



An Interview with
GEORGE ROSSMAN

Conducted in 1990 by educator and mineral collector Dr. Robert Weiss, this interview with the Caltech Professor of Mineralogy discusses and reflects upon many interesting aspects of the science and the practice of mineralogy. The interview forms a part of Dr. Weiss's 2003 book, "The Magicians of Form."

RW: Dr. Rossman, perhaps we should begin by asking you how you became interested in mineralogy.

GR: I became interested in mineralogy the way that many people do, namely an attraction to the beauty, the color, and the shape of minerals. As a child I would go into the fields of Wisconsin and find minerals that had been brought down by the glacier. I'd find crystals. I would find agates. And I became curious about these materials. The shape was obviously attractive, and the color of the minerals was an item of attraction. In time, I began to wonder not only about what the minerals are called but also about their internal contents and chemical composition. One becomes curious about where the minerals come from. Where do they grow? How do they form? That escalating curiosity ultimately led me to be a professional mineralogist.

RW: Was there any one mineral in your childhood that stood out as being particularly special?

GR: I became particularly fascinated with tourmaline. As a child I obtained samples of tourmaline, partly from mail order houses. I was fascinated by the various colors they had, the beautiful shapes of the crystals and the general complexity regarding the mineral tourmaline which I found in the books I read at the time. All excited me and raised the level of curiosity towards minerals in general.

RW: That's very interesting, because I have a blue-green tourmaline crystal which is near my bed stand that I use as a paperweight. What I like about tourmaline is not only the shape but the sound of the word itself.

GR: Fresh tourmaline crystals also give a pleasing sound when you tap them together if they're clean and unaltered. It is almost musical. So there's more than the sound of the word, there's actually the sound of the specimen itself.

RW: And doesn't tourmaline also possess something called a piezoelectric effect?

GR: Tourmaline has some very interesting electrical properties which are even today the subject of industrial or government research. When tourmalines are heated or compressed they develop electric charges, and that feature has a number of potential applications.

RW: And tourmaline has a number of different varieties. I guess rubellite is the magenta-colored tourmaline.

GR: There are a number of varieties of tourmaline, named on the basis of their color. For example, red tourmaline is rubellite and blue tourmaline is called indicolite. However, the name tourmaline actually covers a range of different mineralogical species differentiated by their internal chemical compositions, without regard to the color per se. The most common species in collections is elbaite, named for its occurrence on the Italian island of Elba.

RW: And tourmaline is what one might call a semi-precious gemstone? Or is it a precious gemstone?

GR: I think it would be called semi-precious. The price is the measure of the value in terms of precious or semi-precious, and tourmalines of the highest quality can command rather significant prices, even a significant fraction of the price of a diamond. [Update note: copper-rich elbaite discovered a few years ago can command over \$20,000/carats, which is more than many diamonds.]

RW: Is the specimen worth more if it's in the matrix, or is this purely subjective?

GR: This is strictly a subjective opinion. A beautiful crystal on matrix would commonly command a very high value because of the intrinsic beauty that it would represent to a collector or museum. On the other hand, some people would prefer to cut and facet crystals possessing high internal clarity and rich color into gemstones. Which form would be more valuable in the end depends on the specific features of each crystal.

RW: Okay, let's follow you along on your education. You said you became interested in mineralogy because of the beauty of the crystals, the shape of the crystals, and you got more interested in how these crystals came to be the way they are. Did you ever do crystal growing in chemistry?

GR: I think most young scientists have done some crystal growth experiments by taking solutions of various chemicals, letting them evaporate, and obtaining crystals. Salt crystals are an obvious example. Yes, I've done that. And nowadays you'll notice that there are many stores that sell hobby kits for growing crystals which provide a very nice entry for individuals interested in crystals.

RW: So when you continued your education, I assume you specialized in some facet of mineralogy?

GR: No, I took a very different road in life. I got interested in science in general through minerals, but I became aware early in my high school days that to understand minerals one had to understand the chemical composition of minerals. That awareness took me into the realm of professional chemistry. I took my training in chemistry, both graduate and undergraduate, in inorganic chemistry. It was only after I graduated with my Ph.D. that I returned to mineralogy as a professional scientist in that field.

RW: So that was a shift?

GR: It was a shift. But we have to remember that all natural objects are ultimately chemical in nature so chemistry is one of the underpinnings of many sciences, especially the mineralogical sciences.

RW: In your approach to mineralogy, are you looking more at the deeper structure, the way the atoms are arranged to make up the crystal lattice?

GR: My own view of mineralogy tends to favor the atomistic approach. I'm concerned about what is at the atomic level: the composition, the structure of the minerals, how the chemistry and the structure relate to various properties (physical, mechanical, electrical and chemical properties). And then ultimately one must go into the natural regime and worry about how the natural environmental circumstances of pressure, temperature, time, and large-scale chemistry influence the growth and development of the crystals.

RW: Let's talk about how one identifies a particular mineral. Let's assume someone comes in and shows you an unidentified mineral specimen. We'll say that it's embedded in a matrix. What is the first step you would take to identify it?

