Lite Geology

New Mexico Bureau of Geology and Mineral Resources

Crystals

Fall 2025

Volume 56

Like crystals? We do too! If you want to learn even more about crystals, make sure to check out our next edition of *Lite Geology*.

***Lite Geology 57* will cover crystal habits and how our new X-ray diffraction and electron microprobe instruments can visualize crystal habits microscopically!**

Crystals

Welcome to *Lite Geology 56*! In this edition, we'll explore the many facets of crystals. New Mexico State Mineralogist and Senior Mineral Museum Curator John Rakovan starts this edition with a description of crystals, minerals, and crystallography. New Mexico Bureau of Geology and Mineral Resources (NMBGMR) Emeritus Principal Geochronologist Matt Heizler explains how geochronology is used to date minerals. New Mexico Tech (NMT)/NMBGMR Economic Geologist Alex Gysi discusses how researchers use crystals in the study of ore formation. NMBGMR Lead Research Scientist Virginia McLemore, along with John Rakovan and NMT students Zohreh Kazemi Motlagh and Samantha Beauchaine, describe how critical minerals occur in nature. A crystal word search will have you looking for gems. John Rakovan explains the principles of crystal healing. Finally, meet Emeritus Senior Mineralogist/Economic Geologist Virgil Lueth in our "Through the Hand Lens" article.

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Cover Photo

The New Mexico Mineral Museum, located on the first floor of the New Mexico Bureau of Geology and Mineral Resources Charles and Jessie Headen Building, displays crystals and minerals from New Mexico and around the world. *Photo by John Rakovan*

Crystals, Minerals, and Crystallography

John Rakovan

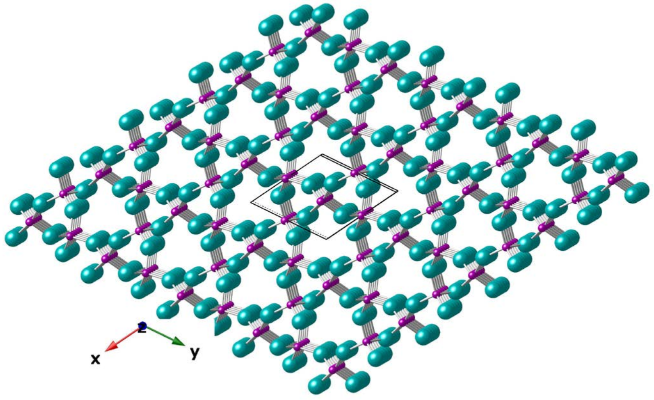
Apatite crystal (pink) on mica crystals. Apatite also forms the mineral component of our teeth and bones. *Photo courtesy of Jeff Scovil*

Crystals are marvelous things. Their flat, shining surfaces and regular geometric shapes are both beautiful and intriguing. They also compose the majority of the solid Earth.

The term “crystal” was first used to describe solids found in nature that have flat surfaces arranged in geometric patterns, such as cubes and prisms. Since the advent of X-ray diffraction, one of the most important scientific discoveries of the 20th century (more on that below), we define a crystal not by its external morphology or appearance, which is something we can simply see, but by the special arrangement of atoms that make up a crystal, which is something so small it is outside the realm of sight.

What do the sun, the Earth, the air you breathe, the water you drink, and you all have in common? One thing is that they are all made of atoms. All matter in the universe is made of atoms.

Matter can exist in various forms (i.e., states of matter). These include solids, liquids, and gases. Water (H_2O), for example, exists as solid ice, liquid water, and gaseous steam, but other states are also possible. In solids, the arrangement of atoms can be disordered or random, and the material is called amorphous. Alternatively, the atoms in a solid can be ordered in a regular and repeating arrangement, and the material is crystalline, i.e., it is a crystal. The morphology of a crystal is the result of this atomic order and also the crystal’s growth history. Yes, crystals grow, not like living things through the process of dividing cells, but by the addition of atoms onto a crystal surface. Depending on growth conditions and all the things that can happen to a crystal after it grows, a crystal may not exhibit flat faces or a geometric shape.



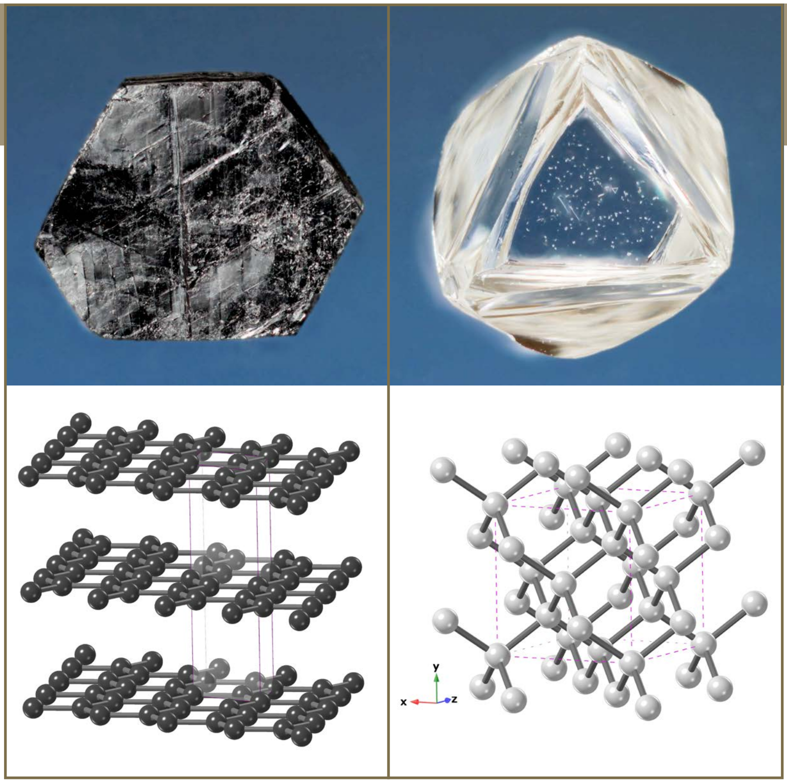
At left, amethyst on milky quartz from Hopkinton, Rhode Island; 5 cm tall. At right, a ball-and-stick model of the quartz atomic structure (balls represent atoms, sticks represent bonds between atoms). Pink balls represent silicon atoms; teal balls represent oxygen atoms. *Photo courtesy of Jeff Scovil*

Naturally occurring crystals are called minerals. The International Mineralogical Association (IMA) defines a mineral as “an element or a chemical compound that is normally crystalline and that has been formed as a result of geological processes.” Rocks are naturally occurring aggregates of minerals or mineraloids (noncrystalline geologic solids).

Each mineral species has a unique combination of chemistry and atomic arrangement (structure). For example, the most common mineral species in the Earth’s crust—quartz—is made of silicon (Si) and oxygen (O) and has the chemical formula SiO_2. The Si and O atoms are arranged as shown in the ball-and-stick model at left.

Minerals with the same chemistry but different structures are known as polymorphs. For example, diamond and graphite are both carbon (C).

Other groups define minerals differently. In the context of nutrition or health science (e.g., vitamins and minerals), a mineral is a chemical element that our bodies need to develop and function normally. Only two of the elements essential for good health occur as minerals in the IMA sense of the word: iron (Fe) and copper (Cu).



Graphite (left photo and ball-and-stick model) and its layered crystal structure compared to diamond (right photo and ball-and-stick model) and its structure. The dramatic property differences between these two minerals are a result of their different structures. Diamond is colorless, transparent, and the hardest known substance, while graphite is black, opaque, and one of the softest minerals. *Photo courtesy of John Jaszczak*

In the mining industry, the term “minerals” refers to any rock, mineral, or other naturally occurring material of economic value, including metals, industrial minerals, energy minerals, gemstones, aggregates, and synthetic materials sold as commodities. Thus, minerals include all inorganic substances as well as hydrocarbons, such as oil and natural gas, and carboniferous deposits, such as coal. In the realm of earth sciences (geology, mineralogy, oceanography, etc.), the IMA definition of a mineral is adhered to unless otherwise indicated.

