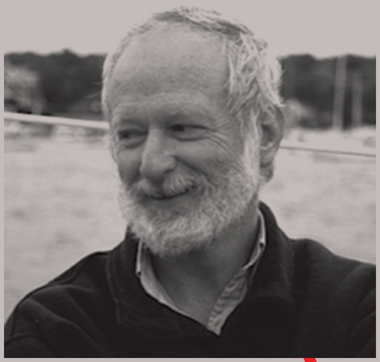
Richard J. O'Connell Symposium



September 5 & 6, 2014
Northwest Building, Harvard University
Cambridge, MA

Supported by the Department of Earth and Planetary Sciences, Harvard University

Richard J. O'Connell Symposium

SEPTEMBER 5 & 6, 2014

NORTHWEST BUILDING, HARVARD UNIVERSITY

CAMBRIDGE, MA

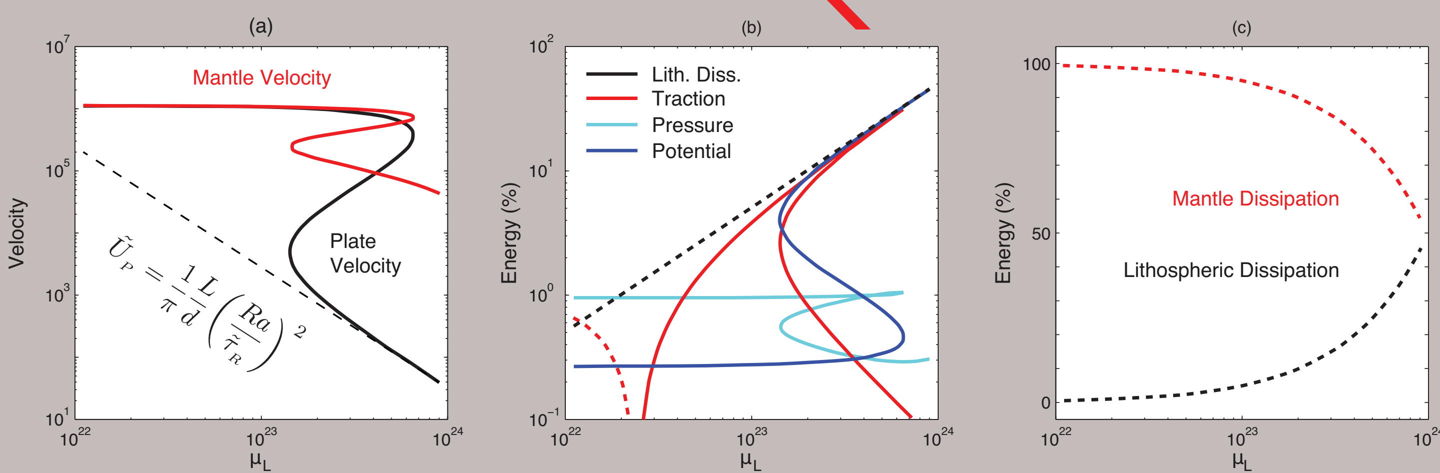


figure from JW Crowley

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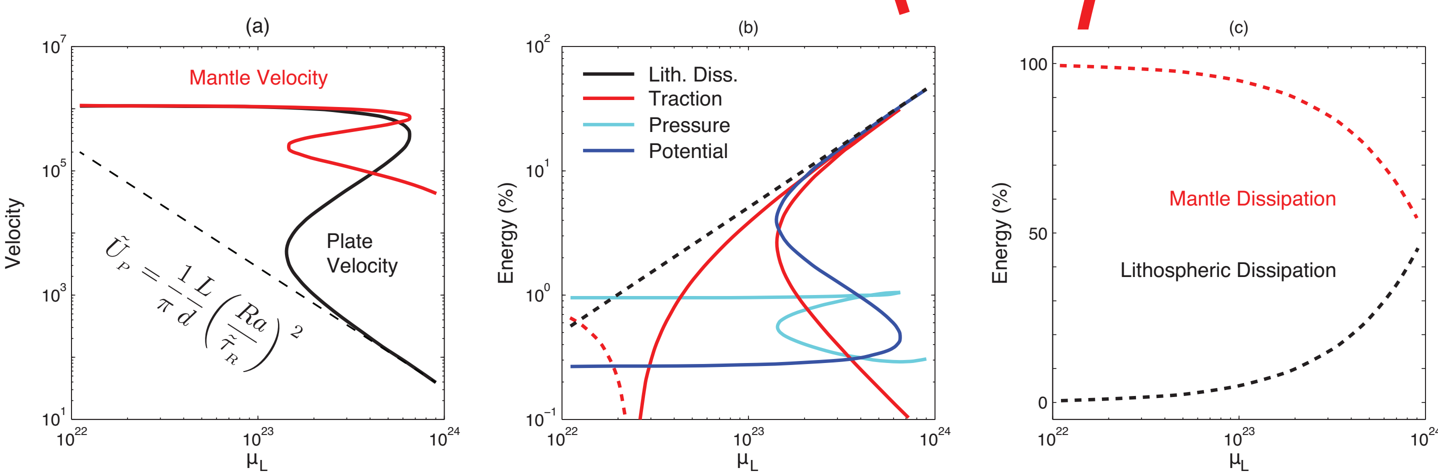
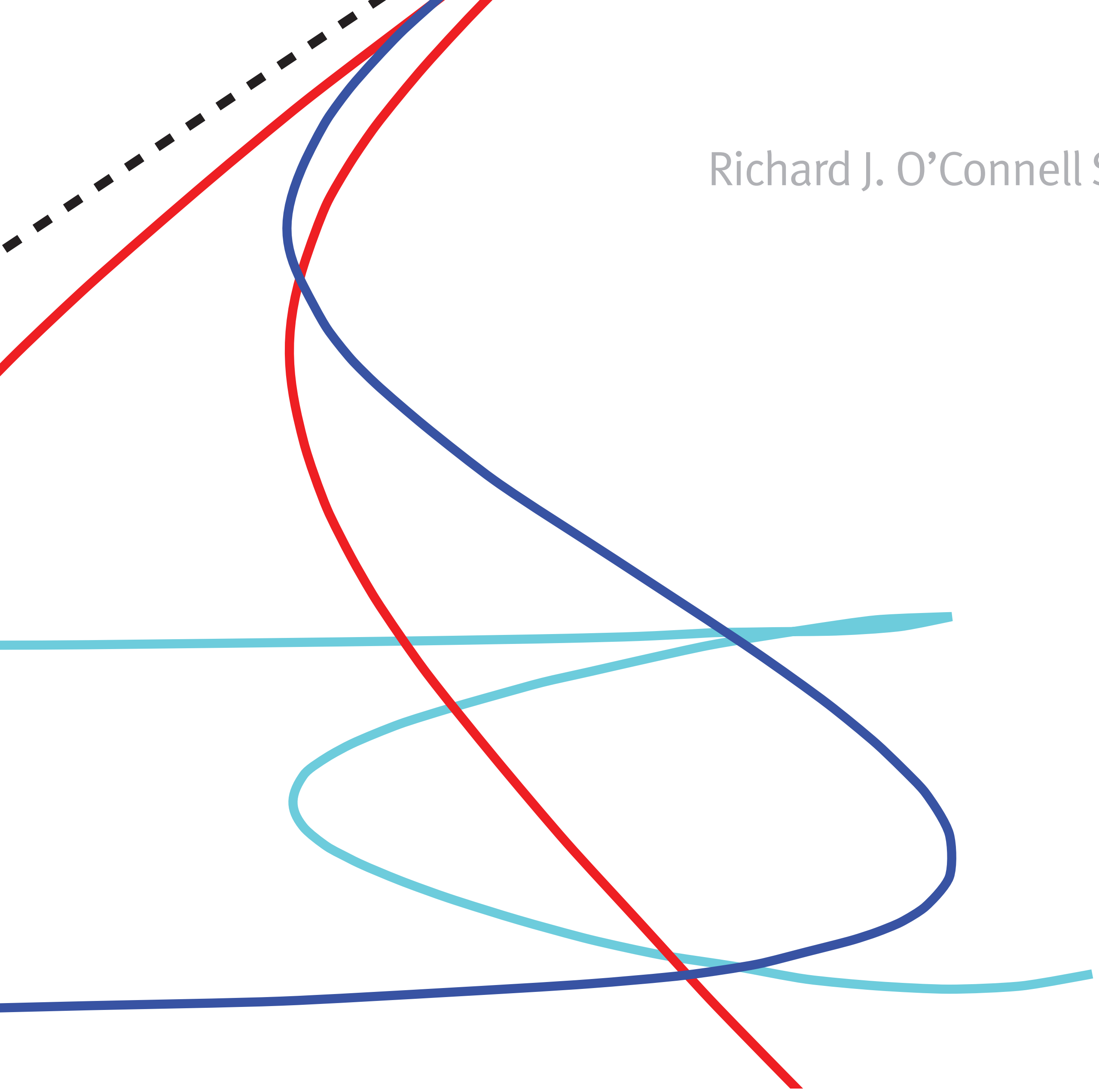
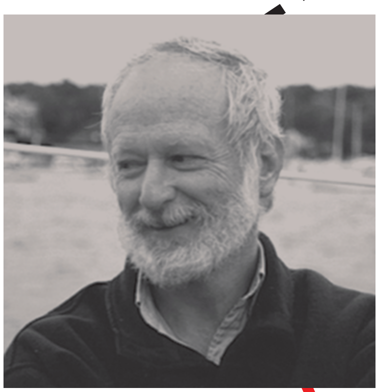


(a)
Mantle Velocity
Plate Velocity
Velocity
$\tilde{U}_P = \frac{1}{\pi}\frac{L}{d}\left(\frac{Ra}{\tilde{\tau}_R}\right)^2$
μ_L
(b)
Lith. Diss.
Traction
Pressure
Potential
Energy (%)
μ_L
(c)
Mantle Dissipation
Lithospheric Dissipation
Energy (%)
μ_L



Results for an isoviscous mantle with a finite strength plate. (a) Dimensionless plate velocity (black) and mantle velocity (red) vs. lithospheric viscosity for a mantle with an overlying lithosphere on top. The plate velocity for the lower branch, predicted by asymptotic results, is plotted as the dashed black line. (b) Lithospheric dissipation (black), work done by basal tractions (red), work done by the pressure gradient (light blue), and the rate of change of potential energy in the lithosphere (dark blue), all from the lithospheric energy balance and normalized by the total rate of change of potential energy in the system. (c) Lithospheric (black) and mantle (red) dissipation from the global energy balance and normalized by the total rate of change of potential energy in the system. Dashed lines indicate negative values (work done by the lithosphere) while solid lines indicate positive values (work done on the lithosphere).

From *On the Dynamics of Plate Tectonics: Multiple Solutions, the Influence of Water, and Thermal Evolution,* John W. Crowley, Ph.D. Thesis Harvard University 2012. See also *An analytic model of convection in a system with layered viscosity and plates,* John W. Crowley and Richard J. O'Connell, Geophys. J. Int. (2012) 188, 6178



Biographical Sketch - Richard J. O'Connell

Richard J. O'Connell was born in Helena, Montana, the son of a ranching family. He earned his BS in Physics, his MS in Geology, and his PhD in Geophysics, all at Caltech. After postdoctoral work at Caltech and UCLA, O'Connell joined the faculty at Harvard, where he has mentored a succession of unusually successful undergraduates, graduate students, and postdoctoral fellows, as well as engaging in cutting edge research with senior colleagues. O'Connell's research is focused on understanding dynamic processes in planetary interiors, their coupled thermo-chemical evolution, and their relation to geological events on the surface. For his seminal work in geodynamics and material properties, O'Connell has been awarded the Inge Lehmann Medal of the American Geophysical Union, the Arthur L. Day Medal of the Geological Society of America, and the Augustus Love Medal of the European Geosciences Union. He is a Fellow of the American Geophysical Union, the American Association of the Advancement of Sciences, and the American Academy of Arts and Sciences.

Richard J. O'Connell Symposium

Introduction

It is a great pleasure and a distinct honor to join all of you – family, friends, colleagues, and students of Richard J. O'Connell – to celebrate the life and accomplishments of a distinguished and wonderful man. We are here for many reasons. Most of us are here because of Rick's pioneering contributions to the science of geophysics, which range from new approaches to understanding the viscoelastic properties of cracked rocks, to unraveling the three-dimensional structure and dynamics of the convection that accompanies and drives motions of the tectonic plates, to anticipating the properties of extra-solar super Earths. Many of us are here because Rick has mentored us directly, or mentored our mentors, or our mentors' mentors. All of us are here because Rick O'Connell has cared about each of us, helping us to thrive.

Rick's signature scientific accomplishment is his seminal work in understanding the three-dimensional structure and dynamics of the global convective circulation in Earth's mantle. The motion of the tectonic plates is the surface manifestation of this global mantle flow, as well as its primary driver. When Rick began his work in global geodynamics, the consensus was that the mantle flow associated with plate motions is confined to the upper 670 km of the mantle. The work by O'Connell and his students overturned this dominant paradigm, providing strong evidence that this flow penetrates deep into the lower mantle, a prediction subsequently verified by seismic observations.