GR: The first step one would take would be to simply look at it, to use the eyeball and to rely upon a memorized database that comes from experience. Certain minerals have certain properties that you can often recognize visually. Probably two-thirds of the identification tasks are solved simply by visual inspection. If that doesn't work, you haul out a magnifying lens or a microscope and look more closely at the material, still in the visual regime. You look at the shape of the crystal, you look at the way it fractures or cleaves, you look at the associated minerals to have a feel for the chemical environment in which it formed. You look at the color of the material which sometimes can be diagnostic. You look at the luster of the material. But by and large, you rely initially very heavily upon observable phenomenology. If that doesn't work, then typically I would resort to a chemical analysis. First, a qualitative analysis to see which elements are present: magnesium, copper, iron, whatever they might be. If that fails, then I would resort to a more detailed analysis such as X-ray powder diffraction, which reveals one of what we might call the "defining" properties of a mineral that can ultimately be used in most cases to finally identify a particular sample. [Update note: Over the last 20 years several new spectroscopic techniques, such as RAMAN analysis, have been developed that can also aid in mineral identification.]

RW: Would different colors be a reflection of what particular chemicals were present?

GR: They are a reflection of what chemical elements are present, but they are also a reflection of their oxidation state; for example, divalent iron (with a charge of +2) versus trivalent iron (+3), and divalent versus trivalent manganese could be identified based on that property. They are a reflection of the local chemical environment and the structure in which a particular atom resides. Garnets with divalent iron are red whereas garnets with trivalent iron are light yellow-green. So by combining some knowledge about which mineral you have and its color one can gain even more detail about the internal composition and structure.

RW: Now I'd like to talk a little bit about the crystal systems. I understand there are six basic crystal systems. Is the number subjective or is there a definite reason for it?

GR: When one looks at a crystal, one can identify certain symmetry properties: for example, both front and back sides may look identical, or there may be certain angles that repeat in the crystal. Many years ago people recognized that, mathematically, only a small number of these symmetry elements are possible. It became apparent that one could classify a mineral based on the various symmetry elements its crystals exhibited. It thus became necessary to design a classification

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scheme, and it was found that one could classify most minerals into one of six categories based on their external geometry. These are the words you refer to: the cubic system, the orthorhombic system, the triclinic system, the monoclinic system, the tetragonal system, and the hexagonal system. They refer to obvious external geometries that one can recognize when looking at a crystal. A six-sided crystal which is obviously hexagonal in shape would belong to the hexagonal system.

RW: Are these idealizations? Do they really occur in terms of strictly organized geometric forms?

GR: We have to look at this on two levels. One is the technically correct level where we are almost in the realm of mathematics, and the other is a more practical level dealing with real materials. From a mathematical point of view we can rigorously define certain types of symmetries. When we look at a real crystal we often find that it deviates in detail from the mathematical ideal. The sides of a cubic crystal are not necessarily always the same dimension. If we have a hexagonal crystal, all six sides are not necessarily the same width. But still one can recognize that there is an apparent six-fold symmetry. The angles between the faces will still be 120 degrees. And when you look at a crystal visually you will be able to see that there are six sides, even though unequal.

RW: What is responsible for some of the inequality of crystals that you were talking about?

GR: The crystals deviate from mathematically perfect symmetry because they don't grow in a vacuum. They grow in a rock. They grow up against other crystals. If a crystal bumps against something else in its growth process, the growth will be halted where the contact occurs, but the other sides will continue to grow. That very commonly is one of the reasons why you get distorted symmetry in crystals. Sometimes the crystal grows in a temperature gradient, where the rate at which the nutrients are delivered to the crystal depends upon the ambient temperature, which can vary even millimeter by millimeter. Sometimes the crystals grow in fluids which are flowing, and they flow in from one side but not the other. And, therefore, there's more nutrient on one side than the other. There can be a variety of different perturbations in nature to distort the shape of crystals.

RW: That's very interesting. Why do certain crystals have six sides or eight sides or twelve sides?

GR: Atoms can only pack together in certain ways. It's like bathroom floor tile. It's impossible to tile a bathroom with pentagonal, five-sided tiles. The just don't fit together without leaving gaps. Similarly, it's impossible to pack atoms together in an infinite three-dimensional solid that has a five-fold symmetry. You simply cannot fill all spaces with the five-fold patterns of pentagons. You can, however, cover any floor with tiles that have square shapes. Likewise you can build crystals that have four sides. You can also cover floors with triangular or hexagonal tiles, and you can, therefore, make crystals out of atoms packed in hexagonal arrangements.

RW: I remember reading Schrodinger's essay "What Is Life?" and I recall him arguing that the human body, for instance, is complex out of necessity, because if you have just a small number of atoms, then they are much more likely to be bounced around according to the laws of thermodynamics. And wouldn't that also be true of crystals? I mean, you would need a goodly number of atoms before you could have anything that resembled a structure.

GR: Very clearly, we are dealing with large numbers of atoms. The elementary unit of a crystal is made up often on the order of twenty or thirty atoms, which will define the basic building block, analogous to the tile in a two-dimensional situation. But a real crystal is made up of countless

millions of these building blocks, and obviously the way they fit together over large dimensions, over millions of atoms, becomes important.

