

# Mineral of the Month Club September 2016

## MOTTRAMITE

This month we are featuring mottramite from Mexico's famed Ojuela Mine. This is the first time we have featured this uncommon basic lead copper vanadate as our Mineral of the Month. Our write-up discusses mottramite's history, properties, and occurrence, and explains the nature of solid-solution series.

### OVERVIEW

#### PHYSICAL PROPERTIES:

Chemistry:  $\text{PbCu}(\text{VO}_4)(\text{OH})$  Basic Lead Copper Vanadate (Lead Copper Vanadate Hydroxide), usually containing varying amounts of zinc.

Class: Phosphates, Chromates, Arsenates, and Vanadates

Subclass: Anhydrous Vanadates

Group: Descloizite

Crystal System: Orthorhombic

Crystal Habits: Usually occurs as drusy growths of tiny, intergrown, equant, dipyramidal crystals that form encrustations, plume-like and arborescent aggregates, and botryoidal masses with radiating, internal structures. Mottramite also occurs in compact and massive forms. Crystals often exhibit stepped growth and zoned coloration.

Color: Usually various shades of green, yellowish-green, or brownish-green; occasionally brownish-red, brownish-yellow, brownish-black, gray, or nearly black. Mottramite is pleochroic, with colors shifting between green and yellowish-green when viewed along different crystal axes.

Luster: Greasy

Transparency: Transparent to opaque

Streak: Yellowish-green to brownish-green

Refractive Index: 2.170-2.320

Cleavage: None

Fracture and Tenacity: Subconchoidal to uneven; brittle.

Hardness: 3.0-3.5

Specific Gravity: 5.9-6.0

Luminescence: None

Distinctive Features and Tests: Green, yellowish-green, or brownish-green colors; high specific gravity; ready solubility in acids; occurrence in oxidized zones of vanadium-bearing, base-metal deposits; and frequent association with malachite [basic copper carbonate,  $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$ ] and descloizite [basic lead zinc vanadate,  $\text{PbZn}(\text{VO}_4)(\text{OH})$ ].

Dana Mineral-Classification Number: 41.5.2.2

**NAME:** Mottramite, pronounced MAH-trahm-ite, is named for Mottram St. Andrew, Cheshire, England, where the type specimens were obtained. Mottramite has also been known as “cuprodescloizite” and “psittacinite.” “Duhamelite” is a calcium- and bismuth-rich variety. In European mineralogical literature, mottramite appears as *Mottramit* and *mottramita*.

**COMPOSITION & STRUCTURE:** Mottramite’s ideal molecular weight is made up of 51.45 percent lead, 15.78 percent copper, 12.65 percent vanadium, 19.87 percent oxygen, and 0.25 percent hydrogen. Mottramite is one of the nearly 300 members of the Phosphates, Chromates, Arsenates, and Vanadates class of minerals. As a vanadate mineral, its basic building block is the vanadate ion  $(VO_4)^{3-}$ , a tetrahedral structure in which four oxygen ions surround and bond covalently to a vanadium ion. Mottramite crystallizes in the orthorhombic system, which is characterized by three mutually perpendicular axes of different lengths, an arrangement that is reflected in the dipyramidal shape of the mottramite crystal. Minerals such as mottramite that have chemical complexity or complex bonding arrangements tend to crystallize in the orthorhombic system. As an idiochromatic or “self-colored” mineral, the basic color of mottramite is caused by its essential elements and the nature of its crystal structure. Copper is a strong, blue-green chromophore (color-causing agent); vanadate anions are also chromophoric and produce orange-red colors. These two chromophores combine in mottramite crystals to produce green, yellowish-green, or brownish-green colors. The presence of accessory elements often modifies these basic colors. Because mottramite is pleochroic, its color varies somewhat when viewed from different directions. Mottramite forms exclusively in the shallow, oxidized zones of vanadium-bearing, base-metal deposits in conditions of relatively low temperature and pressure, and is almost always associated with descloizite and malachite, and often with duftite [basic lead copper arsenate,  $PbCu(AsO_4)(OH)$ ], mimetite [lead chloroarsenate,  $Pb_5(AsO_4)_3Cl$ ], wulfenite [lead molybdate,  $PbMoO_4$ ], cerussite [lead carbonate,  $PbCO_3$ ], and azurite [basic copper carbonate,  $Cu_3(CO_3)_2(OH)_2$ ].

