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Acceptance of the 2015 Roebling Medal of the Mineralogical Society of America

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Ladies and Gentlemen, Colleagues and Friends.

My thanks to Peter Burns for his very kind words and generous citation.

Two hundred years ago the Swedish chemist, Jöns Jacobs Berzelius (1815), first described the physical and chemical properties of what would come to be known as metamict minerals. Ninety-nine years passed before A. Hamberg (1914) correctly proposed that these properties were the result of radiation damage. Fifty years ago, Professor Adolf Pabst received the Roebling Medal, in part, for his classic work on the metamict state (Pabst 1966).

Pabst's citationist was Ian Campbell, the namesake of the Ian Campbell Medal of the American Geoscience Institute. Pabst's acceptance bears reading, particularly his reference of H.L. Menken's concept of "messianic delusion" that Pabst applied to young scientists, as compared to his own "limited objectives" in his research. When I was a graduate student at Stanford and left without an advisor by the death of Colin Hutton, Pabst became a distant mentor from across the San Francisco Bay. Pabst and Hutton were among the few in the world with an interest in metamict minerals, a tradition that I have tried to carry forward.

Over the course of my career, I have been able to expand an early interest in the metamict state in many different directions. I have been able to do this, not out of cleverness, but rather through collaborations. Today, I want to take just a few moments to recognize these collaborators—a number of them graduate students and post-doctoral fellows, as well as colleagues at universities and national laboratories—by describing and citing the published results of our collaborations.

After receiving my Ph.D. at Stanford in 1974, my scientific career got off to an extremely slow start. The world was certainly not waiting to know more about the metamict state. At the University of New Mexico, I listened to a number of talks from scientists at national laboratories that discussed the vitrification of high-level radioactive waste. From a geologic perspective, glass seemed to be a poor choice of nuclear waste form. Years later I learned that Rustum Roy had tried to make the same point through a report of the National Academy of Sciences, but without success. I published a paper in *Science* (Ewing 1976) pointing out that metamict minerals, in the amorphous state, were often altered, showing limited long-term stability. This paper created a bit of a stir and pulled me to the edge of the nuclear waste field. The paper created just enough interest that, with support from Pacific Northwest Laboratory, I hired my first research scientist, Richard Haaker. We published two reports in the gray literature, one on the use of natural glasses as "natural analogues" for nuclear waste glasses (Ewing and Haaker 1979). The results on natural glasses were presented at the first symposium on the *Scientific Basis for Nuclear Waste Management* at the Materials Research Society meeting in Boston (Ewing 1979). This was the first time that the phrase "*natural analogue*" was used in the nuclear waste community. The second report (Haaker and Ewing 1981a) was a survey of durable minerals that contained U and Th—meant as an initial list of potential crystalline candidates for nuclear waste forms. Many of these minerals have since become important waste forms. We also developed a method of synthesis for zircon with the intent of synthesizing Pu-bearing zircons at PNL (Haaker and Ewing 1981b). The Pu-doped zircon eventually became a collaboration with Bill Weber at Pacific Northwest Laboratory. Tom Headley at Sandia National Laboratories introduced me to transmission electron microscopy as we completed the first TEM study of the metamict state (Headley et al. 1981). Thus, we were launched into nuclear issues, transmission electron microscopy and, importantly, into the then fledgling Materials Research Society. The eclectic range of topics at MRS meetings was a gold mine for a young mineralogist.

Because of my "anti-glass" views, Werner Lutze asked me to spend the summer of 1979 at the Hahn Meitner Institute in Berlin so that we could argue out glass vs. crystalline ceramics as waste forms. Our argument lasted some decades, with many papers (Lutze et al. 1985) and finally the tome, *Nuclear Waste Forms for the Future* (Lutze and Ewing 1988). This book took some years to complete—but it introduced me to a full array of excellent mineralogists and material scientists working on nuclear materials: Lynn Boatner, Ted Ringwood, Sue Kesson, Rustum Roy, Dave Shoesmith, Lawrence Johnson, and Gerhardt Ondracek. Most importantly, my life was completely turned on end by my experiences in Berlin and non-scientific explorations of Eastern Europe behind the Iron Curtain.

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The very first research group formed in the early 1980s: Bryan Chakoumakos, Gregory Lumpkin, and Takashi Murakami, all of whom have gone on to very distinguished careers in their own right, immediately worked on radiation damage in pyrochlore (Lumpkin et al. 1986; Lumpkin and Ewing 1988) and zircon (Chakoumakos et al. 1987; Murakami et al. 1991). Collaboration with Bob Greegor and Farrel Lytle, who worked for Boeing, opened us to the opportunity of using X-ray absorption spectroscopy to follow radiation damage effects in amorphous materials (Greegor et al. 1989, 1990). Bill Weber joined as a co-author on one of these early XAS papers.

During the late 1980s, and even until today, Bill Weber and I have been alternately competitors and collaborators. The competition has been good for us, but we did much better work when we collaborated. Our earliest collaboration focused on zircon (Weber et al. 1994). Later, we published a series of high-impact review papers on radiation damage effects (Weber et al. 1997, 1998; Weber and Ewing 2000). In fact, for both of us, our most cited papers are those as coauthors.

