Mineral of the Month Club October 2017

GROSSULAR var. GREEN

This month we are featuring the green variety of grossular, a calcium aluminum silicate and a member of the garnet group of minerals. Our write-up discusses grossular's mineralogy and gemology, and takes an in-depth look at the 13 garnet-group minerals.

OVERVIEW

PHYSICAL PROPERTIES

Chemistry: $Ca_3Al_2Si_3O_{12}$ (also written as $Ca_3Al_2(SiO_4)_3$) Calcium Aluminum Silicate
Often with traces of iron, chromium, manganese, or vanadium.
Class: Silicates
Subclass: Nesosilicates
Group: Garnet
Crystal System: Isometric (Cubic)
Crystal Habits: Usually as dodecahedrons or trapezohedrons, occasionally as octahedrons; also granular, compact, and massive.
Color: Orange, yellow, green, yellow-green, brown, and gray; less often pink, red, and purple; rarely white or colorless; occasionally multicolored.
Luster: Vitreous
Transparency: Transparent and translucent to nearly opaque
Streak: White to pale brownish-white
Cleavage: None
Fracture and Tenacity: Sub-conchoidal to uneven; brittle.
Hardness: 6.5-7.0
Specific Gravity: 3.4-3.7
Luminescence: Occasionally fluoresces pale orange in long-wave ultraviolet light and pale yellow-orange in shortwave ultraviolet light.
Refractive Index: 1.738-1.745
Distinctive Features and Tests: Best field identification marks are dodecahedral or trapezohedral crystal habits; relatively high specific gravity; hardness; and occurrence in contact-metamorphic and skarn environments. Grossular can be easily confused with other garnet-group minerals such as spessartine [manganese aluminum silicate, $Mn_3Al_2Si_3O_{12}$].
Dana Mineral-Classification Number: 51.4.3b.2

NAME: The word "grossular," pronounced GRAHS-yu-lahr, is derived from the Latin *Grossularia*, the botanical genus name for gooseberry, alluding to the gooseberry's similarity in color to certain grossular varieties. Grossular is also known as "grossularite," "African jade," "Transvaal jade," "Mali garnet," "garnet jade," "vilouite," "grossular garnet," "ernite," and "kanelstein." In European mineralogical literature, grossular appears as *grossularia*, *grosularia*, and *Grossularit*. Grossular's color-variety names include emerald-green tsavorite, orange hessonite, raspberry-red rosolite, and colorless leuco-garnet. The word "garnet" stems from the Anglo-French *pume gernete*, or pomegranate, referring to the fruit's pulpy, crimson-colored arils that resemble small, red garnet crystals.

COMPOSITION & STRUCTURE: Grossular consists of 26.69 percent calcium, 11.98 percent aluminum, 18.71 percent silicon, and 42.62 percent oxygen. Grossular often contains variable amounts of iron, chromium, manganese, and vanadium that substitute for calcium and aluminum. Grossular is a member of the silicates, the largest and most abundant class of minerals. Silicates consist of silicon and oxygen combined with one or more metals. The basic silicate structural unit is the silica tetrahedron $(SiO_4)^{4-}$, in which four equally spaced oxygen ions positioned at the corners of a tetrahedron (a four-faced polygon) surround a single silicon ion. All garnet-group minerals are nesosilicates, in which metal cations are packed tightly between isolated silica tetrahedra with no direct silica-silica bonding. Close atomic packing gives the garnet-group members a very substantial hardness, with most species exceeding Mohs 7.0. Garnet-group minerals crystallize in the isometric (cubic) system, which has three axes of symmetry, all of equal length and at right angles to each other. Isometric crystals are usually blocky in shape, with many similar, symmetrical faces. Common cubic-system habits are 6-sided cubes or hexahedrons, 8-sided octahedrons, 12-sided dodecahedrons, and 24-sided trapezohedrons in singular or combined habits. When pure or nearly pure, grossular is colorless. But small amounts of iron and manganese create reds, oranges, yellows, purples, browns, and variations of these colors. Traces of chromium and vanadium result in green colors. Grossular has the widest color range of all garnet-group minerals. It occurs in contact-metamorphic environments such as skarns which form when magma intrudes formations of limestone or dolomite rock.

COLLECTING LOCALITIES: Grossular is collected in Mexico, Canada, Brazil, Austria, Germany, Italy, Switzerland, Sweden, Romania, China, India, Japan, Kenya, Madagascar, Mali, Namibia, Myanmar, Pakistan, Sri Lanka, Tanzania, Russia, and the United States (Alaska, Arkansas, Colorado, Connecticut, Idaho, Maine, Montana, New Mexico, North Carolina, Pennsylvania, Texas, Vermont, Wisconsin).