**COLLECTING LOCALITIES:** Mottramite specimens are collected in Mexico, Bolivia, Brazil, Argentina, Chile, England, Zambia, Morocco, Democratic Republic of the Congo, Namibia, and Russia. In the United States, mottramite is found in Nevada, New Mexico, Pennsylvania, South Dakota, Texas, California, and Arizona.

**HISTORY, LORE & GEMSTONE/TECHNOLOGICAL USES:** Mottramite was first studied in 1868 by the German-American chemist and mineralogist Frederick Augustus Genth (1820-1893). Genth obtained his specimens from an ore stockpile at Mottram St. Andrew in Cheshire, England. Determining their chemical composition required years of study, but Genth finally demonstrated that they consisted of basic lead copper vanadate, and thus represented a previously undiscovered mineral. In 1876, Genth named this new mineral “mottramite” after Mottram St. Andrew. However, it was later learned that Genth’s type specimens had only been stockpiled at Mottram St. Andrew, but were actually mined at the Pim Hill (Pymhill) Mine, a small copper mine in Shrewsbury, 60 miles to the south. The atomic structure of mottramite was determined by X-ray diffraction methods in the 1940s. Mottramite has occasionally served as a minor ore of lead and copper, but has no other technological uses. Because of its tendency to form only very small crystals or drusy coatings, mottramite has no use as a gemstone. Mottramite specimens are collected for their scarcity, unusual colors, and association with such

minerals as malachite, duftite, and descloizite. Modern metaphysical practitioners believe that mottramite aids in personal transformation and reformation, provides balance and respite while working to achieve goals, and generates feelings of well-being and energetic control.

**ABOUT OUR SPECIMENS:** Our mottramite specimens are from the Ojuela Mine at Mapimí in the Mapimí district, Durango, Mexico. One of the Western Hemisphere's most historic and productive mines, Ojuela is located in north-central Mexico some 40 miles northwest of the city of Torreón. The Ojuela Mine has produced ore or mineral specimens continuously for more than four centuries. Since the late 1500s, Ojuela has yielded more than seven million tons of ore that provided huge quantities of silver, lead, and zinc, along with lesser, but still substantial, amounts of gold and copper. Regular production mining at Ojuela ended after World War II. The Ojuela Mine has more than 200 miles of underground workings, the deepest of which are now flooded. On average, a ton of its remarkably rich ore contained 15 troy ounces of silver, 15 percent lead, 12 percent zinc, 0.1 troy ounce of gold, and small amounts of copper. Ojuela mineral specimens first gained public attention in 1946, when miners leasing sections of the mine found large vugs filled with extraordinary adamite crystals. Collectors and dealers from the United States then began visiting the mine regularly to buy specimens from miners or to pay for permission to collect their own specimens. Encouraged by today's high metal prices, mine-owner Compañía Minera de Penoles is now studying the feasibility of resuming production to recover previously overlooked sulfide ores of silver, lead, and zinc. Ranking among the world's top-ten specimen-producing localities, Ojuela has yielded more than 126 different mineral species and is the type locality for 6 species. Today, professional collectors and miners lease sections of the mine to recover specimens to sell on the international collectors' market. Ojuela is best known among mineral collectors for its fine specimens of the arsenate minerals austinite [basic calcium zinc arsenate,  $\text{CaZn}(\text{AsO}_4)(\text{OH})$ ] and adamite [basic zinc arsenate,  $\text{Zn}_2(\text{AsO}_4)(\text{OH})$ ].

## COMPREHENSIVE WRITE-UP

### *COMPOSITION & STRUCTURE*

Since the Mineral of the Month Club was founded in 1996, members have received specimens of 120 different mineral species. But this is the first time that we have featured mottramite as our Mineral of the Month. Mottramite [basic lead copper vanadate,  $\text{PbCu}(\text{VO}_4)(\text{OH})$ ] contains the elements lead (Pb), copper (Cu), vanadium (V), oxygen (O), and hydrogen (H). Mottramite's ideal molecular weight is made up of 51.45 percent lead, 15.78 percent copper, 12.65 percent vanadium, 19.87 percent oxygen, and 0.25 percent hydrogen.