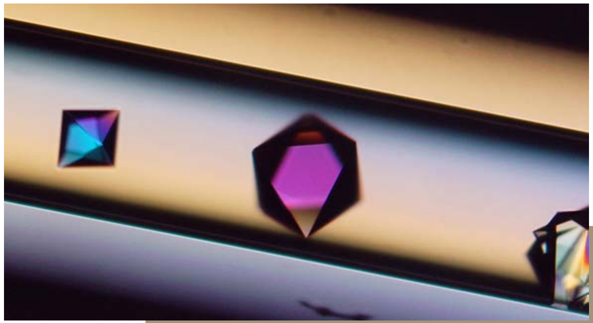
Crystals of just about any mineral can be grown in the laboratory, and some can even be grown in your home using simple household materials (e.g., crystalverse.com). Many chemical compounds that are not found as minerals can also be grown as crystals in the laboratory and are the foundation of material science and the use of crystals in industry.

Surprisingly, organic molecules, including very large molecules like DNA and proteins, can also crystallize. Even viruses can be crystallized, and all of these can form with the beautiful shapes of inorganic crystals like quartz.

Because atoms are periodically arranged in crystals, when waves of an appropriate wavelength pass through a crystal, the physical process of diffraction occurs. The pattern created by diffracted waves allows scientists to calculate the pattern of atoms in the crystal and thus to determine its structure. Accordingly, we don’t see the structure directly; rather, we decipher it from diffraction patterns (i.e., diffraction data). X-rays have the appropriate wavelength for this purpose, and almost all known crystal structures were determined from X-ray diffraction data. In fact, X-ray diffraction is the best way to determine whether something is a crystal. Resolving crystal structures is the foundation of crystallography and gives us the information necessary to better use crystals in technological and scientific applications.

As they are the dominant constituent of the solid Earth, we are all awash in crystals. Crystals are central in making more accurate clocks (e.g., the quartz in your watch), developing antiviral medications to mitigate COVID-19, creating new types of lasers, solving environmental problems associated with heavy metals and radioactive pollutants, creating better and faster computers, and so much more. Crystals are not just beautiful and intriguing; they are natural and technological wonders.

A large plate of copper crystals, on display in the New Mexico Mineral Museum, from the Chino mine near Silver City, New Mexico. Naturally occurring crystals of a single element, like this copper, are known as native elements. *Photo courtesy of Mark Cross*



Protein crystals in a capillary. These crystals were grown in space to test the effect of zero gravity. *Photo courtesy of the Japan Aerospace Exploration Agency*

Geochronology

Matt Heizler

Determining the age of a rock (geochronology) is commonly based on the natural radioactive decay of a parent isotope to a daughter isotope at a known rate (half-life). Geochronology is mostly conducted on minerals. For instance, in zircon, the parent isotope of uranium decays to the daughter isotope of lead, and in potassium-bearing minerals (e.g., micas, amphiboles, and feldspars), potassium decays to argon.

The New Mexico Bureau of Geology and Mineral Resources has a highly sophisticated, state-of-the-art geochronology laboratory that specializes in potassium-argon (K/Ar) dating. Because the daughter isotope argon is a noble gas, it does not chemically bond to the mineral lattice; thus, it is generally not present in a mineral when the mineral crystallizes. Instead, it resides in the mineral because it was derived from the radioactive decay of potassium over time. The lack of chemical bonding allows argon to escape (diffuse) from the mineral when the crystals are heated or are cooled from high temperatures after they crystallize. This mobility of argon means that even though the radioactive clock is ticking along, the mineral is not recording the elapsed time until the system cools to a temperature at which argon is retained. Thus, upon analysis in the laboratory of a crystal that has experienced slow cooling, the measured age will be younger than the time of crystallization, but the crystal will importantly record the time of cooling. This field of science is known as thermochronology. The date recorded by the K/Ar system is the time a crystal cools through a specific temperature, which can be much younger than when it crystallized.

It has long been observed that argon is retained in different minerals at different temperatures. For instance, amphibole can hold on to its argon at temperatures as great as 500°C, whereas microcline (a potassium feldspar) continues to lose argon until it cools to about 250°C. The reason for this lies in the complex nature and variability of crystal structures and internal textures in crystals. It turns out that when argon is diffusing out of the mineral at elevated temperatures, it seeks pathways of least resistance and shortest distance. Thus, rather than trying to squeeze through a tight crystal structure and traverse the entire crystal length, it could encounter a physical crack—a simple example of an easy pathway to escape through. More likely, argon exploits tiny pathways. In the case detailed here for microcline, it uses crystallographic defects that occur along the interface of compositionally different regions, called lamellae, in a textural variety of feldspar referred to as perthite.

Matt Heizler, NMBGMR Emeritus Principal Geochronologist, with one of the mass spectrometers in the New Mexico Geochronology Research Laboratory. The lab has some of the most advanced mass spectrometers in the world, allowing for very precise measurements. *Photo by Cynthia Connolly*

Figure 1. Alkali feldspar crystal showing perthitic texture and albite lamellae (white linear features) interlayered with microcline (pink host mineral). This specimen is from Perth, Ontario, Canada, the original locality where perthite was described. *Photo by John Rakovan*

So what is perthite and why is it important to thermochronology and argon diffusion in feldspar? Upon crystallization at high temperature from a magma, an alkali feldspar crystal (one containing both potassium and sodium [Na]) has a uniform distribution of potassium and sodium throughout its structure. However, during slow cooling, the sodium and potassium atoms of alkali feldspar begin to move away from one another in a process known as exsolution. They congregate with other atoms of the same element, forming lamellae of potassium feldspar (microcline) and sodium feldspar (albite). The unmixed components can be seen with the naked eye in many perthites, like the crystal pictured in Figure 1. Resembling marbled beef, the white lamellae are albite set in the host of pink microcline. Figure 2 is a photomicrograph viewed through a petrographic microscope showing a closer view in which the microcline has a distinct cross-hatched or tarten-twinning microtexture (multiple shades of gray) and the albite has a more uniform tan color. The boundary between the microcline and the albite (red arrow in Fig. 2) provides an escape path for argon, as demonstrated in Figure 3.

Figure 3 is an electron microprobe image of very thin perthite (around 1 micron [µm]; 1 µm = 0.001 mm) and is an example of cryptoperthite or film perthite. Because the sodium atoms in the albite are smaller than the potassium atoms in the microcline, the crystal structures of the albite and the microcline need to bend in order to match up at the boundary between the two intergrown minerals. This bending (strain) can only go so far, and eventually a dislocation (hole) in the boundary between the minerals is required to accommodate the strain. The dislocations can be enlarged by exposure to hydrofluoric acid vapor, making them more easily visible, as shown in Figure 3. These dislocations provide tunnels for argon to use as its escape route out of the crystal, provided the temperature is above about 250°C. Below this temperature, argon transport effectively stops, and thus the K/Ar clock begins recording the time elapsed since cooling (i.e., thermochronology).

