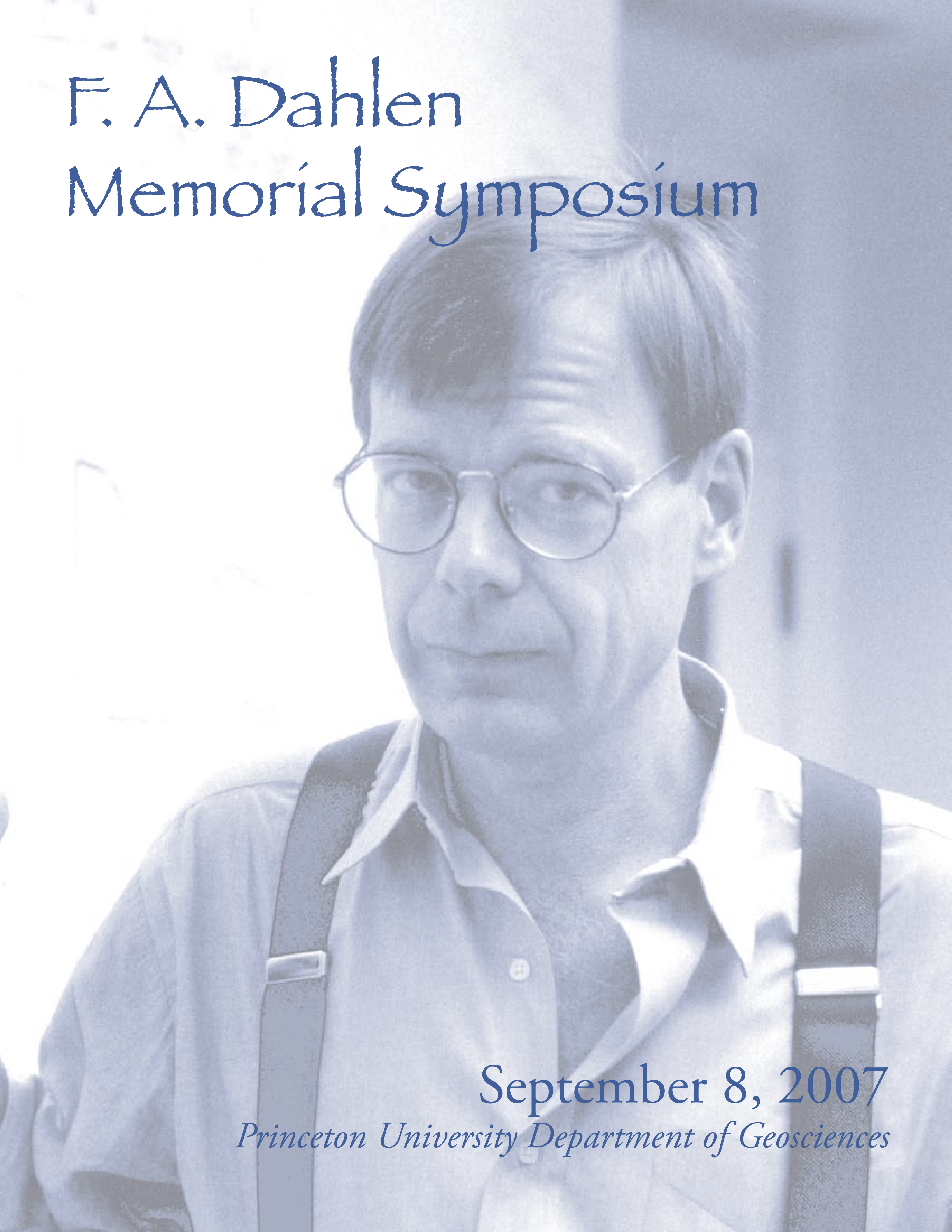
F. A. Dahlen
Memorial Symposium



September 8, 2007

Princeton University Department of Geosciences

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My fondest memories of Tony blur together in a montage of coffee room conversations with a brilliant man who always inquired about me, an undergrad, and always readily listened, advised, and encouraged. I will miss his guiding and calming presence.

--Will Levandowski, UG '07

Agenda

Saturday, September 8, 2007

Program to be held in Guyot Hall Room 10
Reception immediately following in the Friend Center for Engineering, Convocation Room

8:00	Continental Breakfast – Guyot Great Hall
8:50	Welcome by Department of Geosciences Chair, Bess B. Ward
	First Session *Moderator – Karin Sigloch*
9:00 – 9:30	Freeman Gilbert, University of California, San Diego "The Unreasonable Effectiveness of Mathematics in Geophysics"
9:30 – 10:00	John Wahr, University of Colorado at Boulder "Geodetic Constraints on Mantle Anelasticity"
10:00 – 10:30	Martin Smith, New England Research, Inc. "The Normal Modes of a Rotating, Homogeneous Earth"
10:30 – 11:00	Coffee Break – Guyot Great Hall
	Second Session *Moderator – Yue Tian*
11:00 – 11:30	John Woodhouse, University of Oxford "Global Earth Structure from Seismic Imaging"
11:30 – 12:00	Guy Masters, University of California, San Diego "Joint Seismological/Mineral Physics Modeling of the Composition and State of the Lower Mantle"

Tony was a man who left a huge impression on me. It was not just his intellect, his work ethic, and his professionalism that impressed me, but his humanity, his kindness, his humility and even his sense of humor. I was frequently amazed at his ability to lucidly explain incredibly complex concepts and the pleasure he took in teaching was obvious to those of us fortunate to sit in his classroom. To me, he was a model as a scientist and as a man and I am glad to have benefitted from his mentoring and his friendship.

