September 2010 Mineral of the Month: Hematite Pseudomorph after Magnetite

> Our pseudomorphic specimens of this month's mineral, hematite after magnetite, were collected at an extinct Argentinean volcano. Our write-up explains their unusual fumarolic origin, the chemical oxidation of magnetite into hematite, and some of the basics behind the phenomenon of volcanism.

OVERVIEW

PHYSICAL PROPERTIES

Chemistry: $\alpha\text{-}Fe_2O_3$ Iron (Ferric) Oxide (The "α" symbol indicates iron is present in its alpha allotropic phase. For details, see "Composition" in the Comprehensive Write-up.)
Class: Oxides
Subclass: Simple Oxides
Group: Corundum
Crystal System: Hexagonal (Trigonal)
Crystal Habits: Thick-to-thin tabular, platy, or rhombohedral crystals; subparallel growths or circular arrangements of bladed crystals; also radiated, reniform, botryoidal, oolitic, columnar, micaceous, and granular; abundant as earthy grains in compact masses.
Color: Steel-gray and silver-gray to black and reddish-black when crystalline; red or reddish-brown when granular or earthy.

Figure 1. Hematite pseudomorph after magnetite.

Luster: Metallic to submetallic when crystalline; dull when earthy
Transparency: Opaque, occasionally translucent in small, thin crystals
Streak: Blood-red to brownish-red
Refractive Index: 2.94-3.22
Cleavage: None
Fracture: Uneven and splintery to subconchoidal; brittle.
Hardness: 5.0-6.0
Specific Gravity: 5.3
Luminescence: None
Distinctive Features and Tests: Best field marks are crystal form, hardness, and blood-red to brownish-red streak. Streak distinguishes hematite from limonite [an indeterminate mixture of iron oxides and hydroxides] and ilmenite [iron titanium oxide, $FeTiO_3$]; unlike magnetite [iron oxide, Fe_3O_4], hematite is not magnetic.
Dana Classification Number: 4.3.1.2 .1

NAME The name hematite, pronounced HEE-muh-tite, comes from the Greek *haematites*, meaning "blood-like," an allusion to the distinct, reddish color of its earthy or powdered forms. Through long use as a gemstone and as an ore of iron, hematite has acquired many alternative names, including "iron glance," "red iron oxide," "red iron ore," "black diamond," "Roteisenrahm," "Jernglans," "red ferrite," "paint ore," "sanguine," "Persian red," "bloodstone," "red ironstone," and "ruddle." "Ochre" and "red ochre" refer to a reddish, hematite-rich clay; "kidney ore" to a massive botryoidal form; "specularite" to a glittering, micaceous form; and "hematite rose" to flower-like clusters of bladed crystals. Pseudomorphic hematite after magnetite (our specimens) is sometimes called "martite," while "turgite" refers to a hydrated, iridescent form. In European mineralogical literature, hematite appears as *Hämatit*, *hematita*, and *ematite*.

COMPOSITION: Hematite contains the elements iron (Fe) and oxygen (O) in the proportions of 69.94 percent iron and 30.06 percent oxygen. Hematite is a member of the oxide class of minerals, in which

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metals or semimetals bond with oxygen. Simple oxides such as hematite consist of one metal combined with oxygen. As an idiochromatic (self-colored) mineral, hematite's basic red color is due to the essential element iron. All earthy, massive, granular, particulate, and microcrystalline forms of hematite are some shade of red or reddish-brown. But in crystalline hematite, the smooth, crystal-face surfaces absorb white light equally across all wavelengths to reflect a neutral, gray-black color. Crystalline hematite can also have a specular or mirror-like appearance in which its crystal faces reflect light with a bright, silvery glitter. As the most abundant and widely distributed iron mineral, hematite occurs in sedimentary, igneous, and metamorphic rocks.

COLLECTING LOCALITIES: Notable hematite after magnetite localities are found in Mendoza and Jujay provinces, Argentina; Minas Gerais, Brazil; Huasco Province, Chile; Durango, Mexico; Corsica, France; Lower Silesia, Poland; Grischun, Switzerland; Dalarna, Sweden; and Queensland, Australia. In the United States, specimens are collected in Arizona, Colorado, Idaho, Missouri, New Hampshire, New York, Tennessee, Virginia, and in the iron ranges of Michigan and Minnesota.