Mottramite is one of the nearly 300 members of the Phosphates, Chromates, Arsenates, and Vanadates class of minerals. The basic building blocks of these minerals are the phosphate ion  $(\text{PO}_4)^{3-}$ , the chromate ion  $(\text{CrO}_4)^{3-}$ , the arsenate ion  $(\text{AsO}_4)^{3-}$ , and the vanadate ion  $(\text{VO}_4)^{3-}$ , all of which form tetrahedral structures with four oxygen ions surrounding and covalently bonding to the ion of a metal or a semimetal (chromium and vanadium are metals; phosphorus and arsenic are semimetals). In the vanadates, four oxygen ions  $4\text{O}^{2-}$  surround a vanadium ion  $\text{V}^{5+}$ . This

resulting collective -3 charge is distributed evenly over the four oxygen ions to enable the vanadate ion to bond with many positively charged metal cations.

Like all molecules, those of mottramite are made up of cations (positively charged ions) and anions (negatively charged ions). Mottramite's compound cation consists of one divalent lead ion  $\text{Pb}^{2+}$  and one divalent copper ion  $\text{Cu}^{2+}$  that together provide a collective +4 cationic charge. Mottramite's compound anion consists of two radicals, which are groups of atoms that act as entities in chemical reactions, and which function as ions. These are the vanadate radical  $(\text{VO}_4)^{3-}$  and the hydroxyl radical  $(\text{OH})^{1-}$  that together provide a collective -4 anionic charge. The balance of the -4 anionic charge and the +4 cationic charge provides the mottramite molecule with electrical stability.

The creation of the mottramite molecule begins when a vanadium ion  $\text{V}^{5+}$  covalently bonds to four oxygen atoms  $4\text{O}^{2-}$  to form the vanadate ion  $(\text{VO}_4)^{3-}$ . Each vanadate anion then bonds ionically to one divalent lead ion  $\text{Pb}^{2+}$  and one divalent copper ion  $\text{Cu}^{2+}$  to form the incomplete lead copper vanadate radical  $[\text{PbCu}(\text{VO}_4)]^{1+}$ . This vanadate radical becomes balanced when it ionically bonds to one hydroxyl radical  $(\text{OH})^{1-}$  to complete the mottramite molecule. Mottramite crystallizes in the orthorhombic system, which is characterized by three mutually perpendicular axes of different lengths, an arrangement that is reflected in the typical dipyramidal shape of mottramite crystals. Minerals such as mottramite that are chemically complex or that have complex bonding arrangements tend to crystallize in the orthorhombic system. The mottramite crystal lattice consists of chains of edge-sharing  $\text{CuO}_6$  octahedrons and  $\text{Pb}(\text{O},\text{OH})_8$  polyhedrons that are linked through the vanadate radicals into a tight, three-dimensional network. Because of omnidirectional bonding strength, there are no weak, structural planes that exhibit any cleavage properties. Because relatively weak ionic bonding dominates within its crystal lattice, mottramite has a low Mohs hardness of only 3.0-3.5, about that of a copper penny. Mottramite's weak ionic bonding also explains its ready solubility in most acids.

Because mottramite consists primarily of the heavy metal lead (51.45 percent), it has an unusually high density (specific gravity 5.9-6.0). This density gives mottramite crystals a very high refractive index of 2.170-2.320, higher than most other minerals with the exception of diamond [element, C, refractive index 2.417-2.419].

Mottramite participates in a complete solid-solution series (see "Solid-Solution Series: A Melding of Minerals") with descloizite [basic lead zinc vanadate,  $\text{PbZn}(\text{VO}_4)(\text{OH})$ ] through the mutual cationic substitution of divalent copper ions  $\text{Cu}^{2+}$  and divalent zinc ions  $\text{Zn}^{2+}$ . Mottramite also forms a partial solid-solution series with duftite [basic lead copper arsenate] through mutual anionic substitution of vanadate radicals  $(\text{VO}_4)^{3-}$  radicals and arsenate radicals  $(\text{AsO}_4)^{3-}$ .