--Adam Baig, Ph.D. '04

12:00 – 1:30 Buffet lunch – Guyot Great Hall

Third Session
Moderator – Huub Douma

1:30 – 2:00 Dan Davis, Stony Brook University
"Analog Modeling to Test Predictions of Strain and Morphology in Coulomb Wedges"

2:00 – 2:30 Robert Liebermann, COMPRES, Stony Brook University
"Outdoor vs. Indoor Geophysics"

2:30 – 3:00 Jeremy Bloxham, Harvard University
"Magnetic Fields in the Solar System"

3:00 – 3:30 Coffee Break – Guyot Great Hall

Fourth Session
Moderator – Mark Panning

3:30 – 4:00 Guust Nolet, Princeton University
"A Story of Bananas and Doughnuts"

4:00 – 4:30 Tarje Nissen-Meyer, Princeton University
"1D Structure, 2D Space, 3D Wavefields: New Windows to Global Tomography"

4:30 – 5:00 Jeroen Tromp, California Institute of Technology
"Banana-Doughnut Kernels, Adjoint Methods & Seismic Tomography: The Legacy of F.A. Dahlen"

5:30 – 6:30 Reception, Friend Center Convocation Room

Tony was a great advisor, I am grateful for his guidance throughout my Ph.D. work, and for his continuous interest in my research, his generous support, encouragements and discussions. His carefulness and thoroughness in research has been a great influence on me. The days I worked with him at Princeton were inspiring and unforgettable. While realizing he is no longer with us, my memory of him talking at the weekly group meetings feels just like yesterday.

--Ying Zhou, Ph.D. '05

F. Anthony Dahlen – 1942-2007

Pioneering and Versatile Theoretical Geophysicist

Tony Dahlen, probably the most important theoretical geophysicist of his generation, died on 3 June 2007, in Princeton, New Jersey. His seminal research on topics as far apart as seismology, Earth's rotation and the growth of mountains exerted a lasting influence on modern geophysics.

Dahlen was born in 1942 in American Falls, Idaho, while his father was serving in the US Navy in the Second World War, and moved with his reunited family to Winslow, Arizona, at the end of the war. There, in the shadow of the Barringer crater, he grew up searching for fossils and meteor fragments. Although it was a combined passion for geology, mathematics and physics, not American football, that earned him a Sloan Scholarship to the California Institute of Technology, he was nonetheless one of five members of the college football team who later became distinguished professors of geoscience.

His PhD research began in 1964, working with George Backus and Freeman Gilbert at the Scripps Institution of Oceanography of the University of California, San Diego. In the wake of the wartime boom in marine geophysical research, Scripps had become one of the principal US geoscience laboratories. It was a heady time, particularly for global seismology: two huge earthquakes, in Chile in 1960 and Alaska in 1964, had excited Earth's lowest 'eigenvibrations' — modes of oscillation in which the whole planet rings like a bell, with frequencies of a few cycles per hour. Two observed oscillations, with periods of 54 and 36 minutes, showed a splitting, akin to the Zeeman effect, in which an atom's energy levels split in a magnetic field. In this instance, it is the Coriolis force — an effect of Earth's rotation — together with Earth's slightly elliptical shape, that breaks symmetry and splits the spectral line into several closely separated oscillations.

Dahlen's thesis tracked the problem of the coupling of these modes. A fast worker, he could have graduated early in 1968, but decided to satisfy his broad interests by spending a further year sampling

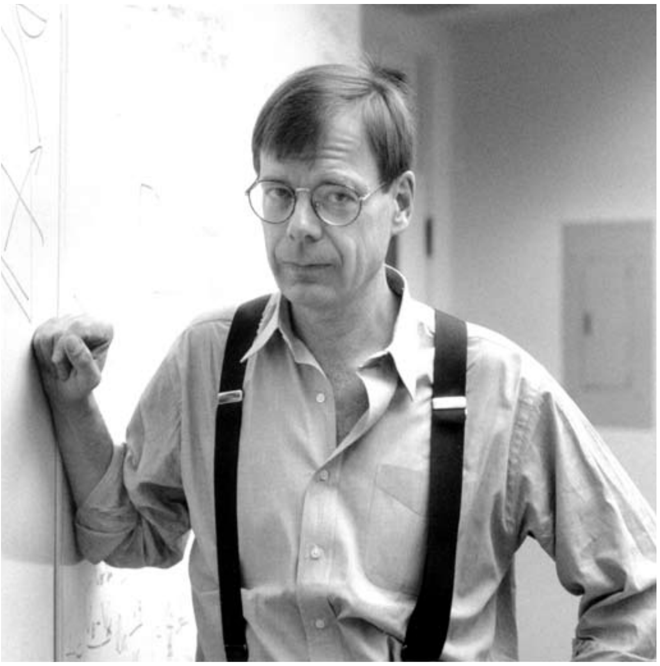


Photo by J.T. Miller

courses in other areas. In addition, in his first year at Scripps, he had caught the attention of a beautiful freshman one afternoon on the beach. She noticed he was reading a physics textbook, and asked if he would tutor her. Tony and Elisabeth Dahlen remained together until his death.

In 1970, Dahlen joined the faculty at Princeton University. His early work on eigenfrequencies provided a starting point for the idea that modes of oscillation split because of anomalous structures in Earth's interior, an idea that culminated in 1979 in a celebrated paper written with John Woodhouse. This work allowed seismologists to use eigenfrequencies for seismic 'tomography', to image small variations in Earth's elastic properties that are mostly caused by temperature variations. In the same period, Dahlen made important contributions to dislocation theory, which models the deformation due to earthquakes. This work led to a seminal paper on the energy balance of earthquakes.

Together with Martin Smith, Dahlen developed a linearized perturbation theory to describe the direction dependence of seismic-wave velocities in the interior of Earth. Today, this is the most practical means of visualizing the directions of the flow in Earth's mantle that is generated by convective processes. The two also determined the mantle's viscous response to stresses using the damping of a phenomenon known as the Chandler wobble, a 14-month precession of Earth's rotation. This followed on from earlier work in which Dahlen had developed a complete description of the effects of the oceans on variations in Earth's rotation.

In the 1980s, Dahlen moved on to work on the mechanics of the fold-and-thrust mountain belts and accretionary wedges that form at the margins of tectonic plates as they collide with each other. Collaborating with geologists Dan Davis and John Suppe, he showed how the formation of mountains in such regions can be explained in terms of a critical taper, mechanically analogous to the wedge of soil that forms in front of a bulldozer. Calculating the energy balance of such a system in western Taiwan, he showed that internal deformation contributes comparatively little energy to rock-transformation processes. Since then, submarine wedges such as those found off the Niger delta have been shown to act similarly. He also modelled the role of erosion of mountains and showed how this dominates the thermal evolution of mountain belts — a subject of much current interest.

