Acceptance of the 2019 Roebling Medal of the Mineralogical Society of America

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Thank you, Mihály, for your generous comments, for many years of enjoyable and productive collaborations, and for co-organizing Sunday's wonderful symposium on "Visions of Minerals at the Nanoscale." Occurring in MSA's Centennial Year made the symposium even more special.

I am delighted to be awarded the Roebling Medal and warmly thank MSA and my nominators. Receiving the Medal in Phoenix is special because I live next door in Tempe. The light rail from Tempe costs only $1, so I congratulate MSA Council for choosing a Roebling awardee whose travel costs are surely a record in frugality.

More seriously, the award feels like a capstone to a most enjoyable career, for which I am indebted to a series of talented students, postdocs, and visiting scientists from 25 countries on 6 continents. How lucky is that!

I also have more personal reasons to be grateful at this time when our government is so harsh to, and critical of, both immigrants and scientists. I, too, am an immigrant. My parents escaped Nazi Germany in 1937 when I was a toddler, and I am everlastingly thankful to the United States for sheltering our family. So I want to remember and acknowledge my parents and grandparents, including those who were unable to escape and were killed by the Nazis.

On a happier note, I would like to recount how an immigrant kid in New York City became interested in minerals and ultimately arrived at this podium. The beautiful red garnets in the Manhattan Schist plus a passion for the outdoors stimulated a fascination with minerals. That fascination was reinforced at Antioch College in Ohio, where I studied specimens donated by Antioch alumnus Connie Hurlbut, the author of our Dana-Hurlbut mineralogy textbook. I held Antioch co-op jobs with the U.S. Geological Survey in mines around Central City, Colorado, and then in Peru and Chile. These experiences led to graduate work in economic geology at Columbia University, followed by experimental work during a postdoctoral appointment at the Geophysical Laboratory of the Carnegie Institution of Washington. I taught economic geology during my first years at Arizona State University (ASU) but soon became disillusioned with the subject for both scientific and environmental/pollution reasons. However, my love of minerals remained strong.

Here I will recount several interweaving research threads involving transmission electron microscopes (TEMs), atmospheric chemistry, meteoritics, and, in passing, mercury geochemistry, fullerenes and related carbon phases, and an innovative way to do high-pressure experiments within a TEM.

Because I yearned to do research that was socially relevant, I took advantage of having been funded by NSF for ASU's first electron microprobe to embark on a venture I called "airborne mineralogy." When I arrived in Phoenix in the 1960s, the region was bedeviled by persistent air pollution, the source of which was controversial. Politicians wanted the problem fixed but, being Arizona, they did not want involvement by "the Feds" (a dismissive term for the government in Washington, D.C.). However, no one in Arizona was doing anything about the air pollution, nor even knew how to determine whether desert dust, vehicles, or the nearby copper smelters were the dominant culprit.

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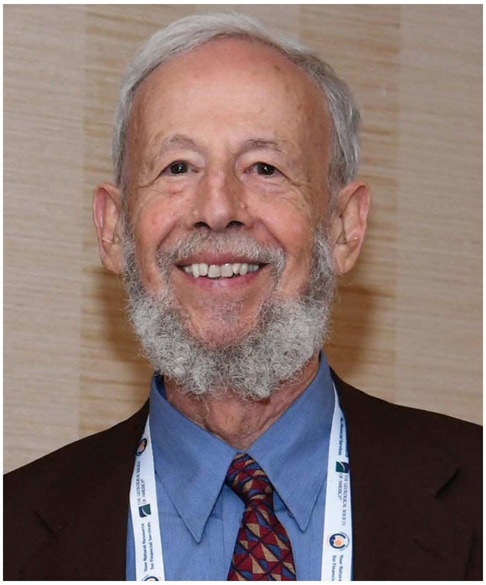

Conventional wisdom was that the small sizes of aerosol particles precluded reliable chemical analyses. I questioned that assumption and wondered whether we might do better? With Ph.D. student John Armstrong, we provided the first quantitative chemical analyses of airborne particles. Thus started my entry into atmospheric chemistry, subsequently sustained by outstanding colleagues that include my distinguished Roebling nominator Mihály Pósfai, Ph.D. students Li Jia, Gary Aden, John Bradley, and postdoc Kouji Adachi.

In 1969, an ASU physics talk showing the first images of crystals at the atom-cluster scale stimulated a fascination with electron microscopy and sparked my interest in its potential for mineralogy. At the time, ASU had a growing program in solid-state chemistry, and colleagues LeRoy Eyring and Michael O'Keeffe had opened my eyes to new ways of understanding mineral structures. My mineralogical interests were reinforced with the hiring of Galvin Professor of Physics John Cowley and his research associate Sumio Iijima. They propelled me into the nascent field of high-resolution transmission electron microscopy (HRTEM).

I convinced Sumio, subsequently famous for the discovery of carbon nanotubes, that intriguing mineralogical problems were waiting to be investigated. The goal was to determine whether imaging the intimate details of mineral structures, made possible with HRTEM, could reveal new information about their formation histories?

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Our 1974 *American Mineralogist* paper (Buseck and Iijima, vol. 59, p. 1–21) demonstrated that crystal structures that had been deduced from X-ray diffraction studies could actually be directly imaged. Equally important, small-scale deviations from those idealized structures were revealed. Many of these nano-deviations record hitherto unexplained geologic events and processes. Many good things followed in short order.