As an idiochromatic or "self-colored" mineral, mottramite's basic color is caused by its essential elements and the nature of its crystal structure. Pure or nearly pure mottramite is green. But mottramite is rarely pure, and the frequent substitution of zinc cations for copper cations and the substitution of arsenate anions for vanadate anions creates a range of green, yellowish-green, and brownish-green colors. Copper is a strong, blue-green chromophore (color-causing agent); the vanadate anion is also chromophoric and creates orange-red colors. These two chromophores

combine in mottramite to produce a basic greenish color. Mottramite is also pleochroic, meaning that the color of its crystals varies somewhat when viewed along different crystal axes. Pleochroism, an optical phenomenon produced by doubly refractive crystals, is caused by variations in the absorption of light wavelengths along different axes. In mottramite crystals, the pleochroic color shift is generally between green and yellowish-green when the viewing angle changes.

The Dana mineral-classification number 41.5.2.2 first describes mottramite as an anhydrous member of the Phosphates, Chromates, Arsenates, and Vanadates class of minerals that contains either halogen ions or hydroxyl radicals (41). It is next defined by the formula  $AB(XO_4)Z_q(5)$ , in which “A” and “B” can be cations of lead, zinc, copper, manganese, or iron, and “X” can be vanadium or arsenic. “Z” signifies either a halogen ion or a hydroxyl radical; “q” is a quantifier. Mottramite is then assigned to the descloizite group (2) as the second (2) of five members. The other members of the descloizite group are related by either cationic or anionic substitution and include:

descloizite	basic lead zinc vanadate	$PbZn(VO_4)(OH)$
pyrobelonite	basic lead manganese vanadate	$PbMn(VO_4)(OH)$
cechite	basic lead iron manganese vanadate	$Pb(Fe,Mn)(VO_4)(OH)$
duftite	basic lead copper arsenate	$PbCu(AsO_4)(OH)$

Mottramite occurs exclusively in the shallow, oxidized zones of vanadium-bearing base metal deposits. It forms under conditions of relatively low temperature and pressure, and is virtually always associated with descloizite and malachite [basic copper carbonate,  $Cu_2(CO_3)(OH)_2$ ]. It is also frequently associated with duftite, mimetite [lead chloroarsenate,  $Pb_5(AsO_4)_3Cl$ ], wulfenite [lead molybdate,  $PbMoO_4$ ], cerussite [lead carbonate,  $PbCO_3$ ], and azurite [basic copper carbonate,  $Cu_3(CO_3)_2(OH)_2$ ]. Of the approximately 60 vanadium-bearing minerals, only mottramite and four others are common enough or form sufficiently large crystals to interest collectors. These include descloizite, vanadinite [lead chlorovanadate,  $Pb_5(VO_4)_3Cl$ ], patrónite [vanadium disulfide,  $V(S_2)_2$ ], and carnotite [hydrous potassium uranium vanadate,  $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$ ].

The core element in the vanadate radical is the element vanadium, which is a silver-white metal with excellent properties of ductility, hardness, structural strength, and corrosion resistance. It has an atomic weight of 50.94, a specific gravity of 5.96, and a melting point of 3434° F. (1890° C). Vanadium has four oxidation states: +2, +3, +4 and, most commonly, +5, the latter being the oxidation state in mottramite. Ranking 19<sup>th</sup> among the elements in crustal abundance, vanadium is as common as chromium and nickel. Vanadium does not occur as a native metal. In 1867, British chemist Sir Henry Enfield Roscoe (1835-1915) became the first to isolate elemental vanadium by chemically reducing vanadium chloride. In the late 1890s, French metallurgists learned that a small percentage of vanadium added to steel refined the grain of the steel and enhanced its tensile strength, toughness, ductility, and corrosion resistance. Vanadium is no longer extracted from primary vanadium ores, but is obtained as a by-product of processing the uranium ore carnotite, vanadiferous iron and titanium ores, slags, and petroleum residues. Most vanadium is used to manufacture alloys, especially vanadium-steels for oil-field steel, pipelines,

high-speed tool steels, and structural girders. Vanadium-chrome steels are used in automotive suspension springs, transmission gears, and high-stress engine components. Lightweight, heat-resistant, vanadium-aluminum-titanium alloys are standard components of high-performance jet and rocket engines.