O'Connell's research is focused on understanding dynamic processes in planetary interiors, their coupled thermo-chemical evolution, and their relation to geological events on the surface. His distinguishing approach includes using models that are realistic enough to include the important processes while at the same time being simple enough to be tractable and provide fundamental insights, all while being tightly linked to observations. His expertise in both geophysical fluid dynamics and the mechanics of Earth materials has guided his formulation of geodynamical models in a unique and powerful way. The development of O'Connell's body of research provides many illustrations of his hallmark style.

As a pre-generals graduate student at Caltech, Rick's first calculation of mantle flow addressed the now-classic problem of glacio-isostatic adjustment. By quantitative comparison of model predictions to observations of variations in the long-wavelength gravity field, Rick showed that, contrary to previous claims, Earth's lower mantle had sufficiently low viscosity to flow in response to loading of the surface by Pleistocene glaciation.

O'Connell's next step in developing a model of mantle circulation was brilliant. First, he realized that the viscous drag on the underlying mantle from the motion of tectonic plates must exert a strong organizing influence on mantle flow. Second, the simple requirement of mass balance associated with the return flow from subduction zones to spreading centers provides a zeroth order constraint on mantle circulation. Third, because most of Earth's heat flow results from the cooling of the plates as they move away from mid-oceanic ridges, the density contrasts associated with the cooling and thickening of the lithosphere should be the dominant source of thermal buoyancy driving the system. Finally, the fact that surface motions are nearly constant within plates and change discontinuously across plate boundaries, including strike-slip plate boundaries like the San Andreas fault, means that this near-surface region cannot be adequately represented as a viscous fluid - the effects of plate boundaries must be explicitly addressed. The resulting simple model of global flow, incorporating piecewise continuous plate velocities, with plate boundaries parameterized via a plastic yield stress, and including the density contrasts in surface plates and subducted slabs, was remarkably powerful. Both the observed plate motions and the observed dip angles of subducted slabs were consistent with the predictions of the model. But only if flow penetrated deep into the lower mantle.

After plate motions, volcanic hotspots provide the next most important geologic constraints on mantle circulation. O'Connell and his team extended their flow calculations back 100 million years and included a simple parameterization of the thermal buoyancy of plumes to predict quantitatively the relative motions among hotspots, as well as explaining the bend in the Hawaiian-Emperor seamount chain. These models also predict the long-term motion of the rotation axis relative to the mantle and show that the viscosity of the deep interior is greater than that of the upper mantle, while still being low enough to deform over geologic time.

Rick has long championed the importance of including geochemical constraints on models of mantle circulation. These include the necessity both for efficient mixing and for a degree of long-lived separation among a number of geochemical reservoirs. The model of mantle circulation developed by O’Connell, with vigorous flow in the upper mantle dominated by the tectonic plates, and with more sluggish flow in the deep interior, is consistent with geochemical observations of isotopic systems.

After establishing himself as a dominant intellect in the dynamics of Earth’s mantle, it seems natural that Rick has extended his influence into the realm of extra-solar planets. Although it will be some time before the observations will exist to test these models in the way that he would find satisfying, O’Connell’s characteristic style of modeling sets a high and much appreciated standard in this community.

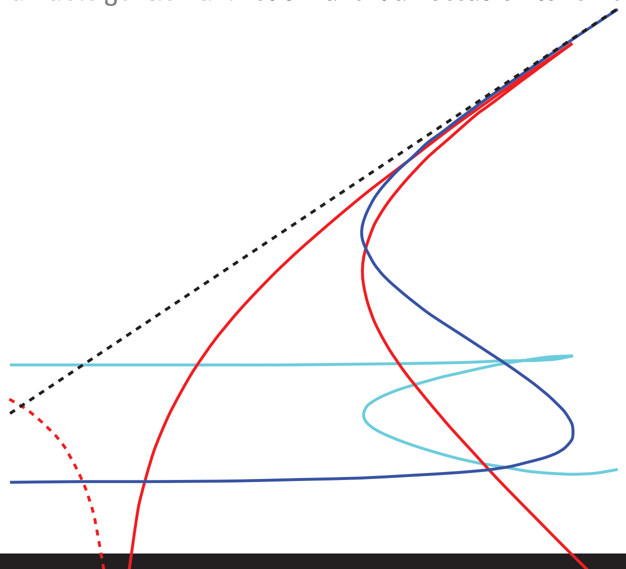
Rick is notable in the extent to which he has involved students in work at the cutting edge. His style is to hand his students world-class problems to work on and to refrain from micro-managing them as they struggle to meet the challenges he poses. This approach has resulted in his attracting an unusually strong creative cohort of students who have gone on to achieve scientific leadership. Among his more than 15 students, more than 40 students of students, and an uncountable number of students of students of students, you will find deans, winners of many medals, and fellows of leading organizations.

Rick should be proud of his myriad contributions to building the scientific community. Here I will single out his contributions to the use by academics of precise Global Positioning System (GPS) that have revolutionized our understanding of continental deformation and the physics of earthquakes. O’Connell played a pivotal role in starting the UNAVCO University GPS consortium and was a key participant in Mike Mayhew’s NSF panels that funded the early measurements, jump starting the field of tectonic geodesy.

In addition to providing outstanding scientific advice to his students, O’Connell showed by example how important it is to get out of one’s lab and see the world. Rick is legendary for the number of contributions he has made to conferences in exotic locations. He has made good use of his sabbaticals, enjoying what Paris, the other Cambridge, Berkeley, and Caltech have to offer. He has also worked as a field assistant in Kenya, South America, and the American West. Not to mention working as a deck hand on an elegant sailing vessel.

In closing, I must mention what we all know but is easy to take for granted – what a strong but gentle man Rick is. Along with his successes, Rick has had his share of challenges, both professional and personal. His positive outlook and great humor in facing these inspires awe and sets an example that is hard to match.

My life was changed the day that I met Richard J. O’Connell. He has shaped me and my scientific career profoundly. I’m sure that the same could be said by most of you. This Symposium provides an opportunity to celebrate the impact of a truly remarkable gentleman. Let’s make it an occasion to remember.



Bradford H. Hager

MIT

Friday, September 5 Museum of Natural History Galleries, 26 Oxford Street

6:00-7:30pm **Reception**

Saturday, September 6 Northwest Building (Level B), 52 Oxford Street

7:30am **Poster set-up**

8:00am **Breakfast & Registration**

8:25am **Brad Hager: Welcome & Introduction**

I. BIG BANG THEORIES - Astrophysics connections

9:00am **Jerry Wasserburg:** Reprocessing of Supernovae debris in AGB stars: A model for explanation of excesses in 54Cr, 58Fe & 64 Ni by the s process

9:30am **Sujoy Mukhopadhyay:** Probing early environments on the terrestrial planets using noble gases

10:00am **Diana Valencia:** From Earth to Super-Earths (and sub-Neptunes)

10:30am **BREAK**

II. UNITED PLATES OF AMERICA - Surface constraints for a convecting mantle

11:00am **Paul Hoffman:** The origin of Laurentia: Rae craton as the backstop for Orosirian (2.05-1.80 Ga) continental assembly by slab suction

11:30am **Robert Smith:** Geodynamics of the Yellowstone Hotspot: Two westerners views on the Yellowstone Hotspot, Bob Smith, south in Jackson Hole, WY, and Rick O'Connell north in Helena, MT

12:00pm **LUNCH AND POSTERS**

III. ACROSS THE SCALES, GLADLY - Multi-scale and multi-physics theories

1:30pm **Carl Sondergeld:** Pores, Cracks and Hydraulic Fracturing models

2:30pm **Michael Manga:** Why do volcanoes erupt in so many ways?

3:00pm **BREAK**

IV. WHEN HAL FREEZES OVER - Deep Earth and mantle dynamics

3:30pm **Bruce Buffett:** Heat transport in the deep mantle: A view from the Earth's core

4:00pm **Carolina Lithgow-Bertelloni:** Thermodynamics and dynamics: the effects of material properties of mantle mineral on dynamical observables

4:30pm **Thorsten Becker:** Oceanic boundary layers

5:00pm **Bernhard Steinberger:** The key role of global solid-Earth processes in the onset of Northern Hemisphere glaciations

5:30pm **POSTERS**

6:15pm **Reception at Loeb House** (17 Quincy Street, Cambridge, MA 02138)

7:00pm **Dinner at Loeb House**

THORSTEN BECKER | Professor of Earth Sciences, University of Southern California

My main research interests are in geodynamics and seismology with focus on the interactions between mantle convection and surface tectonics. I am fascinated by the inner workings of terrestrial planets, and how their mantle and surface systems have co-evolved over time.

We combine field, laboratory, and numerical approaches into dynamical models, focusing on the physics of plate tectonics, from grain-scale deformation to plate-scale flow. Recent research projects include work on seismic anisotropy, mantle heat transport and the mechanics of plate tectonics, subduction dynamics, and fault system mechanics.

My teaching interests include Engineering Geology, Geophysics, Mechanics of Lithospheric Deformation, Quantitative Methods in the Earth Sciences, Numerical Geodynamics, The Mantle System, and the Solid Earth Research and Teaching Environment (SEATREE). We have research opportunities for highly motivated undergrad and grad (PhD) students.

I am also Editor in Chief of Geochemistry, Geophysics, Geosystems (G3), AGU's premier interdisciplinary journal. Please contact me if you have any comments or questions regarding G3.

BRUCE BUFFETT | Chair, Earth & Planetary Science, University of California, Berkeley

Bruce Buffett was an undergraduate at the University of Toronto and received a PhD from Harvard University in 1991. He was a postdoctoral fellow in the Institute of Theoretical Geophysics at the University of Cambridge and later took a faculty position at the University of British Columbia in the Department of Geophysics and Astronomy. He moved to the Department of Geophysical Sciences at the University of Chicago in 2003 before moving to his current position in the Department of Earth and Planetary Science at the University of California, Berkeley.

JOHN W. CROWLEY | Advanced Geophysical Analyst, ESG Solutions

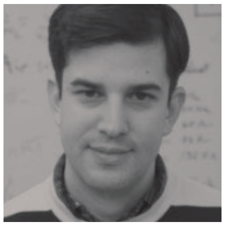
I am interested in studying and understanding global scale mantle convection and how it contributes to and is regulated by plate tectonics. I use both numerical convection simulations and analytic models to try to understand how the plate-mantle system can be characterized by its material properties, physical coupling by basal tractions and slab driving forces, and heat flow. My current analytic models approach the dynamics through the use of energy balances and simple fluid dynamics. I hope to construct a model that provides a basic framework for mantle convection with plates and that allows for various feedbacks to be easily incorporated. I am also interested in applying my models to produce hypothetical thermal and chemical evolution models for the Earth and other planets.

PAUL F. HOFFMAN | Sturgis Hooper Professor of Geology, Emeritus, Harvard University

Paul F. Hoffman is a tectonic and sedimentary field geologist in the Department of Earth and Planetary Sciences at Harvard University, Cambridge, MA (USA). Early in his career he was a pioneer in the comparison of Holocene and Proterozoic carbonates, and in the application of plate tectonics to the Proterozoic. His snowball earth related studies originated in northern Namibia, where he has worked annually since 1993. His graduate students Galen P. Halverson, Adam C. Maloof, Francis X. Macdonald and David S. Jones have conducted stratigraphic, chemostratigraphic and paleomagnetic research in Svalbard, Morocco, Arctic Alaska and northwest Canada.

CAROLINA LITHGOW-BERTELLONI | Professor of Earth Sciences, University College London

Dr. Lithgow-Bertelloni's research is geared towards understanding the connection between the dynamics of Earth's interior and their surface expression, including the influence of dynamics on surface deformation and topography. Research approaches to these questions include numerical simulations and experimental fluid dynamics.



SUJOY MUKHOPADHYAY | Associate Professor of Geochemistry, Harvard University

My research is focused on understanding the feedbacks and linkages between processes operating within the deep Earth and processes operating on the Earths surface. The inert nature of the noble gases make them unique geochemical tracers for studying a variety of processes including the accretionary history of extraterrestrial material to Earth, formation of the terrestrial atmosphere, low temperature thermochronometry, exposure age dating, geochemical evolution of the Earth's mantle, and magma degassing.

The Harvard Noble Gas Laboratory is capable of measuring all the noble gases, from He to Xe. The lab has pioneered multicollector measurements of Ne and Xe.

ROBERT B. SMITH | Emeritus Professor of Geophysics, University of Utah

Bob has conducted research on Yellowstone earthquakes and volcanoes since 1956 and is considered a leading expert on Yellowstone earthquakes, deformation and tectonics. Bob serves as the Principal Investigator and Director of the Yellowstone Seismograph and GPS Network and as the Coordinating Scientist of the Yellowstone Volcano Observatory. He provided the guidance and incentive of instrumenting Yellowstone with modern seismic and GPS instruments beginning in 1987 and planning and permitting the Yellowstone seismic and PBO magmatic GPS network.

A fellow of the American Geophysical Union and Geological Society of America, Smith has served on the board of the Seismological Society of America as well as on several federal advisory committees. Smith has supervised 67 graduate students, published more than 170 scientific articles and made hundreds of presentations at scientific meetings. He is senior author with Lee J. Siegel of the popular science book "Windows into the Earth: The Geologic Story of Yellowstone and Grand Teton National Parks," published by Oxford University Press. Bob served as a consultant and was featured in the BBC production "Supervolcano." He's been featured in several Yellowstone documentaries including the 2012 Nova documentary, "World's Deadliest Volcanoes."