JEWELRY & DECORATIVE USES: Due to their abundance, wide distribution, hardness, durability, workability, and range of attractive colors, garnet-group minerals have served as gemstones since antiquity. With its many colors, grossular has several gem varieties. Tsavorite, the green, transparent gem variety, is one of the most valuable of all garnet gemstones. Mali garnet is a transparent variety with yellowish-brown-to-brown colors; hessonite is a transparent variety with orange and brownish-orange to brownish-red colors; African jade (Transvaal jade) is a green, massive form. Most garnet gemstones are mined from alluvial deposits by hydraulic separation. The value of gem-garnet production in the United States is poorly documented, but the United States Geological Survey estimates that about $250,000 worth of rough gem garnets are mined annually. Grossular and other garnet-group minerals are collected as specimens for their distinctive dodecahedral or trapezohedral habits, wide range of colors, and interesting mineralogical associations. Collectors' gems cut from garnet-group minerals are popular in sizes of 10-20 carats.

HISTORY, USES & LORE: In 1803, German geologist and mineralogist Abraham Gottlob Werner (1749-1817) studied specimens of a previously unknown type of garnet with both reddish and greenish colors from the Isle of Mull in Scotland. He realized that these specimens represented a new species which he named "cinnamon stone" (*Kanelstein* in German). In 1808, after studying an abundance of greenish specimens, he changed the name of the new species to "grossular," alluding to the color similarity to gooseberries (botanical genus name *Grossularia*). Garnet minerals have served as industrial abrasives since the 1880s. Garnet-group minerals are as hard or slightly harder than quartz (Mohs 7.0), but make superior abrasives. Unlike quartz, the density of garnet abrasives allows them to be inexpensively recovered for reuse by hydraulic separation. Also unlike quartz, garnet does not become smooth with wear, but fractures into sharp-edged, durable bits that retain their abrasive properties. About 1.7 million metric tons of crude, industrial-garnet concentrate worth $300 million are recovered worldwide each year. The leading producers of industrial garnet are Australia, China, and India. The United States annually produces 50,000 metric tons of industrial-garnet concentrate worth $9 million. Modern metaphysical practitioners believe that garnet enhances compassion, love, imagination, and creativity, teaches patience, and strengthens the mind and body in times of need. Grossular is specifically thought to facilitate recovery from illness and trauma, soothe and reduce emotional anxiety, release long-held feelings of inadequacy, and encourage trust to increase socialization. Grossular is the official state gemstone of Vermont.

ABOUT OUR SPECIMENS: Our grossular specimens were collected at Sierra de Cruces (Mountain of Crosses) in Coahuila, Mexico. Sierra de Cruces is located in the high plateau country of western Coahuila, 125 miles due south of Big Bend National Park in Texas. Sierra de Cruces is a 6,644-foot-high ridge that is the surface manifestation of a diorite intrusion and a massive, geological skarn. Skarns form when magma intrudes strata of limestone or dolomite rock. Our grossular specimens were collected from outcrops near the base of Sierra de Cruces. Specimen-quality grossular was discovered at Sierra de Cruces in 1947, but its remoteness, along with the small specimen market that existed at the time, initially made commercial collecting impractical. In 1974, a local rancher discovered outcrops with large crystals of pink-to-red grossular and staked mineral claims on the site. Collecting at Sierra de Cruces is difficult because of the rugged terrain, summer heat, arid climate, and numerous rattlesnakes, scorpions, and tarantulas.

COMPREHENSIVE WRITE-UP

COMPOSITION & STRUCTURE

The garnet-group minerals that we have previously featured as Mineral of the Month have included almandine in March 1997, spessartine in August 1998 and March 2005, uvarovite in February 2001, grossular in December 2002, andradite in March 2009, and almandine in July 2016.

