

March 2014 Mineral of the Month

KYANITE

This month we are featuring kyanite, a polymorphic silicate from Brazil that has the greatest variation in directional hardness of all minerals. Our write-up explains how these specimens were recovered as a by-product of gemstone mining and discusses the cause and measurement of mineral hardness.

OVERVIEW

PHYSICAL PROPERTIES

Chemistry: Al_2SiO_5 Aluminum Silicate, often containing small amounts of iron and chromium.

Class: Silicates

Subclass: Nesosilicates (Independent Tetrahedral Silicates)

Group: Subsaturate Nesosilicates (Nesosilicates with one or more oxygen ions in addition to those in the silica tetrahedra.)

Subgroup: Kyanite

Crystal System: Triclinic

Crystal Habits: Most often tabular or bladed, prismatic crystals that are elongated on the main axis and rarely terminated; usually folded or wavy in bladed aggregates; also massive. Twinning common; well-developed, transparent crystals are rare.

Color: Usually blue; sometimes colorless, white, and pale gray, green, or brown; occasionally pale pink, orange, or yellow. Irregular, prominent color zoning is common.

Luster: Vitreous to pearly

Transparency: Transparent to translucent

Streak: White

Cleavage: Perfect in one direction, good in a second direction.

Fracture: Splintery to fibrous, brittle.

Hardness: Hardness is directionally variable; usually 4.5-5.0 parallel to crystal length and 7.0 perpendicular to crystal length.

Specific Gravity: 3.55-3.66

Refractive Index: 1.715-1.732

Luminescence: Sometimes weakly fluorescent

Distinctive Features and Tests: Best field indicators are blue color; vitreous luster; bladed habit; perfect, one-directional cleavage; splintery fracture; variation in directional hardness; and occurrence in metamorphic environments.

Dana Classification Number: 52.2.2c.1

NAME: The name “kyanite,” pronounced KYE-an-ite, stems from the Greek *kyanos*, meaning “blue” and alluding to the mineral’s primary color. Kyanite is also known as “disthene,” from

March 2014 Mineral of the Month

the French *disthène*, meaning “double hardness” and referring to its varying directional hardness. Other names include “rhaeticite,” “cyanite,” “munkrudite,” and “blue mullite.” In European literature, kyanite appears as *Kyanit*, *disthène*, and *kianita*.

COMPOSITION: Kyanite contains 33.30 percent aluminum, 17.33 percent silicon, and 49.37 percent oxygen. It is a member of the silicates, the largest and most abundant class of minerals. As a nesosilicate, kyanite consists of aluminum cations packed tightly between silica tetrahedra that are insular (isolated) and have no mutual bonding. Kyanite is a subsaturate nesosilicate, meaning that it has one or more oxygen ions in addition to those forming the silica tetrahedra. Kyanite crystallizes in the triclinic system, which is characterized by three axes of different lengths, none being perpendicular to the others. Like many triclinic crystals, those of kyanite are generally flattened, with sharp edges, thin cross sections, no right angles on faces or edges, and an elongated central axis. As an allochromatic or “other-colored” mineral, kyanite’s color is due to traces of non-essential elements. Pure kyanite is colorless, but iron and chromium ions often replace the aluminum ions within the crystal lattice to produce its characteristic blue color. Kyanite occurs mainly in aluminum-rich rocks that have been altered by high-pressure, regional metamorphism. Kyanite is polymorphic and one of three aluminum-silicate minerals that share the formula Al_2SiO_5 . Polymorphs have identical chemical compositions, but different crystal structures. Sillimanite and andalusite are the other two aluminum-silicate polymorphs.

COLLECTING LOCALITIES: Kyanite is collected in Brazil, Russia, Zimbabwe, Tanzania, Namibia, Italy, Kenya, Austria, Switzerland, Greenland, Canada, China, India, and Australia. Important localities in the United States are in Virginia, Georgia, South Dakota, North Carolina, South Carolina, Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Alabama, Arizona, Idaho, and California.