In 1990, Lumin Wang joined the group as a research scientist and electron microscopist. With his nuclear engineering background and his recent post-doctoral appointment at Argonne National Laboratory, he brought the idea of using ion beam irradiations to investigate radiation effects in minerals and waste forms. This set the stage for decades of work, as we immediately began to irradiate a wide variety of complex silicates and oxides (Wang et al. 1991; Wang and Ewing 1992). This allowed us to "see" radiation damage accumulate using in situ electron microscopy available at the IVEM-Tandem Facility at Argonne National Laboratory. We used a wide variety of ions with energies of 0.5 to 1.5 MeV to simulate alpha-recoil damage. With a talented array of students and post-docs: Al. Meldrum, Jie Lian, Satoshi Utsunomiya, and Shixin Wang. Shixin's work is noteworthy for his systematic approach to the relation between structure-chemistry-radiation response (Wang et al. 1998a, 1998b) and his discovery that zirconate-pyrochlore was very "resistant" to radiation damage (Wang et al. 1999). This was the first indication, for me, that radiation could be used to induce a wide variety of phase transformations. This work continued through the mid-2000s and continues today in other research groups, but our interest was diverted by new experimental possibilities.

In parallel with the radiation effects work, we continued our waste form research, finally expanding it to include the most important waste form, spent nuclear fuel. The work was initiated by a Ph.D. candidate, Bob Finch, who took a very careful look at the corrosion products of uraninite, UO_{2+x}, in nature (Finch and Ewing 1992). As we realized how complex these uranyl oxyhydroxides were, Mark Miller, a recent, 1992, Ph.D. graduate in the group began to analyze the topology of the uranium oxide structures (Miller et al. 1996). Peter Burns arrived in 1995 and was the first author on two blockbusters on the crystal-chemistry of uranium and the topology of uranium compounds, both published in the *Canadian Mineralogist* (Burns et al. 1996, 1997a). We have always been grateful to Bob Martin, the editor, who appreciated the impact and the need for the length of these two papers. Peter also published a short paper in the *Journal of Nuclear Materials* that showed how his thinking could be applied to studies of the corrosion of spent fuel (Burns et al. 1997b). This work continues today (Burns et al. 2012; Ewing 2015). Now Peter is my boss in our Energy Frontier Research Center on the Materials Science of Actinides.

Sometime in late 2005, Christina Trautman at GSI in Darmstadt gave me a German Ph.D. thesis by Maik Lang with a sense of urgency and the belief that the work was important. I carried the thesis around the world in my briefcase, without reading it. Finally, on a long flight, I had a quick look and discovered that Maik had done experiments using very high-energy irradiations (1 to 5 GeV) of samples in diamond-anvil cells at high pressures. I had no idea that this was even possible, but recognized that it opened up an entirely new research field—"extreme environments." We tried to get support for Maik from various European programs but failed, so I just told Maik to come immediately. He had never heard of the University of Michigan and hesitated to join a research group in a geology department. Luckily, he came (Lang et al. 2009), as had Fuxiang Zhang, an expert in diamond-anvil cell experiments and an excellent beamline scientist (Zhang et al. 2008), and Jiaming Zhang, a superb electron microscopist (Zhang et al. 2010). Udo Becker had just joined the faculty at Michigan and brought much to the collaboration, particularly from the computational perspective—both in radiation effects (Wang et al. 2013) and uranium chemistry (Renock et al. 2013; Wang et al. 2013, 2014). This team is now dispersed, but the work continues at the University of Michigan, the University of Tennessee, and Stanford (Tracy et al. 2015; Park et al. 2015; Lang et al. 2015).

Over time, the scientific research led to policy issues related to nuclear waste management and more extended collaborations. Alison Macfarlane and I edited a volume on Yucca Mountain (Ewing and Macfarlane 2002; Macfarlane and Ewing 2006). I was drawn into the spheres of Frank von Hippel and Richard Garwin on the issue of the fate of plutonium from dismantled nuclear weapons (von Hippel et al. 2012). The fascination has been to understand why so little science finds its way into policy decisions. This work led to my appointment as a Senior Fellow at the Center for International Security and Cooperation at Stanford. Once again, I am on a steep learning curve as I study policy issues related to nuclear materials.

Throughout this story, I enjoyed great support from three universities: University of New Mexico, University of Michigan, and Stanford. I have always appreciated the indulgence of colleagues as my research took me outside of the traditional topics of mineralogy and geology. None of this would have been possible without the continuous support, sometimes modest, from Basic Energy Sciences at the Department of Energy.

In summary, I hope the lesson is clear. If one wants to enjoy the excitement of a scientific career investigating different topics and using many techniques while traveling the world—collaborations are the key. Always be willing to cross the borders of nations and disciplines. To all of my collaborators, named and unnamed, my thanks for a rich life of research and global experiences.

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