### *COLLECTING LOCALITIES*

Our mottramite specimens were collected at the Ojuela Mine at Mapimí in the Mapimí district, Durango, Mexico. In South America, mottramite is found in the Caxata-Yaco area, Inquisivi Province, La Paz Department, Bolivia; the Pedra Preta pit at Serra do Égues, Brumado, Bahia, Brazil; the Cruz del Sur Mine at Comicó, Nueve de Julio Department, Argentina; and the Dulciano de Lamos Mine, Copiapó Province, Atacama Region, Chile.

In England, mottramite sources include the Pim Hill (Pymhill) Mine at Shrewsbury, Shropshire; the Mount's Bay, Lizard Peninsula, and Callington districts in Cornwall; and the Brandy Gill Mine, Carrock Fell, Caldbeck Fells, Cumbria. African sources include the Kabwe Mine at Kabwe, Kabwe District, Central Province, Zambia; the Bou Azer district, Tazenakht, Quarzazete Province, Souss-Massa-Draâ Region Morocco; the Mashanta West Mine, Kolwezi District, Katanga Copper Crescent, Katanga, Democratic Republic of the Congo; and the Tsumeb Mine at Tsumeb in the Otjikoto Region and the Friesenberg Prospect at Otavi in the Otjozondjupa region, both in Namibia. In Russia, mottramite is found at the Berezovskoe gold deposit at Ekaterinburg, Sverdlovskaya Oblast', Middle Urals, Ural Region.

In the United States, mottramite occurs in the Goodspring district in the Spring Mountains, Clark County, Nevada; the Harding Pegmatite, Picuris district, Taos County, New Mexico; the Phoenixville district at Schuylkill, Chester County, Pennsylvania; the Silver Queen Mine at Deadwood, Galena district, Lawrence County, South Dakota; and the Purple Sage Mine in the Indio Mountains, Hudspeth County, Texas. In California, mottramite is found at the Brown Monster and Reward mines in the Russ District in the Inyo Mountains of Inyo County, and the Otto Mine near Baker in San Bernadino County. Arizona specimens come from the Campbell Mine at Bisbee in the Warren district in Cochise County, and the Apache Mine in the Globe Hills district in Gila County.

### *JEWELRY & DECORATIVE USES*

Because it is uncommon and forms only very small crystals or drusy coatings, mottramite has no use as a gemstone. It is collected for its scarcity, unusual colors, and association with such collectible minerals as malachite [basic copper carbonate,  $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$ ], duftite [basic lead copper arsenate,  $\text{PbCu}(\text{AsO}_4)(\text{OH})$ ], and descloizite [basic lead zinc vanadate,  $\text{PbZn}(\text{VO}_4)(\text{OH})$ ].

### *HISTORY & LORE*

Mottramite was first studied in 1868 by the German-American chemist and mineralogist Frederick Augustus Genth (1820-1893), who is credited with identifying 15 new mineral species. Genth obtained his study specimens from an ore stockpile at Mottram St. Andrew in Cheshire, England, 40 miles east of the port city of Liverpool. Determining their chemical composition required years of laboratory work, but Genth finally proved that the specimens consisted of basic lead copper vanadate and thus represented a previously undiscovered mineral. In 1876, Genth named this new mineral “mottramite,” after Mottram St. Andrew, which he assumed was the original source of his specimens. It was later learned, however, that Genth’s type specimens, while stockpiled at Mottram St. Andrew, had actually been mined at the Pim Hill (Pymhill) Mine, a small copper mine in Shrewsbury, 60 miles to the south. Despite this discrepancy, Mottram St. Andrew is still recognized as mottramite’s type locality. Genth’s type specimens are now stored in a repository at London’s Natural History Museum. The atomic structure of mottramite was determined by X-ray diffraction methods in the 1940s.

Modern metaphysical practitioners believe that mottramite aids in personal transformation and reformation, provides balance and respite while working to achieve goals, and generates feelings of well-being and energetic control.