HISTORY, LORE AND GEMSTONE/TECHNOLOGICAL USES: Kyanite was recognized as a distinct mineral species in 1789. It is used mainly in the manufacture of refractory materials with high melting points and resistance to thermal shock, such as insulating brick and firebrick; ceramic molds for metallurgical, plastic, glass, and cement applications; automotive brake shoes and pads; electrical porcelains; and floor and wall tiles. After mining, raw kyanite is crushed, finely ground, concentrated by hydraulic washing, then calcined or heated to 1380°C . to decompose the kyanite into mullite, a synthetic aluminosilicate. In 2012, the United States was the world’s largest kyanite producer, mining 100,000 metric tons of kyanite worth \$31 million from open-pit mines in Virginia. Kyanite crystals are faceted into rectangular and oval gems; translucent kyanite is fashioned into beads for necklaces and bracelets and into cabochons for pendants. Metaphysical practitioners believe that kyanite enhances creativity, broadens perspective, and promotes mutual understanding. It is also considered a stone of attunement that brings calmness and tranquility to enhance meditation.

ABOUT OUR SPECIMENS: Our kyanite specimens were collected in the Brazilian state of Minas Gerais, one of the world’s premier sources of mineral crystals and gemstones. Our specimens were obtained as a by-product of mining pegmatite gemstones. Some 490 million years ago, the present-day surface of Minas Gerais was buried to a depth of about 12,000 feet.

March 2014 Mineral of the Month

The basement rock, which consisted of highly metamorphosed gneiss, schist, and quartzite, was intruded by granitic magma that created gemstone-bearing pegmatites and provided the pressures that formed kyanite crystals in the adjacent schist. Erosion later exposed these pegmatites, which are the basis of Brazil's gemstone-mining industry. Brazil's pegmatite miners employ both open-pit and underground mining methods in their search for gemstones and mineral crystals. To expose the pegmatites, miners must often blast and remove large quantities of the surrounding schist. Sections of schist that are immediately adjacent to the pegmatites sometimes contain well-developed, blue kyanite crystals which are collected and marketed as mineral specimens.

COMPREHENSIVE WRITE-UP

COMPOSITION

The chemical formula Al_2SiO_5 indicates that kyanite contains the elements aluminum (Al), silicon (Si), and oxygen (O). Its molecular weight is made up of 33.30 percent aluminum, 17.33 percent silicon, and 49.37 percent oxygen. Like all molecules, those of kyanite consist of a cation (positively charged ion) and an anion (negatively charged ion). Kyanite's simple cation consists of two aluminum ions 2Al^{3+} , each with a +3 charge to provide a total cationic charge of +6. Kyanite's compound anion includes a radical (a group of different atoms that acts as an entity in chemical reactions) and an isolated oxygen ion. The radical is the silica tetrahedra $(\text{SiO}_4)^{4-}$, in which four oxygen ions 4O^{2-} surround one silicon ion Si^{4+} and provide a collective -4 charge. The compound anion also has a single oxygen ion O^{2-} , which is not attached to the silica radical. To indicate that this one oxygen ion is not part of the silica radical, kyanite's chemical formula Al_2SiO_5 is also expressed as Al_2OSiO_4 . In this formula, the total -6 anionic charge of the $[\text{OSiO}_4]^{6-}$ anion balances the cationic +6 charge to establish electrical stability within the kyanite molecule.

As a silicate, kyanite is a member of the largest and most abundant class of minerals. In the silicates, silicon and oxygen are combined with one or more metals. The basic silicate structural unit is the silica tetrahedron $(\text{SiO}_4)^{4-}$, in which four equally spaced oxygen ions surround a silicon ion and are positioned at the four corners of a tetrahedron. The oxygen ions are bonded to the silicon ion by strong covalent bonding. In silicate minerals, silica anions and metal cations are linked 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).

Kyanite is a nesosilicate that consists of aluminum cations packed tightly between silica tetrahedra. These tetrahedra are insular or isolated and have no direct silica-silica bonding. In the rigid, nesosilicate crystal lattices, silica anions bond only to metal cations and never to each other. Kyanite is subclassified as a subsaturate nesosilicate—a nesosilicate having one or more

March 2014 Mineral of the Month

oxygen ions in addition to those in the silica tetrahedron. In the kyanite lattice, aluminum ions Al^{3+} alternate with silica ions Si^{4+} to form flat layers of silica radicals and thin layers of aluminum ions. In this arrangement, each aluminum center is surrounded by four silica tetrahedra, a configuration known as “four coordination.” The aluminum ions are bonded ionically to both non-tetrahedral and tetrahedral oxygen ions.

