NATIONAL ACADEMY OF SCIENCES

FRANCIS ANTHONY DAHLEN JR.
1942—2007

A Biographical Memoir by

FREEMAN GILBERT

Biographical Memoir

Tony Dahlen

FRANCIS ANTHONY DAHLEN JR.

December 5, 1942—June 3, 2007

BY FREEMAN GILBERT

FRANCIS ANTHONY DAHLEN JR. WAS BORN in American Falls, Idaho, on December 5, 1942. Tony, as he was known throughout his life, moved with his family to Winslow, Arizona, shortly after the Second World War, when his father, known as Fritz, was discharged from the U.S. Navy. There was a brief period in Albuquerque, New Mexico, while Fritz completed his university degree. His mother, Mary Coy Dahlen, taught English composition, grammar, and literature at Winslow High School. His father was an administrator in the school system.

Tony has described his childhood in Winslow as a kind of Tom Sawyer life. He roamed the southern part of the Colorado Plateau and visited, among many other sites, the famed Meteor Crater, 20 miles west of Winslow. It is the best-preserved meteorite crater on Earth. Even with his outdoors orientation toward hunting and fishing he was an excellent student. From his mother he learned how to express himself articulately and elegantly and from his father he learned the value of dedication to academic pursuits. As a result of his academic accomplishments at Winslow High School he received an Alfred Sloan Fellowship to the California Institute of Technology. Tony's decision to major in geology at Caltech was at least partly motivated by the many signs of geological activity in northern Arizona, including Meteor Crater.

As an undergraduate Tony became interested in the quantitative aspects of the Earth sciences. He soon attracted the attention of faculty members with a quantitative bent. Jerry Wasserburg offers the following third-person observation:

> As a sophomore at Caltech in 1962, Tony took the introductory course in Mineralogy taught by Jerry Wasserburg. This was rather challenging as it included lots of solid-state physics and there was no real text. It was an effort to extend "mineralogy" into the realm of chemical physics-with minerals. Tony shined in the class. He could be drawn out to make comments and answer questions. When Tony started to speak, there was always an introductory "Uh" with his head turned sort of shyly down and then, followed a precise and brilliant analysis or comment. He was an exceptional student, modest but very interactive, always interested and generating ideas. It was fun observing him as he turned on intellectual light bulbs. As a sophomore, he was put on by Wasserburg as a summer research assistant doing computer calculations of solid-state diffusion models using an IBM with punch cards. As there was no computer in the Division, the box of punch cards had to be carried well across campus without dumping them. Tony succeeded at this and the calculations that were later published. The cards were carefully stored for a decade for fear of losing the output! What was stored the longest were the memories of the intellectual interactions with the young Tony Dahlen laying out the calculations and watching Jerry plot them on an enormous sheet of drafting paper in the old mineralogy lab.

At Caltech, Tony met Robert ("Bob") Liebermann. They became roommates and teammates on the Caltech football team. Bob was the quarterback and Tony was a tackle. Sometimes Caltech would score and, more rarely, even win a game. Home field was the Rose Bowl. Attendance was light and it was usually easy for the fans to sit on or close to the 50 yard line. Bob was also a geology major, and he and Tony planned to attend graduate school together. They visited La Jolla, California, and learned about the research projects at the Institute of Geophysics and Planetary Physics (IGPP) at the University of California, San Diego (UCSD). Bob decided to attend Columbia University and the Lamont Geological Observatory. Tony decided to attend graduate school at UCSD's Scripps Institution of Oceanography (SIO), home of IGPP. One afternoon on the beach at La Jolla Shores, Tony was reading a textbook on mathematical physics. He was noticed by an undergraduate coed who wanted to be tutored in mathematics. Thus, Tony met his future wife, Elisabeth. They married while Tony was still a graduate student and Elisabeth an undergraduate.