#### *SOLID-SOLUTION SERIES: A MELDING OF MINERALS*

In “Composition & Structure” we explain that mottramite, our Mineral of the Month, forms a complete solid-solution series with descloizite [basic lead zinc vanadate,  $\text{PbZn}(\text{VO}_4)(\text{OH})$ ] and a partial solid-solution series with duftite [basic lead copper arsenate,  $\text{PbCu}(\text{AsO}_4)(\text{OH})$ ]. This special section of our write-up discusses the meaning of the term “solid-solution series.”

Because chemical formulas are specific, minerals are often thought of in terms of fixed and precise chemical compositions. But chemical formulas represent only a pure or “ideal” chemical composition which does not necessarily exist in nature. The composition of most minerals varies considerably within established limits, and such variations are not expressed in ideal chemical formulas. This variation is referred to as “solid solution,” and mottramite is a textbook example of a solid-solution-series mineral.

In the mottramite-descloizite solid-solution series, copper and zinc undergo mutual substitution. This means that zinc substitutes for copper in mottramite, and that copper substitutes for zinc in descloizite. The substitution proportions are continuously graded and vary between 0 percent and 100 percent. In the mottramite-descloizite solid-solution series, when more than 50 percent copper is present, the mineral is mottramite; when more than 50 percent zinc is present, the mineral is descloizite. Mottramite is called the “copper-rich” end member of the mottramite-descloizite solid-solution series; descloizite is called the “zinc-rich” end member. The intermediate members of this series fall between the two end members and contain varying proportions of copper and zinc.

Mottramite also participates in a partial solid-solution series with duftite [basic lead copper arsenate,  $\text{PbCu}(\text{AsO}_4)(\text{OH})$ ] through anionic substitution of vanadate radicals ( $\text{VO}_4$ )<sup>3-</sup> and

arsenate radicals  $(\text{AsO}_4)^{3-}$ . In the mottramite-duftite partial solid-solution series, vanadate and arsenate radicals substitute for each other, but not completely. This partial substitution results in mottramite specimens that often exhibit some characteristics of duftite, and duftite specimens that exhibit some characteristics of mottramite. The proportion of anionic substitution in the mottramite-duftite series is limited to about 20 percent.

In order to participate in the mutual substitution that creates solid-solution series, the substituting cations or anions must have identical electrical charges, similar ionic radii, and similar bonding characteristics. In the mottramite-descloizite solid-solution series, the copper ions  $\text{Cu}^{2+}$  and zinc ions  $\text{Zn}^{2+}$  both have an identical +2 electrical charge and similar atomic radii; they also easily form ionic bonds. Thus, copper ions can readily substitute for zinc ions in the descloizite crystal lattice, and zinc ions for copper ions in the mottramite lattice.

In the mottramite-duftite partial solid-solution series, the vanadate radical  $(\text{VO}_4)^{3-}$  and the arsenate radical  $(\text{AsO}_4)^{3-}$  both have an identical -3 charge and can bond ionically. However the radii of these radicals differ significantly in size. Thus only a limited number of vanadate radicals can replace arsenate radicals and vice versa without disrupting the crystal lattice.

Most solid-solution series consist only of two end members. But some minerals, such as actinolite, tremolite, and ferro-actinolite, participate in a three-way solid-solution series. The nature of the cationic substitution in this three-way series is apparent in their chemical formulas:

tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
actinolite	$\text{Ca}_2\text{Mg}_{<4.5}\text{Fe}_{>0.5}\text{Si}_8\text{O}_{22}(\text{OH})_2$
ferro-actinolite	$\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

In this solid-solution series, tremolite is the magnesium-rich end member, ferro-actinolite is the iron-rich end member, and actinolite is an intermediate-phase member that qualifies as a distinct mineral species. Because iron has much greater density than magnesium, iron-rich ferro-actinolite predictably has the greatest density, while tremolite has the least density. Ferro-actinolite is blackish in color, actinolite is green, and tremolite is white to gray. Ferro-actinolite forms when iron predominates in the crystallization environment. Tremolite forms when magnesium predominates, and actinolite forms when magnesium and iron are present in similar amounts.