In many other silicates, such as quartz [silicon dioxide, SiO_2], strong oxygen-oxygen bonding between adjacent silica tetrahedra create chain- or framework-type structures. But in kyanite, the combination of ionic and covalent bonding forms linear structures with great directional variation in strength. Kyanite’s highly directional bonding, which is primarily ionic and to a lesser degree covalent, provides excellent mechanical strength in one direction, but relatively little in others. Weak ionic bonding dominates along the longest crystal axis, while much stronger covalent bonding prevails in the perpendicular plane. This arrangement accounts for two of kyanite’s most important diagnostic properties: its perfect, one-directional cleavage along the plane of weak ionic bonding and a great directional, or vectorial, variation in hardness. When abraded parallel to the crystal length, that is, along the direction of perfect cleavage and the plane of weak ionic-bonding, kyanite has a Mohs hardness of just 4.5 to 5.0. But when abraded perpendicularly to crystal length along the plane of strong covalent bonding, kyanite has a much greater hardness of Mohs 7.0. Kyanite’s directional variation in hardness is the greatest of any mineral.

Although kyanite has great one-directional hardness, it is brittle because its weak ionic bonding is vulnerable to mechanical stress. Kyanite’s lattice structure also facilitates very close atomic packing. Although kyanite’s essential elements have relatively light atomic weights (aluminum 26.98, silicon 28.09, and oxygen 16.00), its close atomic packing creates a surprisingly high density (specific gravity 3.55-3.66). Kyanite crystallizes in the triclinic system with three axes of different lengths, none perpendicular to the others. Triclinic crystals, including those of kyanite, are generally flattened, have sharp edges and thin cross sections, exhibit no right angles on faces or edges, and are elongated along the central axis.

As a polymorphic (or trimorphic) mineral, kyanite is one of three distinct mineral species that consist of aluminum silicate (Al_2SiO_5). Polymorphs are minerals that have an identical chemistry, but different crystal structures. The other two polymorphic forms of aluminum silicate are sillimanite and andalusite. All form primarily in aluminous metamorphic rocks, but under different pressures. Because pressure affects the sizes of atomic radii, it determines which aluminum silicate trimorph will crystallize under specific pressure conditions. A clear relationship exists between the specific gravities of kyanite, sillimanite, and andalusite and the pressure in which they formed:

Kyanite forms in high pressure, crystallizes in the triclinic system, and has a specific gravity of 3.55-3.66.

Sillimanite forms in medium pressure, crystallizes in the orthorhombic system, and has a specific gravity of 3.23-3.27.

Andalusite forms in low pressure, crystallizes in the orthorhombic system (with a

March 2014 Mineral of the Month

different lattice structure than that of sillimanite), and has a specific gravity of 3.13-3.21.

Kyanite forms in high pressure and has the greatest density, while andalusite forms in low pressure and is the least dense. In all three aluminum silicate trimorphs, density is a function of atomic packing, which is determined by the pressure that existed at the time of crystallization. Because of its closer atomic packing, kyanite has the strongest bonding and thus the greatest chemical stability. Andalusite, with looser atomic packing, has the weakest bonding and the least stability, and often alters structurally into sillimanite.

Kyanite is an allochromatic or “other-colored” mineral, meaning its color is due to traces of nonessential elements. Pure kyanite is colorless, but the trivalent ions of iron and chromium commonly replace the aluminum ions within the crystal lattice to produce its characteristic blue color. Kyanite crystals are strongly pleochroic, exhibiting different color intensities when viewed along different axes. These color shifts are usually from colorless to light blue, or from light blue to dark blue.

The Dana mineral-classification number 52.2.2c.1 first identifies kyanite as a nesosilicate with insular $(\text{SiO}_4)^{4-}$ silica groups with oxygen (O^{2-}), hydroxyl (OH^{1-}), or fluorine (F^{1-}) ions or attached water molecules (52). It next defines kyanite as having silica anions in coordinations of four or less (2). Kyanite is then assigned to the kyanite subgroup (2c) as the first and only member (1). The polymorphs sillimanite (52.2.2a.1) and andalusite (52.2.2b.2) are assigned to their own subgroups to reflect their different crystal structures.

