood in experiments.
Type locality: Cooroura L6 chondrite (recovered in Western Australia).
Crystal system, space group and structure refinement: Isometric, Ia3d.
Synthetic material: Huzen et al. (1994)
Original or oldest description: Smith and Mason (1970)

**Manganberzeliite**
End-member formula: [Ca3][Mn3][Si14]O42
Group: Berzeliite
IMA number: Grandfathered
Modifications: See text.
Etymology: The manganese analog of berzeliite.
Type locality: Längbun, Filipstad district, Värmland, Sweden.
Crystal system, space group and structure refinement: Isometric, Ia3d.
Qualitative description of the structure: Bubek and Machatschki (1935), Nagashina and Armbruster (2012)
Original or oldest description: Igelström (1886, 1894)

**Menzerite-(Y)**
End-member formula: [Y3][Si14]O42
Group: Garnet
IMA number: 2009-050
Modifications: None
Etymology: For Georg Menzer (1897–1989), the German crystallographer who was the first to solve the structure of garnet (Menzer 1928); the suffix Y is a Levinson modifier that indicates that Y is dominant among the sum of Y and the rare-earth elements.
Type locality: Bomeet Island in Georgian Bay, near Parry Sound, Ontario, Canada.
Crystal system, space group and structure refinement: Isometric, Ia3d. Grew et al. (2010)
Original or oldest description: Grew et al. (2010)

**Momoitite**
End-member formula: [Mn3][V3]3[Si14]O42
Group: Garnet
IMA number: 2009-026
Modifications: None; see the “yamatoite” of Momoi (1964), which was not approved because this component was not dominant in the material that they investigated (Fiescher 1965).
Etymology: For Hitoshi Momoi (1897–1989), the Japanese mineralogist who was the first to recognize [Mn3][V3]3[Si14]O42 as a component in garnet.
Type locality: Kurase mine, Ehime Prefecture, Japan.
Crystal system, space group and structure refinement: Isometric, Ia3d. Structure not yet refined, but the atomic coordinates were predicted by Novak and Gibbs (1971).
Original or oldest description: Tanaka et al. (2010)
Morimotoite
End-member formula: \([\text{Ca}_2][\text{TiFe}^{2+}][\text{Si}]\text{O}_12\)
Group: Garnet
IMA number: 1992-017
Modifications: None
Etymology: For Nobuo Morimoto (b. 1925), a Japanese mineralogist.
Type locality: Fuku, Bitchu-Cho, Okayama Prefecture, Japan.
Crystal system and space group: Isometric, \(\text{Ia}\overline{3}d\). Structure not yet refined.
Original or oldest description: Henmi et al. (1995)

Palenzonaita
End-member formula: \([\text{Ca}_3][\text{Na}][\text{Mg}_2][\text{V}^3+]\text{O}_12\)
Group: Berzeliite
IMA number: 1986-111
Modifications: None
Etymology: For Andrea Palenzona (b. 1935), an Italian chemist.
Type locality: Molinello mine, Ne, Val Graveglia, Liguria, Italy.
Crystal system, space group and structure refinement: Isometric, \(\text{Ia}\overline{3}d\). Basso (1987); Nagashima and Armbruster (2012)
Original or oldest description: Basso (1987)

Pyrope
End-member formula: \([\text{Mg}_3][\text{Al}_2][\text{Si}]\text{O}_12\)
Group: Berzelite
IMA number: 1992-017
Modifications: None
Etymology: From the Greek ρυρόπος (pyroos) – firelike for its deep-red color.
Type locality: Bohemia (Czech Republic).
Crystal system, space group and structure refinement: Isometric, \(\text{Ia}\overline{3}d\). Novak and Gibbs (1971)
Synthetic material: Armbruster et al. (1992)
Original or oldest description: Recognized by Georgius Agricola (1546), but the name pyrope was introduced by A.G. Werner in 1800 (Dana 1892; Clark 1993).