Many mineral collectors are familiar with the calcite-rhodochrosite complete solid-solution series. This series, which grades continuously in color from red through a range of pinks to colorless or white, consists of calcite [calcium carbonate,  $\text{CaCO}_3$ ] and rhodochrosite [manganese carbonate,  $\text{MnCO}_3$ ]. In this series, manganese ions  $\text{Mn}^{2+}$  substitute for calcium ions  $\text{Ca}^{2+}$  and vice versa. Calcite contains 50 percent or more calcium; rhodochrosite contains 50 percent or more manganese. Pure calcite is colorless or white; pure rhodochrosite is blood-red. The intermediate members are various shades of pink. Pink rhodochrosite is known as “pale rhodochrosite,” “rose rhodochrosite,” and “calcio-rhodochrosite”; pink calcite is known as “manganocalcite” and “rhodocalcite.”



In the forsterite-fayalite complete solid-solution series, the end members are forsterite [magnesium silicate,  $\text{MgSiO}_4$ ] and fayalite [iron silicate,  $\text{FeSiO}_4$ ]. This series forms when iron substitutes for magnesium and vice versa. Because the intermediate members are difficult to distinguish, the forsterite-fayalite series is generally referred to as “olivine.” Technically, forsterite becomes fayalite when the weight of the iron exceeds the weight of the magnesium. Fayalite ranges in color from dark-brown to brownish-green, while forsterite is brownish-green to pale green. One of the intermediate members of this series is the gemstone peridot. Peridot’s lime-green color occurs only within a narrow compositional range in which forsterite’s iron content is 12-15 percent. From the gemological perspective of color, the amount of iron is critical. Too much introduces brown tones that “muddy” the lime-green color; too little weakens the intensity of the color. Thus, the gemstone peridot is created by just the right proportions of iron and magnesium within a continuously graded, complete solid-solution series.

## TECHNOLOGICAL USES

Mottramite has occasionally served as a minor ore of lead and copper, but has no other technological uses.

## ABOUT OUR SPECIMENS

Our mottramite specimens were collected at the Ojuela (oh-HWAY-la) Mine at Mapimi in the Mapimi district, Durango, Mexico. This historic mine has produced ore or mineral specimens almost continuously for 418 years. It was a rich source of silver for the Spanish Crown and, later, for the Republic of Mexico. Ojuela is located in north-central Mexico northwest of the city of Torreón. From Torreón, it is reached by taking Mexico Route 49 north for 25 miles to Bermejillo, then taking Mexico Route 30 west for 12 miles and following the signs south for 4 miles to Mapimi. In this part of the arid Chihuahuan Desert, rugged mountain ranges separate broad plains. The higher mountain elevations host thin, scrub-oak forests; the plains are sparsely vegetated with cacti, thorny brush, and coarse grass. The elevation of the Ojuela Mine is 6,800 feet.

The Ojuela Mine exploits one of the major carbonate-replacement deposits within the Mexican Fold Belt, a 900-mile-long zone of folded carbonate rocks. The fold-belt sediments are of marine origin and were deposited 150 million to 65 million years ago. They later lithified into limestone, a rock consisting primarily of calcite [calcium carbonate,  $\text{CaCO}_3$ ] and dolomite, a rock consisting mainly of the mineral dolomite [calcium magnesium carbonate,  $\text{CaMg}(\text{CO}_3)_2$ ]. During the late Tertiary Period some 60 million to 40 million years ago, tectonic stresses deformed these limestone and dolomite formations into the convoluted folds of today’s Mexican Fold Belt. Finally, between 40 million and 25 million years ago, regional volcanism and deep magmatic intrusions forced mineral-laden, hydrothermal solutions into fractures within the Fold Belt. Mineralization occurred when these solutions dissolved sections of the limestone and dolomite, replacing them with metal-sulfide minerals. Rich in silver, lead, and zinc, and containing lesser amounts of gold and copper, these deposits formed at depth and were later

exposed by surface erosion. Contact with groundwater and atmospheric oxygen altered the upper portions of the sulfides into many secondary arsenate, phosphate, carbonate, and halide minerals.

Spanish prospectors discovered rich outcrops of chlorargyrite [silver chloride,  $\text{AgCl}$ ] and argentiferous cerussite [silver-bearing lead carbonate,  $\text{PbCO}_3$ ] at Ojuela in 1598. After depleting the rich, oxidized surface ores, the Spanish turned to underground mining and developed Ojuela into a major source of silver. By the early 1800s, Ojuela had yielded millions of troy ounces of silver and huge amounts of lead. Production then declined during the Mexican war of independence. By the time Mexico gained its independence in 1821, the Ojuela Mine and its smelters were largely in ruins. Production subsequently resumed, but was limited by outdated mining practices, poor roads, raids by outlaws, and government instability.