Kyanite is a product of high-pressure, regional metamorphism of aluminum-rich rocks and is usually associated with the trimorphic minerals andalusite and sillimanite, along with other silicate minerals such as quartz; muscovite [basic potassium aluminum silicate, $(\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$]; almandine [garnet group, iron aluminum silicate, $\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$]; biotite micas (a group of basic potassium iron magnesium aluminosilicates); and staurolite [basic iron magnesium zinc oxyaluminosilicate, $(\text{Fe,Mg,Zn})_{3-4}(\text{Al,Fe})_{18}(\text{Si,Al})_8\text{O}_{48}\text{H}_{2-4}$]. Kyanite also occurs in kimberlite pipes with pyrope [garnet group, magnesium aluminum silicate, $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$]. In kimberlite-type environments, the distinctive, light-blue color of kyanite is produced by traces of chromium.

COLLECTING LOCALITIES

Kyanite is a relatively abundant mineral with many occurrences worldwide. Few, however, yield quality specimens. Our specimens were collected in the state of Minas Gerais, Brazil, as a by-product of pegmatite mining. Other localities in Minas Gerais include São José da Safira in the Doce Valley near Governador Valadares, the Barras do Salinas Mine at Araçuaí, the Tripuí Mine at Ouro Preto, and the Capelinha Mine near Capelinha in the Jequitinhonha Valley. Brazilian kyanite is also collected at the Zacharias Mine at Mara Rosa in Goiás, and the mines at Anagé and Serra da Mangobeira near Paramirim, both in the state of Bahia.

March 2014 Mineral of the Month

In Africa, kyanite specimens come from the Prylin kyanite deposit, Rushingo District, Mashonland, Zimbabwe; the Merelani Hills section of the Lelatema Mountains, Arusha region, Tanzania; and Sultan Hamad in the Uмба Valley, Makueni District, Eastern Province, Kenya. Namibian localities include the Gorob Mine, Swakopmund District, Erongo Region; Kyanite Kop, Windhoek District, Khomas Region; and the Abenab Mine, Grootfontein District, Otjozondjupa Region. European specimens come from Monte Folgarito near Pietrasanta in the Alpuan Alps, Lucca Province, Tuscany, Italy; Mt. Greiner near Zillerthal, Tyrol, Austria; and Mt. Campione near Uri and Sponda Alp-Pizzo Forno in the Chironico Valley near Leventina, both in Ticino, Switzerland. Russian specimens come from Ol'khaniskiye Voroto near Lake Baikal, Irutskaya Oblast', Eastern-Siberian Region. Ukrainian specimens are found in the Volodarsk-Volynskii area of Zhytomyr Oblast'.

Kyanite is also collected at the O'Connell kyanite district at Broken Hill, Yancowinna County, New South Wales, Australia; Kangerdluarssuq Firth at the Ilimassug Metamorphic Complex near Narsaq, Kitaa (Western Greenland), Greenland; the Anderson and Stall Lake mines in the Snow Lake district of Manitoba, and the Narco deposit at Tèmiscamingue, Abiti-Tèmiscamingue, Québec, both in Canada; the Qingshuitang iron deposit, Zongyang County, Anqing Prefecture, Anhui Province, China; and the Lepso Mine at Singhbhum, Singhbhum District, Jharkhand, India.