HISTORY, LORE, & USES: Hematite has served as a pigment since antiquity. Powdered hematite is the red pigment in the Paleolithic cave paintings at Lascaux, France, and it has also been used by many cultures worldwide as the red component of tribal body paints. The Egyptians made hematite-based rouges, while the Babylonians engraved crystalline hematite as intaglio seals. Both the Greeks and Romans believed that deposits of red hematite marked the sites of ancient, bloody battles. Medieval physicians used hematite to treat circulatory, heart, and kidney disorders. Although hematite after magnetite has little use in jewelry, specular hematite has long served as a gemstone, achieving its greatest popularity in Victorian-era jewelry. Today, hematite cabochons are set in brooches, while faceted and tumbled beads are strung into necklaces. Small, spherical hematite beads that closely resemble black pearls are strung in necklaces and mounted in earrings. Hematite is the official state mineral of Alabama. Modern metaphysicians believe that hematite enhances energy, vitality, intellect, and memory; helps the body to tolerate stress; and promotes overall healing. As the primary ore of iron, hematite has yielded an estimated 85 percent of all the iron mined throughout history.

ABOUT OUR SPECIMENS: Our specimens were collected at Payún Matrú Volcano (Volcán Payún Matrú) near the city of Malargüe in Mendoza Province, Argentina, a site now recognized as a classic locality for hematite after magnetite. Payún Matrú is located within a provincial nature reserve in west-central Argentina 600 miles west-southwest of the Argentinean capital of Buenos Aires and only 40 miles east of the Chilean border. Our specimens are pseudomorphs in which hematite has replaced magnetite through the chemical process of oxidation. These specimens formed in a fumarolic environment. Fumaroles are vents in the surface that emit steam and mineral-laden gases such as carbon dioxide, sulfur dioxide, hydrochloric acid, and hydrogen sulfide. Mineral-rich vapors first deposited dipyramidal, octagonal crystals of magnetite. But in the reduced temperatures of an oxidizing environment, the magnetite subsequently altered into hematite, while retaining the shape of the original magnetite crystals. After volcanic and fumarolic activity had ceased, the fumaroles collapsed and filled with altered clay. Our pseudomorphic crystals of hematite after magnetite were recovered by digging through the clay of these "fossil" fumaroles.

10 YEARS AGO IN OUR CLUB: Spinel, Pein Pyit, near Mogok, Myanmar (formerly Burma.) We sent Club members a small, well-formed, intensely red spinel octahedron on a white marble matrix that fluoresced bright yellow under shortwave UV light! Coincidentally, spinel is an oxide and commonly crystallizes as octahedrons, just like this month's magnetite–although the spinel did not later alter to hematite!

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COMPREHENSIVE WRITE-UP

COMPOSITION

This is the third time we have featured hematite, first in the form of "Iron Roses" from Ouro Preto, Minas Gerais, Brazil, in June 2002, and then as heavy, botryoidal masses from the Oumjrane Mine, Alnif, Er Rachidia Province, Morocco, in August 2007; and the second time we have featured magnetite, first as sharp octahedral crystals on matrix from Cerro Rico, Potosi Department, Bolivia, in April 2003.

The chemical formula α-Fe_2O_3 indicates that hematite contains the elements iron (Fe) and oxygen (O) in the proportions of 69.94 percent iron and 30.06 percent oxygen. The alpha symbol "α" in this formula denotes the alpha phase of iron. Iron crystallizes in three different thermal phases, called allotropes. "Alpha iron" or ferrite (α-Fe) crystallizes at temperatures below 1700° F. (927° C.) Between 1700° and 2600° F (1426° C.), the metal crystallizes as "gamma iron" or austenite (γ-Fe). Above 2600° F., it crystallizes as "delta iron" (Δ-Fe). All these phases have different crystal structures and magnetic properties. This ability of one material to assume different forms is called polymorphism (from the Greek words *polys*, meaning "many," and *morphē* or "form"; literally "many forms"). When the polymorphic change is reversible, as it is in iron, it is known as allotropy (from the Greek *allos*, "other," and *tropos*, "way"). Alpha iron, the common form of iron, is stable at normal temperatures. Because hematite can form from all iron allotropes with resulting variations in structure, the alpha symbol is used to specify the stable, low-temperature phase of the metal. The mineral maghemite [iron oxide, γ-Fe_2O_3] is dimorphic with hematite and contains the gamma allotrope of iron.