Grossular, chemical formula $Ca_3Al_2Si_3O_{12}$ [sometimes expressed as $Ca_3Al_2(SiO_4)_3$], consists of calcium (Ca), aluminum (Al), silicon (Si), and oxygen (O). Grossular's molecular weight is made up of 26.69 percent calcium, 11.98 percent aluminum, 18.71 percent silicon, and 42.62 percent oxygen. Like all molecules, those of grossular consist of positively charged ions called cations and negatively charged ions called anions. Grossular's compound cation is made up of three divalent calcium ions $3Ca^{2+}$ and two trivalent aluminum ions $2Al^{3+}$ that provide a cumulative +12 charge. Grossular's anion consists of three silica radicals $3(SiO_4)^{4-}$. Radicals are groups of ions of different elements that act as entities in chemical reactions. Within the $(SiO_4)^{4-}$ radical, one silicon ion Si^{4+} is bound to four oxygen ions $4O^{2-}$. The cumulative -12 anionic charge of the three silica anions balances the cumulative +12 cationic charge of the calcium and aluminum cations to provide the grossular molecule with electrical stability. Grossular often contains variable amounts of iron, manganese, chromium, and vanadium that substitute for calcium and aluminum.

Grossular is a member of the silicates, the largest and most abundant class of minerals. Silicates consist of silicon and oxygen combined with one or more metals. The basic silicate structural unit is the silica tetrahedron $(SiO_4)^{4-}$, in which four equally spaced oxygen ions positioned at the corners of a tetrahedron (a four-faced polygon) surround a single silicon ion. The oxygen ions are bonded to the silicon ion by strong covalent bonding. In silicate minerals, silica anions and metal cations link together like polymers (repeating chains) to form seven types of structures: double tetrahedral silicates (sorosilicates); framework silicates (tectosilicates); single- and double-chain silicates (inosilicates); ring silicates (cyclosilicates); sheet silicates (phyllosilicates);and independent tetrahedral silicates (nesosilicates).

All garnet-group minerals are nesosilicates, which consist of metal cations packed tightly between isolated silica tetrahedra with no direct silica-silica bonding. In the rigid nesosilicate crystal lattice, the silica anions are bound only to metal cations. In the grossular molecule, three divalent calcium ions $3Ca^{2+}$ and two trivalent aluminum ions $2Al^{3+}$ are positioned between three silica tetrahedra $3(SiO_4)^{4-}$. Eight oxygen ions closely surround each calcium ion, and six oxygen ions surround each aluminum ion. This close atomic packing strengthens the ionic bonding between the silica anions and the metal cations.

Close atomic packing gives the garnet-group members a substantial hardness, with many species exceeding Mohs 7.0. Grossular is somewhat of an exception, because the large radii of both the calcium and aluminum ions create longer inter-ionic distances within the crystal lattice, thus slightly weakening the bonding strength. As a result, grossular is the least-hard garnet-group mineral at Mohs 6.5-7.0. Grossular is also the least dense garnet-group mineral (specific gravity 3.4-3.7) due to calcium's relatively low atomic weight (40.08), and also to the large radii of the calcium and aluminum ions which increase the inter-ionic distances.

All garnet-group minerals crystallize in the isometric (cubic) system, which has three axes of symmetry, all of equal length and at right angles to each other. Isometric crystals are usually blocky in shape, with many similar, symmetrical faces. Common cubic-system habits are 6-sided cubes or hexahedrons, 8-sided octahedrons, 12-sided dodecahedrons, and 24-sided trapezohedrons, often in combined habits. Minerals that crystallize in the isometric system are usually chemically simple, such as pyrite [iron disulfide, FeS_2] and halite [sodium chloride, NaCl]. The garnet-group minerals, with their moderate levels of chemical complexity, are an exception. They are also among the few silicate minerals that crystallize in the cubic system.

Minerals are categorized either as idiochromatic (self-colored) or allochromatic (other-colored). In idiochromatic minerals, color is caused by essential elemental components and/or the nature of the crystal lattice; the color of allochromatic minerals is caused by nonessential elemental impurities called chromophores (color-causing agents). Grossular is an allochromatic mineral because its two essential metal ions, calcium and aluminum, do not impart colors. When pure or nearly pure, grossular is colorless. But traces of iron and manganese create orange-red, purplish-red, brownish-red, purple, and pink colors. Traces of chromium and vanadium result in green colors. Grossular has the widest color range of all garnet-group minerals because its "looser" crystal lattice and slightly weaker atomic bonding facilitate the acceptance of a variety of accessory chromophoric ions.

Although transparent grossular crystals are not uncommon, most crystals are translucent or nearly opaque due to inclusions. These inclusions consist of tiny, well-developed crystals of fluorapatite [calcium fluorophosphate, $Ca(PO_4)_3F$], zircon [zirconium silicate, $ZrSiO_4$], spinel [magnesium aluminum oxide, $MgAl_2O_4$], and rutile [titanium dioxide, TiO_2]. Some grossular crystals exhibit "feather" and "bubble" inclusions known as "fingerprint" inclusions because they are source-unique.