Kyanite occurrences in the United States are concentrated in the highly metamorphosed rock of the Appalachian Mountains where localities include Graves Mountain in Lincoln County and the F. M. Cagle Mine in Pickens County, both in Georgia; the Willis Mountain Mine at Willis Mountain in Buckingham County, and the Baker Mountain kyanite deposit in Prince Edward County, both in Virginia; the Jefferson Mountain kyanite locality at Gaffney, Cherokee County, South Carolina; the Cook Road staurolite locality at Windham, Cumberland County, Maine; Signal Hill at Lebanon and Pond Hill at Lisbon, both in Grafton County, New Hampshire; the Pike Hill mines at Corinth in Orange County and the Bemis Soapstone Quarry at Townshend in Windham County, both in Vermont; the Chesterfield kyanite locality at Chesterfield, Hampshire County, Massachusetts; the Becker Quarry at Willington, Toland County, Connecticut; and the Heavy Mineral placer district in Montgomery County, Alabama. North Carolina's sources include the Parkway kyanite locality at Asheville, Buncombe County; the J. C. Mills Mine at Brindletown, Burke County; and the Celo Mine in the Spruce Pine district, Yancey County. In the western states, kyanite is collected at the Ogilby kyanite deposit in the Cargo Muchacho Mountains, Imperial County, California; the Consolidated Mine in the Silver District, Trigo Mountains, La Paz County, Arizona; the Goat, Marble Creek, and Freezeout areas of Shoshone County, Idaho; and the Tin Queen Mine in the Hill City district, Pennington County, South Dakota.

JEWELRY & DECORATIVE USES

March 2014 Mineral of the Month

Kyanite is an increasingly popular gemstone. Kyanite's rich, blue color resembles that of blue sapphire [corundum, aluminum oxide, Al_2O_3], while its refractive index of 1.715-1.732, nearly that of sapphire, provides brilliance in properly cut gems. Cutting kyanite is difficult, however, because of its irregular color zoning, great variation in directional hardness, and perfect, one-directional cleavage. Nevertheless, kyanite is faceted into elongated rectangular and oval cuts to maximize cutting retention in its lengthy prisms. Because of directional softness, brittleness, and perfect, one-directional cleavage, kyanite gems are suitable for use only in such low-wear jewelry items as such pendants, necklaces, bracelets, brooches, and earrings. Kyanite gems of 2.5 carats sell for about \$150; 6-carat gems can cost \$400. Although some kyanite gems are as large as 20 carats, only those of 5 carats or less are free of inclusions and color zoning. Translucent kyanite is fashioned into beads for necklaces and bracelets, and into cabochons for mounting in pendants. In rare, cat's-eye kyanite gems, inclusions of fibrous, needle-like crystals of rutile [titanium dioxide, TiO_2] produce a very attractive chatoyant effect.

Collectors value individual and composite specimens of kyanite for their color and long, bladed crystals. In composite specimens, kyanite is usually associated with muscovite [basic potassium aluminum silicate, $\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$], staurolite [basic iron magnesium zinc oxyaluminosilicate, $(\text{Fe},\text{Mg},\text{Zn})_{3-4}(\text{Al},\text{Fe})_{18}(\text{Si},\text{Al})_8\text{O}_{48},\text{H}_{2-4}$], quartz, or the metamorphic rock schist. Especially popular among collectors are cabinet specimens in which long, bladed crystals of blue kyanite contrast with light-colored matrices of quartz or muscovite.

HISTORY & LORE

Kyanite has been collected since antiquity for its attractive, long, blue crystals. Medieval physicians prescribed potions of powdered kyanite to treat sinus congestion and muscular pain. In 1789, German mineralogist and geologist Abraham Gottlieb Werner (1750-1817), studying specimens obtained from Mt. Greiner near Zillerthal in Austria's Tyrol, determined their composition to be aluminum silicate and recognized them as a new mineral which he named *Zyanit*, a German word derived from the Greek *kyanos*, or "blue." Mt. Greiner was originally considered the type locality for kyanite, but because Werner had also studied specimens from other sources, this type locality has been recently discredited. In 1794, the name *Zyanit* was anglicized to "kyanite." However, the popular French spelling *cyanite* remained in use until the mid-20th century.

Kyanite was thought to be the only mineral form of aluminum silicate until 1798, when French philosopher and scientist Jean Claude Delametherie (1743-1817) identified a polymorphic form which he named "andalusite" after Andalusia, the Spanish province where he had obtained his specimens. In 1801, the prominent French chemist and crystallographer René-Just Häuuy (1743-1822) proposed renaming kyanite "*disthène*," a French word stemming from the Greek *di* or "two" and *stenos* or "hardness" that literally means "double hardness," alluding to its directionally variable hardness. Although not formally accepted by mineralogists, "disthène" nevertheless became a popular alternative name for kyanite. In 1824, American mineralogist George T. Bowen (1803-1825) identified sillimanite, the last of the aluminum silicate

March 2014 Mineral of the Month

polymorphs, and named it in honor of Yale University professor of mineralogy Benjamin Silliman (1779-1864). Mineralogists used X-ray diffraction methods in the 1930s to define and differentiate the structures of the three aluminum silicate trimorphs.

