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Acceptance of the 2021 Roebling Medal of the Mineralogical Society of America

George R. Rossman[1,*]

[1]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, U.S.A

Thank you, Ed, for the kind introduction. You certainly have the ability to remember things from many years ago. I also thank all those who nominated me for this award and, of course, the Mineralogical Society of America for providing this honor. I am, indeed, honored and humbled to receive this award.

Minerals, their chemistry and properties, have interested me for many years, even in grade school when I was growing up in Wisconsin, where I collected agates on the shores of the nearby rivers. It was, in part, an interest in the color of minerals that steered me towards chemistry at a young age. I was fortunate that, while I was in grade school, a neighbor gave me a chemistry book, the 5th edition of the *Handbook of Chemistry* by Norbert Lange. This handbook had a list of the properties of minerals that listed the chemical formulas of 708 minerals that included most of the elements on the periodic table. Minerals are, after all, nature's repository of the elements of the periodic table, so it was natural for me to become interested in both mineralogy and chemistry.

In particular, it was interest in the color of tourmaline that sparked my early interest in the origin of color in minerals. How could tourmaline have multiple colors and be so transparent? What chemical elements were responsible? Furthermore, it was also my interest in the color of minerals that led me to learn about the various spectroscopic tools that could be used to interrogate minerals and that have become important instruments in my laboratories over the past several decades.

My path early on was one of analytical inorganic chemistry. I needed these tools to identify the minerals I was collecting. I got a B.S. degree in both chemistry and math at Wisconsin State University, Eau Claire. Two summers were spent in undergraduate research at Bemidji, Minnesota, and Corvallis, Oregon, where my skills in the analytical chemistry of minerals and in the electronics associated with analytical instruments were increased. And, they included a chance to get small amounts of analytical reagents for my home laboratory.

My Ph.D. was from Caltech in inorganic chemistry with Professor Harry Gray. Caltech was a remarkable environment in which to study. There were plenty of opportunities to build instruments, learn new skills, and interact with enthusiastic people. During my Ph.D., I would get samples of minerals from Caltech's geology professors to put in the instruments I was building to study my thesis compounds. The geo people got to know me and ultimately invited me to give a three-month course in modern spectroscopy and chemistry of minerals before I took a "real" job. They must have liked the course I taught because they offered me a job as a mineralogist in the Division of Geological and Planetary Sciences at Caltech.

As a professor at Caltech, I was initially interested in how metal ions interact with one another in crystals in nonlinear ways to enhance color. For example, consider two minerals with high iron contents: hematite and andradite. Even when only a few micrometers thick, hematite crystals are black and opaque, whereas andradite crystals can be millimeters thick yet are pale green and transparent. This is an example of an antiferromagnetic interaction in hematite that does not occur in andradite.

We also used spectroscopic tools to identify the site the metal ion occupied in crystals of amphiboles, pyroxenes, ring silicates, and others. The spectroscopic properties are quite sensitive to the size, coordination number, and distortion of a cation's site in a crystal. For example, it proved quite easy to distinguish Fe^{2+} in the M1 site from Fe^{2+} in the M2 site of pyroxenes.

As I was studying the spectroscopic properties of minerals, I noticed in the infrared spectrum of minerals that we normally consider to be anhydrous that absorption bands from hydroxide ions and water molecules frequently were present in a way that indicated that they were structurally incorporated in the mineral. This work led to our collaborations with the physics community, whose tools of nuclear profile analysis led to the quantification of the hydrous components in nominally anhydrous minerals. That, in turn, led to the realization that minerals such as olivine, pyroxenes, and garnets are a major repository of hydrogen, most likely containing more hydrogen than of all the oceans on the Earth today.

It also quickly became apparent that exposure to background

* E-mail: grr@gps.caltech.edu

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levels of natural radiation over geologic time had much to do with the color of many minerals, particularly those from pegmatites. First, in cooperation with the Jet Propulsion Laboratory and later at Caltech, I was able to conduct irradiation experiments that demonstrated how important this process was in the natural world. Pink tourmaline, in particular, is an important example of this.

I was fortunate to make acquaintances with members of the gem and mineral dealer communities in Southern California. They provided excellent samples for research and posed challenging questions about the properties of minerals they were selling. I also interacted with members of the local mining community. My students and I had some remarkable opportunities to visit the pegmatite mines in the local region and even to go into the Himalaya Mine as it was being worked to obtain materials for study. Particularly helpful were my interactions with the Gemological Institute of America, originally located in the Los Angeles area, and with the local County Museum of Natural History. Interactions and collaborations with their personnel proved to be stimulating and exposed many challenging problems regarding minerals and their properties and provided a resource for materials for study.

It also became clear that minerals are intimately tied to other fields of science and technology such as chemistry, planetary science, materials science, electronics, archeology, and others. My interactions with scientists in these areas gave rise to numerous collaborations that broadened the scope of our research and knowledge.

All of these experiences were team efforts. The accomplishments were possible due in large part to the numerous students, postdocs, collaborators around the world, and my various colleagues at Caltech and elsewhere. Caltech, in particular, gave me access to motivated and industrious students whose efforts are a significant part of the discoveries that gave rise to this award. I am also fortunate that Caltech was willing to hire someone to teach mineralogy in a world-class geology department who never in his life had a formal college course in either mineralogy or geology.

All of this goes to show how our accomplishments are based on the accomplishments of many others around us. In many ways, my success is deeply rooted in the success of my students and collaborators. I have to thank all of you for working with me and hope that some of my excitement associated with minerals and their science has rubbed off on you as well. I hope you will be able to go forward and make great discoveries and accomplishments in your own careers. I extend to all of you my deepest thanks and appreciation.