The influential textbook Theoretical Global Seismology (1998), written with his former student Jeroen Tromp, marked the culmination of three decades of research by Dahlen and others into low-frequency seismic waves. By the time the book came out, however, Dahlen had shifted his attention to the higher-frequency 'body waves'. These seismic waves reveal more detailed information about features deep within Earth if sampled sufficiently densely, although the theory underlying their propagation had barely evolved since the early twentieth century.

Dahlen rejected the paradigm that seismic waves propagate as narrow rays, as they do in classical optics, and he formulated an efficient computational strategy to take into account the diffraction of seismic waves. The advance allowed seismic-wave travel times to be interpreted more exactly as tomographic images. A first application by Raffaella Montelli led in 2003 to the serendipitous imaging of convecting plumes in the lower mantle — the first visual confirmation of a 30-year-old hypothesis that such plumes are the origin of ocean islands such as Tahiti and Hawaii.

Dahlen was an erudite and courteous scientist, unassuming and generous towards students and colleagues alike. Seismology is evolving into a science driven by huge quantities of data, with projects such as the USArray, funded by the National Science Foundation, providing hundreds of sensors to permit the sampling of a whole wavefield, rather than arrival times of individual rays. The scale of these endeavours demands the kind of theoretical advances that Dahlen provided, and the influence of his work is likely to be felt for years to come. Although he received many honours, it is certainly the continuing relevance of his discoveries, and those of his students, that would have pleased Tony Dahlen most. Throughout his life he was driven by his love for science; his greatest pleasure was that his son Alex also decided to pursue a career in science. *by Guust Nolet, reprinted from NATURE Vol 448, 19 July 2007*

1949 - Stick 'em up!

Tony and Liz on their annual ski trip. Photo courtesy of Tracey and Jeroen Tromp

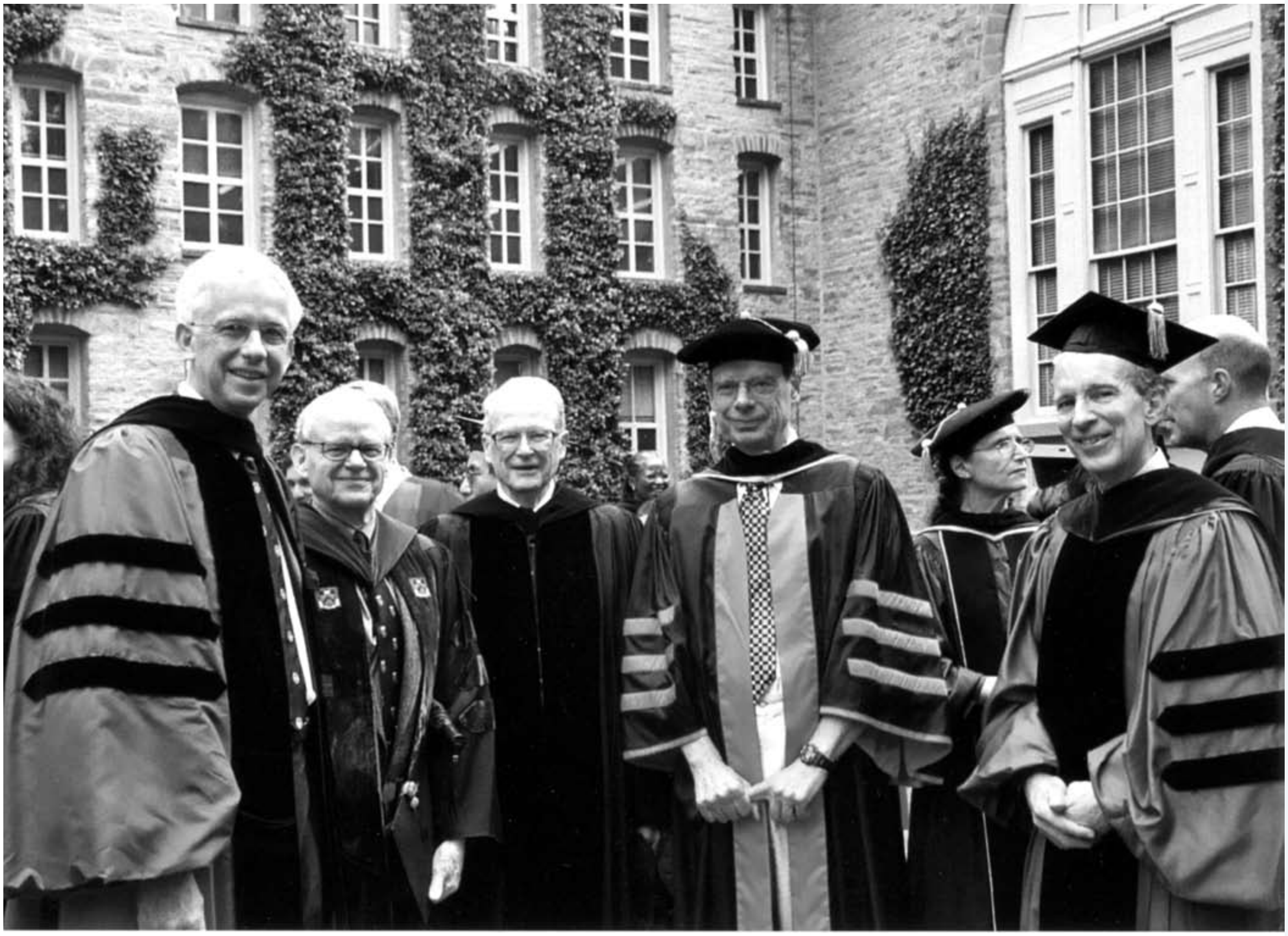
Tony participating in the Coors Light Biathlon c. 1980.