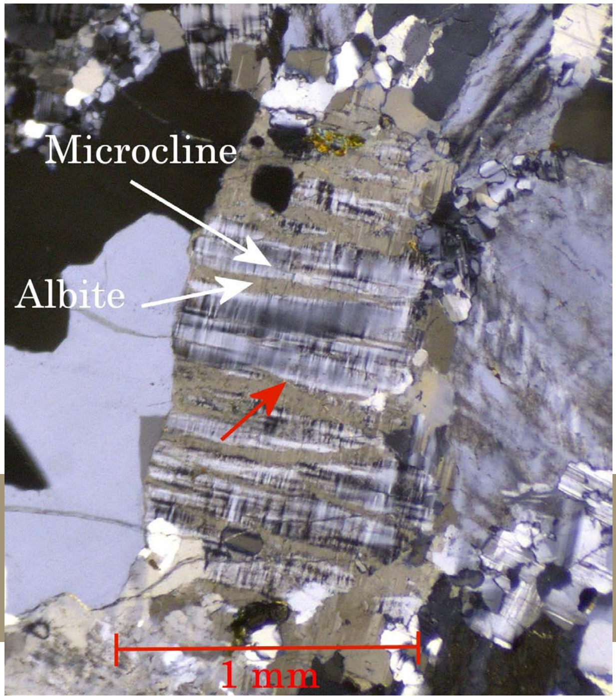


Figure 2. Close-up view of a perthite from Pikes Peak in Colorado. Albite lamellae (tan linear features) interlayered with microcline lamellae display their characteristic cross-hatched pattern. The red arrow marks a boundary between the lamellae. *Image by John Rakovan*

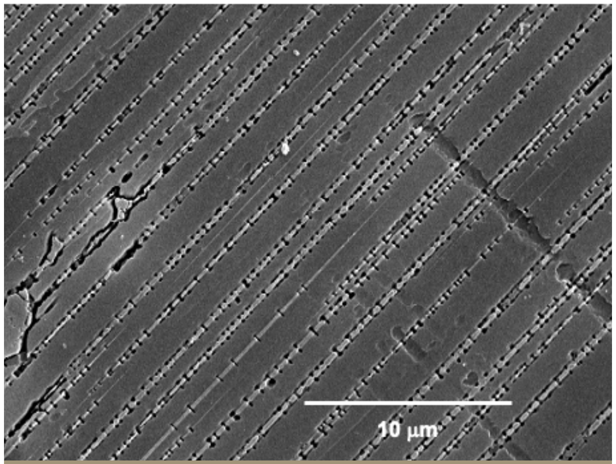


Figure 3. Backscattered electron microscopy image of very thin perthite hosted in an alkali feldspar. Due to differences in the sizes of the sodium and potassium atoms, strain is created at the interface between the albite and microcline lamellae. Strain can be accommodated over short distances in the perthite, but it eventually reaches a threshold where a dislocation (hole) is required to relieve it. These holes (actually tunnels) provide an efficient pathway for argon to escape from the mineral. *Image courtesy of Ian Parsons*

Unmasking Mineral Mysteries: How Crystals Can Reveal the Secrets of Ore Formation

Alex Gysi

An ore deposit can be considered an anomaly in the Earth's crust in which the concentration of minerals is high enough in specific elements (like metals or gemstones) to be economically extracted through mining. Such deposits can be formed through various geologic processes, including crystallization from a magma at depth (e.g., the plumbing system of a volcano), hydrothermal fluid-rock reactions (e.g., geothermal systems or black smokers at mid-ocean ridges), and sedimentary processes (e.g., weathering and river transport at the surface).

In hydrothermal systems, hot fluids circulate through cracks and faults, forming hydrothermal veins upon cooling (Fig. 1), where minerals such as fluorite, calcite, and quartz precipitate. These minerals are also called gangue minerals because they do not form the ore itself (e.g., gold, sphalerite, galena, and others) but rather are the sidekick that accompanies the mineralization of the goodies. During mineral growth from fluids, vein minerals incorporate different elements that give us clues about their formation conditions, such as temperature, fluid chemistry, and pH.

Geochemists and economic geologists use different methods to reveal the secrets of ore formation in geologic systems. Everything starts by studying minerals in hand samples and looking at mineral growth textures and their occurrence with other minerals (Fig. 1). To dive deeper on the micron scale, we cut billets and make thin sections of these field samples and study them under a microscope (Fig. 2). At the micron scale (1 µm = 0.001 mm), minerals such as fluorite, under transmitted light, can be investigated to further look at microtextures and the

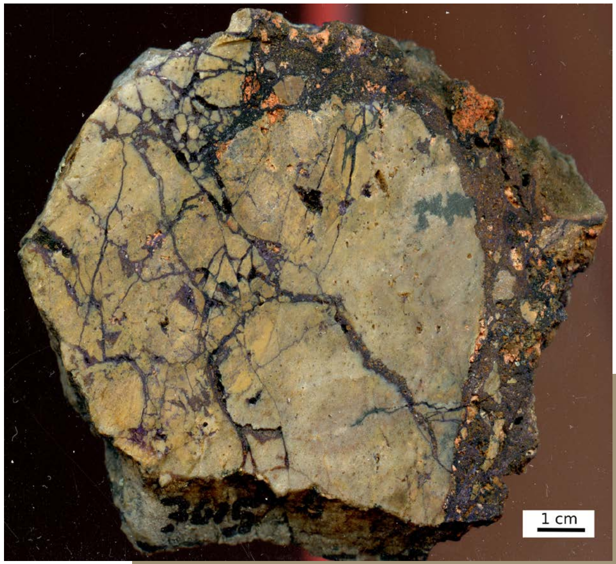


Figure 1. A series of hydrothermal barite-bastnäsite-fluorite veins crosscuts the host rock, Yeso Sandstone. This sample is from the Gallinas Mountains in Lincoln and Torrance Counties, New Mexico. *Photo by Alex Gysi*

Figure 2. At left, a thin section under the microscope in NMBGMR's Ore Deposits and Critical Minerals Lab. At right, a transmitted light view shows a cross section of cubic fluorite crystals. *Photos by Alex Gysi*

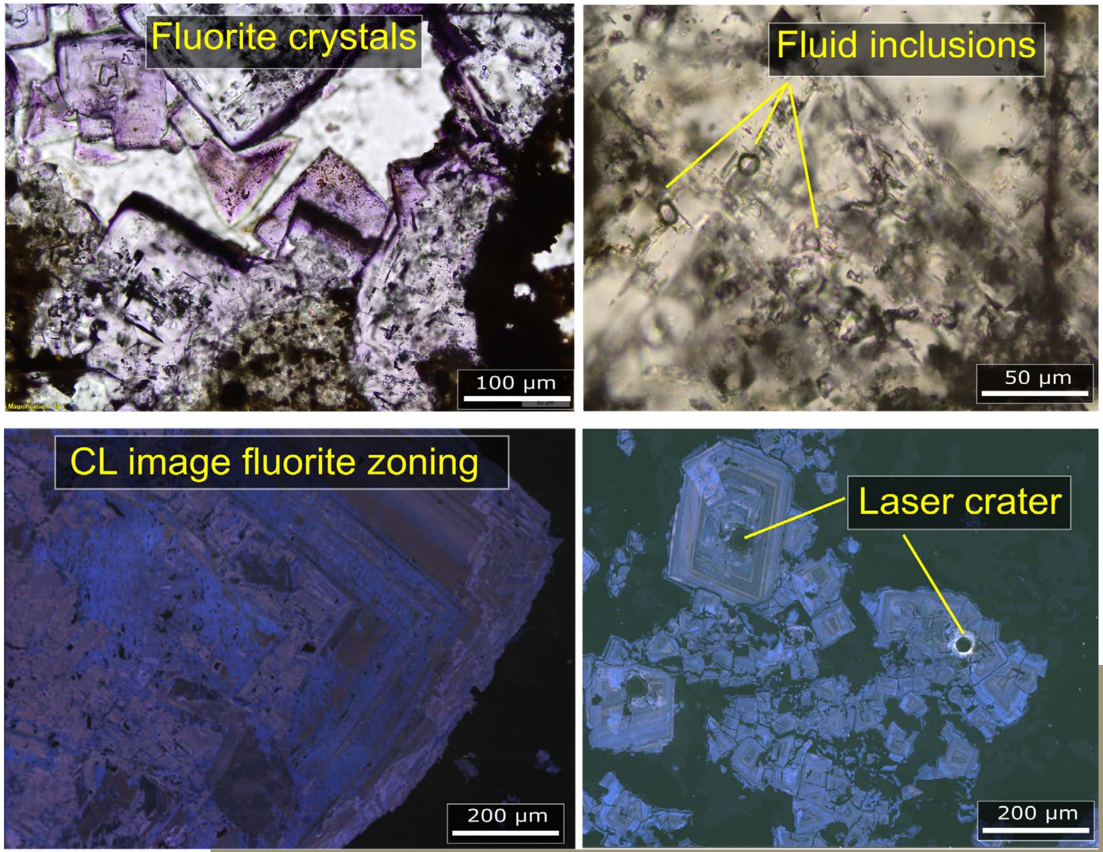


Figure 3. At upper left, purple fluorite crystals under transmitted light; at upper right, fluid inclusions in those crystals displaying bubbles of gas and liquid water. At lower left, a cathodoluminescence (CL) image of zoned fluorite crystals with growth and dissolution textures; at lower right, smaller zoned fluorite cubes with laser craters for further trace element analysis using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). *Upper right image by Aadish Velmani; other images by Alex Gysi*

presence of fluid inclusions (Fig. 3). Such inclusions are tiny pockets of fluids containing a bubble (of vapor or gas) and a liquid (i.e., water) trapped during the growth of a mineral. We can measure their heat of entrapment and determine their salinity via freezing/heating experiments. The freezing temperature, for example, depends on salt concentration—a principle used to salt roads and melt snow in winter. Adding more salt lowers the melting temperature, causing frozen water to melt.