It was obvious to all of Tony's teachers at UCSD that he was an exceptional student. He could have chosen any of them for a mentor for his Ph.D. research. He chose George Backus and Freeman Gilbert. Within a relatively short time Tony had written a superb Ph.D. thesis. It resulted in the first two publications listed in the Selected Bibliography herein. These two papers together constitute Tony's first major accomplishment. All of the current research on the use of low-frequency seismic data for the determination of Earth's three-dimensional structure is based on this early work and subsequent research with M. L. Smith and J. H. Woodhouse.

Both Tony and Elisabeth graduated in 1969, he with his Ph.D. in Earth sciences, and she with her baccalaureate degree. The National Science Foundation awarded Tony a postdoctoral fellowship. He chose the University of Cambridge for his venue, and he and Elisabeth spent the academic year 1969-1970 there. After Cambridge, Tony and Liz moved to Princeton, where Tony had been appointed assistant professor of geophysics in the Department of Geosciences. Thus began a truly remarkable career.

As Tony matured as a professional scientist he continued to enjoy physical exercise as a daily outdoor activity. While a graduate student he participated in the daily volley ball game on the beach. At Princeton he became an avid long-distance bicycle rider and cross-country skier. Even in his forties he trained for and ran in marathons. Good health and physical fitness were important to Tony all his life.

There are two quotes that appealed to Tony as his career developed: "Physics is mathematical not because we know so much about the world, but because we know so little; it is only its mathematical properties that we can discover" (Bertrand Russell) and "Imagination is more important than knowledge" (Albert Einstein).

At Princeton Tony worked on the excitation of the Chandler wobble by earthquakes. The Chandler wobble is the free nutation of Earth. It was predicted in 1755 by Leonhard Euler who used the then known value of Earth's ellipticity and the assumption that Earth is rigid. The predicted period was 306 days. The wobble was discovered by Seth C. Chandler in 1891. It has a period of 433 days that seems to vary slightly as a result of continuous excitation. The longer observed period is attributed to Earth's elasticity and fluid core. In two papers (1973) Tony showed conclusively that earthquakes are not the cause of the excitation of the Chandler wobble. For nearly 30 years there was no definitive explanation for the excitation. Finally, in 2000 Richard S. Gross at the NASA Jet Propulsion Laboratory explained the excitation. Fluctuations of pressure on the ocean bottom account for two-thirds of the excitation and fluctuations in atmospheric pressure account for one-third.

Tony successfully applied mathematical methods to some of the outstanding problems in geophysics and demonstrated a creative imagination that was profound. Shortly after arriving in Princeton, Tony turned his attention to the equation for the conservation of linear momentum in a self-gravitating body with an initial static stress field. This work is relevant to the free oscillations of Earth and to the slow, nearly static deformation of Earth.

In the academic years 1971-1973 Tony was awarded an Alfred P. Sloan Foundation Fellowship, which he used to improve his knowledge of mathematical physics and to travel. Tony and graduate student Martin L. Smith (1973) deduced the azimuthal dependence of surface-wave phase velocity upon the full 21-coefficient elastic tensor of an anisotropic waveguide. Many workers have used this work to invert their data for azimuthal anisotropy.

In 1975 Princeton promoted Tony to associate professor of geophysics. His first sabbatical was taken in 1977-1978 at the Institut de Physique du Globe de Paris (IPG or IPGP). Prior to departure he completed his work on the balance of energy in earthquake faulting (1977). He clarified the role of gravitational energy in faulting by showing that the classical energy release expression, which has no explicit gravitational terms, already includes the gravitational contribution.

At IPG he began his collaboration with John H. Woodhouse, then at Harvard. Their major scientific advance was published in 1978. The theory of the effect of a general aspherical perturbation on the free oscillations of Earth was a very important contribution to the study of the three-dimensional structure of Earth. In fact, it is safe to say that the 1978 paper became the canonical reference for all subsequent studies. Partly on the basis of this work Tony was promoted to professor in 1979.