Tony and Elisabeth at the Geosciences department's holiday party in 2003. Photo by Karin Sigloch

In 1984 I was sitting quietly in my office on the M-Floor of Guyot Hall when Tony came storming in with the latest issue of Geophysics in his hand. "Look at this!" he said. "This guy claims to have found a counterexample to acoustic reciprocity. This can't be right. Let's write a paper!" In short order Tony produced a wave theoretic computation which showed how the intuition of geometric ray theory failed, producing the apparent paradox. Within two and a half days we had mailed the paper, and Tony posted a note by the mailboxes, claiming the fastest time in the department from concept to submission for a scientific article. I don't recall if we had any challenges to the claim, but I don't think so. He was a mentor and friend for many years.

--Bob Odom

Tony, Jeroen, Alex, and Elisabeth. Photo courtesy of Tracey and Jeroen Tromp



Tony at the 2004 Commencement with (among others) John Suppe (far left) and Bill Bonini (2nd from left). Photo courtesy of Sheryl Rickwell.

I first encountered F. A. Dahlen — the name, not the man — as a first-year graduate student taking a geodynamics course. On a slide labeled "The March of Science", Brad Hager had photocopied the title pages of three papers. On Suppe and Dahlen (1983), he had written "The dirty work". On Dahlen and Suppe (1984), "The dirty theory". Finally, on Dahlen (1984) there was: "Elegance". In my recollection, years later, it had said "The Master", and my memory of the time is that what I wanted from then on was to do science, with the Master. Ten years later, and I am left missing the man, Tony Dahlen, my coauthor, my mentor, my friend. I've heard that Leonhard Euler's epitaph reads, simply: "He was a great scientist, and a kind man". This fits for Tony, I'll say no more.

--Frederik J Simons, Princeton University

That 70s' look...

Published Papers

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A few years after I graduated from Princeton, Tony began a foray into the geology of crustal tectonics along with John Suppe and me. After our 1983 paper on critical Coulomb 'bulldozer' thrust belt wedge mechanics won the GSA best paper award, we were asked to pose for the obligatory formal pictures to go into the journal with the award citation. Instead, we decided to have some fun and pose on a real bulldozer that had plowed up its own miniature fold & thrust belt on the Princeton campus. The picture shows Tony astride the bulldozer treads, looking very serious.

--Dan Davis

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Tony with Peter Malin in the Dolomites, northern Italy.

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The Dahlens visit with the Tromp family at their new house in Pasadena, CA. Photo courtesy of Tracey and Jeroen Tromp

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Perhaps Tony's greatest gift to us, his students, was his ability to present complex concepts in simple terms. His clarity of thought was uncommon, his communication skills were exceptional, and his curiosity was infectious. Moreover, he was a kind man who always took an interest in the professional and personal welfare of his colleagues and students. I have lost a good friend and mentor.

--Peter Davis, University of California, San Diego

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Tony climbing Mt. Ranier with Bob Odom.

Tony was as good a friend, as he was scientist and mentor. In 1985 we "climbed" Mt. Fuji in Japan together. After I returned to Seattle, I bugged him for years to come out to Seattle and climb Mt. Rainier. He finally took me up on it during the summer of 2005, and he and his son Alex came out in early July for our climb. At about nine o'clock in the morning on our summit day, we were well over 14,000 ft, and within 100 or 200 feet of the summit, and my vision became so blurry, I could not focus at all. This was an altitude effect, which I had never encountered before. We turned around without quite reaching the actual summit. We descended back to our high camp, and when we were ready to head back down to the cars, he offered to hike along with me, pointing out any hazards in the trail that I might not be able to see. As we hiked along I started to apologize for having to turn around so close to the true summit. As soon as he realized what I was saying, he very sharply interrupted, "Stop that!" I didn't bring it up again. He was a mentor and friend for many years.

--Bob Odom

Team photo is from 1962 Caltech football team. Tony is in the first row at the left, #63. Photo courtesy of Robert Liebermann

Dinners at Fall AGU were sometimes followed by compensatory activities. The picture, taken in the early 1980s, shows Tony and others after running across the Golden Gate Bridge and to the top of Mt. Tamalpais.

(left to right) Bill Brace, Rick O'Connell, Sue and Art Montana, Tony, Leonard Johnson, Tim Grove, Brad and Patty Hager. Photo courtesy of Rick O'Connell and taken by Art Montana

The Evolution of a Geophysicist

1940s

Cowboy Tony

1950s

Stepping out in Winslow

1960s

Tony at CalTech

1970s

The young professor. Photo
Geosciences Archiv

Tony Dahlen had remarkable physical and mathematical insight and intuition. Anyone who ever worked with him can tell you how he was able to look at a result – be it an equation, a figure, or the output of some sort of simulation – and quickly determine whether or not it made sense. He would painstakingly craft his papers, with tremendous attention to detail and careful consideration for notation. It could be difficult to make Tony change his mind about something, as illustrated by the following characteristic remark he once made to me: `I know you have convinced me about this before, but convince me again?'.

--Jeroen Tromp, Ph.D. '92

As a Princeton seismology graduate student, I am most impressed by the fact that Tony Dahlen always considered most for his students. He was on my advisory committee. At my advisory committee meetings, Tony said things like: "This means Yue's first paper may come out later than the average time for our students to publish their first paper. Can we do anything to prevent this?" And: "Yue, these universities have strong programs in both your and your husband's majors. They could be good choices for you two after graduation." I felt that he really thought for my best.

--Yue Tian, current graduate student

courtesy of
es

1980s

Halloween with Alex

1990s

Tony on a departmental raft trip in 1991.
Photo courtesy of Tracey and Jeroen Tromp

2000s

Department chair. Photo by Pryde Brown

Jeremy Bloxham
Harvard University
Cambridge, MA

Magnetic Fields in the Solar System

The planets in our Solar System exhibit a broad range of magnetic fields. Earth and the gas giants have strong, nearly dipolar magnetic fields closely aligned with the rotation axis; the ice giants have magnetic fields that are highly non-dipolar and not aligned with the rotation axis; Mercury has a weak field, not necessarily of dynamo origin; Mars has only the remnants of an extinct dynamo; and Venus has no field. Here we describe steps to understand this range of fields using both numerical modeling and observations. In particular, we outline how some of Tony Dahlen's work with Frederik Simons can be used to glean a little more information from the sparse data.