CARL H. SONDERGELD | Professor and the Curtis Mewbourne Chair, the Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma

Carl Sondergeld earned a Ph.D. in Geophysics from Cornell University and a B.A. and M.A. in Geology from Queens College, CUNY. He spent 19 years at the Tulsa Research Center of Amoco Production Company where he conducted research in petro- and rock physics He holds 14 US patents. He has been at the University of Oklahoma for 15 years; teaching petrophysics, geological well logging, petrophysics of unconventional resources, and seismic reservoir modeling. He is a two-time winner of the Brandon Griffin award and five time winner of SPE student chapter award of professor of the year. He currently conducts research on unconventional reservoir rocks, in particular shales, and in the areas of microstructural characterization, anisotropy, NMR, petrophysics, hydraulic fracturing and seismic reservoir modeling. He served as the SEG Distinguished Lecture for the Fall 2010. He and Dr. Chandra Rai manage two industrial consortia: "Experimental Rock Physics" and "The Unconventional Shale Consortium."

BERNHARD STEINBERGER | Researcher, GFZ German Research Centre for Geosciences

Bernhard Steinberger carried out his undergraduate studies mainly at Munich University, but spent one year at the University of Edinburgh. After writing his diploma thesis, Bernhard obtained the Diploma in geophysics in 1990. Subsequently, he went on to graduate studies at Harvard University, where he obtained a MS degree in Applied Mathematics in 1994, and a PhD degree in Geophysics in 1996. His PhD thesis was concerned with large-scale flow in the Earth's mantle, and how it causes motion of hotspots and true polar wander (TPW). These topics have remained the focus of his interest ever since. After completing his PhD study, Bernhard worked as a post-doctoral researcher at Academia Sinica (Taipei, Taiwan; 1996-1997) and Frankfurt University (Germany; 1997-2001), as visiting researcher at University of Colorado at Boulder (USA; 2001-2002) and Bayerisches Geoinstitut (Bayreuth, Germany; 2002 and 2004), and as a researcher at IFREE, JAMSTEC (Yokosuka, Japan; 2004-2004) and the Geological Survey of Norway (Trondheim, Norway; 2004-2009). Since 2009 Bernhard is a researcher at GeoForschungsZentrum Potsdam (Germany) and Professor II at the University of Oslo (Norway). Through various collaborations he aims to compare his numerical models predictions to observations. These include ages and paleolatitudes along hotspot tracks, which can be compared to model predictions of hotspot motion. Towards that goal, Steinberger also participated in the IODP cruise to the Emperor Chain. He uses models of hotspot motion and true polar wander to devise global absolute reference frames for plate motions.

DIANA VALENCIA | Assistant Professor of Physics, University of Toronto, Scarborough

Diana's current research involves the structure, composition and interior dynamics of super-Earth and sub-Neptune exoplanets. She completed her PhD degree as an Origins of Life graduate fellow at the department of Earth and Planetary Sciences at Harvard University. Diana held the Poincare Postdoctoral Fellowship at the Observatoire de la Côte d'Azur before moving to the Massachusetts Institute of Technology to hold the NASA Sagan Postdoctoral Fellowship.

GERALD J. WASSERBURG | Gerald J. Wasserburg, John D. MacArthur Professor of Geology and Geophysics, Emeritus, California Institute of Technology

Wasserburg is known for his work in the fields of isotope geochemistry, cosmochemistry, meteoritics and astrophysics. He has visited Harvard on occasion. After dropping out of high school as a JD, he enlisted underage in the US Army, where he received the Combat Infantryman's Badge. After WWII, he went back to high school and graduated. He then attended college on the G.I. Bill. Wasserburg got a BSc. in Physics & then went on to complete his Ph.D. from the U. of Chicago in 1954 under the sponsorship of Prof. H. C. Urey (Dept. of Chemistry) and Prof M. G. Inghram (Dept. of Physics). His thesis was on the development of 40K-40Ar dating of meteorites, igneous rocks & sedimentary rocks. He joined the faculty at Caltech in 1955 as Assistant Professor & became Professor of Geology and Geophysics in 1962. In 1982 he became the John D. MacArthur Professor; he retired in 2001. Wasserburg was deeply involved in the Apollo Program with the returned Lunar samples & became an advisor to NASA for 20 years. He pioneered the precise measurement of ultra-small samples under strict clean room conditions with minimal contamination. He was the co-inventor of the Lunatic Spectrometer (the first fully digital, mass spectrometer with computer controlled magnetic field scanning & rapid switching) and founder of the "Lunatic Asylum" research laboratory specializing in high precision, high sensitivity isotopic analyses of meteorites, lunar and terrestrial samples. He and his co-workers were major contributors to establishing a chronology for the Moon & its bombardment history. He, Typhoon Lee and D.A. Papanastassiou discovered the presence of short-lived radioactive 26Al in the early solar system and short-lived 107Pd with William R. Kelly. They also found a host of isotopic anomalies in CAI inclusions in meteorites. This research led to keeping a a large number of people very busy & hopefully has led to a better understanding of the origins and history of the solar system and its component bodies and the precursor stellar sources contributing to the solar system; it established a time scale for the development of the early solar system, including the processes of nucleosynthesis and the formation and evolution of the planets, the Moon and the meteorites. More recently he is investigating models of stellar evolution & the chemical evolution of the Galaxy.

OCEANIC BOUNDARY LAYERS

Thorsten W Becker | University of Southern California, Los Angeles

The thermo-chemical structure and dynamics of oceanic boundary layers controls plate tectonic heat loss and so plays a key role in Earth's solid earth system and its co-evolution with the exosphere. Rick and his students and collaborators have made a number of fundamental contributions in this field and I highlight some of our recent efforts along those lines. I do that not because they are as fundamental, but because I think they can serve to exemplify two aspects of Rick's philosophical approach to science: trying to combine geodynamic modeling with integration of data, and drawing on multi-disciplinary constraints. My example is from ongoing work on combining mineral physics, seismology, and geodynamics to interpret seismic anisotropy in terms of the dynamics of oceanic lithosphere and mantle. The azimuthal flavor of seismic anisotropy can be used to infer oceanic plate rheology and anisotropy formation mechanisms. I also highlight some recent, joint tomographic imaging efforts that speak to the state of the sub-oceanic plate asthenosphere which turns out to be significantly different for the Atlantic and the Pacific. The same tomographic models also show radially anisotropic structure underneath the plates that seems at odds with findings from azimuthal anisotropy imaging, and I discuss some of the outstanding questions as to what this may mean. This line of work also highlights another aspect of Rick's science philosophy, that of supporting sustained, collegial collaboration. Related joint work with Rick perhaps starts with Brad Hager, was expanded by Bernhard Steinberger and Carolina Lithgow-Bertelloni, and then later refined by Jamie Kellogg and Claudio Faccenna, in collaboration with Lapo Boschi, Bogdan Kustowksi, and Goran Ekstrom, just to name a few colleagues, many of whom I continue to work with to this day. Both Rick's scientific contributions and efforts to facilitate open exchange and collaboration within his group and within the community at large layed the foundations for decades of productive research, and will no doubt continue to inspire us all in the years to come.

HEAT TRANSPORT IN THE DEEP MANTLE: A VIEW FROM THE EARTH'S CORE

Bruce Buffett | University of California, Berkeley

A group of distinguished scientists descended on Villa Monastero, Italy, in 1979, to participate in a summer school program on the Physics of Earth's Interior. A remarkable series of papers were published the following year, including an influential assessment of the thermal state of the Earth by Rick O'Connell and coauthor, Brad Hager. They combined theoretical insights and simple models to quantify important physical processes and identify key questions for future research. One of their questions concerned the temperature dependence of mantle viscosity and its role on the thermal evolution of the Earth. Cooling is expected to have a large influence on the vigor of mantle convection, primarily through the strong (exponential) dependence of viscosity on temperature. Extrapolating back in time leads to a thermal runaway when the present rate of cooling is too large.

One solution is to increase the abundance of heat-producing elements, which reduces the rate of cooling for the present-day heat flow. In effect, a small change in temperature moderates larger changes in viscosity. On the other hand, there is little geochemical evidence to support an increased inventory of heat-producing elements. Alternative solutions may come from the liquid iron core. Recent estimates of thermal conductivity in liquid iron suggest that a substantial amount of heat is conducted through the liquid core when this region is mixed by convection. Some of this heat accumulates at the top of the core when the heat flow through the mantle is unable to keep pace. We expect a layer of warm, stably stratified fluid to develop at the top of the core, permitting waves with periods of several decades. Evidence for these waves can be sought as fluctuations in the Earth's magnetic field. Observations of fluctuations in the dipole field support the presence of long-period waves and constrain the mantle heat flow to roughly 13 TW. This value is large enough to avoid a thermal runaway, given plausible estimates of heat-producing elements, but it also raises new questions about the initial temperature of the core and how these high temperatures are maintained during the earliest stages of Earth evolution. The framework outlined by Rick and Brad will ultimately guide the answers to these questions.

SIMPLE MODELS FOR PLATE TECTONICS AND THEIR IMPLICATIONS FOR PLANETARY EVOLUTION

John W. Crowley | Advanced Analytics Group, Engineering Seismology Group, Kingston, Canada

Both numerical and analytic models of coupled mantle convection and planetary tectonics are used to show that the dominant plate driving force depends not only on the material properties of the mantle and lithosphere, but also on the velocity of the plate. Multiple solutions are possible for the same planetary energy content with three solution branches for the plate velocity representing three distinct modes of thermal convection. This means that different groups can find different solutions, all potentially viable and stable, using identical models and identical system parameter values.

Simulations with strong plates demonstrate transitions between distinct modes of thermal convection. As such, these results have important implications for unraveling the early thermal evolution of the Earth, where a warmer mantle would have likely permitted the existence of multiple stable tectonic modes.

The models demonstrate that a planets specific geologic and climatic history may play a more pivotal role in determining its tectonic state than previously thought. This implies that models of tectonics and mantle convection may not be able to uniquely determine the tectonic mode of a terrestrial planet without the addition of historical data and emphasizes the potential importance of the initial condition in determining a planets evolutionary path.

THE ORIGIN OF LAURENTIA: RAE CRATON AS THE BACKSTOP FOR OROSIRIAN (2.05-1.80 GA) CONTINENTAL ASSEMBLY BY SLAB SUCTION

Paul F. Hoffman | Harvard University

The core of Laurentia is an aggregate of six Archean cratons welded together by Orosirian collision zones. Subduction polarities and the collisional age sequence are used to infer the gross dynamics of tectonic aggregation. If "slab pull" (rollback) was dominant, aggregation would have originated around the Superior craton, which was the subducting plate relative to neighboring cratons. If "slab suction" (Faccenna et al., 2013) was dominant, aggregation would have originated around the Rae craton, which was the overriding plate relative to neighboring cratons. All other cratons had mixed subduction polarities. U-Pb zircon geochronology shows that the oldest collisions (1.97 and 1.92 Ga) bound the Rae craton, and collisions become progressively younger with distance from its center. The Superior craton is bounded by the youngest collision zones (1.85-1.82 Ga) and there is no systematic age progression with distance from its center. An active role for slab-induced mantle flow (slab suction) during the aggregation of proto-Laurentia is inferred. It remains to be determined if the Rae craton was also the origin of the coeval supercontinent Nuna.

THE ROLE OF MATERIAL PROPERTIES AND SELF-CONSISTENT THERMODYNAMICS IN UNDERSTANDING MANTLE STRUCTURE, DYNAMICS AND SURFACE OBSERVATIONS.

Carolina Lithgow-Bertelloni | University College London

The interpretation of the 3-D seismic structure of the Earth revealed by seismic tomography and its use in mantle dynamics requires an understanding of the causes of lateral and depth variations in velocities and therefore of material properties. Density, elastic moduli and anelasticity depend on composition in its broadest sense, temperature, pressure and crystallographic phase transitions. Over the top 800 km of Earth's mantle, phase changes are ubiquitous and in many cases continuous, the static and transport properties of minerals differ substantially from each other, and the latent heat of reaction can hinder or enhance convection. At any given depth phase assemblages depend on temperature so that the stable minerals in a plume differ greatly from those in a slab even at constant composition. The effects on dynamics can be profound. In 2D convection there is a marked asymmetry in the convective pattern with very narrow downwellings and broad upwellings, even in the absence of internal heating. The asymmetry is clear in the average temperature profiles.

The importance of phase transitions is also evident in the velocity to density conversion as a function of depth for a constant bulk composition along any given adiabat. A background decrease reflects the changes in thermal expansivity with pressure, but it's punctuated by large positive and negative jumps at all the phase transitions, all of which depend on temperature. These effects can lead to a factor of two difference in the dynamic topography above upwellings as compared to downwellings.

WHY DO VOLCANOES ERUPT IN SO MANY WAYS?

Michael Manga (Berkeley, former student), Helge Gonnermann (Rice; former postdoc)

Volcanoes can erupt in a range of styles. In the broadest sense, eruptions are effusive, to make lava domes and flows, or explosive. The diversity of eruption styles reflects the interplay between the forces causing the ascent of magma and its evolving rheology.

In a seminal set of papers O'Connell and Budiansky showed how bulk, macroscopic properties can be determined from physics at the microscale. We adopt a similar approach for determining the rheology of magma, in particular the effect of bubbles on bulk rheological properties. These properties affect the ascent of magma, which in turn controls the properties of bubbles.