Through cationic substitution, grossular forms partial solid-solution series with the garnet-group minerals pyrope [magnesium aluminum silicate, $Mg_3Al_2Si_3O_{12}$], almandine iron aluminum silicate, $Fe_3Al_2Si_3O_{12}$], and spessartine [manganese aluminum silicate, $Mn_3Al_2Si_3O_{12}$]. In these series, magnesium, iron, and manganese partially substitute for calcium in the grossular crystal lattice.

Grossular occurs primarily in contact-metamorphic environments and in skarns, which form when magma intrudes limestone or dolomite rock. The heat and pressure that accompany magmatic intrusions initially causes contact metamorphism wherever magma contacts the host rock. Associated hot, acidic solutions then circulate to react with the carbonates in the limestone or dolomite rock to create unusual minerals. In skarn deposits, grossular is associated with such minerals as calcite [calcium carbonate, $CaCO_3$], hedenbergite [calcium iron silicate, $CaFeSi_2O_6$], magnetite [iron oxide, Fe_3O_4], tremolite [basic calcium magnesium silicate, $Ca_2Mg_5Si_8O_{22}(OH)_2$], andradite [garnet group, calcium iron silicate, $Ca_3Fe_2(Si3O_{12}$], vesuvianite [basic calcium aluminum magnesium iron oxyfluorosilicate, $Ca_{19}(Al,Mg,Fe)_{13}Si_{18}O_{68}(O,OH,F)_{10}$], diopside [calcium magnesium silicate, $CaMgSi_2O_6$], and wollastonite [calcium silicate, $CaSiO_3$]. Like other garnet-group minerals, grossular that weathers free from its host rocks has sufficient density to concentrate in placer deposits.

The Dana mineral-classification number 51.4.3b.2 first identifies grossular as a nesosilicate with silica groups present in the $(SiO_4)^{4-}$ configuration (51). Grossular is subclassified (4) by silica anions in coordinations of six or less. As seen in its formula $Ca_3Al_2Si_3O_{12}$, grossular's silica-anion coordination is three. Grossular is then assigned to the garnet group (3) and the "ugrandite" series (b) as the second (2) of four members. The other members of this garnet subgroup are andradite [calcium iron silicate, $Ca_3Fe_2Si_3O_{12}$], uvarovite [garnet group, calcium chromium silicate, $Ca_3Cr_2Si_3O_{12}$], and goldmanite [calcium vanadium silicate, $CaVSi_3O_{12}$]. These all have similar chemistries that vary only in cationic composition (see "A Close Look at the Garnet-Group Minerals").

COLLECTING LOCALITIES

Our grossular specimens are from Sierra de Cruces, Sierra Mojada, Coahuila, Mexico. Canadian sources include the Jeffrey Mine at Asbestos, Les Sources Regional County Municipality; and the Maple Leaf, Montreal Chrome, Lake Asbestos, and British Canadian Nos. 1 and 2 mines near Thetford Mines in Chaudiér-Appalaches Regional County Municipality, all in Québec. Among Brazil's localities are the Bola do Laje Mine at Currais Novos, Rio Grande do Norte; the Romaria Mine in the Coromandel District, Minas Gerais; and the mines at Itajubatiba, Paraíba.

In Europe, grossular is found at the Wollanig marble quarry in the Afritz Mountains near Villach, Carinthia, Austria; the Schneeberg mines at Erzegebirge, Saxony, Germany; the San Vito Quarry at Mt. Vesuvius, Naples Province, Campania, Italy; Piz Lunghin in the Bregaglia Valley near Casaccio, Grischun, Switzerland; the Långban mines at Filipstad and the Jakobsberg Mine at Nordmark, both in Värmland, Sweden; and the Cerboaia Valley, Albo County, Romania.

Other sources are the Fushan iron deposit, Xingtai County, Xingtai Prefecture, Hebei Province, China; the Ambaji deposit, Sirohi District, Rajputana, India; Mt. Ohsa at Ohsa-cho, Okayama Prefecture, Chugoku Region, Honshu Island, Japan; the Turkana and Kaiado districts in Rift Valley Province, and the Scorpion Mine in the Taita Taveta district in Coastal Province, both in Kenya; the Tsavorite Mine, Gogogogo Commune, Ampanihy district, Diana Region, Tuléar Province, Madagascar; the Sandaré and Diakon communes, Keyes Region, Mali; the Schonfeld and Rodina tungsten prospects in the Karibib district in the Erongo Region and the Kombat Mine at Kombat in the Grootfontein district in the Otjozondjupa Region, both in Namibia; the Mogok mines, Pyin-Oo-Lwin district, Mandalay Region, Myanmar; Alchuri, Skarov district, Shigar Valley, Baltistan, Northern Areas, Pakistan; the Ratnapura gem gravels, Ratnapura district, Sabagamuwa Province, Sri Lanka; and the Melani Hills, Simonjiro district, Manyara Region, Tanzania. In Russia, grossular occurs at the Lupikko Mine in the Pitkyakanta district, Karelia Republic, Northern Region; and the Yoko-Dovyrensky Massif near Lake Baikal in Irkutskaya Oblast' and the Vilyui River Basin, Sakha Republic, both in Eastern-Siberian Region.