RW: So you're arguing that these forms are a result of the internal atomic way of, as you said, filling up a room with bath tiles, and only certain kinds of symmetries work in filling up a particular structure.

GR: You can also think of individual atoms as spheres. There is a limited number of ways to pack them together to efficiently fill volume. You don't have a lot of choices.

RW: And are all these rigidly packed? Or would those that are more tenacious be packed more tightly together?

GR: It's not necessarily tightness. If we take the example of mica or talc, minerals that readily peel apart and have a certain cleavage, we're looking at the strength of the bonds between individual layers of atoms more so than the physical proximity. In the case of talc, there are no strong bonds between individual layers. In the case of minerals like quartz, the bonding is three-dimensional in all directions, so in every direction there are strong bonds holding the next group of atoms together. Thus talc is soft and quartz is hard.

RW: That's very interesting. What about Mohs' scale of hardness? How was this scale derived, and is the difference between a hardness of one and two on the scale the same as the difference between five and six?

GR: The Mohs' scale is an empirical scale that was devised by Frederick Mohs to allow people to classify and identify minerals. Mohs arranged a set of minerals according to their hardness, beginning with the softest and ending with the hardest: (1) talc, (2) gypsum, (3) calcite, (4) fluorite, (5) apatite, (6) orthoclase, (7) quartz, (8) topaz, (9) corundum, and (10) diamond. Each mineral is harder than the one preceding it on the scale. In other words, a diamond will scratch minerals 1 through 9. But an orthoclase crystal (6) will only scratch minerals 1 through 5, those that are softer.

Why each mineral has a particular hardness is not fully understood. It apparently has to do with the nature of the chemical bonding in the minerals. The gradations in Mohs' scale are not linear. Technically precise measurements of the hardness of minerals (using more sophisticated instruments) reveals that the difference in hardness increases radically as you go up the scale. The scale was devised primarily as a useful tool for identification, rather than a precise method of measuring hardness.

The underlying reason for the hardness of minerals is, as I said, very much dependent upon the strength of the chemical bonds between individual atoms. Furthermore, in many minerals the hardness even depends upon the direction. If you have a crystal of kyanite and scratch it along one direction, you will get one hardness, but if you scratch it in a perpendicular direction you get a very different hardness. The reason is that you're disrupting different bonds within the crystal. In fact, even diamonds don't have a single hardness. Diamonds can be ground and polished more easily on some faces than on others. And even on a single face of a diamond, the speed at which it can be ground away depends on the direction in which you polish it.

RW: Could you have a mineral, let's say quartz, that could be softer or harder than seven because of other chemical elements that enter into it?

GR: Such examples are not unknown, but by and large the differences in hardness tend to be relatively minor compared to the size of the divisions of this whole scale. Many minerals have a wide range of chemical elements that can enter into substitutions for each other, and depending upon the degree of chemical substitution, there will clearly be some differences in the hardness of the material.

You've got to talk to a gem cutter, actually. Some gem cutters have stories about minerals or gemstones from particular localities cutting more readily than the same kinds of stones from other localities—which may, in fact, represent nothing other than small differences in the chemical composition of the mineral.

RW: I'm trying to get a better understanding of the concept of hardness versus tenacity. When we talk about tenacity we're talking about how a mineral holds together, its resistance to being broken in some sense.

GR: Yes, these concepts are quite different. A good example might be jade, which is comprised of the minerals jadeite and nephrite. Jade is a very tough material to break, though not especially difficult to scratch. Ancients used it for tools. Its toughness has to do with the jumbled nature of the interpenetrating fibers that compose this rock. If a break or fracture starts somewhere, it propagates only within one little crystal. Then it comes to a boundary between that crystal and another crystal, and the crack stops propagating at that point. So it is never able to work its way into the mass of material. But, if I have a crystal like quartz and start a crack going, it will propagate all the way through the crystal. If you take a rod of quartz and hit it with a hammer, it shatters; if you take a rod of jade and tap it with a hammer, it simply goes "twang" and bounces right back at you.

RW: I remember I had a piece of pink spodumene, a kunzite, that fell and broke in a particular manner.

GR: It has what is called "cleavage direction." It separates preferentially along certain crystallographic directions. These are planes where the atoms are not as tightly held together as in other directions.

RW: A person might think, "Well, diamond is super hard; nothing can scratch it, so, therefore, nothing is going to break it." But that's not true. Diamonds do break, although nothing can scratch them.

GR: Yes, scratch resistance and toughness or tenacity are two very different properties. It's very difficult to get technically precise about this difference, but it's very easy to present an example. A good example would be a steel wire. A steel wire is strong. You could pull very hard. You could twist it, and bend it. You could push it, and you would have great difficulty breaking a steel wire. On the other hand, steel is soft. It's readily scratched by quartz and by the other hard minerals. But if you had a wire or a rod made out of the mineral quartz or even diamond and just put moderate pressure on it with your fingers you'd readily snap it. It could not take the twisting, or bending motion. So clearly hardness ("scratch resistance") is a very different property from tensile strength or flexibility.