Modern metaphysical practitioners believe that kyanite enhances creativity, broadens perspective, and promotes mutual understanding. It is also thought to be a stone of attunement, bringing calmness and tranquility to enhance meditation. Kyanite crystals have appeared on Kenya's 30-cent stamp of 1977 and the 1980 Malawi one-kwacha stamp.

TECHNOLOGICAL USES

Kyanite, sillimanite, and andalusite are important industrial commodities used mainly in the manufacture of refractory materials. The term "refractory," which literally means "stubborn," refers to materials with high melting points and resistance to thermal shock and expansion. In industry, kyanite, andalusite, and sillimanite, which have the same uses, are considered together under the term "kyanite-mineral group." The kyanite-group minerals first gained attention in the early 1900s when a special ceramic material was needed for automotive spark-plug porcelain that had high electrical and thermal resistance, excellent insulation properties, good casting properties, and the ability to withstand the stresses of expansion and contraction that accompanied repetitive heating and cooling. The kyanite-mining industry in the United States began in 1910 in the southern Appalachians, after kyanite was shown to be exceptionally well-suited for automotive refractory-ceramic applications.

In 2012, 408,000 metric tons of kyanite-group minerals were mined worldwide. South Africa is the production leader, mining about 200,000 metric tons of andalusite each year. The United States is second with an annual production of 100,000 metric tons of kyanite. Although the U. S. ranks second in output of kyanite-group minerals, it leads the world in production of kyanite. The sole American producer is the Kyanite Mining Corporation, which operates two open-pit mines in central Virginia. France ranks third in kyanite-group-mineral production with 65,000 metric tons of andalusite, followed by India with 43,000 metric tons of andalusite and sillimanite.

Mined kyanite is crushed and finely ground. Because of its substantial density (specific gravity 3.55-3.66), kyanite is easily concentrated by hydraulic washing. Concentrated kyanite is then calcined or heated to about 1380° C (2516° F.) to drive off volatile matter and decompose the kyanite into synthetic mullite, an aluminosilicate compound. Synthetic mullite is named after natural mullite [aluminum silicate, $\text{Al}_{4+2x}\text{Si}_{2-2x}\text{O}_{10-x}$], a rare mineral with a variable aluminosilicate composition. Synthetic mullite is thermally stable at temperatures of 1800° C. (3272° F.), considerably higher than the melting temperature of iron and most steels. Sixty-five percent of synthetic mullite is used to manufacture furnace and firebrick for the iron and steel industries; the remainder is used to manufacture nonferrous-metal parts, automotive brake shoes and pads, electrical porcelains, floor and wall tiles, and ceramic molds for plastic and glass.

March 2014 Mineral of the Month

Kyanite, sillimanite, and andalusite are also indicator minerals that further the understanding of metamorphic processes. The relative proportions of these three polymorphs in such rocks as gneiss and schist enable geologists to estimate the degree of pressure (and thus, burial depth) that existed at the time of metamorphism.

MINERAL HARDNESS: CAUSE AND MEASUREMENT

Variable hardness, a property of kyanite, is very unusual in minerals. As explained in “Composition,” kyanite’s hardness varies from 4.5-5.0 to 7.0, depending upon the direction in which it is abraded. Kyanite’s variable hardness presents an opportunity to look further into the subject of mineral hardness.

In mineralogical usage, the word “hardness” is defined as the ability to resist abrasion. Hardness is determined primarily by the nature of a mineral’s atomic bonding. Atomic bonding refers to the attractive forces that hold molecules and crystal lattices together. To understand the great difference in strength between types of atomic bonding as related to mineral hardness, consider the halide and silicate minerals. The halides consist of halogens bonded ionically to metals. Ionic bonding is inherently weak. Such halides as halite [sodium chloride, NaCl] and fluorite [calcium fluoride, CaF₂] are quite soft with respective Mohs hardness ratings of 2.0-2.5 and 4.0. Silicates, which consist of silicon, oxygen, and various metals, have much stronger covalent bonding. As examples, quartz [silicon dioxide, SiO₂] and zircon [zirconium silicate, ZrSiO₄] have respective Mohs hardness ratings of 7.0 and 7.5. Thus, stronger atomic bonding is directly related to greater resistance to abrasion.

