American Mineralogist, Volume 98, pages 1086–1087, 2013

Acceptance of the 2012 Roebling Medal of the Mineralogical Society of America

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Mr. President, Members of the Society, Ladies, and Gentlemen:

Thank you, Larissa, for your very kind words and for nominating me for this great honor. Many thanks also to those who supported my nomination and to the Roebling Committee that selected me. I am extremely honored to be chosen as the 2012 Roebling Medalist, as I am sure you can already conclude by my dress today. I am humbled when I look back over the list of earlier recipients of this award—William Lawrence Bragg, N.L. Bowen, Linus Pauling, and many outstanding mineralogists and mineral physicists, including the last dozen or so, most of whom are my friends and admired colleagues.

Like so many others have said before me, I am indebted to many people in my past who have contributed to my successes in large and small ways. I am deeply indebted to my parents who raised me with no doubts that I would become a scientist one day. I am similarly indebted to Gary Ernst from whom I learned basic mineralogy and the embryonic beginnings of Ultra-High Pressure Metamorphism (UHPM), and for whom I separated minerals as an undergraduate. And to David Griggs, my Ph.D. mentor, who taught me that one should never accept coincidence as an explanation for something surprising without first exhausting all other available possibilities. As Pasteur said, "Luck favors the prepared mind"—i.e., you have to be prepared to be lucky by maintaining an outlook receptive to surprising results that may open new doors. With time, and the help of John Christie (my other Ph.D. mentor), I gained the deep insight that information about the fundamental physics of geological phenomena is found at the smallest scales and stored as microstructures in the rocks.

The quest to understand microstructures and a determination not to believe in coincidence have been the guiding principles of my career and are the primary contributors to my two most important scientific contributions:

(1) The mechanism of deep earthquakes, in which incipient transformation of metastable olivine to its higher-pressure polymorphs in the mantle transition zone (MTZ) triggers a faulting instability that drives runaway nucleation fueled by the heat of transformation. Seismologists have now verified the presence of metastable olivine in 5 subduction zones, making the probability extremely high that this is the mechanism underlying initiation and propagation of deep earthquakes.

(2) Discovery that some rocks have been exhumed from depths of hundreds of kilometers. Among these are one-way travelers, like the Alpe Arami Garnet Peridotite of the Swiss Alps that has surfaced from approximately 400 km, and two-way travelers, like a pelitic gneiss from the Alten Tagh of western China that carries unambiguous evidence of equilibration in the stishovite stability field at greater than 350 km before being returned to the surface.

I had the spectacular good luck to share my graduate years at UCLA with Jim Blacic, Jan and Terry Tullis, and Ivan Getting, along with visitors Rob Coe, Bruce Hobbs, and Rudy Wenk. I learned many things from them all and established life-long friendships with them all. I then had the great good fortune to take a post-doctoral position in Materials Science at Case Western Reserve University where Arthur Heuer was taking delivery of the very first commercial instrument for ion-bombardment thinning for preparation of electron-transparent foils of nonconducting materials. With that instrument available to me, I was able to pioneer a new dimension in structural geology and geophysics—the use of transmission electron microscopy to pursue microstructures to the ultimate level—the nanoscale.

With Griggs as my scientific "father," that makes Percy Bridgman (Griggs' mentor) my scientific "grandfather." In 1945, Bridgman laid out the criteria by which a solid-solid phase transformation could trigger earthquakes. The list had several "ifs" in it, all of which would have to be fulfilled simultaneously, and he concluded that the probability of such instability was small. However, over the ensuing 40+ years, one by one his criteria were fulfilled by the discovery of plate tectonics and the realization that subducting slabs might be sufficiently cold to preserve metastable olivine into the MTZ. In 1989, Pamela Burley and I found just such an instability that now is confirmed by identification of metastable olivine in the MTZ.

The first 20+ years of my professorial career were at the University of California, Davis. Shortly after arriving there, I received a U.S./France exchange fellowship from NSF and spent five months in Nantes with Adolphe Nicolas, the master of using microstructures to understand deformation of mantle rocks. Upon arrival there, I met Yves Gueguen and we produced the first quantitative model of kimberlite genesis, the essence of which remains valid to this day. I returned to Nantes again in 1978–1979 where Gueguen and I extended our theory and I developed my theory of the thermodynamics of solids under nonhydrostatic stress,

0003-004X/13/0506–1086$05.00/DOI: http://dx.doi.org/10.2138/am.2013.613

a subject I had become fascinated with as a graduate student. Upon my return to Davis, my career took a fateful turn when Peter Vaughan brought his Mg_2GeO_4 specimens with him to my lab from his Ph.D. work with Rob Coe at U.C. Santa Cruz on the effect of the olivine-spinel transformation on the rheology of this material. Seeing the microstructural effects of stress on the olivine-spinel transformation stimulated me to extend my theory of nonhydrostatic stress to the mechanisms of phase transformations. At the time (1984), there was a controversy concerning whether the mechanism was coherent and martensitic or incoherent by nucleation and growth. I pursued that interest after Peter had moved on and, a few years later, Pamela Burnley and I demonstrated that there are two mechanisms for the olivine-spinel transformation and that the incoherent nucleation and growth mechanism is the one most likely to be geophysically relevant. That discovery was published in *Nature* early in 1989.