There are 3 key processes that occur during ascent and eruption of magma: the nucleation and growth of bubbles; the loss of gas from the ascending magma; the fragmentation of magma. All three processes are controlled by the evolving microstructure. We thus integrate a model for large-scale dynamics with a model for the evolution of microstructure to identify the controls on eruption style. In particular we identify a set of dimensionless numbers that characterize microstructure properties and evolution that can be mapped into the eruption style.

We show that viscous magmas, such as rhyolite or crystal-rich magmas, do not allow bubbles to ascend buoyantly and may also hinder bubble growth. This can lead to significant gas overpressure inside bubbles and brittle magma fragmentation. During fragmentation in vulcanian, subplinian and plinian eruptions gas is released explosively into the atmosphere, carrying with it magma fragments. Alternatively, high viscosity may slow ascent to allow gas to be lost from the ascending magma, leading to lava effusion to produce domes and flows. In low viscosity magmas, typically basalts, bubbles may ascend buoyantly, allowing efficient magma outgassing and relatively quiescent magma effusion. Alternatively, bubbles may coalesce and accumulate to form meter-size gas slugs that rupture at the surface during strombolian eruptions. At fast magma ascent rates, even in low viscosity magmas, melt and exsolved gas remain coupled allowing for fast acceleration and hydrodynamic fragmentation in hawaiian eruptions.

PROBING EARLY ENVIRONMENTS ON THE TERRESTRIAL PLANETS USING NOBLE GASES

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Using new noble gas data and giant impact calculations, we present a synthesis of the effects of impact events during Earth's accretion on the composition of the early atmosphere and the differences in the early atmospheric compositions of Earth, Mars and Venus.

While noble gas data from the deep mantle record a signature of nebular $^{3}He/^{22}Ne$, the $^{3}He/^{22}Ne$ ratio in the depleted mantle is at least a factor of 6.5 higher. The high $^{3}He/^{22}Ne$ of the depleted mantle requires at least 2 atmospheric loss and partial mantle magma ocean events after the nebula disperses, the last of which was associated with the Moon-forming impact. A partial mantle magma ocean could be the result of perovskite's high liquidus temperature and low entropy gain during shock compression, which inhibits full mantle melting during giant impacts. We propose that the viscosity contrast between a fully-melted upper mantle and partially-melted/solid lower mantle inhibits complete mixing after a giant impact and preserves a nebular signature trapped in the lower mantle. Furthermore, the occurrence of at least two atmospheric loss events is consistent with a new giant impact model for the Moon that posits an impact onto a fast-spinning Earth to generate a lunar disk with bulk silicate Earth composition. A giant impact prior to the Moon-forming event would be required to spin up the Earth to near its stability limit. We find that planets with high spin rates more easily lose their atmospheres via ground motion induced by the shock wave from a giant impact. As a result, the volatiles on a fast-spinning Earth would have been susceptible to loss via atmospheric blow-off during the Moon-forming giant impact. Atmospheric loss episodes, particularly if a water ocean were present, also provide an explanation for other curious features of the terrestrial volatile budget such as the larger depletion of N compared to C relative to their chondritic abundances.

Our new measurements indicate that noble gases in the Earth's atmosphere cannot be derived from any combination of fractionation of a nebular-derived atmosphere followed by outgassing of deep or shallow mantle volatiles. While Ne in the mantle retains a nebular component, the atmospheric noble gases have a close affinity to chondrites. On the other hand, Venus's atmosphere has a $^{20}Ne/^{22}Ne$ ratio closer to the solar value than Earth's atmosphere and ^{20}Ne and ^{36}Ar abundances that are 20 and 70 times higher, respectively. While the present atmosphere of Mars is significantly fractionated in the lighter noble gases due to long term atmospheric escape, the Kr isotopic ratios in martian atmosphere are identical to solar. Thus, while Earth's atmosphere has no memory of accretion of nebular gases, atmospheres on both Venus and Mars preserve at least a component of nebular gases.

To explain the above observations, we propose that a common set of processes operated on the terrestrial planets, and that their subsequent evolutionary divergence is simply explained by planetary size and the stochastic nature of giant impacts. Multiple episodes of magma ocean outgassing on Earth, as required by the $^{3}He/^{22}Ne$ data, led to efficient transfer of volatiles to the surface. The outgassed volatiles were largely lost during the final sequence of giant impacts onto Earth. Earth's noble gases were therefore dominantly derived from late-accreting chondritic planetesimals. In contrast, Venus did not suffer substantial atmospheric loss by a late giant impact and retains a higher abundance of both nebular and chondritic noble gases compared to Earth. Fast-accreting Mars has a noble gas signature inherited from the solar nebula, and its low mass allowed for gravitational escape of the volatile components in late accreting chondritic planetesimals due to vaporization upon impact.

GEODYNAMICS OF THE YELLOWSTONE HOTSPOT: TWO WESTERNERS VIEWS ON THE YELLOWSTONE HOTSPOT, BOB SMITH, SOUTH IN JACKSON HOLE, WY, AND RICK O'CONNELL NORTH IN HELENA, MT

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We integrate multiple seismicity, deformation, and volcano/tectonic history datasets to formulate new geodynamic models of the Yellowstone hotspot. The Yellowstone volcanic system resulted from interaction of a mantle plume with the overriding N. America plate producing a ~600-km wide ~300-m high topographic swell centered on Yellowstone National Park and the center of the Quaternary Yellowstone volcanic field. Plume-plate interaction has produced the 800 km long, 17 Ma Yellowstone-Snake River Plain-Newberry (YSRPN) volcanic field with Yellowstone as the active element at the NE end of the bimodal rhyolite-basalt progression. Large-scale geophysical experiments of the YSRP provided seismic and GPS images of the hotspot and its kinematic and dynamic properties. Seismic tomography reveals a shallow crustal low velocity body that is imaged "to be 90 km long, and 2.5 times times larger" than last imaged in 2000 and extends NE-SW ~17 km beyond the Yellowstone caldera, i.e. the image of the Yellowstone crustal magma reservoir. It notably shallows from ~15 km beneath the caldera to near-surface km, ~17 km north of the caldera, the same distance that the plate has overridden the mantle plume since the last super eruption at 640,000 yrs. This suggests that the SW plate motion overrides the upper magma plume providing basaltic magma fueling the Yellowstone crustal volcanism. The newly teleseismically and MT imaged Yellowstone mantle plume reveals a low velocity body that is made up made up of melt blobs, 80 km wide with an upper mantle annulus of highly conductive material an additional 70 wide making the plume up to 150 km wide. The newest tomography reveals that the plume extends to depths of ~1000+ km, tilting 60º NW. Contemporary deformation of Yellowstone measured by GPS is dominated by SW-crustal extension at up to ~0.3 cm/yr, a fourth of the total Basin-Range opening rate, but with superimposed volcanic uplift and subsidence at decadal rates, averaging ~2 cm/yr and as high as 7 cm/yr. An unprecedented episode of caldera uplift, up to 7 cm/yr totaling ~25 cm from 2004-2010, was modeled as recharge of the crustal magma body at 10-km depth. The recent M4.8 April 2014 Norris area earthquake, the largest in 30 years in Yellowstone, occurred following a sudden increase in deformation of 7 cm at the NW edge of the caldera that was followed rapidly by a return to caldera-wide uplift. Mantle convection models are characterized by eastward upper-mantle flow beneath Yellowstone at 5 cm/yr and opposite in direction of the overriding plate motion. This suggests that the strong eastward flow deflects the ascending melt into a tilted configuration, i.e. "like the smoke caught in the mantle wind". Dynamic modeling however reveals relatively low excess plume temperatures, up to 120°K, consistent with a weak buoyancy flux of ~0.25 Mg/s but strong enough to produce the notable topographic swell. Integrative kinematic and dynamic modeling of GPS, fault slip, and seismic data reveal excess gravitational potential of the Yellowstone swell that drives the SW motion of the YSRP lithosphere "downhill" as part of a pattern of clockwise rotation of western U.S. intraplate block motions. High lithospheric temperatures reduce the average effective lithospheric viscosity of the YSRP increasing magmatic reworking of the lithosphere and thermal subsidence that reduces the gravitational potential of the Snake River Plain and reducing stresses along the hotspot track. We extrapolate the location of the Yellowstone mantle-source southwestward 800 km to an initial position at 17 million years ago beneath eastern Oregon and the southern Columbia Plateau basalt field "Large Igneous Province", suggesting a common origin for the YSRP and LIP volcanism. We thus propose that the original plume head ascended vertically behind the subducting Juan de Fuca plate, but at ~12 Ma was entrained in faster mantle flow beneath continental lithosphere and tilted SE into its present configuration. In this model, Yellowstone plume-plate processes have "continentalized" oceanic lithosphere, enhanced intraplate extension, and modified the topography of over much of the northwest U.S. interior.

PORE, CRACKS AND HYDRAULIC FRACTURING

Carl H. Sondergeld | University of Oklahoma

Rick's seminal contributions to modeling the influence of cracks and pores on the elastic and viscoelastic properties of rock will be very briefly reviewed. He, like Gus Archie, made the qualitative descriptions quantitative. He, along with Budiansky, overcame the dilute concentration limit with the embodiment of the Self-Consistent approach. Through considerations of pore shape, strain and stress, the pore structure can be conceptually modeled simply as dichotomy of cracks and pores which enter the equations as crack density and porosity. Moreover, his work allowed for implicit interactions between these two void populations which captured the dissipative behavior of rock-fluid systems. Extension of these concepts to allow distributions of cracks provided a powerful modeling basis to interpret lab measurements as well as seismic field data. If we move forward some 40 years, these concepts and models still provide a basis to understand and interpret unconventional shale reservoirs. As will be shown, the dichotomy of pores and cracks is still evident in shale, only at a much more challenging scale. Furthermore, the economic success in a shale resource play is critically dependent on the stimulated "crack density" or as it is called in the industry the "Stimulated Reservoir Volume" (SRV). To quantitatively evaluate SRV we are carrying out controlled hydraulic fractures under triaxial stress conditions and using the SEM to quantify the resultant "crack densities". With sufficient calibration and scaling, we plan to use the O'Connell and Budiansky viscoelastic models to assess SRV remotely.

THE KEY ROLE OF GLOBAL SOLID-EARTH PROCESSES IN THE ONSET OF NORTHERN HEMISPHERE GLACIATIONS

Bernhard Steinberger | University of Oslo

Major Northern Hemisphere glaciations occurred only during the Plio-Pleistocene, after >500 Myr absence, with Greenland leading the other northern areas. It is unknown why these extreme global climatic transitions were initiated there, and why at this time and not much earlier. Here we propose that three major solid-Earth processes underpinned the build-up of the Greenland ice-sheet. These processes were active since at least ~60 Ma and we suggest they collectively led to conditions of sufficiently high topography and northern latitude of Greenland for glaciations to initiate. First, a strong mantle-plume pulse, causing the North Atlantic Igneous Province at ~60 Ma, regionally thinned the lithosphere, while much younger pulses led to uplift that accelerated at around 5 Ma. Our numerical mantle flow models also suggest recent uplift caused by Iceland plume material flowing northward. Second, a ~700 km northward movement of Greenland (continental drift) relative to the mantle since ~60 Ma is featured in recent plate tectonic reconstructions. Third, a concurrent northward rotation of the entire mantle and crust toward the pole, dubbed True Polar Wander (TPW), contributed an additional 12o (~1300 km) change in latitude. Our study emphasizes the role of mantle plumes, plate tectonic motions, and in particular TPW for driving long-term global climatic transitions.