The concept of mineral hardness took centuries to understand. Some early scholars and alchemists assumed that hardness was a function of dryness and age, and that harder minerals simply contained less water and were older. Very hard gemstones such as diamond [carbon, C] and the ruby and sapphire varieties of corundum [aluminum oxide, Al₂O₃] were thought to be the result of eons of slow “drying.” Some medieval alchemists even attempted to create hard gemstones by heating softer, brightly colored mineral crystals in an effort to “drive off” the assumed water content.

But by the 1600s, European miners had realized that mineral hardness was unrelated to water content. They also routinely scratched mineral specimen to determine relative hardness for identification purposes. But it was not until 1774 that German geologist and mineralogist Abraham Gottlieb Werner (1750-1817), head of the Freiburg (Germany) Mining Academy (Technische Universität Bergakademie Freiberg) and author of the first modern textbook on descriptive mineralogy, systematically categorized minerals by assigning them to “hard,” “semi-hard,” “soft,” or “very soft” groups.

The first useful mineral-hardness scale was developed by Friedrich Mohs. Born in the Harz Mountain region of Germany in 1773, Mohs attended the Freiburg Mining Academy where he studied under Werner. While working as a mineralogical curator at the Johanneum

March 2014 Mineral of the Month

Landesmuseum in Graz, Austria, he began creating his mineral-hardness scale. In 1820, after Mohs had replaced his mentor Werner as professor of mineralogy at Freiburg, he published his scale of mineral hardness. The Mohs scale, published in both German and English, was immediately put to use by mineralogists worldwide.

Mohs arranged his scale according to observations that certain minerals could scratch some minerals, but not others. In its current form, the Mohs scale has 10 ranks that are numbered 1 through 10 (the original scale also had a “0” rank representing fluids). Each rank is assigned a mineral of appropriate hardness as a reference species. Mohs chose these specific minerals because they were common, represented general levels of hardness, and were readily available to mineralogists. These minerals, in order of their Mohs ranking and compared with familiar materials of comparable hardness, are:

1. Talc [basic magnesium silicate, $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$], certain soft plastics
2. Gypsum [hydrous calcium sulfate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$], fingernail
3. Calcite [calcium carbonate, CaCO_3], bronze coin
4. Fluorite [calcium fluoride, CaF_2], iron nail
5. Apatite [apatite-(CaF), $\text{Ca}_5(\text{PO}_4)_3\text{F}$], bottle glass
6. Feldspar (orthoclase) [potassium aluminum silicate, KAlSi_3O_8], penknife blade
7. Quartz [silicon dioxide, SiO_2], steel rasp
8. Topaz [basic aluminum fluorosilicate, $\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$], emery
9. Corundum [aluminum oxide, Al_2O_3], knife sharpener
10. Diamond [carbon, C], certain synthetic silicon carbides

The Mohs scale of mineral hardness is not an absolute scale because it lacks orderly arithmetic or geometric progression. As examples, diamond (10) is about 3.5 times harder than corundum (9). Corundum is twice as hard as topaz (8), which in turn is three times harder than quartz (7). At the lower end of the scale, fluorite (4) is only about two or three times as hard as talc (1).

The Mohs scale is not the only mineral-hardness scale in current use. In 1896, Austrian geologist August Rosival (1860-1913) devised a cutting-pressure test to measure the absolute hardness of minerals. Still in use today, the Rosival scale assigns talc a value of 0.03 and diamond a value of 140,000. In 1925, British researchers established another absolute scale that incorporates the element of cutting time together with cutting pressure and is currently being used by the International Mineralogical Association. In 1939, the United States National Bureau of Standards introduced the Knoop mineral-hardness scale, an absolute system which ranks talc at 1.0 and diamond at 7,000. But the Mohs scale remains the only mineral-hardness scale that does not require laboratory equipment. Without question, it is also the most widely known.