In the formula α-Fe_2O_3, "Fe" refers specifically to the trivalent or ferric form of iron Fe^{3+}. The chemical symbol for iron, Fe, derives from *ferrum*, the Latin word for the metal. Iron ions (charged iron atoms) occur in two oxidation states: the trivalent or ferric form Fe^{3+} and the divalent or ferrous form Fe^{2+}. In chemical reactions, ferric iron (Fe^{3+}) shares three electrons, while ferrous iron (Fe^{2+}) shares only two electrons. Ferric and ferrous iron form minerals with different chemical compositions and structures. In chemical formulas written to denote specific oxidation states, the hematite formula appears as $Fe^{3+}_2O_3$.

Hematite is a member of the oxide class of minerals in which metals or semimetals combine with oxygen. Simple oxides consist of one metal and oxygen; compound oxides combine two or more metal ions with oxygen ions. Molecules consist of cations (positively charged ions) and anions (negatively charged ions). As a simple oxide, the hematite molecule has a simple cation containing two ferric ions ($2Fe^{3+}$); its simple anion consists of three oxygen ions ($3O^{2-}$). The collective +6 cationic charge balances the collective -6 anionic charge to provide the hematite molecule with electrical stability. In hematite's crystal lattice, two ferric ions covalently share electrons with three oxygen ions to form a three-dimensional structure in which six oxygen ions surround each ferric ion. This configuration explains hematite's hexagonal (trigonal) crystal structure. The hexagonal system is characterized by four axes, three of which are of equal length and lie in a parallel plane. The fourth axis, unique to the hexagonal system, is perpendicular to the planes of the other three and can be of any length. In hematite, this "hexagonal axis" is considerably shorter than the other three and produces platy or tabular hexagonal crystals.

Hematite's considerable density (specific gravity 5.3) provides it with a very high index of refraction (a measure of the ability to bend light). Although hematite is opaque, its index of refraction can nevertheless be measured because it is sub-transparent when cut in very thin section. Hematite's index of refraction of 2.94-3.22 is nearly a third greater than that of diamond. Unlike most oxides, hematite crystals exhibit a

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metallic to submetallic luster. Even though six oxygen ions surround each ferric ion within the hematite lattice, the large size of the ferric ions prevents complete shielding. This makes possible a small degree of metallic bonding that creates the metallic luster of hematite crystals.

As an idiochromatic (self-colored) mineral, hematite's color is caused by the essential element iron and the nature of its crystal structure. Hematite's basic color is red, but impurities, usually of ferrous iron (Fe^{2+}), titanium, or manganese, along with distortions in the crystal lattice, create some color variation. All earthy, massive, granular, particulate, and microcrystalline forms of hematite are some shade of red or reddish-brown. Because of large amounts of impurities, the color of hematite-rich earths and clays can be yellowish-brown, yellow, or yellowish-red. And because particulate hematite consists of randomly oriented particles with irregular surfaces, these impurities only minimally alter the basic reddish color. But this is not the case with macrocrystalline and botryoidal hematite. Because hematite is opaque and does not transmit light, the color of macrocrystalline and botryoidal forms is determined by surface reflection and the absorption of white light. The smooth, crystal-face surfaces of these forms absorb white light equally across all wavelengths to reflect a neutral, gray-black color. And because the hematite crystal lattice has a small degree of unshielded metallic bonding, this dark color is often accompanied by a submetallic luster. Hence macrocrystalline hematite has a distinctive, nearly black color and a bright, specular luster. However, the streak of all forms of hematite is always a diagnostic red.

As the most abundant and widely distributed iron mineral, hematite occurs in sedimentary, igneous, and metamorphic rocks. It occurs with albite [$NaAlSi_3O_8$] and barite [$BaSO_4$] in carbonatites (carbonate-rich igneous rocks); with diopside [$CaMgSi_2O_6$] and epidote [$Ca_2Al_2(Fe,Al)Si_3O_{12}(OH)$] in hornfels of contact and regional metamorphic rocks; with quartz [SiO_2] and siderite [$FeCO_3$] in mesothermal and epithermal veins; and with fluorite [CaF_2], barite, and calcite [$CaCO_3$] in lode and disseminated replacement deposits. Specular or crystalline hematite is deposited by volcanic gases or high-temperature hydrothermal fluids as euhedral or platy crystals associated with quartz in veins and cavities. Hematite is a weathering (oxidation) product of such iron-bearing minerals as magnetite [Fe_3O_4], siderite [$FeCO_3$], and pyrite [FeS_2]. Chemical and organic processes also precipitate hematite in marine and lacustrine environments. Large ore deposits of earthy, granular, and massive hematite usually consist of altered sediments. Reddish soils and sedimentary rocks worldwide from the Gobi Desert of China and Mongolia to the red clay of Georgia and the red-rock country of Utah are colored by finely divided hematite particles.