RW: In the one example you gave dealing with tenacity you made it very clear how atomic structure is involved. Could you use a parallel example with hardness based on the atomic structure? Or is it that people still don't really understand what hardness is?

GR: Hardness is not that well understood. I am somewhat at a loss to be able to give you convincing rigorous examples of why, for example, diamond that is nothing other than carbon-carbon bonds is much harder than something like quartz which is silicon-oxygen bonds. We have many

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examples of things that have comparable structures but very different hardnesses. We have a lot of examples of minerals that have the same chemical composition but different hardnesses—graphite and diamond being a good example. This has a lot to do with the intimate atomic details of exactly how the bonding is taking place between the carbon atoms. I find this quite difficult to present in a way that would be conceptually understandable. That may be a good indication that I don't understand it at the level I would need to, in order to be able to convey these concepts in a simple fashion.

RW: If we don't have that clear an understanding of hardness, does this mean that it's unlikely that we could construct something which is harder than diamond? Or is that, in fact, impossible according to physical laws?

GR: Physical laws do not give us any restraint on what might be harder than diamond. There have been claims in the past about substances being harder than diamond. The status of these claims is still somewhat ambiguous, in my opinion. But there is nothing in the laws of physics that says you cannot make something harder than diamond. For example, one might even envision high pressure technology taking a diamond itself and squeezing it to a denser form of matter which could turn out to be harder than diamond. That's a possibility that has not been well explored.

RW: If we could obtain a material that was harder than diamond, what would the application be?

GR: Abrasives. Very clearly we use diamonds to a large measure for abrasives, and anything that would be harder than diamond could potentially have superior abrasive properties.

RW: Okay, let's speak about the discovery of new minerals.

GR: A large fraction of minerals which are discovered today are found through the application of micro-analytical techniques. Two hundred years ago it was easy to go out into the world, crack open some rocks, and find big crystals that one could look at and recognize as new and different mineral species.

Most of the species occurring in big crystals have probably already been discovered and described. The frontier of mineral identification today is at the level of discovering, categorizing, and characterizing very small bits of matter, frequently microscopic in size, that are found in the geologic regime. That is everything from meteorites that fall on the planet to new and exotic minerals that are found in mines. But most of these new discoveries are so small that one can only see them under a microscope. The amount of material described as a new mineral may only weigh a few milligrams at most. It's very uncommon nowadays to find large macroscopic crystals (by that I mean on the order of the size of your thumbnail, for example). Finding a new mineral species in crystals of that size is a most unusual occurrence, although it still happens on rare occasions. Not too long ago there was a remarkable discovery of a mineral named "zektzerite" in the granitic rocks of the state of Washington. Large crystals several centimeters in size were discovered. It was a mineral that was related to a family of known minerals, but the composition was entirely new and different.

Most minerals nowadays are being described from ore deposits where some unusual combinations of metals and sulfur are found. Weathering zones in ore deposits are acted upon by water, carbon dioxide, and perhaps slightly acidic solutions that corrode the ore minerals and form tiny precipitates, often microscopic, on the surfaces of the primary crystals. New minerals are also occasionally found in meteorites.

RW: One thing I've always been interested in is why in a rock called pegmatite one is likely to find beautiful crystals, such as tourmaline and beryl.

GR: Pegmatites are fascinating. They represent what is almost like the last gasp of crystallization of an enormous body of rock. Let's take California as an example. California is at the boundary between two large tectonic plates of the earth, and one of these, the Pacific Ocean plate, is being driven underneath North America. As the ocean floor is subducted under the continent, the rocks heat up as they get deeper in the heat of the earth, ultimately melt and work their way upward towards the earth's surface. Very, very large volumes of molten rock have been working their way up slowly for the past hundred million years or so. As these large bodies of rock crystallize, minerals like feldspar, quartz, pyroxene, and mica precipitate out of the slurry of molten material. But exotic elements like boron, lithium, niobium, and beryllium are *not* readily incorporated into the major minerals because their ions are either too large or too small to fit in the structures of those minerals. Instead, they become enriched in the dwindling amount of residual melt that has not yet solidified. Ultimately, after a large fraction (99.99%) of this rock has crystallized, most of the exotic components are concentrated in small pockets and stringers of still molten material that become the pegmatites. As the rocks fracture from tectonic processes, residual bits of melt work their way into the fractures and form the veins. They cool down and in these veins all the exotic elements begin to crystallize into a whole suite of exotic minerals, of which tourmaline, beryl and kunzite (a variety of spodumene) are some examples.

RW: What determines how large these crystals are going to become? For instance, tourmaline sometimes occurs as black grains, and sometimes grows to be a foot long.

GR: One of the major criteria for big versus small is the amount of open space into which the crystals can grow. The small granular tourmaline crystals typically form in an area which is basically a mush of partially molten rock with very little pore space. In the case of the big crystals, the pegmatites, you're talking about veins that contain fluids which are between the gaseous and the liquid state—where there's a lot of steam volume and where the fluids have very low viscosity. Crystals can readily poke their way into the residual fluid without bumping into other things which stop their growth. This is where you get the big crystals.