Schäferite
End-member formula: \([\text{Ca}_2][\text{Mg}_3][\text{Na}][\text{V}^3+]\text{O}_12\]
Group: Garnet
IMA number: 1997-048
Modifications: None
Etymology: For Helmut Schäfer (b. 1931), an amateur German mineralogist who discovered the mineral.
Type locality: Bellberg volcano near Mayen, Eifel, Germany.
Crystal system, space group and structure refinement: Isometric, \(\text{Ia}\overline{3}d\). Krause et al. (1999)
Original or oldest description: Krause et al. (1999)

Schorlomite
End-member formula: \([\text{Ca}_3][\text{Ti}_3][\text{SiFe}^{2+}]\text{O}_12\)
Group: Schorlomite
IMA number: Grandfathered
Modifications: Extensive; see main text.
Etymology: For its resemblance to schorl.
Type locality: Magnet Cove, Hot Springs County, Arkansas, U.S.A.
Crystal system, space group and structure refinement: Isometric, \(\text{Ia}\overline{3}d\). Chakhmou radial and McCammon (2005)
Original or oldest description: Shepard (1846), Whitney (1849), and Rammelsberg (1850a, 1850b)

Spessartine
End-member formula: \([\text{Mn}^{2+}][\text{Al}_2][\text{Si}]\text{O}_12\)
Group: Garnet
IMA number: Grandfathered
Modifications: None
Etymology: From the Spessart Mountains, Germany.
Type locality: Sommer quarry, Wendelberg Mt., Spessart Mountains, Bavaria, Germany.
Crystal system, space group and structure refinement: Isometric, \(\text{Ia}\overline{3}d\). Novak and Gibbs (1971); for F-bearing, Smyth et al. (1990).
Synthetic material: Geiger and Armbruster (1997)
Original or oldest description: Recognized by M.H. Klaproth (1797), but the name spessartine was introduced by F.S. Beudant (1832) according to Dana (1892) and Clark (1993).

Toturite
End-member formula: \([\text{Ca}_3][\text{SiFe}^{2+}][\text{V}^3+]\text{O}_12\)
Group: Schorlomite
IMA number: 2009-033
Modifications: None
Etymology: From both the Totur River situated in Eltybyba village near the type locality and the name of a Balkarian deity and ancient warrior.
Type locality: Upper Chegem caldera, Kabardino-Balkaria, North Caucasus, Russia.
Crystal system and space group: Isometric, \(\text{Ia}\overline{3}d\). Structure not yet refined.
Original or oldest description: Galuskina et al. (2010c)

Usturite
End-member formula: \([\text{Ca}_3][\text{SiFe}^{2+}][\text{Zr}][\text{Fe}^{3+}]\text{O}_12\)
Group: Bitikleite
IMA number: 2009-053
Modifications: Originally described as bitikleite-(ZrFe) with the same formula.
Etymology: From the Ustur Mountain near the type locality.
Type locality: Upper Chegem caldera, Kabardino-Balkaria, North Caucasus, Russia.
Crystal system and space group: Isometric, \(\text{Ia}\overline{3}d\). Structure not yet refined.
Original or oldest description: Galuskina et al. (2010b)

Uvarovite
End-member formula: \([\text{Ca}_3][\text{Cr}^{3+}][\text{Si}]\text{O}_12\)
Group: Garnet
IMA number: Grandfathered
Modifications: None
Etymology: For Count Sergei Semenovich Uvarov (1786–1855), a Russian historian.
Type locality: Saranovskiy mine Biserskoye chromite deposit, Perm district, Urals, Russia (Pekov 1998).
Crystal system, space group and structure refinement: Isometric, \(\text{Ia}\overline{3}d\). Novak and Gibbs (1971)
For birefringent uvarovite: Wildner and Andrut (2001)
Original or oldest description: Hess (1832)

Yafsoanite
End-member formula: \([\text{Ca}_3][\text{Ti}^{4+}][\text{Zn}][\text{Si}]\text{O}_12\)
Group: ungrouped
IMA number: 1981-022
Modifications: Introduced with the idealized formula \((\text{Zn},\text{Ca},\text{Fe})_{0.3}\text{Pb}_{0.58}\text{Ti}_{0.04}\text{Zr}_{0.06}\text{O}_2\); current formula from Jarosch and Zemann (1989) and Mills et al. (2010).
Etymology: From the acronym Yafytskii Filial Sibirskogo Otdeleniya Akademii Nauk (Yakut Filial of the Siberian Branch of the Academy of Sciences).
Type locality: Kurunakh gold deposit, near Aldan, Yakutia, Russia (Pekov 1998).
Crystal system, space group and structure refinement: Isometric, \(\text{Ia}\overline{3}d\). Mills et al. (2010)
Original or oldest description: Kim et al. (1982)