The Dana classification number 4.3.1.2 first identifies hematite as a simple oxide (4). The subclassification (3) defines it by the general formula A_2O_3, in which "A" is a trivalent metal ion such as ferric iron (Fe^{3+}) or aluminum (Al^{3+}), chromium (Cr^{3+}), or vanadium (V^{3+}), while "O" is the divalent oxygen ion O^{2-}. Hematite is then assigned to the corundum group (1) as the second (2) of four members. The other group members are corundum [aluminum oxide, Al_2O_3], eskolaite [chromium oxide, Cr_2O_3], and karelianite [vanadium oxide, V_2O_3].

COLLECTING LOCALITIES

Because hematite is abundant and widely distributed, we are listing only localities that yield collectible specimens of pseudomorphic hematite after magnetite. Our specimens were collected at Payún Matrú Volcano (Volcán Payún Matrú) near Malarqüe, Mendoza Province, Argentina. Another Argentinean source is the Vela Yareta Mine at Cerro Pululus, Jujay Province. Brazilian specimens come from Nova Lima and Itabira in the Iron Triangle geological area in Minas Gerais in the Southeast Region. Specimens are collected in Chile in the Los Colorados district and at Altodel Carmen in Huasco Province; the Cerro Bandurrias iron deposit at Punta de Diaz in Copianó Province; and Magnetita Pedernales, Chañaral

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Province, all in the Atacama Region. Colombian specimens come from the Marmato district at Manizales, Caldas Department. Mexican specimens are found at the Cerro de Mercado Mine at Cerro de Remedios, Ciudad Durango, Durango.

Europe's localities include Cervioni and Ghisoni near Corte, Haute-Corse, Corsica, France; the Ludwig Mine at Oelsnitz, Vogtland, Saxony, Germany; the Jelenia Góra district in the Karkonosze Massif, Lower Silesia, Poland; the Cabeço da Mua Mine at Torre de Moncorvo, Bragança District, Portugal; Alcañices, Castilla y León, Spain; the Cavradi Gorge at Tujetsch, Grischun, Switzerland; and the Stollberg iron mines at Ludvika, Dalarna, Sweden. Russian specimens come from the Magnitaya Mine at Magnitogorsk, Chelyabinsk Oblast', Southern Urals; and the Pankovo and Tavolzhanskoe iron deposits at the Kursk Manet geological anomaly, Kurskaya Oblast', Central Region. Other sources include the Magnetite and Biggenden iron mines at Biggenden Shire, Queensland, Australia; Oursi, Oudalan Province, Sahel Region, Burkina Faso; the Mayo Binka iron deposit, Nkambe, North-West Region, Cameroon; the Manandriana Commune in the Ambosita district, Amoron'i Mania Region, Fianarantsoa Province, Madagascar; the Okorusu mines in the Otjiwarongo District, Otjozondjupa Region, Namibia; the Tarraouadji Massif at South Aïr, Aïr Region, Agadez Department, Niger; and the Camibogazi Arnastal iron deposit in Gümüşhane Province, Black Sea Region, Turkey.

In the United States, hematite after magnetite specimens are found in mines in the Gogebic Iron Range in Gogebic County and the Marquette Iron Range in Marquette and Ishpeming counties, Michigan. Specimens are also collected in the Cayuna North Range iron mines in Crow Wing County, Minnesota. Other sources include Sunset Crater in the San Francisco Volcanic Field, Coconino County, Arizona; the Indian Trail Ridge magnetite deposit, La Plata district, Montezuma County, Colorado; the Marsha iron prospect, McDevitt district, Lemhi County, Idaho; the Iron Mountain Mine in St. Francis County, Missouri; the Iron Mountain mines at Bartlett, Carroll County, New Hampshire; the Mineville district, Essex County, New York; the Rabbit Station, Mays Ridge, Lunsford and Black Bear hematite-magnetite deposits in the Walnut Mountain District, Carter County, Tennessee; and the Round Mountain mines in the James River-Roanoke River manganese-iron-barium district, Amherst County, Virginia.

JEWELRY & DECORATIVE USES

Hematite after magnetite has little use in jewelry. Well-formed octagonal crystals are occasionally wrapped in silver wire for wear as pendants. Specular hematite, however, has long served as a gemstone, achieving its greatest popularity in Victorian-era jewelry. Today, hematite cabochons are set in brooches, while faceted and tumbled beads are strung into necklaces. Small, spherical hematite beads that resemble black pearls are popular in necklaces and earrings. Botryoidal hematite, polished to display intricate surface patterns, is mounted in pendants. Specular hematite is also fashioned into paperweights, figurines, and spheres. The "magnetic hematite" used in inexpensive jewelry, beads, and in other forms is neither natural nor hematite–it is a man-made magnetic material whose exact composition is kept secret by its manufacturers. An analysis of one piece found it contained barium, strontium, iron and oxygen.