RW: And this is common in the pegmatites?

GR: It is the very nature of pegmatites. The fluids that are in the pegmatite and contain the exotic components are also typically rich in water and carbon dioxide. They have a lot of volatile components in them that make them very fluid and very gassy, although the temperatures are such that the difference between liquid and gas essentially vanishes and you have a single phase, a hypercritical fluid (very unintuitive in terms of our everyday concepts), but this is still a very runny, mobile fluid in which crystals can readily find room to crystallize.

RW: Let's suppose someone is trying to find these exotic minerals. How do they know where to go to pick them up? Are there any hints aside from the colors they might see on the surface?

GR: The vast majority of the deposits of these exotic minerals are discovered as surface exposures. Someone sees crystals of tourmaline on the surface of the ground, and if he is smart enough to recognize what they are, he realizes that there is a potential tourmaline deposit there. The chances of finding one at random are virtually nil. In principle, one could go somewhere in San Diego County and drill a hole at random and maybe if you got down far enough into the ground (be it 1,000 feet or a mile), you might find a tourmaline crystal. But that's a totally impractical way of locating such minerals. You really do have to locate them from surface exposures—primarily by

walking over regions where you know geologically you have the right environment for this type of pegmatite to form.

RW: So when the U.S. Geological Survey publishes detailed quadrangles of mineral constitution, this means these minerals were located just by observation? Someone went in there and said, “Well, I saw tourmaline, zircon and apatite” and that’s why they are on the maps?

GR: Very commonly, yes, exactly that. It seems like every square foot of this country was prospected at some point in time, probably by people who walked the ground looking for gold or anything else that was valuable. You may have heard about modern analytic or prospecting tools based on high-altitude aircraft or large-scale geochemical surveys where people measure the gold content in plant leaves. These types of techniques have been very successful in locating large deposits of low-grade ore that often have no surface expression. But the type of things that we are discussing, crystal mines (tourmaline is the case in point), are inevitably found by humans walking the ground and visually finding indications on the surface.

RW: Well, I was just thinking of a personal experience. When I went to the Pacoima Dam with my mineral pick, and began picking into the mountain, I came up with an apatite crystal. And according to what the quadrangle said, apatite was one of the crystals to be found. So I figured maybe there were some more, and I kept picking for a couple of hours, but nothing came out except for biotite-mica, quartz, and feldspar. There wasn’t anything too exciting after that.

GR: That’s the fate of many prospectors! All the unusual elements, such as the phosphorus in apatite, have to go somewhere in a rock. Either they’re dissolved at low concentration in the major minerals or they’re concentrated in a particular phase that contains most of the phosphate. If you have a component like phosphorus that is present at low concentration, there can only be a small number of apatite grains in the rock, so your chances of finding one of those are relatively modest.

On the other hand, you could go to a pegmatite where you have lots of exotic elements concentrated in a small body, and you could have a much higher concentration of unusual minerals because nature has done the concentration for you to bring all the necessary components together.

RW: What about a mineral like benitoite, which is only found, I believe, in San Benito County?

GR: There is only one significant deposit: the Benitoite Gem mine in San Benito County. We have a situation where a very unusual set of chemical and geological circumstances had to come together at the right temperature and pressure in order for this mineral to form. There is no reason in the world why there should not be other localities where benitoite has been formed, but as yet no one has found them.

RW: Benitoite occurs with neptunite, another rare mineral.

GR: Neptunite is quite rare. For benitoite to form you need barium, titanium and silicate ions to be present. Neptunite, however, contains titanium and silicate, but no barium.

RW: Of all the minerals I am acquainted with, benitoite is the most interesting to me.

GR: It has several interesting aspects. Number one, from an aesthetic point of view, the combination of beautiful blue benitoite crystals, white natrolite matrix, and the dark, almost black, crystals of



neptunite is very appealing. Secondly, the neptunite and benitoite are rare minerals, especially the benitoite. Thirdly, there's the value. Benitoite is a gemstone that has been adopted as the state gemstone of California. And that also adds a certain excitement and appeal to this mineral.

RW: Natrolite, I would assume, is found in many places.

GR: Natrolite is a very common mineral. It is a mineral that commonly fills the gas bubbles in basalt flows. After the basalt cools and the gas bubbles remain behind as voids, water percolating through the basalt dissolves portions of the basalt and then precipitates the natrolite inside the bubbles, oftentimes completely filling what used to be a gas bubble with little needles of natrolite.

RW: You mentioned earlier that natrolite belongs to the zeolite group. What are some of the characteristics of the zeolites?

GR: They are all low-temperature minerals that contain both aluminum and silicon and have rather complex internal structures.

RW: But they're all related?

GR: They're all related from the point of view of being three-dimensional polymers of aluminum, oxygen, and silicon.

RW: Are any of them semi-precious stones?