Grossular sources in the United States include the Green Monster Mine, Prince of Wales Island, Prince of Wales-Outer Ketchikan Borough, Alaska; the Kimzey, Jones Mill, and Cover Creek quarries at Magnet Cove, Hot Spring County, Arkansas; the Camp Bird Mine at Ouray, Ouray County, Colorado; the Worth and Selden quarries, East Hampton, Middlesex County, Connecticut; the Peacock Mine, Cuprum, Seven Devils district, Adams County, Idaho; the

Pulsifer Quarry, West Mount Apatite district, Auburn, Androscoggin County, Maine; the Pipestone Mine at Bald Mountain, Jefferson County, Montana; the Magdalena district mines, Socorro County, New Mexico; the Foote Lithium Mine, Kings Mountain district, Cleveland County, North Carolina; the French Creek mines, St. Peters, Warwick Township, Chester County, Pennsylvania; Blount Mountain in Llano County and the Silver King Mine in the Quitman Mountains of Hudspeth County, both in Texas; the Belvedere quarries at Lowell and Eden in Orleans and Lamoille counties, Vermont; and the Rotten Granite quarries in the Wausau Intrusive Complex, Marathon County, Wisconsin.

JEWELRY & DECORATIVE USES

Because of their abundance, hardness, durability, and wide range of attractive colors, garnet-group minerals have served as gemstones since antiquity. Red garnet cabochons, called "carbuncles," were fashioned as early as 4000 B.C. Archaeologists have recovered grossular amulets and talismans from 5,000-year-old Egyptian tombs and from 3,000-year-old cultural sites in northern Europe. By 1400 A.D., red garnet, including grossular, was popular as a faceted gem due to its resemblance to the ruby variety of corundum [aluminum oxide, Al_2O_3]. Garnets are among the few gemstones that are never treated to enhance their colors. Because scientists did not differentiate individual garnet species until the 1800s, all garnet-group gemstones were traditionally referred to simply as "garnet." Today, the jewelry industry continues to market red garnet-group gems under the generic name "garnet," rather than the actual species names. Only non-red garnet gems, such as the green tsavorite variety of grossular and the green demantoid variety of andradite [calcium iron silicate, $Ca_3Fe_2Si_3O_{12}$], are marketed under their mineral or variety names.

The primary grossular gem varieties include:

Tsavorite: This transparent, emerald-green variety of grossular is among the most valuable of all garnet gems. Its distinctive green color is due to traces of chromium and/or vanadium. Tsavorite was discovered in 1967 by Scottish geologist Campbell Bridges (1938-2009) in the mountains of Tanzania. Although Bridges' samples interested jewelers, he could not, at the time, obtain a government permit to mine the stones. Noting that the geological structure in which the stones occurred extended beyond the Tanzanian border, Bridges began prospecting in adjacent Kenya. In 1971, he discovered a deposit near Kenya's Tsavo East National Park and began mining the stones. In 1974, the New York City-based, international jewelry designer and retailer Tiffany & Co. named the stone "tsavorite" after its source and promoted it widely. Although the largest known tsavorite crystal weighed 925 carats and was cut into a 325-carat gem, most tsavorite gems rarely exceed four or five carats in size. Today, top-quality, transparent, bright-green tsavorite gems of three or four carats sell for as much as $4,000 per carat. Yellow-green tsavorite gems are much more affordable. Campbell Bridges, the geologist who discovered tsavorite, was killed in Kenya in 2009 in a violent dispute over his gemstone properties.

Mali Garnet: Another newcomer to the gemstone markets, Mali garnet is transparent with yellowish-brown-to-brown colors. Mali garnet is part of the grossular-andradite solid-solution series and contains significant amounts of iron. It was discovered in Mali in 1994. Initially Mali garnet prices were very high, but when increased mine production brought prices down, its popularity soared. Mali garnet gems now cost about $300 per carat.