Mineral collectors value hematite in both its crystalline and botryoidal forms, both as individual and composite specimens. Pseudomorphic specimens of hematite after magnetite are widely collected.

HISTORY & LORE

Hematite has served as a pigment since antiquity. Powdered hematite is the red pigment in the 15,000-year-old Paleolithic cave paintings at Lascaux, France. It has also been used worldwide as the red

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component of tribal body paints. The Egyptians made hematite-based rouges; the Babylonians engraved crystalline hematite as intaglio seals. The reflective faces of crystalline hematite also served as mirrors, hence the name "specular" hematite. By 3500 B.C., decorative objects were being fashioned from metallic iron that had been crudely smelted from hematite. Both the Greeks and Romans believed that deposits of red hematite marked the sites of ancient, bloody battles. Medieval physicians used hematite to treat circulatory, heart, and kidney disorders.

Hematite is the official state mineral of Alabama. In 1998, specimens of specular hematite appeared on the 400-franc stamp of Central Africa. Modern metaphysical practitioners believe that hematite enhances energy, vitality, intellect, and memory; helps the body to tolerate stress; and aids in overall healing.

TECHNOLOGICAL USES

Hematite has always been the primary ore of iron, thanks to its great abundance, a composition of nearly 70 percent iron by weight, a simple-oxide chemistry that facilitates reduction to metallic iron, and a tendency to form large, shallow, sedimentary deposits suitable for large-scale, open-pit mining. Hematite has yielded an estimated 85 percent of all the iron mined throughout history. Some 1.3 billion tons of iron ore, mostly of hematite, are mined worldwide each year. China is the leading producer, followed by Australia, Brazil, and India. Small amounts of hematite are used in red pigments, polishing powders, and industrial abrasives.

VOLCANOES

The volcanic origin of our hematite after magnetite specimens provides an opportunity to discuss the geologic phenomenon of volcanism. Volcanoes, a word that stems from the Latin Volcanus (Vulcan), the Roman god of fire, are frequently in the news. In 2010, enormous clouds of ash from Iceland's Eyjafjallajokull volcano disrupted transatlantic air travel. According to the United States Geological Survey, 50 to 60 volcanoes erupt each year, and 500 volcanoes have erupted at least once during the past 5,000 years. Volcanoes are surface formations that consist of the accumulation of extruded magmatic material. They have many forms, from gently or steeply sloping hills and mountains to flat plateaus and plains.

Any discussion of volcanoes must begin with magma, the molten rock that forms under high temperature and pressure at a depth of 50 to 60 miles below the earth's surface. Magma tends to rise into the Earth's crust first because it is less dense then solid rock and second, because it is under great pressure and moves in the direction of least resistance. Rising magma tends to accumulate in relatively shallow, subterranean reservoirs. It can then rise farther upward through fissures, faults, and weakened sections of the crust to erupt onto the surface. Eruptions can be explosive or nonexplosive. Erupting materials are classified as lava, tephra (rock fragments), or gases. The type and amount of eruptive material depend on the chemical composition of the magma and the pressure to which it is subjected.

Lava: Once magma erupts or extrudes from a volcano, it technically becomes lava, which is described using Hawaiian terms of texture and consistency. Lava with a continuous, smooth, ropy, or billowy surface is called pahoehoe (pronounced pah-HO-ee-ho-ee) flows; lava with a rough, jagged surface composed of loose, irregularly shaped chunks is called aa (ah-ah). Once cooled, pahoehoe forms smooth rock, while aa forms jagged rock. Lava is also described by its mineral (silica) composition:

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Basaltic: silica-poor, dark-colored (intrusive equivalent is gabbro)
Andesitic: low silica content (intrusive equivalent is diorite)
Dacitic: medium silica content (intrusive equivalent is grandiorite)
Rhyolitic: high silica content (intrusive equivalent is granite)

Tephra: *Tephra is pyroclastic (from the Greek words pyro, "fire," and klastos, "broken," literally "fire-broken") material that consists of rock fragments formed by explosive shattering of thick magma and includes ash, cinders, pumice, and bombs. These fragments are produced when gas explosions eject magma into the air where it cools and solidifies rapidly. Volcanic ash refers to fragments smaller than 2 mm (0.08 in) in diameter, while bombs can weigh several pounds to many tons each.*