One method to evaluate how crystals grow from a hydrothermal fluid is called cathodoluminescence. This is when we interact an X-ray with a mineral, which generates a characteristic luminescence color (Fig. 3). Elements such as manganese, iron, rare earth elements, and others change the color of these minerals depending on the fluids from which they crystallize. Minerals like fluorite and calcite are particularly affected by their trace element compositions and are perfect gangue minerals to study in ore deposits because they are very common.

To dive a step deeper in our understanding of these minerals, we can conduct chemical analyses of the crystals, generally from core to rim, where the core forms earlier and the rim later. Zonation in a crystal can indicate episodic crystallization processes from hydrothermal fluids (Fig. 3). We use a method called laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to measure trace element compositions in different zones of a crystal. The name seems complicated, but essentially we dig a crater with a laser (Fig. 3), transport the particles to a plasma torch, and use a detector that separates isotopes of elements based on mass.

We use rare earth elements in fluorite and apatite, for example, to distinguish whether these minerals crystallized from a magma (like in volcanoes but at depth) or from a hot hydrothermal fluid. Rare earth elements are found everywhere in the Earth's crust, in every rock, and can be a good indicator of geologic processes. We plot the rare earth elements normalized to chondrite to indicate their relative enrichment or depletion, and we can further subdivide them into light and heavy rare earth elements. Chondrites are meteoric samples that are remnants from the formation of the solar system and are used to represent the chemical composition of the solar system. They serve as standards for calibrating analytical equipment and verifying the accuracy of geochemical experimental data. Some geologic systems we are studying include the Lemitar and Gallinas Mountains in New Mexico, which are not currently economically viable but serve as excellent natural laboratories to study fluorite and calcite associated with the formation of critical mineral deposits. The latter are important indicator minerals for exploration because rare earth elements are used to build components for high-tech and green energy industries. Such components include permanent magnets used in wind turbines, computers, cell phones, and medical devices.

How Do Critical Minerals (Elements) Occur in Nature?

Virginia T. McLemore, Zohreh Kazemi Motlagh, Samantha Beauchaine, and John Rakovan

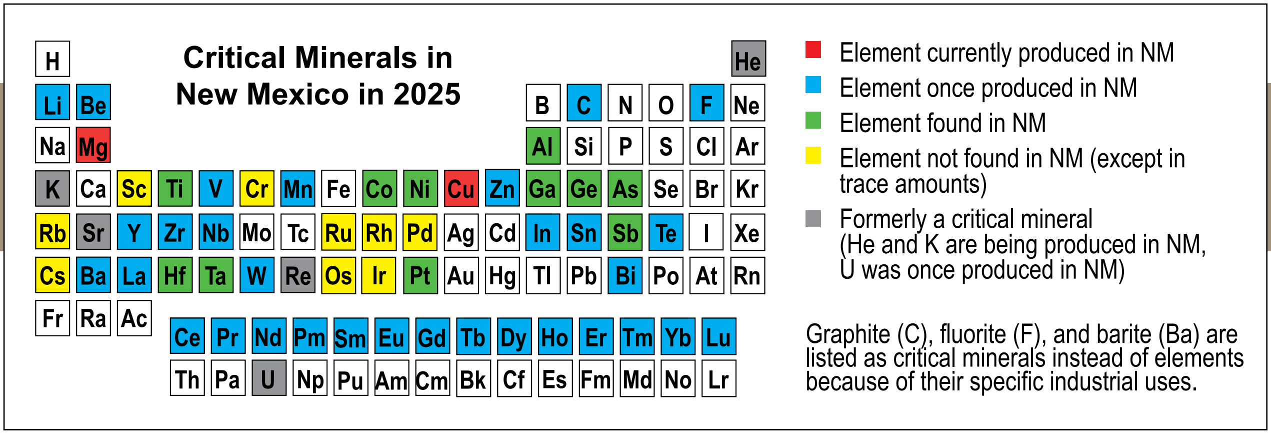


Figure 1. Critical minerals (elements) found in New Mexico (modified from McLemore and Gysi, 2023, "Critical Minerals in New Mexico," *New Mexico Earth Matters*, v. 23, no. 1, p. 1–4, ***geoinfo.nmt.edu/publications/periodicals/earthmatters/23/n1/em_v23_n1.pdf***).

Critical minerals have become a focus of research due to their importance in many products we use every day. Critical minerals are defined by three criteria: (1) economic vulnerability (essential to economic, strategic, or national defense), (2) high risk of supply disruption, and (3) trade exposure (dependency on foreign supplies; many critical minerals are 100% imported into the United States). Critical minerals are therefore a subset of the mining industry's definition of minerals. The criticality of critical minerals changes with time as supply and society's needs evolve. Critical minerals found in New Mexico are shown in Figure 1. Unlike the International Mineralogical Association (IMA) definition of a mineral (see "Crystals, Minerals, and Crystallography" in this issue), most critical minerals are elements. Some of these do form minerals in the IMA sense of the word, and these are called native elements. For example, crystals of copper (Cu) are found at the Chino and Tyrone mines in Grant County, New Mexico. For the rest of this article, we will use the term "critical element" instead of "critical mineral" and constrain the use of "mineral" to the IMA definition.

But how are most critical elements found in nature? Although some critical elements, like copper, form unusual and beautiful crystals, most critical elements exist naturally in combination with other elements, that is, as chemical compounds. If these compounds are crystalline, as is usually the case, they are minerals. Critical elements are found either as essential constituents in minerals or as impurities, for example as substitutions for other elements that are essential to the mineral species.

Critical Elements as Essential Constituents in Minerals

Each mineral species has a unique combination of chemistry and atomic arrangement (structure). If an element is in the defining chemistry of a species, it is an essential constituent. For example, tungsten (W) in the mineral scheelite ($CaWO_4$; Fig. 2) is essential, and scheelite is the primary source (ore mineral) of tungsten, which is used in tungsten carbide drilling and cutting tools and in electronics and special steels. The WO_4 molecule in scheelite activates fluorescence under ultraviolet light, which can be used to prospect for it in the field.

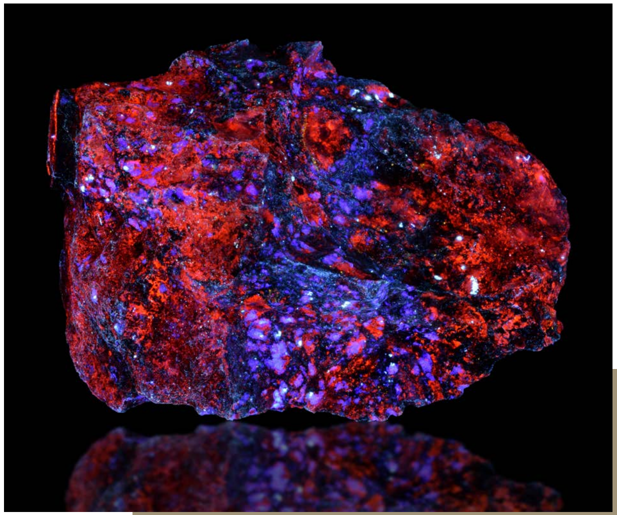


Figure 2. Fluorescent specimen taken under full-spectrum ultraviolet light of calcite (red), fluorite (blue), and bright white scheelite ($CaWO_4$) from the Victorio mining district, Luna County, New Mexico. *Photo courtesy of Chris Clemens*

Figure 3. Copper from the Chino mine, Santa Rita mining district, Grant County, New Mexico; 9 cm tall (NMBGMR #16593). *Photo courtesy of Jeff Scovil*

Few critical elements are found as native metals, but as mentioned previously, copper is commonly found in the native state (Fig. 3).