JUMPING FROM EARTH TO SUPER-EARTHS (AND SUB-NEPTUNE PLANETS)

Diana Valencia | University of Toronto, Scarborough

With more than a few dozen of low-mass exoplanets with known masses and radii, it is now possible to start identifying properties of this population. So far, most of these planets have a gaseous envelope despite their small masses. There is also a second group of high-density low-mass exoplanets that are believed to be rocky. While some of these super-Earths seem to have a composition consistent with that of Earth, many have a different Fe/Si ratio. These different characteristics tell a story about their possible origin and conditions for habitability. Focusing on the planets that are solid, it is worth investigating their internal dynamics to answer if these planets can outgas an atmosphere that lends itself to sustaining a temperate surface temperature

METEORITIC ISOTOPE ANOMALIES IN THE FE-GROUP ELEMENTS AND CONNECTIONS TO NUCLEOSYNTHESIS IN AGB STARS

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We investigated the effects of slow neutron captures in AGB stars on isotopes of the ''iron group'' group elements Ti, Cr, Fe, Ni and Zn. The ''iron group'' nuclei are predominantly the product of supernovae (SNe) & most interpretations of the observed "isotopic anomalies" of these elements, as found in meteorites, attributes them to SNe. However, the bulk of material in the interstellar medium (ISM) has been processed in AGB stars. Thus, it is reasonable to assume that the Fe group nuclei (originally produced in SNe) that are processed in AGB stars would exhibit the isotopic shifts associated with the slow neutron capture process that takes place in AGBs. We have calculated the compositions of stellar envelopes for a variety of stellar masses & metalicities. The results show that 54Cr, 58Fe & 64Ni are indeed produced in all cases and with patterns that appear to be very similar to those observed in Calcium-Aluminum rich inclusions in meteorites. Further, the degree of enrichment of these isotopes in AGB envelopes is ~30-100% near the end stages of their evolution when they lose most of their envelopes & then become White Dwarfs. It follows that a plausible, self consistent model may be AGB reprocessing of SNe debris and not direct SNe contributions. It is also now evident that a high degree of enrichment of some isotopes is not at all a requirement for SNe sources of many "special" grains, but such grains are just AGB ejecta. The relationships of the above model to reprocessing of Ti & Si isotopes (originally SNeII products) is clarified. Ca is also a SNeII product, but the isotope pattern remains a deep mystery. It is the intrinsic heterogeneity of the ISM that makes simple theoretical models fail. Stars are formed from sources of different, not quite Solar isotopic abundances

SEA LEVEL CHANGE SINCE THE PLIOCENE: CONNECTING MANTLE CONVECTION TO PALEOCLIMATE

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The mid-Pliocene warm period (~3.3 to 2.9 Ma; MPWP) is the time period preceding the onset of extensive northern hemisphere glaciation. It was the last time in Earth's history that atmospheric CO2 levels were as high as today and temperatures were elevated by ~3ºC relative to preindustrial values. This period is therefore an important testing ground for studies of climate sensitivity and polar ice volume changes in a slightly warmer world. The database of paleo shoreline elevations dating to the mid-Pliocene is steadily increasing, however the inference of global mean sea level (GMSL) change (or, equivalently, changes in ice volume) based upon them is complicated by their post-depositional deformation. Indeed, estimates of GMSL during the MPWP range from 0-40 m above present day. Thus, refining estimates of ice volume during this time requires a correction for these contaminating processes, including glacial isostatic adjustment (GIA) and mantle flow induced dynamic topography (DT). Several groups have modeled changes in GIA (Raymo et al., 2011) and dynamic topography (Moucha et al., 2008; Müller et al., 2008; Spasojević et al., 2008; Rowley et al., 2013) since the mid-Pliocene. Using a combination of GIA and DT modeling, Rowley et al. (2013) reconciled the long wavelength variation in elevation along the extensive mid-Pliocene shoreline along the US East coast (the Orangeburg Scarp and it is correlatives); however, smaller scale features in the shoreline, as well as MPWP observations in South Africa and Australia have not been simultaneously fit using a combination of GIA and DT together with a single value of GMSL change. With this aim in mind, we have implemented a dynamic topography post-processor in the mantle convection code Aspect and have successfully run several 2-D benchmark comparisons. We are currently performing global calculations of dynamic topography that we are benchmarking with published results and once this is complete we will explore a much wider parameter space than has been considered to date.

In previous work, numerical predictions of dynamic topography based on mantle flow models have generally been compared to the elevation of GIA-corrected paleo-shorelines. This approach neglects deformation of the Earth in response to changes in the ocean load driven by DT. Furthermore, it does not account for mantle flow induced perturbations in the gravitational field, which alters the equipotential surface representing the upper bounding surface of sea level. We have derived a new, generalized and gravitationally self-consistent formalism for computing sea-level changes that incorporate the effect of mantle convection, including DT and geoid perturbations, and GIA. The formalism is based on an extension of sea-level theory developed within the GIA community and it accounts for viscoelastic deformation of the solid Earth, associated perturbations in the gravity field, migration of shorelines and the feedback into sea level of contemporaneous (load-induced) changes in Earth rotation. We demonstrate that the results differ significantly from calculations that adopt DT predictions as a proxy for sea level changes.

RESULTS PUBLISHED AT THE END OF THE PREVIOUS MILLENNIUM SHOWED THAT PLUMES THAT MAKE HOTSPOTS HAVE RISEN ONLY FROM SHARPLY DEFINED PLUME GENERATION ZONES (PGZS) ON THE CORE MANTLE BOUNDARY (CMB)

Kevin Burke | University of Houston

Rick O'Connell's example has shown that (i) Thinking about a variety of very different topics can be rewarding and (ii) That the convecting mantle is a particularly interesting object. My poster illustrates those considerations by showing a close match between: (i) A map of the Earth's present uppermost solid surface showing hotspots from Bernhard Steinberger (2000). (ii) A map of the very different CMB surface (Kuo et al. 2000) showing the footprints of the 2 Large Low Shear Wave Velocity Province (LLSVP) bodies (TUZO and JASON) and 8 smaller LSVPs. Kuo et al. mapped the footprints on the CMB of a total of 10 bodies.

Dropping perpendiculars from Bernhard's hotspots to the CMB shows that all the 44 hotspots that he identified when projected vertically downward to the CMB lie close to the edges of 8 of Kuo's 10 bodies in Plume Generation Zones (PGZs). The other 2 LSVPs cannot be mapped in that way because there are no active hotspots above their footprints, although they can be mapped in other ways (e.g. Lekic et al. 2012). The loci of the downward projected hotspots define PGZs at the edges of 8 bodies on the CMB at the shear wave velocity contour of Kuo et al. (2000) that is ~ 0.25% slower than average mantle shear wave velocity. Matt Cannon and I

(2014) have added about 30 more hotspots to Bernhard 's 44 hotspots in the surface map shown here. Those additional hotspots also project down in the 8 PGZs very close to the "0.25% slow contour". At depths below ~ 1000 km plumes from the CMB rise vertically but three recent seismological studies indicate a correlation between inclined top ~ 1000km depths of plumes and the velocity of the overlying plate wrt the footprints of TUZO and JASON. The Hawaiian plume under the fast moving Pacific plate is tilted at ~ 20 degrees from the vertical, attributable to interaction with the overlying plate that results in a ~ 4o displacement of the top of the plume from its location at ~ 1000 km depth (Wolfe et al.2011). The Yellowstone plume under the slower moving N. American plate is inclined at ~ 100 from the vertical (Schmandt et al.2012) and the Afar plume under the African plate that is stationary wrt TUZO and JASON is not inclined but rises vertically all the way to the base of the lithosphere (Burke and Wilson 1972, Rohde et al. 2012, Montelli et al.2006). It appears likely that with better information on the structure of plumes in the upper mantle maps of the structure of plumes from the CMB to the surface can be made.

A question that I ask myself, now that I have come to appreciate the significance taken together, of the results published by Bernard Steinberger and by Kuo et al. in 2000 is: Why did none of us put these two results together nearly 15 years ago? I fear that we were not thinking broadly enough.

TESTING LINKS BETWEEN MANTLE PLUMES AND TRUE POLAR WANDER

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True polar wander (TPW) is the motion of the crust and mantle relative to the spin axis due to changes in the Earth's moment of inertia. Paleomagnetic studies assume that plate tectonic speeds have been relatively constant through time, and thus observations of large, rapid movements in paleomagnetic poles have been attributed to true polar wander. A large TPW event would result in a dramatic repositioning of the continents relative to the equatorial oceanic bulge and the ecliptic, causing changes in relative sea level, potentially altering the Earth's global oceanic circulation patterns and biogeochemical cycles. Mantle density anomalies such as plumes, which are linked to large igneous provinces, can affect Earth's moment of inertia and cause TPW. It has been suggested that the mantle plume associated with the ca. 615-535 Ma Central Iapetus Magmatic event and rifting of Laurentia's eastern margin has been proposed as a possible trigger for TPW (Kirschvink et al., AGU, 2005). Here we combine plume advection and rotational dynamics models to investigate the hypothesis that Neoproterozoic TPW events were initiated by mantle plumes. For each plume event, we estimate plume radius and current location of the plume center from published geologic observations. The location of plume center is rotated using paleomagnetic data to obtain the paleolatitude of the plume at the time of eruption. Plumes consistent with the estimated sizes are advected from the core mantle boundary. The spherical flow fields are calculated using the propagator matrix method and advection is done via a flux-corrected transport algorithm. Using the output from the advection model and the estimated paleolatitude of eruption, the TPW is calculated using the quasi-fluid approximation to the nonlinear rotational dynamics equations. For each event investigated, we explore variations due to changing the viscosity contrast between the upper and lower mantle, adding a lithosphere, and changing the reference shape. The TPW generated by the model is compared to paleomagnetic data. Current results suggest that the Ediacaran TPW seen in the paleomagnetic record may be consistent with that expected from the mantle plume associated with the Central Iapetus Magmatic event.

THE INTENSITY OF EXPLOSIVE VOLCANIC ERUPTIONS – A CASE STUDY OF KILAUEA, HAWAI‘I

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Understanding of what controls eruptive intensity during sustained explosive eruptions of basaltic magma remains incomplete. In particular the question of pre-eruptive “charging” of the magma reservoir with CO_2-rich vapor and magma pressure relative to lithostatic are key, not least because gas emissions and volcano deformation are frequently monitored at active volcanoes.

We have modeled eruptive magma ascent for two explosive eruptions of Kilauea volcano, Hawai‘i. They are the Hawaiian style Kilauea Iki eruption in 1959, and the subplinian Keanakako‘i eruption dating to 1650 CE. We integrate the fluid dynamics of magma ascent within the volcanic conduit and the exsolution of H_2O and CO_2 from the erupting magma. To better assess the relative importance of conduit and magma chamber processes, we have coupled conduit flow and magma chamber through mass balance and pressure. We predict magma discharge rates, superficial gas velocities, H_2O and CO_2 concentrations of the melt, magma chamber pressure and height of the volcanic jet.

Models are in part constrained by H_2O and CO_2 measured in olivine-hosted melt inclusions and by decompression rates recorded in melt embayment diffusion profiles. We present a parametric analysis, indicating that the pressure within the chamber feeding the subplinian Keanakako‘I eruption was significantly higher than lithostatic pressure. In contrast, chamber pressure for the Hawaiian Kilauea Iki eruption was close to lithostatic. Furthermore, the volume of pre-eruptive vapor is unlikely to have contributed significantly to either eruption. In both cases the superficial gas velocity, which affects the geometrical distribution of gas-liquid mixtures during upward flow in conduits, may have exceeded values at which bubble coalescence did not affect the flow, as well as the conditions for magma fragmentation.

A NEOPROTEROZOIC CARBONATE SHELF BREAK SHAPED BY GLACIAL TOPOGRAPHY, FRANSFONTEIN RIDGE, KUNENE REGION, NAMIBIA

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We present a new fence diagram composed of 64 measured sections from a continuously outcropping homocline in northern Namibia that exposes a Neoproterozoic carbonate shelf break in oblique cross-section. The Otavi Group is a 2-2.4-km-thick carbonate platform sequence, which was deposited between 770 and 590 Ma on the southwest promontory of the Congo craton. The platform was glaciated twice during the Cryogenian (~720-635 Ma), and regionally extensive erosion surfaces beneath the respective glacial deposits divide the carbonate succession into three subgroups (S1 to S3). Subsidence of the platform occurred in two stages, the first in response to north-south crustal stretching and the second to post-rift cooling. The rift-to-drift transition occurs in the middle of S2, during the Cryogenian nonglacial interlude. After the transition, a south-facing shelf break developed, dividing a shallow-water platform in the north from a distally tapered foreslope and basin in the south. Fransfontein Ridge is a steeply-dipping homocline of the Otavi Group that obliquely transects the shelf break. We investigated the stratigraphic architecture of shelf break development with closely-spaced measured sections and high-resolution δ13Ccarb data. To our surprise, the location and development of the shelf break are not structurally controlled—no significant sedimentary growth fault intersects the transect. Instead, the dominant control on S2 stratigraphy and sedimentation was ‹1.8 km of local paleotopography on the older glacial surface, which is underlain by crystalline basement in this area. The exact location of the shelf break is dictated by ›0.5 km of relief on the younger glacial surface, which ramps across the 0.3-km-thick upper S2 carbonate platform (Ombaatjie Fm) on farm Kranspoort 475 with a cutoff angle of 8 degrees in the line of section. Preservation of ‹1.8 km of paleorelief on the older glacial surface, inferred from stratigraphic onlap relations, is consistent with a nonglacial medial Cryogenian epoch (S2) of short duration (‹20 Myr), consistent with combined Re-Os and U-Pb geochronology in NW Canada (Rooney et al. 2014).

TIDAL TOMOGRAPHY: CONSTRAINING LONG-WAVELENGTH DEEP MANTLE STRUCTURE USING EARTH'S BODY TIDE SIGNAL

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Luni-solar gravitational forcing drives the Earth's body-tide response over periods ranging from 8 hours to 18.6 years, a timespan that extends far beyond the seismic band. A finite volume numerical study of body tides in the semi-diurnal (SD) band by Latychev et al. (2008; EPSL) demonstrated that aspherical density and elastic structure inferred from seismic tomography perturbed the radial crustal displacement response by ~1 mm, a level at which they can be observed with modern space-geodetic inferences of body tide signals (Yuan et al., 2012; EPSL). Thus, site-specific estimates of the body-tide response to the known luni-solar forcing potentially provides a new, independent and powerful method for probing long-wavelength, deep mantle structure. To this end, we have used advances in seismic free oscillation theory to derive a new normal mode treatment of the SD body tide response of an aspherical, rotating and anelastic Earth. The accuracy of the theory is demonstrated by benchmarking our body tide predictions against both finite volume treatments of aspherical structure and previous theoretical and observational constraints on the effects of anelasticity. We begin by summarizing these results, as well as a series of synthetic tests that indicate that the body tide response is particularly sensitive to long wavelength, deep mantle structure – a sensitivity that is ideal for investigating the elastic and density structure of the two large low shear velocity provinces (LLSVPs) that exist below the Pacific and southern Africa. We aim to explore sensitivities of the body tide signal to the relative size of thermal and chemical effects within the LLSVPs and ultimately implement a tidal tomography to gain new insight on the buoyancy state of the deep mantle.