ABOUT OUR SPECIMENS

Our kyanite specimens are from the state of Minas Gerais in east-central Brazil. One of Brazil's 26 states, Minas Gerais is nearly the size of the American state of Texas and has a population of

March 2014 Mineral of the Month

18 million. Minas Gerais, which includes most of the Planalto Central (Brazilian Highlands), has the highest average elevation of any Brazilian state, with much of its area higher than 2,000 feet above sea level. In the 1700s, Brazil, then a Portuguese colony, was the world's largest gold producer, with most mines located in Minas Gerais (Portuguese for "general mines"). Today, Minas Gerais has one of Brazil's strongest state economies, thanks to the steady growth of its mining (gold, gemstones, iron, manganese, zinc, and aluminum), agricultural (coffee, sugarcane, cotton, and oranges), and industrial sectors.

Minas Gerais is famed for mineral crystals and gemstones, and our kyanite specimens were recovered as a by-product of gemstone mining. The Minas Gerais pegmatite belt, an area of gemstone-rich, granite pegmatites, extends 170 miles east-west and 360 miles north-south in the northeast part of the state. Granite pegmatites are bodies of very coarse-grained granite that originate as pockets of residual magma that cooled slowly and crystallized on a fractional, or mineral-by-mineral, basis into irregular pods, lenses, veins, and dikes. Residual magma is often enriched with accessory or rare minerals, while mariolitic cavities produced by gases sometimes provide space for the growth of large and well-developed crystals. Minas Gerais is noted for extraordinary specimens of topaz [basic aluminum fluorosilicate, $\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$]; cat's-eye chrysoberyl [beryllium aluminum oxide, BeAl_2O_4]; beryl [beryllium aluminum silicate, $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$], including its many color varieties; quartz, especially purple amethyst; spodumene [lithium aluminum silicate, $\text{LiAlSi}_2\text{O}_6$], including yellow-green hiddenite and pink kunzite; spinel [magnesium aluminum oxide, MgAl_2O_4]; greenish-yellow brazilianite [basic sodium aluminum phosphate, $\text{NaAl}_3(\text{PO}_4)_2(\text{OH})_4$]; and elbaite [tourmaline group, basic sodium aluminum lithium borosilicate, $\text{Na}(\text{Al}_{1.5}\text{Li}_{1.5})\text{Al}_6(\text{BO}_3)_3(\text{Si}_6\text{O}_{18})(\text{OH})_4$].

These pegmatites formed some 490 million years ago when the present-day surface was buried to a depth of 12,000 feet. The basement rock then consisted of highly metamorphosed gneiss, quartzite, and schist. As bodies of granitic magma surged upward, they were initially capped by these metamorphic rocks. But as these lower intrusions cooled and the overlying metamorphic "roof" fractured, columns of residual magma surged upward into fissures in the schist to form granite pegmatites and to further metamorphose the schist to create well-developed crystals of kyanite. Erosion later exposed these pegmatites, which are the basis of Brazil's gemstone-mining industry.

Brazil's pegmatite miners employ both open-pit and underground mining methods to search for gemstones and mineral crystals. To expose the pegmatites, miners often blast and remove large quantities of the surrounding schist. Sections of schist that are immediately adjacent to the pegmatites sometimes contain well-developed, blue kyanite crystals which are collected and marketed as mineral specimens.

When studying your kyanite specimen, note first its considerable "heft" or weight in the hand. With its relatively high specific gravity of 3.55-3.66, kyanite weighs about 25 percent more than a piece of quartz of similar size. Your specimen is an aggregate of long, bladed crystals with few, if any, terminations, a habit that is characteristic of kyanite. To appreciate kyanite's great variation in directional hardness, use a needle to make small scratches on an unobtrusive part of

March 2014 Mineral of the Month

the kyanite. Notice that the hardness perpendicular to the crystal length is much greater than the hardness parallel to the crystal length. The soft blue color of your kyanite is due to traces of iron that replace aluminum in the crystal lattice. Your specimen has been professionally prepared to remove schist other minerals to better expose the kyanite crystals. Traces of these minerals—sheet-like crystals of silvery muscovite and bits of massive, gray-white quartz—may still appear on your specimen. Your kyanite specimen is a keepsake from Minas Gerais, Brazil, one of the world's great sources of mineral specimens.

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