GR: They're all very soft. None of them have any value as gemstones except as exotic collector material. But they have substantial industrial value. Zeolites can be used as the whitening agent in paper and as the agent that makes textiles and papers take dye more readily.

RW: There's one other mineral I'd like to talk about, spinel, because it has always fascinated me by its many colors. It seems to be a very difficult mineral to obtain in the matrix.

GR: Matrix specimens are uncommon. Most of the spinel which is sold for gemstone purposes comes from gemstone mines in southeast Asia. But it's usually found in alluvial deposits; river beds or ancient river beds that have now been covered over. The host rock in which the spinel occurs probably has a very low concentration of spinel in it, so it's usually impractical to mine it.

RW: Does it occur in pegmatite?

GR: No, it's not in a pegmatite. It forms in a limestone-based rock, calcium carbonate, where spinel is one of the minor phases found in the rock. Over hundreds of millions of years of geologic time, these limestones have weathered away, dissolving in weakly acidic rainwater and freeing the spinel crystals which have simply fallen out and been carried into the stream beds. This is why they are now obtained from the alluvial deposits rather than from the primary host rock.

RW: And spinel's most common crystal form is the octahedron?

GR: Octahedral crystals are the typical habit of spinel.

RW: Which brings me to another question. Why does the same mineral occur in different crystal forms? Fluorite would be a good example. It occurs in both cubes and octahedrons.



GR: Well, fluorite occurs more commonly as cubes than as octahedrons. If it fractures, it breaks into an octahedral shape, but it tends to grow in cubic shape, by and large. But there can be octahedral shaped crystals of fluorite. Just as many different minerals have different crystal shapes from different growth environments. Now what do I mean by that? I mean that the shape of a crystal will depend upon the temperature at which it grows. It will depend upon which particular chemical elements are in the bath from which it is growing. It may even depend upon the pressure of the growth environment.

Let me give you an example. If we take a beaker of sodium chloride, common table salt, and evaporate it, it will form little cubic crystals. But if you add urea to the solution from which the salt is crystallizing, you will get octahedral shaped crystals. This is an indication that what we call impurities in the growth environment absorb selectively on certain faces so other faces can grow more rapidly and therefore change the overall appearance of the crystal.

RW: And this can occur within the same chemical solution? Because in the case of fluorite, you have purple octahedrons and purple cubes.

GR: We have no way of knowing in detail the exact history of that particular growth environment, but it could have been that some of the crystals grew when there was a little bit more, let's say, potassium in the solution, and a few days later the potassium went away and you had a purer water with less potassium in it. That might have caused the differences. Or it might have been a function of the gradually declining temperature of the growth environment.

RW: And we don't know why fluorite is an exception, because most minerals do crystallize in one form. I mean, quartz is basically six-sided, and tourmaline is pyramidal in form.

GR: I would disagree a little bit with you and say that there's really an awful lot of flexibility in these minerals. Take, for example, tourmaline and examine the dravites from Australia. They tend to be almost rounded in shape, equidimensional, whereas some of the tourmalines from Brazil are elongated and pointy like rods. I can show you examples of remarkable differences in the appearance of even tourmaline.

RW: Dravite is a species in the tourmaline group, which brings me to another question: how a mineral is named. I guess to a certain extent it's arbitrary.

GR: The rule, if you can call it that, for naming minerals is that the person who submits the first description of the mineral has the right to name it. There are many criteria used for this purpose. Sometimes people name minerals based on the properties of the minerals (the shape, the color). For example, orthoclase is named after its orthogonal cleavage. Sometimes the names of the minerals are a reference to the chemical composition: native platinum after the element platinum. Sometimes the minerals are named after the localities, such as elbaite, tourmaline from the isle of Elba. Sometimes the minerals are named after a friend or an eminent person, either in science or elsewhere, whom you wish to honor: the earliest of these is prehnite, named after Colonel Hendrick von Prehn.

A commission of scientists from the International Mineralogical Association has been established to evaluate and approve proposed new minerals and mineral names. And it is only after this committee has reviewed and approved the description of the mineral, the completeness of the description of the properties, the locality where it was found, the analytical methods and results, the information regarding where a representative sample of the mineral has been deposited, and

where the original discovery specimen has been deposited that the substance is formally recognized as a new mineral.

RW: We've been talking about minerals and you stated earlier, I think, that it's very difficult to explicitly define just what a mineral is and what it isn't.

GR: In general, a mineral is a naturally occurring inorganic compound with some well-defined structure and some defined limits on the chemical composition. There are areas where we can stretch the limits of definition into a realm that is somewhat nebulous. For example, is a naturally occurring inorganic liquid a mineral? One example might be native mercury. Most people would say that it is indeed worthy of being called a mineral. But what about a biological precipitate? Calcium oxalate crystals can be found in nature as natural minerals in strictly inorganic environments. But they can also be found in some lifeforms; for example organisms in the Weddell Sea precipitate calcium oxalate. When the organism dies, the calcium oxalate falls to the ocean bed. Are these minerals? Most people would say yes. Do you want to call ice a mineral? What about the ice that forms temporarily in the snowfields of the northern portions of North America? It is a naturally occurring inorganic material. At a certain point, some of these definitions become somewhat ambiguous.