HOW WELL DOES THE PRESENT-DAY OCEAN RIDGE SYSTEM SAMPLE THE UPPER MANTLE?

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The global ridge system is a sparse network of long, linear segments sampling a marbled mantle source that is heterogeneous from the sub-segment to the basin scale. Although the ridges migrate over the surface of the Earth on ~100 Myr timescales, geochemists focus on near zero-age basalts to characterize the chemistry of the upper mantle. Thus, our understanding of the upper mantle is restricted to what we see through the lens of the present-day ridge system. Given the size spectrum of heterogeneities evident along-ridge, it is not clear whether the average composition sampled by the present-day global ridge network should capture the bulk composition of the upper mantle. Estimates of bulk upper mantle composition based on the mean composition of mid-ocean ridge basalts may be subject to some inherent uncertainty that is independent of the uncertainties in measurement. Here we investigate possible uncertainties in bulk composition estimates due to the geometry of the present-day ocean ridge system relative to the geometry of mantle heterogeneities.

We conduct a series of numerical tests to constrain the accuracy and precision of the mean sampled ridge composition relative to the true bulk mantle composition. We explore the effects of lengthscale, shape and distribution of heterogeneities on mantle sampling. Broadly, as the lengthscale of heterogeneity increases, the standard deviation of the mean sampled ridge composition from the true mean increases. We find that sampling uncertainties of ~10 to 50% of the total mantle range may exist for a mantle heterogeneities on 1,000 km to 10,000 km lengthscales. However, the importance of the sampling uncertainty depends on its magnitude compared to the measurement errors and the natural dispersion in the ridge data relative to the total mantle range. For example, the total mantle source range in 129Xe/130Xe is from ~6.9 to ~7.8, with typical measurement uncertainties of ±0.1, corresponding to ~10% of the total mantle range. In this case, an uncertainty due to sampling of 10% of the mantle range (e.g, for 1,000 km mantle heterogeneities) would be comparable to the measurement uncertainty but small relative to the dispersion in the distribution of ridge basalt Xe isotopic data (~7.1 to 7.8, or ~80% of the total mantle range). On the other hand, mantle 87Sr/86Sr ratios vary from ~0.7020 to 0.7070 and can be measured with very high precision (usually better than ± 10 ppm or ±0.000007, corresponding to 0.1% of the total mantle range). 95% of ridge basalt Sr isotope data fall within a restricted range comprising ~15% of the total mantle range (0.7029 + 0.0008). If the mantle were heterogeneous on ~5,000 km lengthscales, a sampling uncertainty of ~30% of the total mantle range would far exceed the analytical uncertainty and would be larger than the dispersion in the ridge data. Therefore, studies that use the mean isotopic composition of erupted ridge basalts to estimate the mean composition of the upper mantle may need to incorporate uncertainties inherent to imperfect sampling of the upper mantle.

POSSIBLE TRIGGERING OF THE LARGEST DECCAN ERUPTIONS BY THE CHICXULUB IMPACT

Mark A. Richards[1], Walter Alvarez[1,5], Stephen Self[1], Leif Karlstrom[2], Paul R. Renne[1,3], Michael Manga[1], Courtney J. Sprain[1,3], Jan Smit[4,5], Loÿc Vanderkluysen[6], and Sally A. Gibson[7]
1. University of California | 2. Stanford University | 3. Berkeley Geochronology Cente | 4. Vrije Universeit, Netherlands
5. Osservatorio Geologico di Coldigioco, Italy | 6. Drexel University | 7. University of Cambridge, UK

New constraints on the timing of the Cretaceous-Paleogene (K-Pg) mass extinction and the Chicxulub impact, together with a particularly voluminous and apparently brief eruptive pulse toward the end of the "main-stage" eruptions of the Deccan continental flood basalt province, suggest that these three events may have occurred within less than about a hundred thousand years of each other. Partial melting induced by the Chicxulub event does not provide an energetically-plausible explanation for this coincidence, and both geochronologic and magnetic-polarity data show that Deccan volcanism was underway well before Chicxulub/K-Pg time. However, historical data document that eruptions from existing volcanic systems can be triggered by earthquakes. Seismic modeling of the ground motion due to the Chicxulub impact suggests that the impact could have generated seismic energy densities of order 0.1-1.0 J/m3 throughout the upper ~200 km of the Earth's mantle, sufficient to trigger volcanic eruptions worldwide based upon comparison with historical examples. Triggering may have been caused by a transient increase in the effective permeability of the existing deep magmatic system beneath the Deccan province, or mantle plume "head." It is therefore reasonable to hypothesize that the Chicxulub impact might have triggered the enormous Poladpur, Ambenali, and Mahabaleshwar (Wai sub-group) lava flows that account for >70% of the Deccan Traps main-stage eruptions. This hypothesis is consistent with independent stratigraphic, geochronologic, geochemical, and tectonic constraints, which combine to indicate that at approximately Chicxulub/K-Pg time a huge pulse of mantle plume-derived magma passed through the crust with little interaction, and erupted to form the most extensive and voluminous lava flows known on Earth. High-precision radioisotopic dating of the main-phase Deccan flood basalt formations may be able either to confirm or reject this hypothesis, which in turn might help determine whether this singular outburst within the Deccan Traps (and possibly volcanic eruptions worldwide) contributed significantly to the K-Pg extinction.

RECONSTRUCTING THE MANTLE VOLATILE CONTENT THROUGH THE VEIL OF DEGASSING

Jonathan M. Tucker[1], Sujoy Mukhopadhyay[2], Helge M. Gonnermann[3]
1. Harvard University | 2. University of California, Davis | 3. Rice University

The abundance of volatile elements in the mantle reveals critical information about the Earth's origin and evolution such as the chemical constituents that built the Earth and material exchange between the mantle and exosphere. However, due to magmatic degassing, volatile element abundances measured in basalts usually do not represent those in undegassed magmas and hence in the mantle source of the basalts. While estimates of average mantle concentrations of some volatile species can be obtained, such as from the 3He flux into the oceans, volatile element variability within the mantle remains poorly constrained. Here, we use CO_2-He-Ne-Ar-Xe measurements in basalts and a new degassing model to reconstruct the initial volatile contents of 8 MORBs from the Mid-Atlantic Ridge and Southwest Indian Ridge that span a wide geochemical range from depleted to enriched MORBs.

We first show that equilibrium degassing (e.g. Rayleigh degassing), cannot simultaneously fit the measured CO_2-He-Ne-Ar-Xe compositions in MORBs and argue that kinetic fractionation between bubbles and melt lowers the dissolved ratios of light to heavy noble gas species in the melt from that expected at equilibrium. We present a degassing model (after Gonnermann and Mukhopadhyay, 2007) that explicitly accounts for diffusive fractionation between melt and bubbles. The model computes the degassed composition based on an initial volatile composition and a diffusive timescale. To reconstruct the undegassed volatile content of a sample, we find the initial composition and degassing timescale which minimize the misfit between predicted and measured degassed compositions.

Initial ^3He contents calculated for the 8 MORB samples vary by a factor of ~7. We observe a correlation between initial ^3He and CO_2 contents, indicating relatively constant $CO_2/^3He$ ratios despite the geochemical diversity and variable gas content in the basalts. Importantly, the gas-rich popping rock from the North Atlantic, as well as the average mantle ratio computed from the ridge ^3He flux and independently estimated CO_2 content fall along the same correlation. This observation suggests that undegassed CO_2 and noble gas concentrations can be reconstructed in individual samples through measurement of noble gases and CO_2 in erupted basalts.

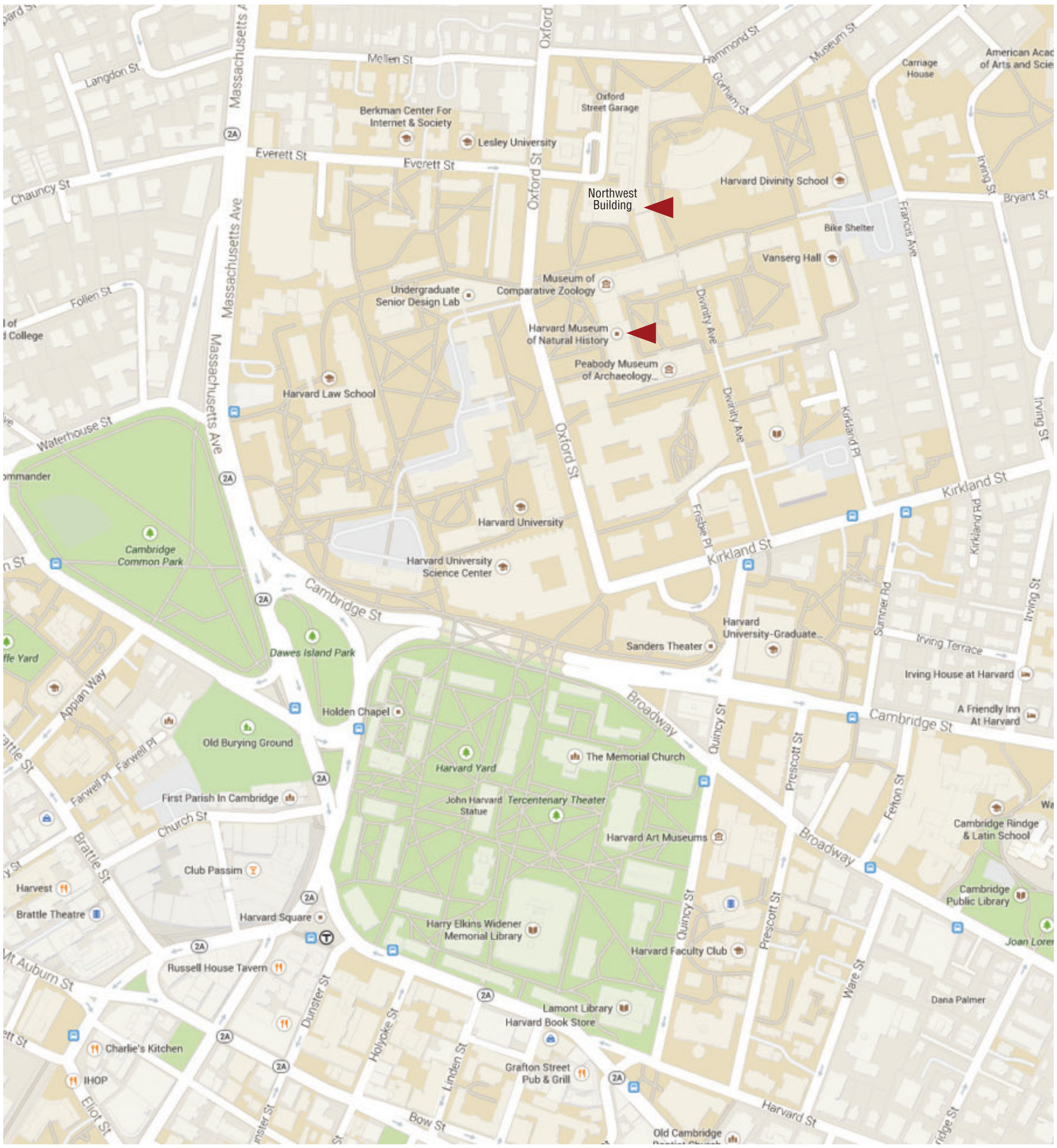
PLATINUM CONCENTRATIONS AND TUNGSTEN ISOTOPE RATIOS OF EARTH'S MANTLE AS TRACERS FOR LATE VENEER MIXING INTO THE EARLY MANTLE

Li Zeng, Stein Jacobsen, Dimitar Sasselov | Harvard University

Platinum (Pt) and tungsten (W) are both depleted in Earth's mantle. Due to their siderophile nature, they were both strongly partitioned into the Earth's core during its formation. However, in particular the Pt concentration in the Earth's mantle is much higher than expected from experimental data on metal-silicate partitioning appropriate for the conditions of core formation. A plausible explanation for this high Pt concentration is the late veneer hypothesis, where volatile-rich chondritic type material was delivered to Earth's surface after core formation. This can in principle explain both the volatiles in the Earth's ocean-atmosphere as well as the high Pt concentrations in the Earth's mantle. There are tungsten isotopic heterogeneities ($^{182}W/^{183}W$ variations) in the early Earth that have been explained as being due to late veneer addition, as this material would have lower $^{182}W/^{183}W$ than the post-core formation mantle. There is also the gradual increase of Pt abundance through history in mantle as measured in mantle-derived rocks of various old ages. Both observations are thought to be caused by gradual mixing of late veneer material into Earth's mantle through plate subduction and mantle convection through geologic time. This would increase the Pt concentration and decrease the $^{182}W/^{183}W$ ratio in the mantle with time, as observed. Here we model the late veneer material as a thin sheet which is subducted into the mantle, and get stretched and mixed with the mantle material gradually. The stretching is assumed to follow a simple exponential law of decrease of the characteristic size of heterogeneity regions. The melting events that produce the rock samples of various ages measured on the surface are modeled as random geometric sampling of a sampling box with a certain length-scale. We are testing various scenarios of this mathematical model to see if both the variations in W isotopic ratio and the Pt concentration in Earth's history can be made consistent with each other within our model.