Hessonite: Hessonite is transparent with orange, brownish-orange, and brownish-red colors. Traces of manganese account for its color. The name "hessonite" derives from the Greek *hēsson*, meaning "inferior," alluding to the fact that its hardness is somewhat less than that of other garnets. Hessonite gems with rich colors cost about $200 per carat.

African Jade, also called Transvaal jade, is massive, green grossular. Translucent to opaque, it has an olive-green color and is fashioned into cabochons, beads, and decorative items. It is named for its origin in southern Africa and its similarity in color to certain types of jade.

Most garnet gemstones are recovered from alluvial deposits by hydraulic separation. The value of gem-garnet production in the Unites States is poorly documented, but the United States Geological Survey estimates that about $250,000 worth of rough gem garnets are mined annually.

All garnet-group members, including grossular, are collected as specimens for their distinctive dodecahedral or trapezohedral habits, range of colors, and interesting mineralogical associations.

HISTORY & LORE

Some historians have suggested that grossular was one of the 12 gemstones of the biblical breastplate of Aaron, high priest of the ancient Hebrews. In medieval times, European crusaders wore red garnets for protection in battle and to ensure their safe return; physicians of that era believed that red garnets offered protection from poisons and helped cure infections and blood-related maladies.

Because of their chemical complexity, similar physical properties, and tendency to form solid-solution series, mineralogists were unable to distinguish between individual garnet species until the early 1800s. Improved chemical-analysis techniques first enabled them to distinguish pyrope from almandine in 1803. That same year, German geologist and mineralogist Abraham Gottlob Werner (1749-1817) was studying specimens of a new type of garnet with both reddish and greenish colors from the Isle of Mull in Scotland. Determining that this mineral was rich in calcium and thus constituted a new species, he named it "cinnamon stone" (*Kanelstein* in German). In 1808, after studying an abundance of greenish specimens, he renamed this new species "grossular," alluding to their color similarity to that of gooseberries (botanical genus name *Grossularia*).

The ability to positively distinguish all garnet species required the later development of mass-spectrography and other advanced quantitative-analysis methods capable of detecting subtle differences in chemical composition. Mineralogists most recently described a new garnet-group mineral in 2009.

Red garnet-group gems are the birthstone for January. Grossular was named the official state gemstone of Vermont in 1991. At least six garnet-group minerals have been featured on postage stamps. Grossular has appeared on Kenya's 40-shilling stamps of 1977 and 1992.

Modern metaphysical practitioners believe that garnet enhances compassion, love, imagination, and creativity, teaches patience, and strengthens the mind and body in times of need. Grossular is specifically thought to facilitate recovery from illness and trauma, soothe and reduce emotional anxiety, release long-held feelings of inadequacy, and encourage trust to increase socialization.

A CLOSE LOOK AT THE GARNET-GROUP MINERALS

In its mineralogical context, the word "garnet" is a group name for 13 closely related, isomorphic (same form), nesosilicate minerals. These isostructural minerals crystallize in the isometric (cubic) system, usually as dodecahedrons or trapezohedrons with rhombic (diamond-shaped) or modified-rhombic faces. Garnet-group minerals are most familiar in shades of red, but occur in every color except blue.

In the Dana mineral-classification system, the general formula for garnet-group minerals is $A_3B_2Si_3O_{12}$, with "A" representing the divalent metal ions calcium (Ca^{2+}), magnesium (Mg^{2+}), iron (ferrous, Fe^{2+}), and manganese (Mn^{2+}); "B" represents the trivalent metallic ions aluminum (Al^{3+}), chromium (Cr^{3+}), iron (ferric, Fe^{3+}), vanadium (V^{3+}), titanium (Ti^{3+}), and zirconium (Zr^{3+}).

Only 6 of the 13 garnet-group minerals are common. In order of abundance, these are almandine, pyrope, andradite, grossular, spessartine, and uvarovite. These six minerals are classified into two subgroups: the "pyralspite" (PYRope, ALmandine, and SPessartine) subgroup and the "ugrandite" (Uvarovite, GRossular, and ANDradite) subgroup. The aluminum ion Al^{3+} is the common trivalent cation in the pyralspite subgroup; the calcium ion Ca^{2+} is the common divalent cation in the ugrandite subgroup. The Dana mineral-classification system chemically classifies the garnet-group members into the pyralspite, ugrandite, and schorlomite-kimzeyite subgroups as follows:

51.4.3a Pyralspite Subgroup

51.4.3a.1	pyrope	magnesium aluminum silicate	$Mg_3Al_2Si_3O_{12}$
51.4.3a.2	almandine	iron aluminum silicate	$Fe_3Al_2Si_3O_{12}$
51.4.3a.3	spessartine	manganese aluminum silicate	$Mn_3Al_2Si_3O_{12}$
51.4.3a.4	knorringite	magnesium chromium silicate	$Mg_3Cr_2Si_3O_{12}$
51.4.3a.5	majorite	magnesium silicon silicate	$Mg_3(SiMg)Si_3O_{12}$
51.4.3a.6	calderite	manganese iron silicate	$Mn_3Fe_2Si_3O_{12}$

51.4.3b Ugrandite Subgroup

51.4.3b.1	andradite	calcium iron silicate	$Ca_3Fe_2Si_3O_{12}$
51.4.3b.2	grossular	calcium aluminum silicate	$Ca_3Al_2Si_3O_{12}$
51.4.3b.3	uvarovite	calcium chromium silicate	$Ca_3Cr_2Si_3O_{12}$
51.4.3b.4	goldmanite	calcium vanadium silicate	$Ca_3V_2Si_3O_{12}$

51.4.3c Schorlomite-Kimzeyite Subgroup

51.4.3c.1	schorlomite	calcium titanium iron silicate	$Ca_3(Ti,Fe)_2Si_3O_{12}$
51.4.3c.2	kimzeyite	calcium zirconium titanium alumnoferrisilicate	$Ca_3(Zr,Ti)_2(Si,Al,Fe)_3O_{12}$
51.4.3c.3	morimotoite	calcium titanium iron silicate	$Ca_3TiFeSi_3O_{12}$

These formulas represent ideal chemical compositions that may not occur in nature. With the exception of kimzeyite, all garnet-group members adhere to the general chemical formula $A_3B_2Si_3O_{12}$. The members of each subgroup substitute metal cations to form partial or complete, graded, solid-solution series. Because of their similar crystal structures and tendency to form solid-solution series, positive identification of the garnet-group members often requires laboratory analysis.

TECHNOLOGICAL USES

Since the 1880s, grossular and other garnet-group minerals have served as industrial abrasives. Abundant and about as hard as quartz, garnet is the preferred abrasive for industrial uses. Unlike quartz abrasives, garnet abrasives can be reused. Because of their density, they can be inexpensively recovered by hydraulic separation. Also unlike quartz, garnet does not become smooth with wear, but fractures into sharp-edged, durable bits that retain their abrasive properties. Garnet abrasives fill an economic niche between inexpensive quartz sand and costly synthetics. Garnet is the grit in “garnet paper” used to smooth and polish wood, plastic, glass, and metal; highly refined garnet dust is a polishing agent for fine optics. Garnet also serves as a water-jet cutting agent. The petroleum industry uses large quantities of garnet abrasives to scour drill steel and well casings. Garnet has replaced quartz in many abrasive applications for health reasons: Inhaling quartz dust causes the industrial pulmonary disease silicosis, but garnet dust does not damage lung tissues.

Although garnet-group minerals are relatively abundant, commercial deposits are scarce. Most industrial-grade garnet is recovered from alluvial deposits by dredging and sluicing. Lesser amounts are obtained as by-products of feldspar mining. About 1.7 million metric tons of crude, industrial-garnet concentrate worth $300 million are recovered worldwide each year. The leading producers are Australia, China, and India. The United States annually produces about 50,000 metric tons of crude, industrial-garnet concentrate worth $9 million. Crude garnet concentrate costs $180 per metric ton; sized and cleaned, it sells for $280 per metric ton. Four American companies operating mines in Montana, Idaho, and New York account for all domestic, industrial-garnet production. In the United States, 35 percent of the garnet supply is used as water-jet-cutting agents, 30 percent as abrasive-blasting agents, 20 percent as water-filtration material, and 10 percent as polishing powders. The remaining five percent is used as polishing grit for fine optics and metal surfaces, and to manufacture abrasive papers and coated abrasives. Small quantities of garnet are also mined as gemstones (See "Jewelry & Decorative Uses").

ABOUT OUR SPECIMENS

Our grossular specimens were collected at Sierra de Cruces (Mountain of Crosses) in Coahuila, Mexico. One of Mexico's 31 states, Coahuila is located in north-central Mexico and is bounded by the United States (Texas) on the north, and the Mexican states of Chihuahua and Durango on the west, Zacatecas on the south, and Nuevo León on the east. Coahuila has a population of 3.2 million; with an area of 57,727 square miles, it is roughly the size of the American state of Iowa.