Tony riding Snow Dragon in the Tromps' pasture on Ayer Rd., Harvard, MA. Photo courtesy Tracey and Jeroen Tromp.

Dear Tony,

You taught us seismology
until you
no longer could,
You signed our
bibles from Dahlen & Tromp,
"With best regards, Tony",
all equal and
none special,
You took off your hat
laughing you
"got a different haircut",
and then
offered to write a
letter of reference,
just before
you went ....

How come I am so
fortunate to have
met you?

--Huub Douma, Princeton University

Dan Davis
Stony Brook University
Stony Brook, NY

Analog Modeling to Test Predictions of Strain and Morphology in Coulomb Wedges

In the 1980s, Tony Dahlen was responsible for building much of the theoretical groundwork for the Coulomb 'bulldozer' wedge model, which has proved very useful in explaining many aspects of the thin-skinned tectonics of foreland fold-and-thrust belts and accretionary wedges. There is a long history of using analog models to test theoretical predictions for the growth of mountain belts, as well as to compare them with natural orogens. Such models match well the expectations of critical wedge theory, with wedge taper, thrust sequencing and structural styles that depend in predictable ways upon yield criteria in the wedge and along its base.

We have developed a technique that allows us to monitor the evolution of topography in a model orogen throughout its development and compare it with the distribution of quantitatively determined strain rate and bulk strain. Among the simplest predictions of critical Coulomb wedge theory is the assertion that cohesionless wedges should grow in a self-similar manner. This has been demonstrated many times for frictional analog models with normal convergence. With a simple series of experiments, we demonstrate that this is also true for critical frictional wedges in oblique convergence. In normal convergence, deformation begins with a symmetric pop-up structure, but (with fluctuations as individual thrust packets are accreted) the slopes of the pro-and retro-wedges rapidly evolve to distinct values, with the much steeper retro-wedge displaying a maximum (as opposed to minimum) critical taper. The same is true for models with small to moderate obliquities. At very high convergence obliquity θ, however, the distinction between pro-and retro-wedge breaks down. By an obliquity of θ=70°, there is essentially no difference between the tapers of the two sides of the double model orogen, in which principal stresses have rotated and changed relative values toward a strike-slip domain. The transition from asymmetric to symmetric behavior as a function of obliquity is quite abrupt – despite accommodating substantial shear, the model orogen has a form like that for normal convergence at obliquities as high as θ=50° to 60°. Even at moderately high convergence obliquities, strain partitioning within the wedge allows the shortening direction at the deformation front to remain close to normal to the strike of the margin. With increasing convergence obliquity, the distribution of that shear becomes more concentrated toward the inner parts of the model orogen.

Thin-skinned wedges with very different convergence obliquities appear very similar structurally, both in the lab and in nature. In both cases, an analysis of strain indicators may be required in order to differentiate them unambiguously from normally-convergent wedges. Regardless of obliquity, purely frictional wedges never undergo extension, but they can be demonstrated even at low obliquity to become supercritical. This lack of extension for a frictional orogen is entirely consistent with theoretical work pioneered by Tony Dahlen, who showed that the predicted minimum tapers for extension and for stability under compression are quite distinct. For this reason, a frictional wedge that is stronger than its décollement will not begin to undergo gravitational spreading when slightly over-steepened or when dynamic (plate motion) support is removed – in sharp contrast to the behavior of a ductile wedge.

with Saad S. B. Haq, Purdue University

Freeman Gilbert

Institute of Geophysics and Planetary Physics
University of California, San Diego
La Jolla, California

The Unreasonable Effectiveness of Mathematics in Geophysics

The title is taken from a paper published by Eugene Wigner in 1960, "The Unreasonable Effectiveness of Mathematics in the Natural Sciences." Wigner explored examples from Quantum Mechanics and General Relativity, two apparently very different subjects. In the present paper I explore several subjects in Geophysics, drawing on the published works of Tony Dahlen. These include papers on critical-taper wedge mechanics and mountain building, free oscillations of the earth, surface wave seismology, 3-D banana-doughnut travel-time tomography, and a few odds and ends. I speculate that mathematics is so unreasonably effective because we are so ignorant about how the world really works.

On April 2, 1986, the lead article on page 1 of the New York Times *was headlined "C.I.A. CHANGES WAY THAT IT MEASURES SOVIET ATOM TESTS". The article described the interagency battles that had been going on for years, concerning a technical issue in seismology which had risen to the highest political levels in the Reagan Administration. The article said that technical arguments had prevailed in interagency decision-making, and they undercut the Administration's claim that the Soviet Union had likely been cheating on the Threshold Test Ban Treaty.*

The article was full of information about agency positions that is not normally published, or allowed to be published. This was an inside story on how a really bad decision had been reversed in the biggest bureaucracy we have.

I was also quite concerned that I was going to be in trouble, because I'd been interviewed by the reporter who wrote it, and although I hadn't communicated anything I wasn't supposed to, would that be believed? Amid the flood of messages the next day, it was wonderful to get a short note from Tony. He simply wrote "Congratulations", signed it, and got several of his Princeton colleagues to sign it too.

I deeply appreciated that Tony, the theoretician, knew very well this battle had been important. He knew I had taken leave from Columbia and had worked full time on it for more than a year; that the battle had been won; and that this win was worthy of acknowledgment. When we spoke about it later, we both took great pleasure in how it all worked out.