ASU Ph.D. student Larry Pierce obtained the first dark-field HRTEM images of point and column vacancies in the Fe and Cu sulfide minerals pyrrhotite and bornite. Jeff Post and Shirley Turner showed defects in Mn oxide minerals hollandite, nsutite, and todorokite from surface deposits, deep-sea nodules, and dry-cell batteries. They also revealed the systematics of tunnel-structure Mn oxide minerals.

Our papers inspired Harvard professors Charlie Burnham and Jim Thompson to inquire whether I might have a postdoctoral position for David Veblen, a Ph.D. student studying the biopyribole minerals. Electron microscopy was the ideal experimental approach for unraveling the complexities of the biopyriboles and their abundant linear chain-width defects and transitional intergrowths among their namesake pyroxenes, amphiboles, and micas. Thus began a long, productive collaboration and friendship that lasts to this day. Similar friendships exist with my former postdoc Mike O'Keefe, who helped pioneer computer modeling of high-resolution TEM images, which was needed to properly interpret our observational data, and with former Ph.D. student and now ASU faculty colleague Tom Sharp.

The impacts of changes in science are not always immediately evident. A spectacular example occurred while I was in graduate school and shortly thereafter, when I experienced (unknowingly because it took several years for the facts to accumulate) the shift from continental drift to plate tectonics. Although less consequential, the awareness of what could be seen and discovered by examining minerals at high magnification using HRTEM gradually changed our understanding of their most private details. Most conspicuously, it showed how commonly minerals deviate from ideality and how that affects their properties and reactions.

It gradually became clear that we were "riding the crest of a wave" in which almost everything was new. Students and postdocs in my group almost routinely had their results published in *Science*, *Nature*, and *PNAS*, sometimes more than once per year and commonly with cover photos. Considering how hard we struggled in subsequent years to have papers appear in those journals makes me realize just how special that time was.

At the same time as our HRTEM results were revealing new mineralogical details, my prior work on pallasite meteorites morphed into a fascination with the fine-grained minerals of carbonaceous chondrite meteorites. Their mineralogical details had been impossible to determine by existing methods. The motivating question was whether HRTEM could provide information regarding their origin, and perhaps also about life's carbonaceous precursors. Work on these chondritic meteorites was initiated by postdoc Kazu Tomeoka, followed by nominator Lindsay Keller, Laurence Garvie, Hua Xin, Tom Zega, and other talented young scientists.

To round out this story, I return to "airborne mineralogy" because that is perhaps the research area that is least familiar to this audience. Following early feasibility studies, our participation in field campaigns across the globe produced much new science. Our TEM studies led to, among other things, (a) the discovery of the widespread carbonaceous particles we called "tar balls," which were subsequently shown to be abundant in wildfire emissions; (b) experimental understanding of the details of the particle deliquescence that contributes to droplet and cloud formation; and (c) recognition that many, and perhaps most, solid atmospheric aerosol particles have irregular shapes and consist of multiple phases much like tiny rocks. Each has climate impacts.

Prior to our work, scientists assumed that most atmospheric aerosol particles are chemically simple and spherical. These assumptions are appealing because such idealized particles are easier to incorporate into climate models than the complexly shaped real particles that we found to be typical. For particles that contain more than one phase, the configuration was assumed to be that of layered "core-shell" spheres, but we showed that these are extremely unusual in solid particles. Our TEM studies have had important implications for climate models. TEM capabilities, combined with mineralogical knowledge, provided a productive research niche for the study of atmospheric chemistry and aerosol effects on climate.

People in my group also pursued creative research into mercury geochemistry and its relation to geothermal energy; poorly graphitized carbon, fullerenes, and diamond; possible new carbon species both on Earth and in the interstellar medium; and Jun Wu is pioneering high-pressure experiments within a TEM, with relevance to the origin of terrestrial water.

It has been fun to write about scientific successes but, especially for scientists early in their careers, it may be useful to know that there were also ideas that I thought were truly great, only to find that they did not go anywhere. In some cases, it took years to figure that out. It was always with regret that my group and I moved on, and at times I still wonder whether some of those decisions were correct. The first challenge facing a scientist is choosing good questions to address. The second is recognizing when that choice is incorrect or premature. This aspect of science reminds me of the observation that "the two happiest days in a boat owner's life are the day you buy the boat and the day you sell it."

Finally, I want to publicly remember Alice, my beloved wife of 50 years, who so enjoyed the many people who spent time in my research group over the years. I also want to acknowledge our four lovely children, their partners, as well as my partner for the last few years, Cindy Greeley, widow of Ron Greeley, my friend and colleague for over 30 years, who died shortly after Alice.

I also wish to recognize my valued colleague, Susan Lowry, and especially the many people who were part of my research group over the decades. Their collective efforts made it possible for me to stand here today. It is a special pleasure that many are among my best friends to this day! What could be better than that for a career? There are too many people to name here, but 70 who used TEMs are acknowledged in a slide from my Roebling talk this afternoon, and there is an equal number who worked in other areas. It is pleasing that many of the students and postdocs mentioned above, plus others who worked with me, are here today, all with successful careers and all of whom share the credit for my receiving the Roebling Medal.

I am grateful for the academic freedom provided by ASU's Geology and Chemistry Departments (now the School of Earth and Space Exploration, SESE, and School of Molecular Sciences, SMS), augmented by many talented students and postdoctoral scientists. I consider myself truly fortunate, and I deeply appreciate the award of the Roebling Medal. Thank you Mineralogical Society of America for selecting me.