Or what if we have a mine? Water percolates from the surface into the mine and forms precipitates on the top of the mine tunnel. That material would not exist if it were not for the activity of human beings. Do we call these materials minerals or not?

This is the stuff of debate. This is the stuff of philosophy. The International Mineralogical Association has certainly tried to establish sensible criteria, but not everyone agrees with their decisions. The implications of the word "mineral" often depend on the context of the conversation.

RW: But you can tell the difference between a mineral and a rock?

GR: A rock is a substantial mass of minerals, sometimes even just a single mineral. So we can define what a rock is, although we might argue about how to name a particular rock. We have three main classifications of rocks. Igneous rocks are those which have crystallized directly from a cooling melt. Sedimentary rocks formed from the accumulation of sediments. Metamorphic rocks are igneous or sedimentary rocks that have later been changed by the effects of heat and pressure, sometimes with the aid of penetrating hydrothermal fluids.

RW: Could you give a few examples of minerals that occur within each of these environments?

GR: In the igneous environment, we can take a look, for example, at basalts that come out of volcanoes. We can find crystals of olivine in basalt. We can find feldspars in basalt. We can find iron oxides like magnetite or iron titanium oxides like ilmenite in basalt.

RW: And for sedimentary?

GR: In sedimentary environments we commonly find clay minerals.

RW: Like shale?

GR: Shale would be a rock that contains clay. We find the mineral chlorite. We find bits of mica. We find bits of quartz, sometimes bits of feldspar in the shales. In sedimentary environments we often

find there are times when the sediments have fluids in them and other times when the sediments evaporate and the fluids go away leaving crystals behind. So minerals like gypsum and salt and sylvite (potassium chloride) are commonly found in sedimentary basins, often in very large and beautiful crystals.

In some of the sedimentary environments we find that the minerals that were originally deposited have changed. So, for example, in some sedimentary environments you have bits of volcanic ash which have been reworked by groundwater and converted into zeolites. Oftentimes large beds of zeolites can form in sedimentary environments.

In the metamorphic environment we have a wide variety of possibilities because all kinds of chemical transformations take place. In the metamorphic environment we have micas of various sorts, we have feldspars, we have quartz, we have minerals like kyanite and andalusite forming, cordierite can form, and several amphiboles can form in these environments.

RW: For someone who is entering the field of mineralogy today, what kinds of mineralogical investigations might he/she be involved in?

GR: There are many, many facets of mineralogy. Let me try to give you some examples. One aspect of mineralogy is concerned with economics and the discovery of ore deposits. Many companies have exploration mineralogists whose job it is to discover new deposits of economic value.

Some people who work in mineralogy are involved in the processing of minerals, how to transform minerals into economically valuable, useful materials.

Some people are involved in more academic pursuits, such as the study of matter to gain a better understanding of where it comes from and what its properties might be.

Other people who deal with mineralogy are in an industrial environment trying to design synthetic materials for technological applications that have their basis in natural minerals. Lasers and ceramics are the two most prominent examples. Catalysts are another example.

Some people in mineralogy are involved in the discovery, manufacture, and fabrication of gem materials. The study of gem materials (gemology) is a branch of mineralogy.

Other people are concerned with the geologic history of minerals. Where do they come from? How much time does it take for them to form? In what chemical environment do they form? What pressure, what temperatures are involved in the formation of minerals? This is a case where mineralogy begins to merge into petrology, the study of rocks.

Some people in mineralogy are concerned with the deep interior of the earth. What is the composition of the earth 100, 200 or 300 kilometers below the surface? These are people who get into the regime of extremely high-pressure studies and ask questions like, "What happens to common minerals when they are subjected to pressures and temperatures that exist at great depths in the planet?"

Other people pursue mineralogy from a cosmo-chemical point of view. Look at meteorites. Look at the planetary bodies. Try to understand not only the origin of the solar system but the nature of the various materials that exist (both in the solar system and the cosmos in general).

So there are many aspects of mineralogy that one could ultimately pursue as a career objective or as a technical pursuit.

RW: What about synthetic minerals?

GR: The synthesis of minerals has many applications. The major application is in the realm of ceramics. Technological materials, everything from the plates upon which we eat our food to the catalysts that support the emission control systems of our automobiles, involve ceramics. There are other people who grow synthetic crystals. The synthetic crystal industry is largely conducted for three purposes in this country. One is for telecommunications, and that is centered upon synthetic quartz. Every crystal-controlled computer, ham radio, citizens-band radio, or watch has a synthetic quartz crystal in it. The second major application for synthetic crystal growth is lasers. There are still major efforts under way to develop new kinds of laser crystals. The neodymium-doped YAG is one that comes to mind. "YAG" is short for yttrium-aluminum garnet. It's a synthetic aluminum material that has no natural counterpart, but has the structure of natural garnet. The third major application for growing synthetic crystals is gemstones. Synthetic emeralds, rubies and sapphires have found a large market. Other synthetic minerals are widely used as abrasives. Diamond is a notable example.