--Paul G. Richards

Robert Liebermann
COMPRES
Stony Brook University
Stony Brook, NY

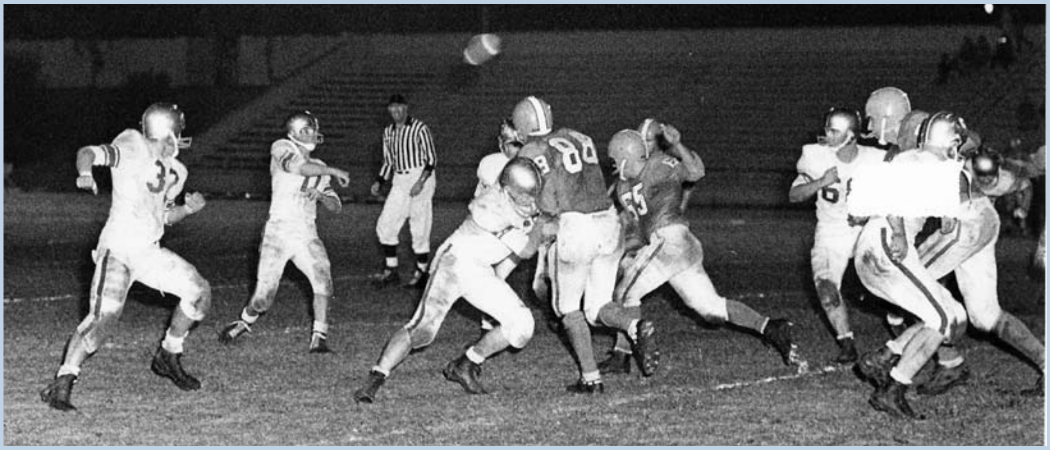
Outdoor vs. Indoor Geophysics

Research in mineral physics is essential for interpreting observational data from many other disciplines in the Earth Sciences, from geodynamics to seismology to geochemistry to petrology to geomagnetism to planetary science. The field of high-pressure mineral physics is highly interdisciplinary. Mineral physicists do not always study minerals nor use only physics; they study the science of materials which comprise the Earth and other planets and employ the concepts and techniques from solid-state chemistry, condensed matter physics, and materials science.

Observations from geochemistry and geophysics studies lead to the development of petrological, seismic and geodynamical models of the Earth's deep interior. The goal of mineral physics is to interpret such models in terms of variations of pressure, temperature, mineralogy/crystallography, and/or chemical composition with depth.

The discovery in 2004 of the post-perovskite phase of $MgSiO_3$ at pressures in excess of 120 GPa and high temperatures has led to an explosion of both complimentary experimental and theoretical work in mineral physics and remarkable synergy between mineral physics and the disciplines of seismology, geodynamics and geochemistry. Similarly, the observation of high-spin to low-spin transitions in Fe-bearing minerals at high pressures has important implications for the lower mantle of the Earth.

We focus in this talk on recent advances in the use of ultrasonic interferometry to conduct "indoor seismology" experiments to measure sound wave velocities of minerals under the pressure and temperature conditions of the Earth's mantle. Many of these acoustic experiments are now performed in conjunction with synchrotron X-radiation sources at national and international facilities.



Guard Tony is #63 [the 3 is obscured by some cropping tape from a news publication] and is seen blocking for quarterback Bob Liebermann [#11]. This is most likely from one of our games in the 1962 or 1963 seasons; note the large crowd in the stands! Photo courtesy of Robert Liebermann

Guy Masters
Institute of Geophysics and Planetary Physics
University of California, San Diego
La Jolla, California

Joint Seismological/Mineral Physics Modeling of the Composition and State of the Lower Mantle

We revisit the question of the composition and thermal state of the lower mantle by matching 1D seismic velocity and density profiles between 30 and 120GPa. While this part of the mantle is thought to be mineralogically simple, the procedure is complicated by the lack of reliable mineral physics data for some of the phases (particularly the shear modulus of calcium silicate perovskite) and by the potential for significant seismological effects from spin crossover. In particular, it has been proposed that this latter effect can cause anomalous compressional velocity gradients throughout much of the lower mantle. It turns out that the compressional velocity in the lower mantle is extremely well-known and we review some of the literature describing the seismological constraints. These constraints potentially put significant limits on the effect of spin crossover on elasticity.

If we neglect potential effects of spin crossover, we find that we can match the seismological profiles with a composition which is slightly more silica rich than pyrolite (Xpv=0.68) and with a reasonable temperature at the top of the lower mantle. We use this composition to investigate the physical cause of 3D velocity anomalies in the lower mantle.

I first met Tony in my first teaching job, at Caltech, in 1961. He took my field geophysics course in the Panamint Valley, and played intercollegiate football for Caltech as a split end, in the Rose Bowl (typical attendance, 100). When Princeton started building geophysics, in the sixties, Freeman Gilbert said that Tony was the most talented theoretical geophysicist he had ever met, and that we should hire him. He was, and we did! Faculty hiring was so easy then. Tony has been an inspiring, generous, and thoughtful colleague for all these years. I miss him very much.

--Robert A. Phinney, Princeton University

Tony at Mt. Snow, Vermont during a trip with the Nolets. Photo courtesy of Tracey and Jeroen Tromp

Tarje Nissen-Meyer
Princeton University
Princeton, NJ

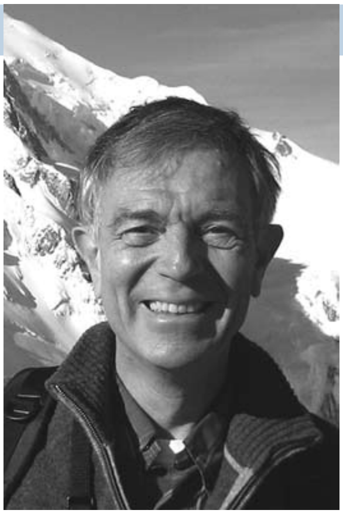
1D Structure, 2D Space, 3D Wavefields: New Windows to Global Tomography

In most recent years, one of Tony Dahlen's many scientific interests lead to a generalized foundation for finite-frequency tomography without limitations as to which part of a seismogram may be utilized. Reformulating his previous ray-based banana-doughnut kernel developments which culminated in plume imaging, this necessitates the knowledge of 3D time-space wavefields for the Greenfunctions that form the backbone of Fréchet sensitivity kernels. Although known for a while, this idea is still computationally intractable in 3D, facing major simulation and storage issues when global wavefields up to 1 Hz are considered.