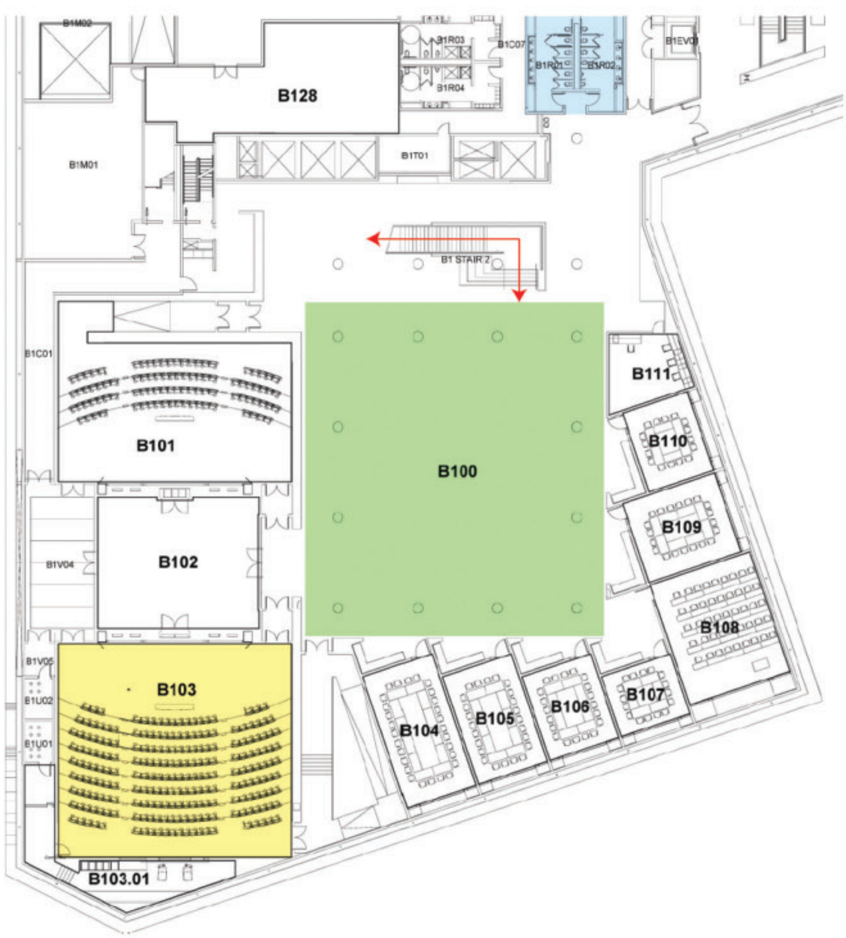
Harvard University Campus Map

- Museum of Natural History Galleries, 26 Oxford Street, Cambridge, MA 02138
- Northwest Building (Scientific Sessions) 52 Oxford Street, Cambridge, MA 02138



Northwest Building, Harvard University Basement Floor Plan

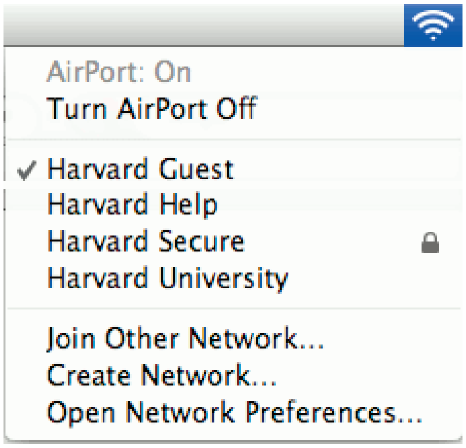
- B100: Prefunction Area (Breakfast, Lunch, Posters)
- B103: Lecture Hall (Talks)
- B1R01 & B1R02: Bathrooms



Wireless Access on Harvard Campus

MAC OSX Harvard Guest Wireless Access Steps

Click on the Airport icon and select Harvard Guest from the available networks.



Windows 7 Harvard Guest Wireless Access Steps

To select the Harvard Guest wireless network and be connected to the Internet, please follow the following steps on Windows 7 supported devices:

1. Open Connect to a Network by right-clicking the network icon ( or ) in the notification area

2. In the list of available wireless networks, click on Harvard Guest, and then click Connect

CAREER PATH CROSSINGS OF RICK O'CONNELL AND BOB LIEBERMANN

I have known and admired Rick O'Connell for more than half a century. We have been undergraduates together at Caltech, contemporaries in graduate school, colleagues in different academic institutions, and good friends. It is an honor and a pleasure to offer a few words for the EPS Symposium in Honor of Rick at Harvard on September 5-6, 2014.

I first met Rick O'Connell in September 1960 when we both moved into Ruddock House, one of the new residential houses at Caltech. Rick was a sophomore majoring in physics and I hoped to become a mathematics major. In the event Rick graduated in 1963 in physics and I wandered from math to electrical engineering and finally found a good home in the geology department [having been strongly influenced by Professor Bob Sharp, who taught GE1 and shared a locker next to mine in the football locker room in Winnett Gym].

In addition to sharing geology field trips to Rainbow Basin led by Clarence Allen or Hugh Taylor, Rick and I briefly played together on the Caltech football team in fall, 1962. Unfortunately, I cannot find him in the team photo for 1962, which leads me to conclude that he thought better of continuing such an athletic adventure.

After graduating in 1963, Rick spent a year in Europe before returning to Caltech to pursue his doctoral studies under the supervision of Gerry Wasserburg. We both defended our PhD theses in the same week in 1969 [in fact, I attended the celebration after his defense].

We overlapped again in 1970 when we both worked with Hartmut Spetzler in his new ultrasonics facility in the old Seismo Lab. Rick was kind enough to find us a house on Michigan Avenue to rent and then helped my wife, Barbara, and our young baby, Karen, move in. One night when he was baby-sitting for Karen, Rick heard a scream and found her crawling on top of the floor radiator and finding it too hot.

We both were recruited by Ted Ringwood to build an ultrasonics lab at the Australian National University in Canberrra, but Rick's family did not want to be so far away, and so I got the job.

Wasserburg encouraged Rick to learn how to measure something, so from Spetzler's lab he moved on to UCLA to work in George Kennedy's lab with Ivan Getting. Rick was highly recruited by several universities for faculty positions, but eventually chose Harvard.

During his early years at Harvard, I visited Rick often, including in 1976 when I was a candidate for a faculty position there. I offended Dean Rosovsky when I asked him how he could be committed to the geology department, when he had denied tenure to Adam Dziewonski.

In 1976, I was the co-convener with Vladislav Babuška and Jarka Plomerová of a Workshop on Anisotropy and Lateral Heterogeneity in the Lithosphere at the Castle of Liblice in eastern Bohemia [in what was then Czechslovakia]. See photo of Rick with his Harvard colleague Tom Shankland and my future Stony Brook colleague Don Weidner along with Plomerová and Babuška.

Attendees at Workshop on Anisotropy and Lateral Heterogeneity in the Lithosphere at the Castle of Liblice in Czechoslovakia.

Front Row. L to R: Jarka Plomerovà, Vladislav Babuška, Rick O'Connell, Tom Shankland.

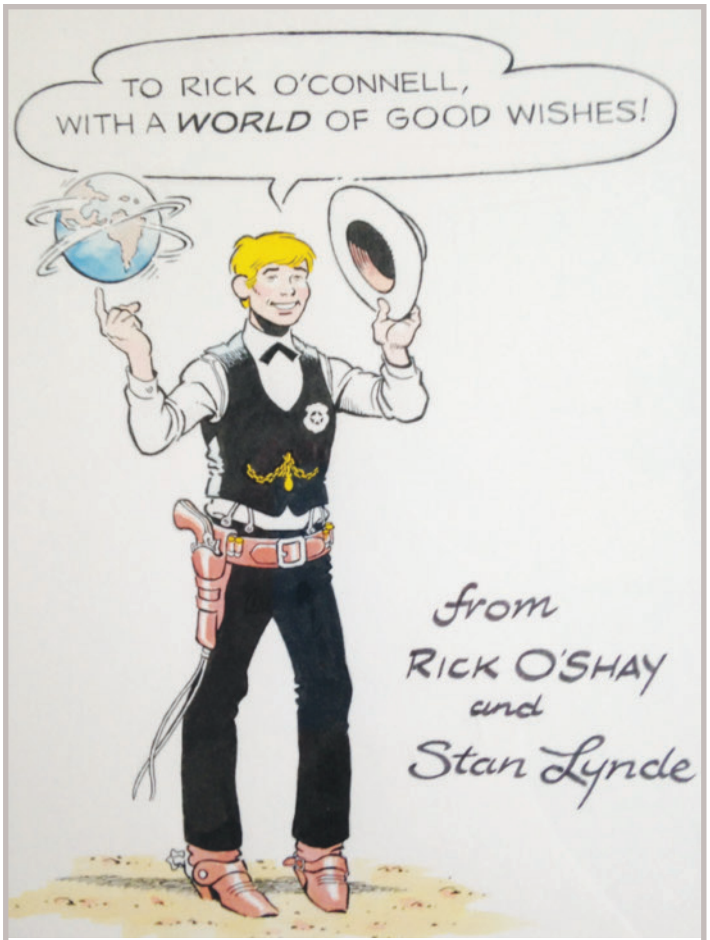
Don Weidner in second row between Rick and Tom.

Also attending the Liblice Workshop in 1976 were Enzo Boschi and Francesco Mulargia from Italy, Hartmut Spetzler from Colorado, and Rick's son, Brian. See photo above.

Some years later, I was proud to serve on the Lehmann Medal Committee of the AGU and see it awarded to Rick, the first non-seismologist chosen. When the Consortium for Materials Properties Research in Earth Sciences [COMPRES] was established by the NSF Division of Earth Sciences, Rick and his buddy Guy Masters from La Jolla were big advocates and served together on its Advisory Council for many years,

It was during Rick's service for COMPRES that Barbara and I met Rick's wife, Susan Playfair. We have spent many wonderful times with them at AGU and COMPRES meetings and are still hoping to have exchange visits on Long Island and/or Cape Cod. Susan has introduced me to the history and culture of fishing in New England via her fine books.

So Rick, in closing, may Barbara and I offer our best wishes for a successful symposium and many happy and productive years ahead.



Upon hearing that R. J. O'Connell had received some medal, I felt that a congratulatory note was in order for him. He was an old student, an old friend & a greatly respected, truly imaginative scientist. He is also, for some unknown reason, very modest. He was also a Montana boy who was nicknamed by me (~47-50 years ago) after the comic strip character Rick O'Shay. So rather than just send an e-mail or a scribbled note, I felt that if I could get Stan Lynde, the Montana artist, to draw a cartoon, that would be the best.

From G.J. "Hip Shot" Wasserburg

CONGRATULATIONS, RICK!

I am truly grateful for your generous wit, enthusiasm, encouragement, and best of all, your company. All the best wishes, — Rita

DEAR RICHARD,

We wish you a successful and friendly event, and all the best for the future. We hope that our paths cross several times on some landscape or other. — Alan and Lisa Thompson

MY BEST WISHES TO RICK,

who is surely one of the great Geophysicists and mentors of his day. — Robin Reichlin

DEAR RICK,

Mimi and I are so sorry to miss this event. I was hoping to get some of your ex-students gassed to cut through your smoke screen and find out what the hell you've really been up to for forty years. Now I'll have to work the single malt strategy on you (hopefully with your scotch because it'll take gallons!). Looking forward to seeing you and Susan soon and hearing all about the shindig. —Al Doughtery

THANK YOU, RICK, for guiding a fantastic senior thesis and for years of mentorship before and since. My particular gratitude for your advice on horseback riding and cattle herding- I've put it to good use!

All the best to you and Susan, —Roger Fu

I often think of Rick's chairmanship of the UNAVCO Steering Committee in its early years. Even though Rick was not a geodesist, but rather someone interested in applying geodesy to problems in geodynamics, I think of the period in which Rick was the chairman as being the golden age of UNAVCO. He went out of his way to visit the CAP project in Chile, along with NSF's Michael Mayhew (who was very influential too, making big bets on GPS geodesy as a scientific technique when very few others were willing too). They observed training, they set up tripods along with everyone else, and they entered the field to participate in the actual measurement campaign. Rick was very hands-on, and he provided the fledgling organization with the broader perspectives and also the gravitas that it needed in order to fulfill its remarkable promise. He helped fashioned sensible policies and lean but effective systems of governance, and kept a young but very dynamic organization on track. While most of the people at the Rick-fest will focus in his remarkable and diverse scientific contributions, his critical early contributions to the crustal motion geodesy community are also very worthy of mention. I greatly regret that I cannot attend the Rick-fest, but send my greetings to him and all the attendees, and I hope to watch the Symposium on You-tube!