The U.S. Department of Energy considers copper a critical material because of its ability to transmit heat and electricity. Approximately 4.7 tons of copper are needed in a 3-megawatt wind turbine (for cables, wiring, turbines, and transformers), and 5.5 tons of copper are needed to provide a single megawatt of solar power (for heat exchangers, wiring, and cables). Copper is needed in cables, wiring, and switches used for energy storage devices and transmission of electricity. A hybrid car uses 88 pounds of copper, while a fully electric car uses 183 pounds of copper, compared to 48 pounds of copper needed in a regular car powered by an internal combustion engine.

Rare earth elements (REE) are a set of 17 chemical elements in the periodic table (Fig. 1) that, because of their unique geochemical properties, are typically widely dispersed in the Earth's crust and are not often found in concentrated and economically exploitable forms. Most REE deposits in production are mined for the mineral bastnäsite (Fig. 4). Significant quantities of REE are used in the production of clean energy technologies, including advanced automotive propulsion, wind turbines, batteries, fuel cells, electric motors, high-efficiency light bulbs, and generators in wind turbines. Most modern defense technologies, such as radar and sonar systems, precision-guided weapons, and cruise missiles, require REE and the materials produced from them.

Critical Elements as Substitutions in Minerals

Apatite ($Ca_5(PO_4)_3(F,Cl,OH)$) is the most abundant phosphate mineral on earth and is our most important ore of phosphate (PO_4), which is an essential fertilizer. The crystal structure of apatite allows for numerous other elements, many of them critical elements, to substitute for either calcium (Ca) or phosphorus (P; Fig. 5).

Figure 4. Yellow, tabular crystals of bastnäsite ($(Ce,La,Y)CO_3F$), an REE fluorocarbonate, on fluorite from the Gallinas Mountains, Lincoln County, New Mexico. The field of view is about 20 mm. *Specimen courtesy of Fred Parker; photo courtesy of Scott Braley*

Figure 5. At top, apatite from Cerro Mercado, Durango, Mexico. The yellow color is the result of REE substitutions for calcium in the sample. Below, ball-and-stick model of the apatite crystal structure. Calcium resides in the M1 and M2 sites, while phosphorus is in the T site. The green sphere represents an REE that has substituted for calcium in an M1 site. *Photo by John Rakovan*

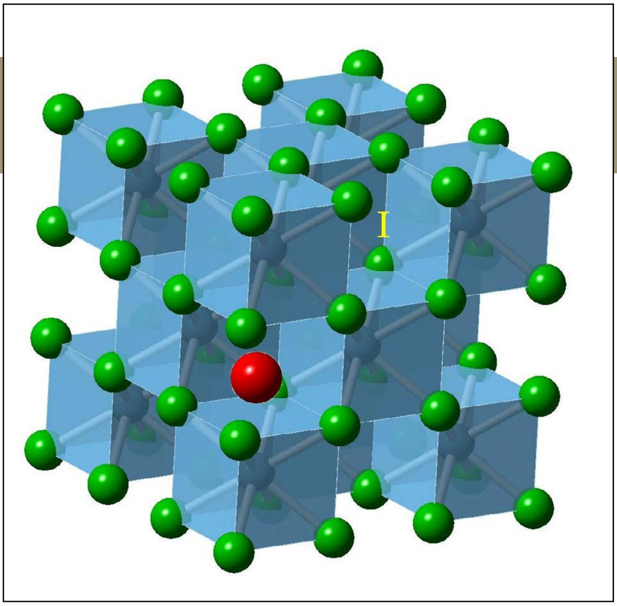


Figure 6. Ball-and-stick and polyhedral model of the fluorite (CaF_2) structure. Green spheres represent F^- ions. Eight F^- ions bond to a central calcium with a cubic geometry (cubic polyhedron). The CaF_8 polyhedra alternate with cubic void spaces (interstitial sites; I). The incorporation of an impurity atom (red sphere) into an interstitial site is shown.

Of the critical elements listed in Figure 1, strontium (Sr), manganese (Mn), arsenic (As), antimony (Sb), uranium (U), and all of the REE can substitute into apatite. In some deposits, the concentration of these substituents is high enough that apatite can be used as an ore for these elements, including the REE.

Other Ways Critical Elements Can Be Incorporated Into Crystal Structures

In addition to elemental substitutions, like an REE substituting for calcium in the apatite structure (Fig. 5), the incorporation of critical elements can involve crystal defects (regions where the regular atomic structure is disrupted) or interstitial sites (void spaces within a crystal structure where atoms usually do not reside).

Eudialyte is a complex mineral composed of sodium, calcium, zirconium, niobium, and other essential elements. It can incorporate other critical elements, including REE. The incorporation of REE in eudialyte can involve substitution for another element in the structure as well as incorporation in an interstitial site, analogous to the one shown in Figure 6.

Figure 7 shows an unusual sample of eudialyte from the Cornudas Mountains, New Mexico. Discovering an almost completely eudialyte-bearing vein is of extreme interest. This level of mineral concentration is rare and suggests unique geochemical conditions. It raises important questions about the nature of the magmatic or hydrothermal fluids involved, their temperature and composition, and how they evolved during vein formation. Additionally, the textural relationships between the eudialyte and surrounding minerals in the vein can provide insights into the timing of crystallization events and the mobility of REE-bearing fluids. With its great compositional variability, eudialyte has the potential to be a primary source of REE, particularly in the Cornudas Mountains of southern New Mexico.

Intergrown Critical Element–Bearing Minerals Indicate Complex Hydrothermal Processes

In many ore deposits, minerals are not easily separated. Instead, two or more minerals grow together in intricate patterns. Hot, mineral-rich fluids (hydrothermal fluids) flow through cracks in rocks. As the fluids cool or mix with other waters, different minerals begin to crystallize. Sometimes, these minerals form at the same time, while at other times, one mineral begins to grow and another forms on top of or between its crystals. When minerals bearing critical elements are intergrown (Fig. 8), geologists know the hydrothermal system that formed them was complex and dynamic. Variations in temperature, pressure, and chemistry during the mineralization process cause minerals to grow together in an interwoven texture. By studying these textures, scientists can understand the history of the deposit better.

By using microscopes and chemical analyses, geologists can see the order in which minerals formed, how the fluids changed over time, and what conditions existed deep underground. This information is not only valuable for science; it also guides responsible mineral exploration and mining for the resources needed in a clean-energy future.

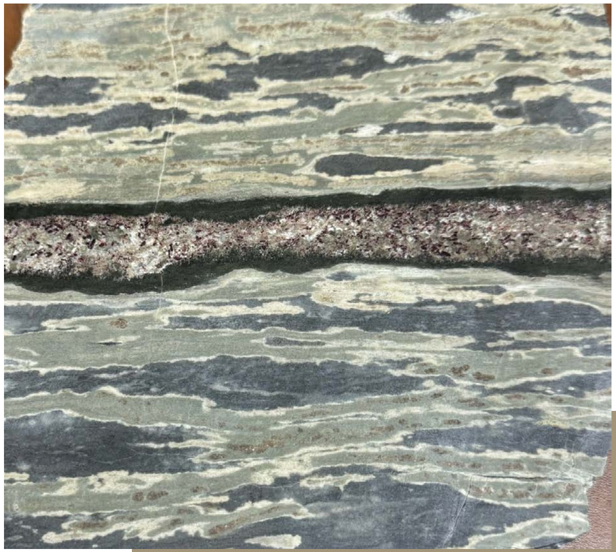


Figure 7. A eudialyte-bearing (red crystals) nepheline syenite vein was identified within a boulder in the Cornudas Mountains, Otero County, New Mexico. *Photo by Evan Owen*

Critical Element–Bearing Minerals Can Form by Alteration of a Primary Mineral

Minerals bearing critical elements can form later in an assemblage, when one or more minerals change into new minerals through a process called alteration. Alteration occurs when minerals are exposed to hot fluids, changes in pressure, or other environmental conditions in which minerals are unstable. These new conditions can cause atoms in a mineral to rearrange or some elements to be added or removed, creating a new mineral. For example, primary copper minerals such as chalcopyrite can change into secondary minerals like digenite when fluids carrying iron move through the rock.