This motivated Tony to dive into the underlying numerical theory of the spectral-element method, proposing a new "collapsed-dimension," 2D version thereof that solves the 3D equations based upon exploring symmetries of the seismic-wave radiation patterns. The mathematical framework was swiftly finalized, thus opening new doors to high-resolution inversions using e.g. diffracted phases around the core-mantle boundary. Before pursuing this endeavor, it was of utmost importance to him that such a numerical brainchild would be computationally advantageous for years to come in that full 3D wave propagation would not swallow its practicability in any nearer future. After thorough consultation in this regard, we set out to implement the method step-by-step adhering to Tony's infamous "scribbly notes," eventually passing its crucial 1.0 incarnation for (continental, non-gravitating) SNREI models. The advantage of such a once-and-for-all construction of reference-model waveform databases is its immediate, flexible applicability to arbitrary resolutions on moderate cluster infrastructures. This comes at the expense of being generally limited to 1D reference models, i.e. excluding iterative waveform fitting in contrast to adjoint tomography. However, we believe that it is timely for a complementary exploitation of all previously neglected time-frequency windows within a broadband seismogram for linearized inversions at the global scale.

I will present the ideas behind, development of, and proposed directions for this project which absorbed much of Tony's research planning into the next few years, drawing upon his minute diligence, infectious excitement and firm conviction of anticipating lowermost mantle images with unprecedented detail and sharpness in a collaborative effort within the seismology group at Princeton. His eager drive to mentor, support, and teach the entire group throughout these last few years made them a scientifically rewarding, thought-provoking, interesting, and always humorously painted journey – just one of many inspiring examples of his exceptional scientific rigor, strength of clearest thought, and ubiquitous modesty.

Guust Nolet
Princeton University
Princeton, NJ



A Story of Bananas and Doughnuts

Tony Dahlen made his early marks in low-frequency seismology, but the last ten years his attention shifted towards the interpretation of P and S arrivals, body waves of much higher frequency. In this talk I will tell some of the early history of how the Princeton seismology group stumbled upon banana-shaped sensitivity kernels for body waves and had long discussions on the paradoxes posed by the doughnut-like hole.

Tony's paraxial theory allowed us to incorporate the banana-doughnut kernels into seismic tomography. Raffaella Montelli's discovery of plumes in the lower mantle, below many known hotspots such as Tahiti, cast the method of 'finite-frequency tomography' into the heated debate on the existence of mantle plumes, and confused an already garbled debate on the theoretical validity of the banana-doughnut kernels.

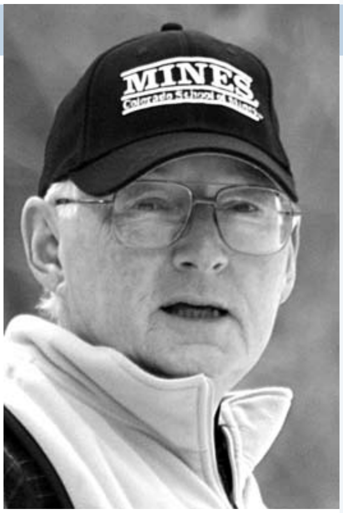
By now the debate seems to have largely subsided. Banana-doughnut kernels are accepted and finding their way into everyday practice. The observed lower mantle plumes are substantial in size and force us to reconsider accepted notions about how the Earth is cooling. They may even lead to reconcile geochemical observations that seem to require a two-layered convective system, with tomographic observations of slabs subducting below the 670 discontinuity and geophysical theory, both of which favour mass exchange between upper and lower mantle.

On the deck at home.

To me, Tony is the type example of many things. When I think of fairness, I think of Tony. I can't say why something so unflashy comes to mind first, except that it seems like such a fundamental part of his nature. When I think of people appearing to be 10-15 years younger than their age, I think of Tony. That was before the chemotherapy, but I was away for much of that. When I think of successful scientists who are concerned primarily with the careers of those who got their Ph.D.'s more recently, I think of Tony. That was his nature also.

--Allan Rubin, Princeton University

Martin Smith
New England Research, Inc.
White River Junction, VT



The Normal Modes of a Rotating, Homogeneous Earth

If you're going to write dull, theoretical papers, you can at least make sure they're correct.

-- F.A. Dahlen to an early student (1973)

During the time that two of us were employed in the petroleum industry, we observed that our colleagues would occasionally go to considerable lengths to construct laboratory-scale physical models of subterranean environments of interest, such as a fluid-filled borehole in an elastic formation. A frequent goal of these efforts was to provide an independent check on the results of mathematical (and in some quarters suspect), computational models. We noted that, despite this intention, when the physical and mathematical models were divergent the deficiencies were assumed to lie in the physical model.

In the hope of contributing to the spirit of this meeting, and because we believe that you're never too old to ignore experience, we three have undertaken to perform a laboratory measurement of a phenomenon that inspired one of Tony's first majorcontributions to geophysics: the rotational splitting of the normal modes of a rotating, elastic body. The thorough development of the relevant theory was the topic for Tony's Ph.D. Thesis, under Freeman Gilbert and George Backus.

We've undertaken this measurement specifically for this meeting and there are still a ***few more kinks*** to be worked out before we have results. We'll keep you posted.

with John A. Scales, Colorado School of Mines (jscales@mines.edu) and Brian Zadler, Colorado School of Mines, (bzadler@ruelle.mines.edu)

I have fond memories of our days together at Caltech: geology field trips to Rainbow Basin and Panamint Valley, playing on the same football team for two years, a stop in Tony's home in Winslow, Arizona, enroute to a summer job in Texas, and an Alfred P. Sloan Scholars dinner in New York in 1963.

Tony was known as an undergraduate at Caltech as a country boy, who was simultaneously a dedicated and talented physics student and an important lineman on the football team, which included five boys who later held faculty positions in Geosciences in U. S. universities.

Since graduating in 1964, Tony and I have pursued similar career paths in geophysics and I have admired and respected his many professional contributions.