From Michael Bevis

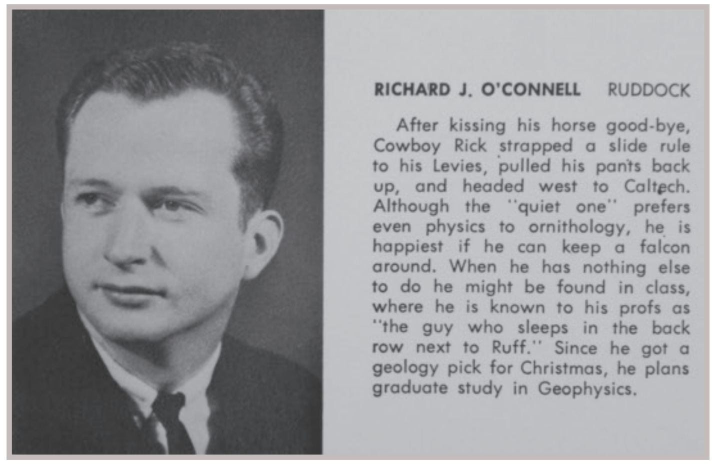
Photo: Michael Mayhew, Rick, Michael Bevis, Bob Smalley and Jim Normandeau enjoying a post-work beer in the Plaza de Armas of Santiago, Chile in the early 1993/1994.

FOR RICK,

WE BACKTRACKED THAT DAY CROSSING OLD GROUND, REMEMBERING EVENTS OF THIRTY YEARS PAST. WE FOLLOWED ROCK CREEK UP THE LITTLE GORGE IN BACK OF THE BIG HOUSE TO A PLACE WE WHERE WE CAME TO SWIM AS CHILDREN IN THE POND BELOW THE WATERFALL.

RICHARD HE RIDES

Rick and I have been pals since 1961 when we met at Caltech (undergrads). Rick was from Helena and Wolf Creek (current population 510), MT. I was from Beverly Hills. Rick introduced me to Montana, gathering cattle, and fixing cars. I introduced him to Beverly Hills, Hollywood, jazz music, and sailing.
A good friendship.



RICHARD J. O'CONNELL RUDDOCK

After kissing his horse good-bye, Cowboy Rick strapped a slide rule to his Levies, pulled his pants back up, and headed west to Caltech. Although the "quiet one" prefers even physics to ornithology, he is happiest if he can keep a falcon around. When he has nothing else to do he might be found in class, where he is known to his profs as "the guy who sleeps in the back row next to Ruff." Since he got a geology pick for Christmas, he plans graduate study in Geophysics.

Caltech 1963 Yearbook page provided by Mike Wells

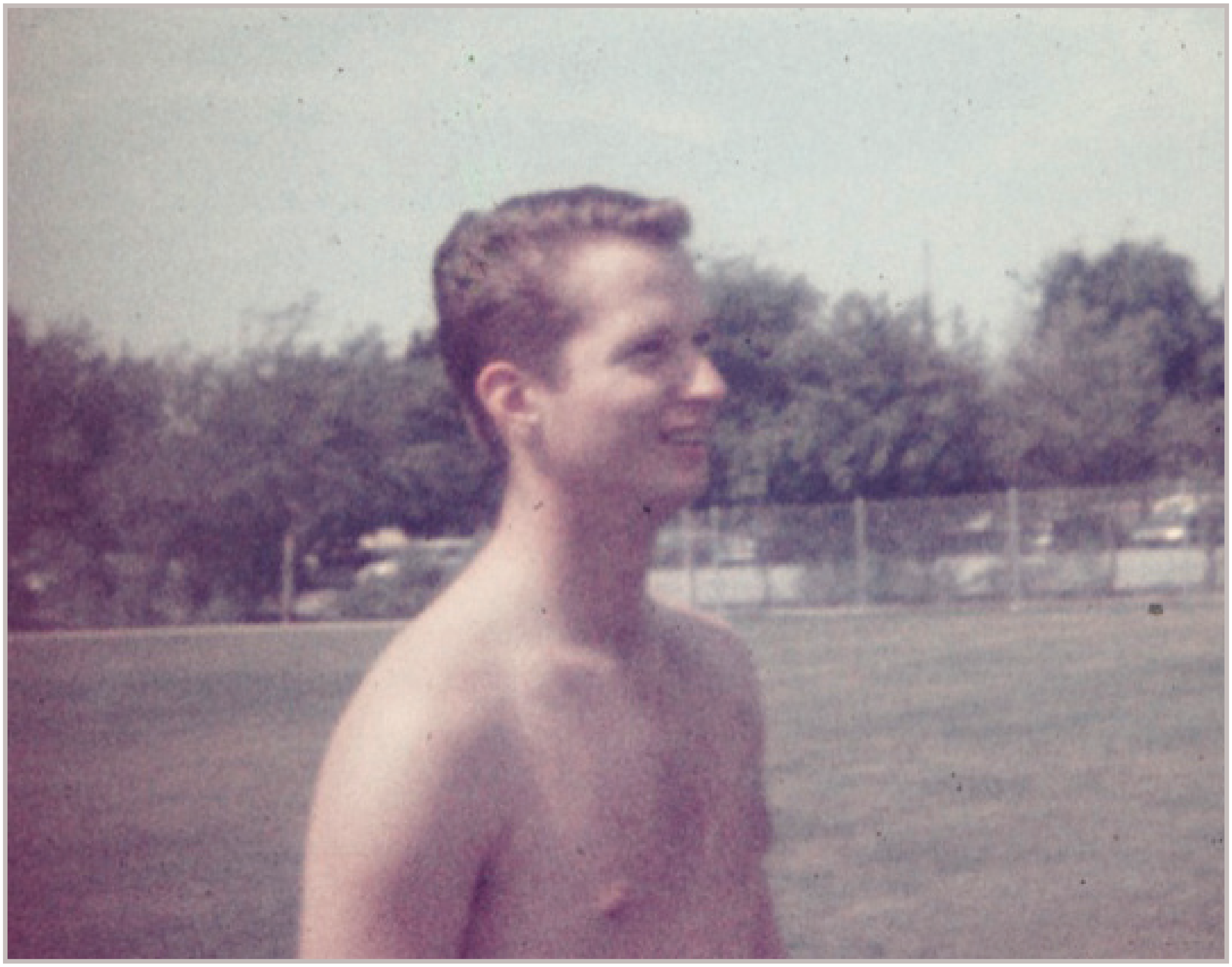
We graduated from Caltech in 1963 and took time off before grad school to travel around Europe together for about one year. We both came home from Europe with a Porsche.

From the slow lane of Wolf Creek, MT, Rick ended up at Harvard in Cambridge, MA. From the fast lane of Beverly Hills, I ended up Montana State in Bozem an, MT. Go figure.

Cheers from Mike

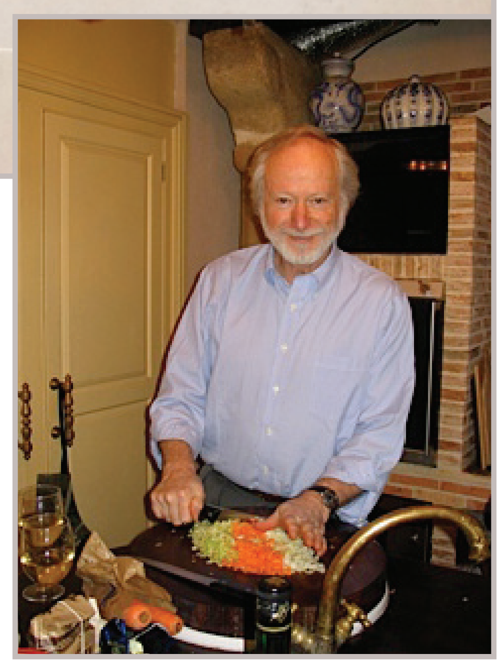
When I was a young professor at Harvard I arrived at a time when there was very little active fluid mechanics research activity in the Division (now School) of Engineering and Applied Sciences. There were two pieces of good luck, at least for me. First, I was part of a very supportive and wonderfully collegial mechanics group and second I was fortunate to have in the very first graduate course I taught two students from EPS (Michael Manga and John Bush). As luck would have it, both features would lead to Rick O'Connell. In the mechanics group I am quite sure it was Bernie Budiansky, a long time collaborator and friend of Rick's, who introduced me to Rick. Second, Michael Manga was Rick' s student and I became Michael' s co-advisor. Rick was always a wonderful and supportive colleague. He was patient explaining to someone like me, with no real understanding of the physics of the solid earth, the important physical and mathematical features of flow in the earth's mantle and many related dynamical features. I am quite sure that part of my ability to survive as a young professor was because of Rick and my colleagues in mechanics – they helped to educate me and give me a framework to work on problems outside my training. I look back very fondly on those times. All best wishes to Rick and Susan and please give them a big hug from me.

With best regards, — Howard Stone

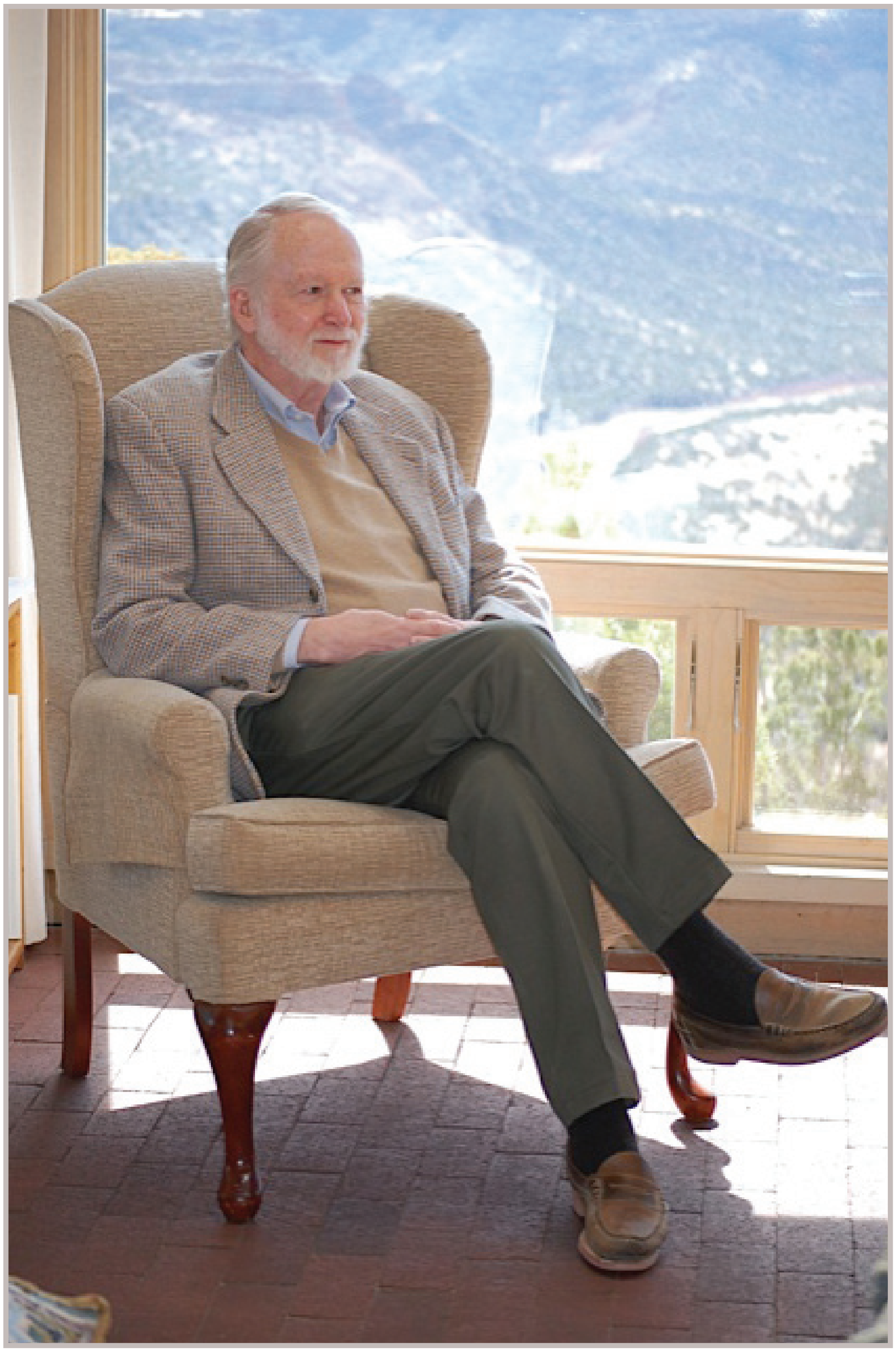


Montana youth

Cambridge Class of 76



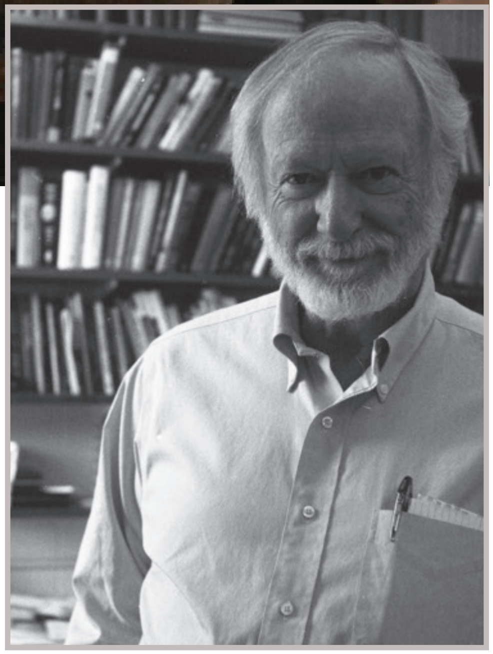
Cooking in Paris



Working in New Mexico

Preparing to go to sea

In the field



In his office

At sea

Hawaii

Hawaii