RW: What do you foresee as being one of the areas of greatest research in mineralogy in the future?

GR: Trying to predict the future, I look at a very cloudy crystal ball. It's very hard to predict what will happen a year from now, much less a decade from now. But certainly we see a number of frontiers. One of the frontiers is the study of the planet at great depths. What is the nature of geological materials under conditions of pressure and temperature at which direct sampling is essentially impossible? We're talking about the lower crust, the upper mantle, the mid-mantle of our planet. What is down there? What chemical compositions, what structural phases, what are the properties of these materials, how do they relate to things like earthquakes, to seismic studies?

A second major area in mineral research is going to deal with the interface between minerals and fluids. We're talking here of the properties of weathering, for example. Intimately speaking, what is going on when a crystal of quartz is put into a body of water like a lake? What are the detailed chemical transformations that take place? How does that surface layer of atoms change? We're dealing with the interface between geochemistry and mineralogy at this particular level.

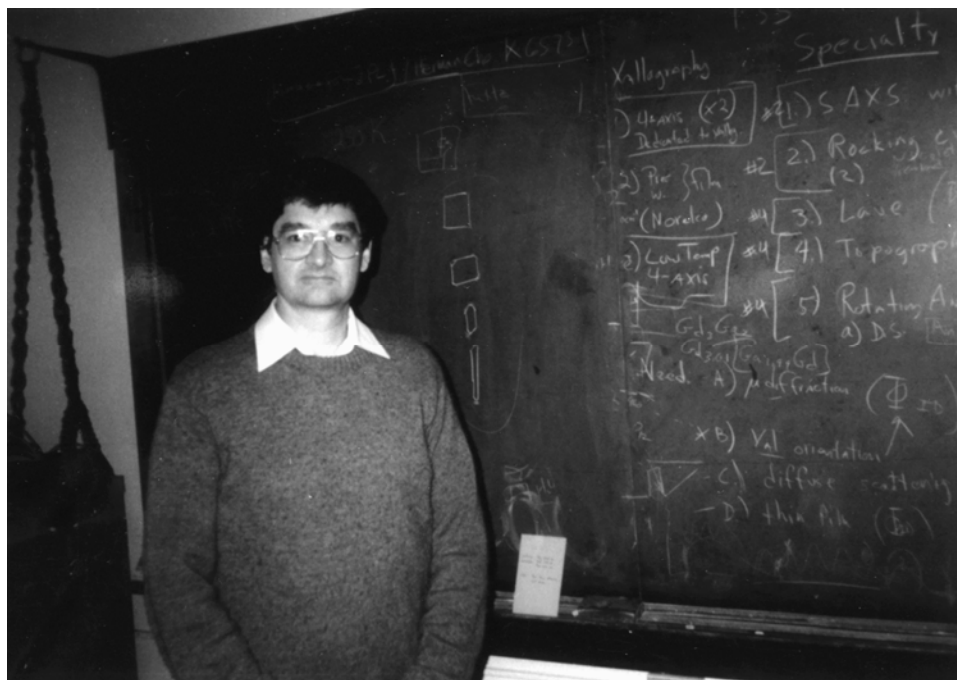
We certainly see a lot of studies continuing in the more cosmic scale of things. Where did the earth and moon come from? What story can we read from the meteorites? What do the various minerals in meteorites tell us about the history of the solar system and our planet in particular? There are many, many unanswered questions in that regard.

There are also opportunities in what I'll call the utilization of minerals, the technological aspect. Such studies would include finding new minerals or mineral analogs that have economically valuable properties. The need for ceramics that can be used in engines having higher combustion temperatures comes to mind. We see electronic materials, many of which are developed based on mineral-like materials. For example, we may soon see the advent of diamond semi-conductors. [Update note: Twenty years later, progress has been made, but such semi-conductors have yet to become commercialized.]

We see from an academic point of view a continuing desire to pursue a fundamental understanding of the properties of minerals. The chemical analysis, classification and nomenclature of minerals are fairly mature sciences. On the other hand, as you saw when I was

trying to address the problems of what makes a mineral hard, there are many, many areas where the fundamental understanding of properties—be they mechanical properties, physical properties, chemical properties, geological properties, or elastic properties of minerals—is still poor.

Dr. George R. Rossman



George R. Rossman was educated at Wisconsin State University, Eau Claire, where he received his BS degree in chemistry and mathematics, and at the California Institute of Technology where he received his PhD in Chemistry and where he now serves as McMillan Professor of Mineralogy. He continues a life-long interest in minerals through his research, which includes studies of the color and spectroscopic properties of minerals, poorly crystalline minerals, the incorporation of water in nominally anhydrous minerals, and the effects of high-level ionizing radiation on minerals. Dr. Rossman has written or co-authored more than 240 articles in the field of mineralogy, many in the area of spectroscopy. He has served as associate editor of the journal *American Mineralogist*, and is on the editorial review board of *Gems and Gemology*. His many honors include The Dana Medal from the Mineralogical Society of America (2001), and The Richard P. Feynman Prize awarded for Excellence in Teaching at the California Institute of Technology (2004).