--Bob Liebermann

Jeroen Tromp
California Institute of Technology
Seismological Laboratory
Pasadena, CA

Banana-Doughnut Kernels, Adjoint Methods & Seismic Tomography: The Legacy of F. A. Dahlen

We discuss the theory behind seismic tomography based on 3D Earth models, numerical simulations of 3D wave propagation, and adjoint methods. Our approach involves computing the Fréchet derivatives for tomographic inversions via the interaction between a forward wavefield, propagating from the source to the receivers, and an "adjoint" wavefield, propagating from the receivers back to the source. Both wavefields are computed using a spectral-element method (SEM) and a heterogeneous wave-speed model. We specify an objective or misfit function that defines a suitable measure of misfit between data and synthetics. For a given receiver, the differences between the data and the synthetics are time reversed and used as the source of the adjoint wavefield. For each earthquake, the interaction between the regular and adjoint wavefields is used to construct finite-frequency sensitivity kernels, which we call "event" kernels. These kernels may be thought of as weighted sums of the measurement-specific "banana-doughnut" kernels first introduced by F.A. Dahlen, with weights determined by the measurements. The overall sensitivity is simply the sum of event kernels, which defines the "misfit"' kernel, i.e., the Fréchet derivative. A conjugate gradient algorithm is used to iteratively improve the model while reducing the misfit function. We illustrate the characteristics of these 3D finite-frequency kernels based upon adjoint simulations for a variety of global arrivals, e.g., Pdiff, P'P', S650S, and SKS, and we demonstrate how the approach may be used to investigate body-and surface-wave anisotropy.

In "adjoint tomography," any time segment in which the data and synthetics match reasonably well is suitable for measurement, and this implies a much greater number of phases per seismogram can be used compared to classical tomography, in which the sensitivity of the measurements is determined analytically for specific arrivals, e.g., P or S. We use an automated picking algorithm based upon short-term/long-term averages and strict phase and amplitude anomaly criteria to determine arrivals and time windows suitable for measurement. For shallow global events the algorithm typically identifies of the order of 1000 windows suitable for measurement, whereas for a deep event the number can reach 4000. For southern California earthquakes the number of phases is of the order of 100 for a magnitude 4.0 event and up to 450 for a magnitude 5.0 event.

Unfortunately, I do not have enough to tell about Tony, as I only knew him during the last year of his life while here at Princeton. But as a long-period seismologist, I have constantly used his works as a reference, in particular The Book (I think of it this way in capital letters). My best memories of Tony now are from the class he decided to teach in his last semester from The Book, in which he somehow made it all seem comprehensible, and actually quite easy.

--Mark Panning, Princeton University

John Wahr
University of Colorado at Boulder
Boulder, CO

Geodetic Constraints on Mantle Anelasticity

Among Tony Dahlen's many significant contributions were a number of exquisite studies of the Earth's variable rotation. In one of these studies, published in 1981, Martin Smith and Tony looked at the effects of mantle anelasticity on the period and damping of the Earth's 14-month Chandler Wobble (CW). The physical processes responsible for anelasticity are not well understood, even today. The dissipation of seismic energy seems to be caused by different mechanisms than those controlling viscous mantle flow. But the details of those mechanisms and their relative importance at intermediate periods and stress levels is unclear. Smith and Dahlen were able to use CW observations to place constraints on the difference in the strength of anelasticity between seismic periods and 14-months.

In this talk I will describe an extension of Smith and Dahlen's general formalism to include other types of geodetic observations as well. Geodetic observations offer perhaps the only means of probing mantle anelasticity at periods between one hour (the longest seismic period) and thousands of years (the time scale of post glacial rebound). We find we are able to explain a number of these observations (the fortnightly and monthly tidal variations in the length-of-day, and the M2 and 18.6-year gravity tides, in addition to the CW period and damping) with a single frequency-dependent mantle Q model. We find the observations are consistent with a single absorption band stretching from seismic frequencies out to periods of at least 18.6 years. The frequency-dependence of Q within that band is consistent with a power law with an exponent of between 0.2 and 0.3.

Tony and I were at Caltech together and nearly at UCSD together (I changed my plans to go there). We met regularly at various meetings throughout our careers, and usually arranged a dinner at a very good restaurant during the Fall AGU meetings along with Leonard Johnson and later with Jeroen Tromp. We shared an appreciation of good food and company, as well as having grown up in the West and being thrown into Caltech with a lot of smart and well prepared kids. We both ended up in geophysics, and I am glad that I had the opportunity to know and interact with Tony over the years. I have fond memories of Tony's graciousness, gentle humor and clear intellect, as well as his beaming smile and red suspenders.

--Rick O'Connell

John H. Woodhouse
University of Oxford
Oxford, UK

Global Earth Structure from Seismic Imaging

The Earth is imaged by a variety of techniques, ranging from free oscillations to short period body waves. The basic long wavelength features are well known and reproducible. The continents have deep (~250 km) keels which are particularly pronounced in the ancient cratonic regions, and have the largest anomalies at approximately 110 km depth. The cooling signature in the oceans is clearly mapped, although reconciling the seismic signature with the expected addition of heat as evidenced by seafloor topography poses questions, possibly associated with the contribution of anisotropy. At depths in excess of 250 km the magnitude of lateral variations is much smaller, and the signature of subduction emerges as one of the clearest signals, persisting to great depth. The subduction signature persists through the 670 km discontinuity indicating that this boundary is not an impenetrable barrier to subduction At the base of the mantle the amplitude of heterogeneity increase markedly, suggesting a high level of compositional and/or phase heterogeneity.

As data volumes have increased it has been possible also to map anisotropy, although the level of agreement between different groups is much less than is the case for the isotropic shear velocity. The need for anisotropy, however, is clear, and some of the features robust. Among such features is the approximate alignment of the fast directions for Rayleigh wave propagation with the directions of absolute plate motion. The determination of shear attenuation distribution is also difficult but some of the large scale features are reproducible.

Another way to probe the deep mantle is to investigate reflected and scattered body waves. Precursors to SS and PP have provided valuable information on the topography of discontinuities and also on their *complexity*. Both the 520 km discontinuity and the 670 km discontinuity have been found to consist of more than one discontinuity in some regions, placing constraints on possible composition. The geographical distribution of the Lehmann discontinuity and its depth variations have been mapped and the dependence of its depth on temperature has been inferred by comparison with tomographic models. Scatted shear waves from the lowermost mantle have identified high velocity features consistent with the laterally varying occurrence of post-perovskite. A general feature of these results is that the observations cannot be explained in terms of temperature variations alone; rather, the seismological results indicate a complex superposition of temperature, composition and/or other effects.

Recent results will be summarized and discussed.

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