Gases: *Gases, primarily water vapor (steam), accompany all eruptions. Gases come from the magma itself or from the reaction of magma with groundwater. Volcanic gases usually consist of water vapor, carbon dioxide (CO_2), and sulfur dioxide (SO_2), with lesser amounts of chlorine (Cl) and fluorine (F) gases.*

Whether an eruption will be explosive or nonexplosive is determined by the composition and viscosity of the magma, the amount of gas in the magma, and the type of vent from which it erupts. In general, viscous magmas produce violent, explosive eruptions, while less viscous magmas produce nonexplosive eruptions. Explosive eruptions can eject liquid and semisolid lava as well as solid fragments of volcanic or nonvolcanic rock that have been carried along by the rising magma. Explosive eruptions can last for several hours to several weeks and eject huge amounts of pyroclastic material. Nonexplosive eruptions produce lava flows that emanate from rifts in the sides of volcanoes and are accompanied by little pyroclastic ejection. Thin, basaltic magma usually produces nonexplosive eruptions.

Volcanoes can develop radically different shapes depending on the magmatic composition and the type and frequency of eruption. The major types of volcanoes, in order of increasing size, are cinder cones, composite volcanoes (stratovolcanoes), shield volcanoes, calderas, and plateaus.

Cinder Cones: *Cinder cones consist exclusively of finely fragmented lava that was erupted explosively. Typically small with symmetrical, cone-like shapes, they are created by a single, minor eruption of basaltic cinder that does not travel far from the vent. Arizona's Sunset crater is an example of a cinder cone.*

Composite Volcanoes: *Like cinder cones, composite volcanoes also have symmetrical cones but are much larger. These are the classic, symmetrical volcanic cones exemplified by Mexico's Volcán Paricutín and Japan's Mount Fuji. Composite volcanoes can be many thousands of feet high and consist of the accumulated products of repeated eruptions, usually of andesitic or dacitic lava, from the same vent over long periods of time. They are called "composite" volcanoes because they are composed of explosively erupted pyroclastic materials layered with nonexplosively erupted lava flows.*

Shield Volcanoes: *Shield volcanoes are named for their distinctive, gently sloping mound-like shapes that resemble the shields carried in battle by ancient warriors. They consist primarily of countless flows of thin, basaltic lava that erupted nonexplosively and flowed great distances from its vents. Shield volcanoes vary radically in size from very small to quite large. Classic shield volcanoes include Argentina's Volcán Payún Matrú, the source of our specimens, and Hawaii's Mauna Loa and Kilauea volcanoes.*

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Calderas: Calderas are round or oval-shaped, low-lying areas that are collapsed volcanic structures. Reduction in magmatic pressure, caused either by an actual eruption or a receding subterranean magmatic reservoir, can cause the surface around a volcano to subside. Calderas can be many miles in diameter and sometimes have hills, called resurgent domes, rising within them that were produced by post-collapse volcanic activity. Yellowstone National Park has prominent caldera structures. Some calderas fill with water to form lakes such as Oregon's Crater Lake.

Plateaus: Some of Earth's largest volcanic features are extensive, nearly flat-topped accumulations of erupted materials that form plateaus or plains covering thousands of square miles. Plateaus form from huge, repetitive flows of thin, basaltic lava called "flood basalts" that erupt from many fissure vents. India's Deccan Traps and the Columbia Plateau in Oregon, Washington, and Idaho are flood-basalt plateaus.

Some volcanoes, including Argentina's Volcán Payún Matrú, the source of our specimens, are compound in nature and exhibit more than one type of structure or lava. Payún Matrú is classified as a shield volcano with an extensive basaltic lava flow. But the cone itself actually has an intermediate composition that includes both explosively erupted pyroclastic materials layered with nonexplosively erupted lava flows. Much of the lava within the cone is of andesitic, rather than basaltic, composition. The compound structure and andesitic lava explains Payún Matrú's lofty summit elevation of 11,442 feet, which is much higher than that of most shield volcanoes.

Volcanology, a formal branch of geology, is the study of the processes, products, hazards, and environmental impacts of volcanic eruptions. A major challenge to volcanologists is to accurately predict future eruptions of active and dormant volcanoes. Scientists consider a volcano active if it has erupted at least once during historical time. Dormant volcanoes are currently inactive but considered to have the potential for future eruption. Long-dormant volcanoes believed to lack the potential for renewed activity are defined as extinct.