A few months after resolving that problem, Pam and I discovered the high-pressure faulting mechanism in Mg_2GeO_4 olivine as it transformed to the spinel polymorph, and we formulated the anticrack self-organization hypothesis to explain our observations and deep earthquakes. I established a collaboration with Chris Scholz and, with Tracy Tingle (God rest his soul), we demonstrated that the mechanism generates acoustic emissions. As Chris and I were setting up the collaboration, David Walker heard about our work from Chris and suggested we use his newly developed multi-anvil module to test our high-pressure faulting mechanism in "real" olivine. Tom Young and I took him up on his suggestion and the result was confirmation of the mechanism at 14 GPa, published in *Nature* in 1990. Eric Riggs and I later added new information and ideas about this instability, using previously unrecognized microstructures. Very recent work in collaboration with Alexandre Schubnel and colleagues in France has now, with acoustic emission measurements and real-time stress/strain observations using synchrotron radiation, established this faulting mechanism to 5 GPa in Mg_2GeO_4 and collected important new observations concerning the basic physics underlying the instability (submitted for publication).

Returning to the timeline of my career, during a sabbatical leave with Bruce Hobbs in Australia in 1984, I designed a molten salt cell to increase the precision of the Griggs machine to almost that of the Paterson Gas Apparatus but at much higher pressures. Serendipitously, during my time in Hobbs' laboratory, I had a full-time machinist at my disposal and after 6 months the cell was worked out and performed beyond my wildest dreams. Back in Davis, we built a 4-poster Griggs Rig to extend rock deformation to 5 GPa pressure. Replicas of that machine now exist in Germany and China and we have plans to build another in Paris.

Shortly after returning from Australia, I started a life-long collaboration and friendship with Zhenmin Jin from Wuhan that also extended to my visiting Wuhan under the auspices of the World Bank in 1988. During Zhenmin's second extended stay in my lab in the early 1990s, we moved the lab to U.C. Riverside and during his third stay he brought with him Junfeng Zhang and we embarked on the first study of the rheology of eclogite. More recently, Zhenmin has sent to my lab Sutao Zhao and Feng Shi. Sutao, using a titanate analogue, showed that breakdown of ringwoodite as it enters the lower mantle in subducting slabs does not lead to weakening, resolving a controversy over symplectite rheology. Feng is currently in his second year in the laboratory working on both brittle and ductile phenomena.

A couple of years after my arrival in Riverside, Larissa Dobrzhinetskaya, my citationist for this award, joined the lab and together we discovered the high-pressure history recorded in the microstructures of the Alpe Arami peridotite, and we have gone on to many other studies of UHPM and metamorphic diamonds, the latter under her able leadership. Great controversy erupted concerning the depths we proposed for origin of the Alpe Arami garnet peridotite. The road to a resolution of the controversy began with an invitation by Guido Gosso and Iole Spalla to a meeting in the Alps. My presentation there, followed by additional work with Larissa using a new electron microscopy laboratory and the great skills of Krassimir Bozhilov, yielded abundant new data that eventually overcame the nay-sayers about Alpe Arami and our studies of UHPM flowered. Two of the exciting aspects of our subsequent findings are the very high pressure minerals in massive chromitite of a Tibetan ophiolite with Jingsui Yang, and evidence within an inclusion in diamond that it probably has traveled to the surface from very deep in the lower mantle. The first of these findings (coesite-after-stishovite and the high-pressure form of TiO_2) require origin at depths in excess of 350 km, giving us our first glimpse of rocks from the upwelling limb of mantle convection. The second, with Richard Wirth and Ben Harte, is a work still in progress but may be able to tell us interesting things about the very deep mantle.

Other collaborations brought Gayle Gleason, Haemyeong Jung, and Gang Xia to the lab. Gayle showed, using the breakdown reaction albite to jadeite + coesite as a proxy for ringwoodite breakdown at the base of the MTZ, that the anticrack faulting mechanism cannot function during such decomposition reactions, thereby explaining why deep earthquakes stop at the base of the upper mantle. Haemyeong demonstrated that dehydration embrittlement of serpentinized peridotite does not require a positive volume change. With the late Paul Silver, we demonstrated acoustic emissions during this reaction. Haemyeong is now embarked on a successful career in Korea. Gang is just finishing his dissertation on rheology and faulting of serpentinized peridotite with implications for intermediate-focus earthquakes and water transport into the mantle. He also has produced an excellent series of experiments on forsterite that he, Pamela, and I will use to provide calibration of stress measurement in the D-DIA apparatus used in synchrotron studies of rheology.

I cannot finish here without expressing my profound gratitude to the National Science Foundation that has provided continuous financial support of my research for 43 years and counting. I wish to thank particularly the Geophysics Program (Robin Reichlin), the Petrology and Geochemistry Program (Sonia Esperanza), and the EAR Instrumentation Program (Dan Weil and David Lambert).

Beyond all of these exciting and productive collaborations over many years, I thank the love of my life -- my wife of almost 40 years, Manuela. A noted biological scientist in her own right, Manuela has always been there to support me. We are now blessed with 9 grandchildren, the latest of which is scheduled to arrive next month. (NOTE ADDED IN PROOF – Baby arrived; mommy and daughter doing well.)

In closing, I once again extend my thanks to the Mineralogical Society of America and the Roebling Committee for this great honor.