In the late 1870s, when the Mexican government was encouraging foreign mining investment, an American company took over Ojuela, only to go bankrupt. In 1890, Compañía Minera de Penoles, backed by American and European capital, bought the mine and hired American mining engineers to modernize the operation. The company built a railroad and a modern smelter, electrified the town and the mine, constructed employee housing, and brought in American civil engineer Washington Augustus Roebling (1837-1926), the noted designer and builder of New York's Brooklyn Bridge, to construct a narrow, 1,000-foot-long, cable-suspension bridge over a 250-foot-deep arroyo to connect the town with the mine. Roebling also increased the mine's depth to access an overlooked ore body. By 1910, some 1,200 Ojuela miners were recovering one million troy ounces of silver per year, along with large tonnages of lead and zinc. But operations ceased again with the onset of the Mexican Revolution. During the post-Revolution years of the early 1920s, core-drill exploration revealed deeper ore bodies. Production soared during the late 1920s, but profits were soon curtailed by the Great Depression, and Ojuela never again approached its former production rates. In 1946, Compañía Minera de Penoles ended its unified management and began leasing mine sections to independent cooperatives of miners, a system that survives today among specimen miners.

Ojuela's fame as a world-class specimen locality is due to the extraordinarily large volume and depth of its oxidized mineralization. Much of its original sulfide mineralization has oxidized into colorful carbonates, oxides, phosphates, and arsenates. Ojuela ores are quite rich in arsenic, and thus in unusual iron, lead, zinc, and copper arsenates. Ojuela specimens first gained public attention in 1946, when lease miners found large vugs filled with extraordinary crystals of adamite [basic zinc arsenate,  $\text{Zn}_2(\text{AsO}_4)(\text{OH})$ ]. Collectors and dealers from the United States then began visiting the mine regularly to buy from the miners or to pay Compañía Minera de Penoles for permission to collect their own specimens.

The Ojuela Mine has more than 200 miles of underground workings, the deepest of which are flooded. Throughout its long history, miners have extracted more than seven million tons of ore. On average, a ton of this remarkable ore contained 15 troy ounces of silver, 15 percent lead, 12 percent zinc, 0.1 troy ounce of gold, and small amounts of copper. Encouraged by today's high metal prices, mine-owner Compañía Minera de Penoles is currently studying the feasibility of resuming full-scale operations to recover previously overlooked sulfide ores of silver, lead, and

zinc. Although Ojuela has not produced ore in decades, teams of independent miners continue to lease mine sections from Compañía Minera de Penoles to recover mineral specimens.

As you study your mottramite specimen, note first its brownish-green color, which is caused by its essential, chromophoric copper cations and vanadate anions, along with a substantial amount of the accessory element zinc. This color may vary somewhat among individual specimens. The mottramite in your specimen forms adjoining, botryoidal structures composed of radiating, internal crystals. Notice also that the specimen is unusually heavy for its volume and has a substantial “heft” in the hand. This reflects mottramite’s very high specific gravity (5.9-6.0), which is due to its high lead content of about 51 percent. The matrix consists of massive, orange-brown limonite, an indeterminate mixture of hydrous iron oxides, which is common in most oxidation environments, along with dark-brown goethite [basic iron oxide,  $\text{FeO}(\text{OH})$ ]. Goethite is an alteration product of the oxidation of such iron-sulfide minerals as pyrite [iron disulfide,  $\text{FeS}_2$ , cubic], marcasite [iron disulfide,  $\text{FeS}_2$ , orthorhombic], and arsenopyrite [iron arsenic sulfide,  $\text{FeAsS}$ ], all of which are abundant at Ojuela. This orange-brown matrix is an identifying characteristic of virtually all oxidized-mineral specimens from the Ojuela Mine. Your mottramite specimen is an example of an uncommon vanadate mineral from a classic locality.

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Bridge leading to the Ojuela Mine