In addition, alteration plays an important role in enhancing the concentration of critical elements. Hot fluids can selectively dissolve some elements while introducing or concentrating others. This process often causes valuable elements to become mobilized and redeposited in more concentrated forms. As these fluids interact with rock, they may remove unwanted components and leave behind or precipitate minerals containing critical elements.

Summary

Critical elements (minerals) are essential to society and sustainability, but these elements are not always as abundant in nature as others, are subject to supply disruptions, and are not always found in economic concentrations in the United States. Therefore, understanding the various ways in which critical elements are found in minerals (crystals) is important so geologists can successfully prospect for new deposits and help mitigate issues of adequate supply.

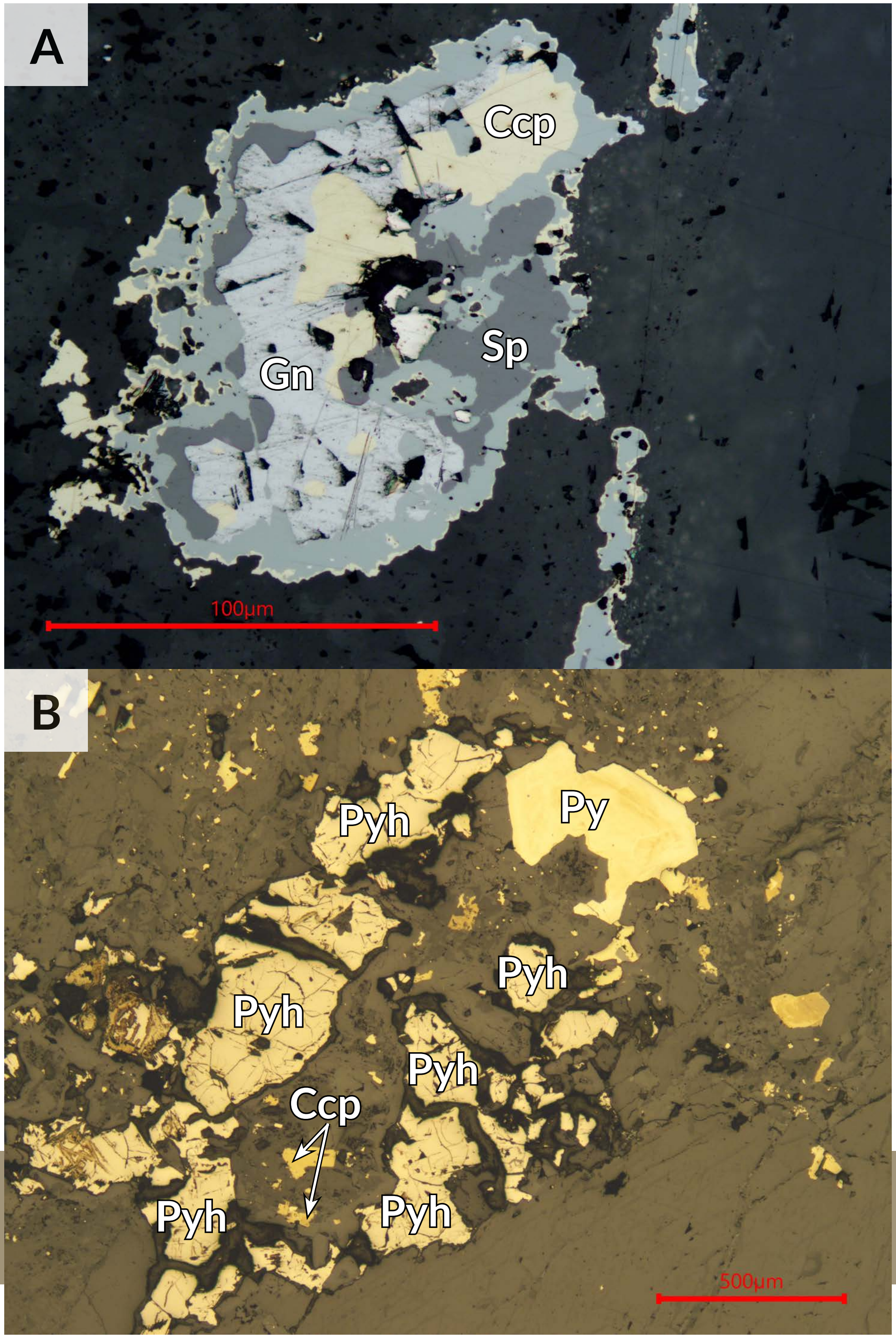


Figure 8. Examples of critical element–bearing minerals. (A) Ccp = chalcopyrite, Gn = galena, Sp = sphalerite. (B) Py = pyrite, Pyh = pyrrhotite, Ccp = chalcopyrite. *Photos by Zohreh Kazemi Motlagh*

Rock Riddler Puzzle

Crystal Word Search

A	N	L	C	T	L	D	Y	D	O	I	P	S	A	A	H	S	B	O	U	N	O	M	C	M
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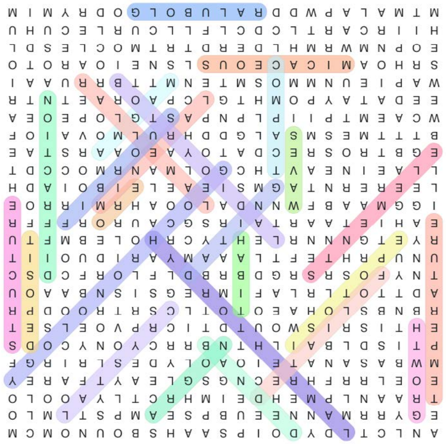


Crystal Healing

John Rakovan

Crystals have many different properties, and the utilization of these properties in technological, industrial, medical, and scientific applications is extensive. The breadth of uses is touched on in the first article of this issue of *Lite Geology* ("Crystals, Minerals, and Crystallography").

As mentioned in that article, the two common forms (polymorphs) of carbon—diamond and graphite—have amazingly different properties despite both being composed of the same element. Because of their different crystal structures, their properties are so varied that both minerals and their synthetic (human-made) equivalents are used in many different practical, real-world applications. For example, diamond is not only the hardest known material in the world; it also conducts heat faster than any other material. When it has impurities like atoms of boron substituting for carbon, it becomes a semiconductor for electricity. Because of its extreme hardness, diamond is used as an abrasive in drills and cutting tools in many different industries. Likewise, its thermal conductivity makes it an ideal material for heat spreaders (thermal management systems in renewable energy technologies) and computer chips. These two applications alone generate billions of dollars of commerce every year.

All of these properties of diamond can be objectively measured (i.e., through scientific observation or testing). We prove our observations are correct when we apply diamonds to different applications and they work the same way over and over again (i.e., reproducibility)!