ABOUT OUR SPECIMENS

As noted, our specimens were collected at Payún Matrú Volcano (Volcán Payún Matrú) near Malargüe, Mendoza Province, Argentina, a site recently recognized as a classic locality for hematite after magnetite. Payún Matrú is located in west-central Argentina 600 miles west-southwest of the Argentinean capital of Buenos Aires, 40 miles east of the Chilean border, and 200 miles east of the Chilean coastal city of Concepción. The nearest Argentinean city is Malargüe, population 23,000, 75 miles to the north. Malargüe lies in the shadow of the high Andes at an elevation of 4,400 feet. Its economy is based mainly on agriculture, summer eco-tourism, and winter skiing.

A two-hour drive south of Malargüe is La Payúnia Provincial Reserve (Reserva Provincial La Payúnia), a 1,730-square-mile, public nature preserve. Created in 1988 by Mendoza Province to protect the unusual flora and fauna of the Payún Matrú Volcanic Field, the reserve consists mainly of volcanoes and large, desolate expanses of windswept, arid, black volcanic ash known as the Pampas Negras (Black Plains). This undeveloped reserve, the size of the state of Rhode Island, has no paved roads, electricity, or facilities. The dominant geological feature of La Payúnia Provincial Reserve is the extinct Payún Matrú Volcano. From its summit elevation of 11,442 feet, Payún Matrú overlooks a surrounding volcanic field with more than 300 volcanic vents and fumeroles, a few of the latter still periodically active. The regional fauna includes puma, the ostrich-like rhea, and guanacos, which are related to llamas. Only about 100

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ethnically indigenous individuals are permitted to live within the reserve. These individuals, working together as Cooperativa Payún Matrú, supplement their earnings as goatherds through a sustainable system of trapping guanacos, shearing their fine wool, and returning them to the wild. The guanaco wool is then cleaned, spun into yarn, and exported, mainly to the United States.

Volcán Payún Matrú is a large shield volcano (see "Volcanoes"). Radiometric potassium-argon dating indicates that its eruptions began 280,000 years ago, late in the Pleistocene Epoch (1.6 million years to 10,000 years ago). Volcanic activity peaked some 168,000 years ago, then gradually decreased, finally dying out just 7,000 years ago. According to oral tradition among indigenous tribes, the region was already populated during the final phase of eruptions. Major eruptions from Payún Matrú created the 80-mile-long Pampas Onduladas lava flow, the Earth's longest known lava flow of the Quaternary Period (3 million to 10,000 years ago). Late in the life of the Payún Matrú Volcanic Field, magmatic pressures decreased and lava eruptions were largely replaced by fumarolic activity. Fumaroles (from the Latin *fumus*, "smoke") are surface vents that emit steam and mineral-laden gases such as carbon dioxide (CO_2), sulfur dioxide, (SO_2), hydrochloric acid (HCl), and hydrogen sulfide (H_2S). They are found on the surface of lava flows or around fissures and faults and form where shallow magmatic bodies or hot igneous rocks react with groundwater to create steam and gases. They could be described as hot springs in which all water has boiled off before reaching the surface. Fumaroles are common in Alaska's Valley of Ten Thousand Smokes and Yellowstone National Park.

Fumaroles often create environments for unusual mineral formation. To be of mineralogical interest, fumaroles must first produce highly acidic vapors that contain quantities of hydrochloric acid and/or sulfuric acid (H_2SO_4) and, second, overlie or vent through rock rich in such elements as sulfur, iron, chlorine, fluorine, sodium, potassium, calcium, and even copper and zinc. At depth, circulating hot, acidic groundwater leaches minerals from surrounding rock. These mineral-rich solutions are then vaporized and forced upward through fumarolic vents. At the surface, the sudden drop in temperature causes these vapors to undergo a rapid change in physical state. Some of the mineral-rich vapors condense on rock surfaces and, with further cooling, crystallize into solid encrustations. Most of the vapors, however, condense directly into solid encrustations (sublimates). Because of unrestricted space for crystal growth, fumarolic crystals can often be large and very well developed. Fumarolic encrustations often consist of brightly colored oxides, sulfides, and chlorides. Minerals common in fumarolic encrustations include sulfur [S]; gypsum [$CaSO_4·2H_2O$]; halotrichite [$FeAl_2(SO_4)_4·22H_2O$]; thenardite [Na_2SO_4]; glauberite [$Ca_2Ca(SO_4)_2$]; anhydrite [Ca_2SO_4]; melanterite [$FeSO_4$]; alunite [$KAl_3(SO_4)_2(OH)_6$]; halite [NaCl]; and the iron minerals magnetite and hematite.