Sierra de Cruces is 125 miles due south of Big Bend National Park in Texas in the high plateau country of western Coahuila. The regional plateau topography is broken by the foothills of the northern Sierra Madre Oriental. This part of the Chihuahuan Desert is very arid with vegetation largely limited to agave, mesquite, and creosote. Western Coahuila is sparsely populated, with sprawling cattle ranches and small, remote villages, the largest being the company town of Hercules that serves the Hercules Mine, Mexico's largest iron mine.

Sierra de Cruces is a 6,644 foot-high ridge that is the surface manifestation of a diorite intrusion and a massive, geological skarn. Skarns form when magma intrudes strata of limestone or dolomite rock. Limestone is a sedimentary rock consisting mainly of calcite [calcium carbonate, $CaCO_3$]; dolomite rock is a sedimentary rock consisting primarily of the mineral dolomite [calcium magnesium carbonate, $CaMg(CO_3)_2$]. The heat and pressure associated with magmatic intrusions initially causes contact metamorphism where magma contacts the host rock. Associated hot, acidic solutions then react with the carbonates in the host rock to create unusual minerals. The host rocks supply calcium, magnesium, and carbon dioxide, while the magma provides silicon, aluminum, iron, and other elements. Skarns are characterized by such silicate minerals as grossular, vesuvianite [basic calcium aluminum magnesium iron oxyfluorosilicate, $Ca_{19}(Al,Mg,Fe)_{13}Si_{18}O_{68}(O,OH,F)_{10}$], wollastonite [calcium silicate, $CaSiO_3$], diopside [calcium magnesium silicate, $CaMgSi_2O_6$], tremolite [basic calcium magnesium silicate, $Ca_2Mg_5Si_8O_{22}(OH)_2$], and andradite [garnet group, calcium iron silicate, $Ca_3Fe_2Si_3O_{12}$]. Skarns often host economic mineral deposits.

The limestone and dolomite rock at Sierra de Cruces was laid down in mid-Cretaceous time when the region was covered by a shallow sea. At the end of the late Cretaceous Period some 65 million years ago, tectonic stresses fractured the crust to enable dioritic magma to rise into the limestone and dolomite rock and create a massive skarn. Erosion later reduced the surface, but the diorite intrusion and its associated skarn formations—both consisting mainly of durable silicate minerals—resisted erosion, leaving the large, weathered intrusion and skarn elevated above the surrounding plateau as today's Sierra de Cruces.

Sierra de Cruces is reached by a dirt road from the town of Hercules, 25 miles to the north on the Coahuila-Chihuahua state line. Hercules and the Hercules iron mine are located at the northwest end of Sierra de Cruces. The Hercules iron deposit consists primarily of magnetite [iron oxide, Fe_3O_4], with lesser amounts of goethite [basic iron oxide, FeO(OH)] and hematite [iron oxide, Fe_2O_3]. This deposit was discovered in 1890, but its remoteness and inaccessibility, along with confusion over the disputed Coahuila-Chihuahua boundary prevented mining for decades. Altos Hornos de Mexico, S.A. de C.V., a major Mexican mining company, finally developed the deposit in the 1970s and built a company town for its employees. Today, all 3,200 adult residents work directly or indirectly for the Hercules Mine, which consists of both open pits and underground workings. The ore is crushed and concentrated at the site, then converted to slurry and pumped through a 180-mile-long pipeline to the Altos Hornos steel plant at Monclova, Coahuila.

Specimen-quality grossular was discovered at Sierra de Cruces in 1947. But the site's remoteness, along with the limited specimen market that existed at the time, made commercial collecting impractical. In 1974, a local rancher discovered outcrops with large crystals of pink-to-red grossular and staked mineral claims. By then, a graded gravel road serving the Hercules iron mine had improved access to Sierra de Cruces. Since that time, quantities of reddish and greenish grossular have reached specimen markets in the United States. Collecting at Sierra de Cruces is difficult because of the rugged terrain, summer heat, arid climate, and numerous rattlesnakes, scorpions, and tarantulas.

As you study your specimen, note first the basic dodecahedral structure and pentagonal faces of the grossular crystals, which are diagnostic garnet features. Some crystals may exhibit a modified dodecahedral-cubic habit with diamond-like, rhombic faces. The crystals are translucent to nearly opaque and have a pale, olive-green color. The grossular crystals rest in a matrix of wollastonite [calcium silicate, $CaSiO_3$].

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