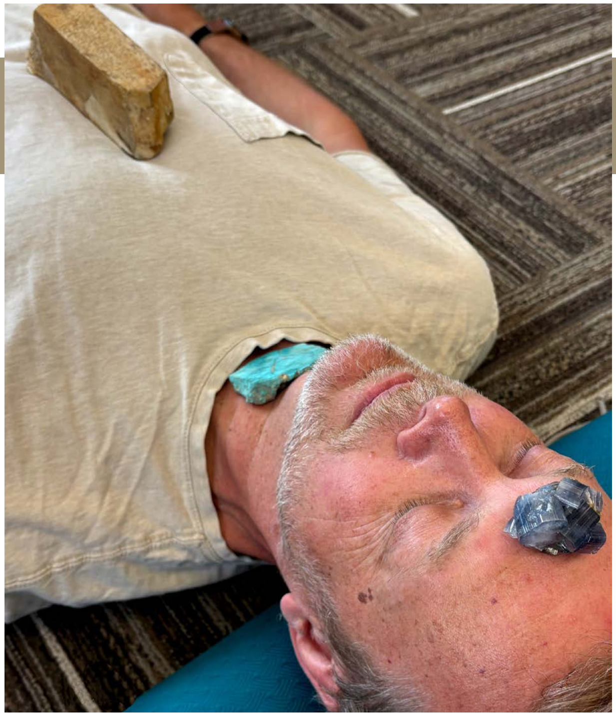
We live in an unprecedented time in history. By greatly improving our understanding of the world and the materials it is composed of, science has enabled technological advances that were unfathomable only a century ago. It is awe-inspiring to think of the things we do every day, with very little consideration, because of these advances, especially in comparison to life in the middle of the 19th century. Cars, airplanes, cell phones, computers, prosthetics, dialysis machines, medicines, and literally tens of thousands of other innovations that make our society what it is today are the result of science. Without it, we would still be in the dark ages.

Crystals are used in myriad applications, with reproducible results. Without reproducibility, would you spend hundreds of dollars on a cell phone whose function depends on semiconducting silicon crystals? A more dubious application is crystal healing. As the term is commonly used, crystal healing is the idea that crystals can have medicinal or therapeutic effects when placed in close proximity to a person. This is different from ingesting a mineral as medicine, which, when it dissolves, adds its constituent atoms, which may be beneficial, to the body. A good example is ingesting the mineral calcite (calcium carbonate), the active ingredient in many antacid medications. The healing property in this case is the relief of acid indigestion.

Color-zoned (purple and blue) fluorite crystals from Bingham, New Mexico (NMBGMR #17452). The colors are the result of crystal defects like those shown in the molecular figure at the end of this article. *Photo courtesy of Jeff Scovil*

Calcite, or calcium carbonate ($CaCO_3$), antacid and a specimen of calcite crystals from Chihuahua, Mexico (NMBGMR #15357). *Photo by John Rakovan*

Cell phone and silicon wafer (a single crystal of silicon [Si]). In electronics like this phone, a wafer is used for the fabrication of integrated circuits. The background on the phone screen is a composite image of synthetic apatite crystals that were engineered to grow in the shapes you see. *Photo by Kelsey McNamara*



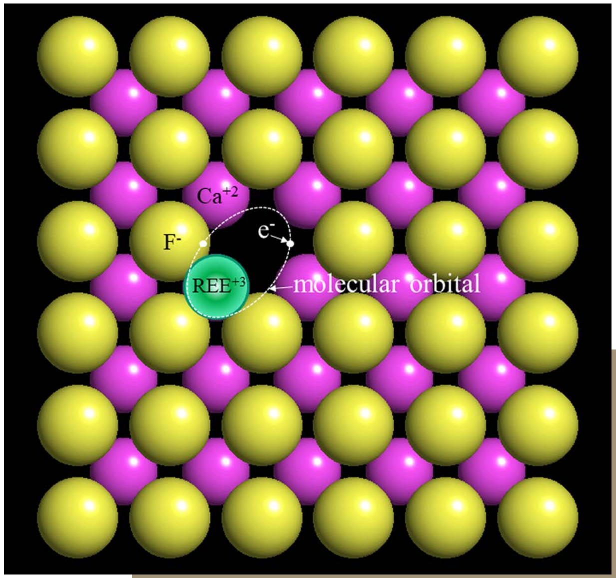
A typical practice in the application of crystal healing is placing crystals on different points on the body, called chakras. Here we have microcline from Hirukawa, Japan, on the heart chakra; turquoise from Carico Lake, Nevada, on the throat chakra; and apatite from Panasqueira, Portugal, on the crown chakra. *Photo by Kelsey McNamara*

The most common belief related to crystal healing is that the flow of "positive" energy from the crystal into the body has healing effects. Luckily for us, quantifying and measuring flows of energy is something scientists are very skilled at, and even extremely minute amounts of energy flow are detectable. Thus, we can credibly and objectively test this claim, and we have. In fact, no such flow of energy has been observed.

What science has been able to accomplish is truly miraculous, but science has not come close to solving all of humanity's problems. It is understandable that people in need, especially those suffering from an affliction, might turn to alternatives if science has not yet found a cure. But if one really wants to look for the best path forward to solve a problem, then put the metaphysics of crystal healing on the scales of objective reality with science. Do they balance? In human history, has metaphysics advanced our society even a modicum of the amount that science has?

If you dig into the subject, you will find that crystals are professed to cure just about every possible ailment, even bad gas mileage for your car. If that is not enough reason for pause, there is also a suspicious lack of reported negative side effects. If the claims are true, then crystal healing should do just about anything. My job as a scientist at the New Mexico Bureau of Geology and Mineral Resources includes evaluating scientific data, and there is simply no credible, reproducible evidence that crystals can accomplish any of these claims. Although crystals may give someone a sense of tranquility due to the power of positive thought, so can many other things, like a flower, a rainbow, or a loved one.

On a lighter note—this is *Lite Geology* after all—the term "crystal healing" could be applied to the healing of crystals themselves. All crystals, even the most perfect, have defects within them, as shown in the molecular graphic on this page. Because a crystal is defined by the regular periodic arrangement of atoms, interruptions to that periodicity constitute defects. There are many types of crystal defects, including substituted atoms (like boron in diamond), vacancies in the structure where an atom normally resides, additional atoms occupying a space where an atom normally does not reside, extended linear defects called dislocations, and others. By applying very high temperatures to a crystal, defects like these can be removed from its structure. In metallurgy and ceramics, this is called annealing, which can be thought of as a type of crystal healing. Annealing is essential to manufacturing with metals and has been practiced for millennia. Today, it also allows mineralogists to study the crystal structures of minerals whose atoms have become disordered due to decay of radioactive constituents, such as uranium (U) in the mineral uraninite (UO_2). Recrystallization by annealing allows for X-ray diffraction (see "Crystals, Minerals, and Crystallography" in this issue) of these once-amorphous materials.



Schematic of the fluorite (CaF_2) crystal structure with several types of defects shown, including an F^- vacancy (i.e., a missing fluorine atom) and a rare earth element substituting for a calcium atom. This particular combination of defects can cause color in fluorite, which, when pure and nondefective, is colorless. The blue-and-purple color-zoned fluorite at the beginning of this article is caused by this combination of defects.

Through the Hand Lens with Virgil Lueth

Virgil Lueth at the 2023 New Mexico Mineral Symposium. *Photo by Cynthia Connolly*

What is your educational and professional background?

I received a BS in geology from the University of Wisconsin at Eau Claire in 1981. While working on my undergraduate degree, I had the opportunity to work for the Wisconsin Geological Survey under the tutelage of two of my professors. We were mapping Proterozoic rocks found in river valleys in north-central Wisconsin. Interestingly, one of those projects is currently being developed by a mining company today. After graduating, my wife Lisa Peters (also a geologist) and I worked for the U.S. Geological Survey in northern Washington, mapping rock units on the Colville Reservation for a summer.

We attended graduate school at the University of Texas at El Paso (UTEP), the former Texas College of Mines. I worked on skarn deposits for my master's degree under Dr. Kenneth Clark. I really liked skarns—a type of coarse-grained metamorphic rock—because of their complex mineralogy and beautiful crystals. I had hoped to work for an exploration or mining company after finishing my master's degree, but jobs were hard to find. I had ultimately hoped to teach geology at a small university, so I started that path a bit earlier than planned. I worked on sulfosalt minerals for my PhD under the direction of Dr. Philip Goodell at UTEP. We worked on trying to understand the distribution and energetics of these minerals in ore systems to better define their conditions of formation. I graduated in 1988 and headed off to teach geology at Tarleton State University in Stephenville, Texas.

I had taught at Tarleton for five years when I received a call from Phil that my dream job had come open at the New Mexico Bureau of Mines and Mineral Resources (which is what it was called then). I immediately applied and got the job as mineralogist and museum director. I worked there until 2022, when I retired after 27 years.

What inspired you to become a geoscientist?