Our pseudomorphic hematite after magnetite specimens are fumarolic in origin. A pseudomorph is a mineral that has replaced or coated a previously deposited mineral while retaining the exterior crystalline shape of the original mineral. Pseudomorphism involves chemical change and can occur by replacement (substitution), alteration, or encrustation. Our pseudomorphs were produced by alteration, in which the original mineral (magnetite) became altered by chemical oxidation into a secondary mineral (hematite) that retains at least one elemental component of the original mineral. The original mineral can be completely or partially altered, with changes to both its chemistry and its crystal structure. (For an in-depth discussion of pseudomorphism, see our July 2010 write-up on quartz-after-aragonite.)

Our hematite after magnetite specimens initially condensed and crystallized as magnetite [iron oxide, $Fe^{2+}Fe^{3+2}O_4$] on the rock walls of fumarolic vents on the side of Payún Matrú. Given the availability of free atmospheric oxygen in a fumarolic environment and proper conditions of temperature and chemistry, iron can condense in either its ferrous (Fe^{2+}) or ferric (Fe^{3+}) oxidation states (or both), and thus either as

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hematite or magnetite. Our specimens were initially deposited as sharp-edged, dipyramidal, octagonal, black magnetite crystals protruding from, and completely covering, the rock walls of an active fumarole.

Later, as fumarolic activity and temperature decreased, the magnetite became chemically unstable and began to slowly oxidize into hematite. Chemical oxidation is a complex energy-transfer process with several definitions. For the purpose of understanding the transition of magnetite to hematite, think of oxidation as the loss of electrons. The magnetite formula $Fe^{2+}Fe^{3+2}O_4$ can be rewritten as $Fe^{2+}O \cdot Fe^{3+2}O_3$. In the magnetite oxidation process, the magnetite molecule breaks down into its ferrous and ferric components $(Fe^{2+}O)^{2-}$ and $Fe^{3+2}O_3$. The ferric component $Fe^{3+2}O_3$ is already stable as hematite. But because the ferrous component $(Fe^{2+}O)^{2-}$ is not stable, its ferrous ion Fe^{2+} first loses an electron (oxidizes) to convert to ferric iron Fe^{3+}. It then bonds with free oxygen according to the following formula: $2(Fe^{2+}O)^{2-} + \frac{1}{2}O^{2-2} \rightarrow Fe^{3+2}O_3$ (hematite). This oxidation process takes place on a molecule-by-molecule basis, eventually converting all or most of the magnetite to hematite. Although the internal crystal lattice now has the hexagonal (trigonal) structure of hematite, the outer shape precisely retains the cubic, bipyramidal form of the original magnetite crystal.

After fumarolic activity had ceased, the fumarole vents on Payún Matrú eventually collapsed and became packed with altered clay minerals. Light surface erosion eventually uncovered some of these "fossil" fumarolic vents with the hematite after magnetite crystals packed tightly within a brownish clay. These vents were discovered in 2002. Specimens of hematite after magnetite soon reached dealers in Buenos Aires who immediately recognized their unusual size, quality, and brightness. These specimens were shown at the 2004 Tucson (Arizona) Gem & Mineral Show and acclaimed as some of the finest pseudomorphs of their type ever seen. In response to strong collector demand, quantities of these specimens have since been collected and marketed internationally, commanding steep prices.

In examining your hematite after magnetite specimen, note first that the crystals are bi-pyramidal octagons, a shape that is typical of magnetite. A few specimens exhibit a lateral, progressive growth in which some crystals are "capped" by others. Some mineralogists speculate that each crystal represents a specific phase of fumarolic activity! Your specimen consists mostly or entirely of hematite. Because the oxidation process that created these pseudomorphic specimens began on the surface and progressed inward, some specimens may retain a partial, internal magnetite core. To determine if your specimen does retain a partial magnetite core, pass it near a compass needle. Specimens consisting entirely of hematite will not affect the needle; those with a magnetite core will cause the needle to swing! The color of magnetite is basically black, but your specimen shows the characteristic color of crystalline hematite—steel-gray with a specular, silver glitter. Very few specimens on matrix are collected, though some contain a residue of the brownish clay in which they were found. Most crystals are coated with a layer of very small hematite crystals in fascinating patterns, discernable under magnification. As you examine your piece, imagine the many forces that were involved in its creation and its shimmering beauty!

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