I was inspired to become a geoscientist while attending Spring Valley High School in Wisconsin, although I probably didn't realize it then. I really enjoyed science classes and took them all—biology, chemistry, physics. In my senior year, a geology class was offered. When I went to college, I started as a business major for two years. It was after I took a class in geology as an elective that I rediscovered my passion for science and decided to become a geoscientist.

I always loved the outdoors and natural history. My parents were both teachers, so lifelong learning was part of our lives. They were constantly teaching my brother and me about the world, and it nurtured a curiosity about how things worked that I have to this day.

What are you most proud of professionally?

I have been fortunate to have done a wide range of things during my career, ranging from teaching to research, museum curation, fundraising, and public speaking. I have also been fortunate to receive recognition from the public and my peers for the work I've done. Graduate students I've taught have gone on to PhDs, and others have had great success in industry. The success of my students has always been most gratifying.

Probably the most significant recognition I've received was having a mineral named after me: virgilluethite. There are slightly over 6,000 named minerals, and to have one named for me is both humbling and a great honor.

What hurdles have you had to overcome to be a successful scientist?

I really can't say I had to overcome any hurdles to be a successful scientist other than earning the degrees and learning how to do research. My parents were always supportive of me going to college. My friends, colleagues, and teachers helped me along the way, and that is one reason I wanted to give back in the same way, as a professor, museum director, and researcher.

Why is it important for teachers to focus on geoscience in their classrooms?

I was intrigued early on that geoscience utilizes all science disciplines; you don't have to choose one. You can teach or learn biology, physics, and chemistry (and other subfields) with natural geoscience examples that everyone can see. Then you add the "magic ingredient" to geoscience—time. The vastness of geologic time requires another dimension of thought, one I find fascinating and humbling. We tend to always dwell in the present, but geoscience forces us to think beyond our time, both past and future.

Virgil Lueth shares facts about crystal formation and shows stunning examples from the New Mexico Bureau of Geology's Mineral Museum in this fun and informative video: ***https://youtu.be/ZE5BYMP7kAs?si=CZn-iuLzmeeRso99***.

About

New Mexico Bureau of Geology and Mineral Resources

Museum and bookstore hours, excluding New Mexico Tech holidays:

Monday through Friday, 9 am to 5 pm
Saturday, 10 am to 3 pm
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Photo by Frank Sholedice

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Our bookstore offers a wide variety of popular and educational geology publications, topographic maps for the entire state of New Mexico, and an assortment of field guides. We also carry a selection of great gifts like jewelry, children's science kits, puzzles, clothing, field notebooks, and more. Kids can check out the play space stocked with plushies of New Mexico animals. Visit us in the Bureau of Geology building on the corner of Bullock Boulevard and Leroy Place in Socorro, or shop online at geoinfo.nmt.edu/publications/featured/home.cfml.

Photo by Frank Sholedice

Mineral Museum

Our world-class mineral collection contains over 20,000 specimens from New Mexico, the United States, and around the world. About 4,000 specimens are on display at a time. Exhibits include not only minerals but also mining artifacts, gemstones and lapidary art, fossils, and meteorites. We also offer educational programs like tours, demonstrations, and scavenger hunts for school groups and other visitors. Visit us in the Bureau of Geology building on the corner of Bullock Boulevard and Leroy Place in Socorro, or online at geoinfo.nmt.edu/museum/home.cfml.

Mineralogist/Senior Mineral Museum Curator:
Dr. John Rakovan
(575) 835-ROCK (7625)
john.rakovan@nmt.edu

Museum Curator:
Kelsey McNamara
(575) 835-5418
kelsey.mcnamara@nmt.edu

Education Outreach Manager:
Cynthia Connolly
To schedule a museum tour, contact Cynthia:
(575) 835-5264
cynthia.connolly@nmt.edu

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Our publications sales office has a wide selection of resources for teachers. Many of our publications, including those about New Mexico's geology, are written for amateur geologists and the general public.

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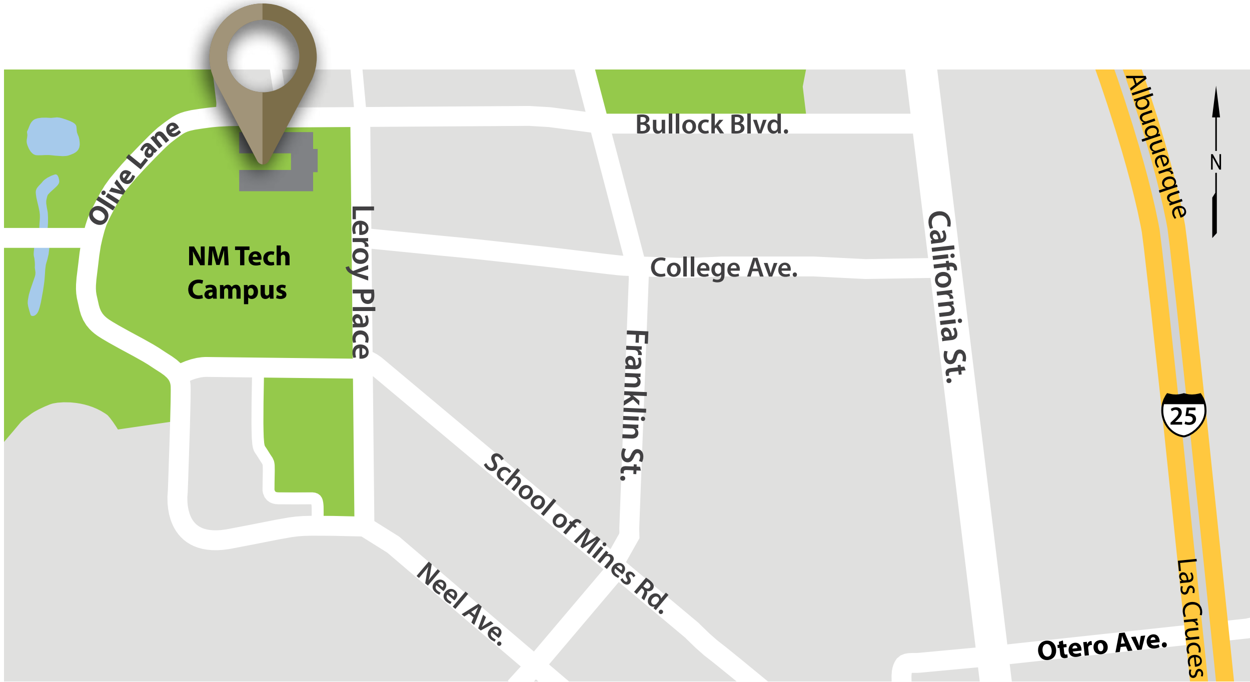

Visit the Mineral Museum and Publication Sales Office

The Mineral Museum and Publication Sales Office are housed in the Bureau of Geology and Mineral Resources building on the New Mexico Tech campus in Socorro, on the corner of Leroy Place and Bullock Boulevard.

Visitor parking on the east side of the building provides convenient access.

Click here to access our interactive campus map.

Photo by Frank Sholedice

About the Bureau of Geology

Founded in 1927, the New Mexico Bureau of Geology and Mineral Resources in Socorro is the New Mexico state geological survey. We are a research and service division of the New Mexico Institute of Mining and Technology, serving New Mexico through a wide range of geologic and hydrologic mapping, research, and analytical services, as well as educational and outreach activities.

About *Lite Geology*

Lite Geology was started in the fall of 1992 as a publication intended for earth science teachers in New Mexico. It is written in a format that is less technical than most of our other publications. Included with the main articles are cartoons, puzzles, and other features designed to make learning fun. We also include information about resources for teachers and upcoming geological and scientific events. Teachers and students may make unlimited copies of *Lite Geology* for educational use. Any other use of these materials requires permission.

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Editorial Assistance: *Shari Kelley, Luke Martin, and John Rakovan*

Copyediting: *Carrin Rich and Frank Sholedice*

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New Mexico Bureau of Geology and Mineral Resources
A research and service division of New Mexico Tech
geoinfo.nmt.edu
801 Leroy Place
Socorro, NM 87801
(575) 835-5490