In 1981 Tony returned to the study of the Chandler wobble. He and Martin L. Smith used the observed period and Q (a measure of attenuation) of the wobble to constrain the frequency dependence of Earth's anelasticity. They provided the first correct calculation of the effects of the fluid core and the oceans on the Chandler period and clarified the nature of the Chandler energy budget, which is complicated by the strong effect of the Coriolis force.

After some preliminary work on seismic-ray theory, a subject of great interest in later years, Tony's attention was stimulated by discussions with a colleague, John Suppe, a structural geologist at Princeton. The stimulation blossomed into a series of papers on the mechanics of fold-and-thrust belts and accretionary wedges. This subject area was far removed from Tony's previous interests but he approached it with his increasingly sophisticated methods. During this period of work on fold-and-thrust belts, 1982-1990, Alexander J. Dahlen was born to Tony and Liz, in 1984.

In a series of definitive papers with D. Davis and J. Suppe, Tony showed that active fold-and-thrust belts and accretionary wedges are mechanically analogous to a wedge of unconsolidated material (e.g., soil or snow) being pushed by a bulldozer. His theoretical development represents an exact solution in all regions of parameter space. Consequently, a host of seemingly disparate tectonic features in submarine wedges are shown to be developed by the same dynamical process. This synthesis is a profound result. The analytical results and conclusions have been confirmed in a large number of sandbox experiments and finite-element models. The work was presented at the annual Geological Society of America meeting in 1986. It won the Best Paper Award, Structural Geology and Tectonics Division, Geological Society of America. In that year Tony was elected a fellow of the American Geophysical Union.

The two papers with I. H. Henson (1985, 1986) on asymptotic normal modes of Earth use the Einstein-Brillouin-Keller (EBK) semiclassical quantization theory to analyze the adiabatic invariants of the constituent multiorbit surface waves. In 1998 he and Jeroen Tromp, a former student, published their treatise, Theoretical Global Seismology, a book that has become the gold standard on the subject.

During a second sabbatical (1993-1994) at the Institut de Physique du Globe de Paris Tony worked on a series of definitive papers on the splitting and coupling of free oscillations on an aspherical Earth, asymptotic normal modes of Earth, and ray theoretical analysis of waveguide modes. During this period, the American Academy of Arts and Sciences elected Tony a fellow. In addition, he collaborated with H. Marquering and G. Nolet (1998, 1999) on three-dimensional sensitivity kernels for finite-frequency travel times and the banana-doughnut paradox. The work was a major departure from geometrical ray theory and led to the development of what has come to be called "banana-doughnut" theory. The basic idea is that a perturbation located on a Fermat ray path has negligible effect on the travel time. Perturbations in the first Fresnel zone that surrounds the geometrical ray path have a more profound effect. The banana is the lateral view of the Fresnel zone and the doughnut is its cross-section.

In 2000, on the basis of his large body of impressive research Tony was elected to the National Academy of Sciences. His citation reads: "Tony Dahlen has made highly creative contributions to theoretical seismology and to theoretical geodynamics and tectonophysics. A very large part of three-dimensional seismic tomography is based on his work. Moreover, our current understanding of all near-surface accretionary processes results from his contributions."

Tony continued to work on banana-doughnut theory with Guust Nolet and graduate student S.-H. Hung (2000). After becoming chair of the Department of Geosciences in 2001, Tony continued his impressive pace of research. With several colleagues he used banana-doughnut theory with finite-frequency tomography to reveal the presence of a variety of plumes in the mantle. This work was published in Science (2004) and was named a "hot paper" in Essential Science Indicators (http://esi-topics.com/nhp/nhp-may2005.html). Geophysicists had long argued, in the absence of much evidence, whether mantle plumes existed at all and if so, whether they originated near the core-mantle boundary or in the upper mantle. During this productive period Tony was named the Beno Gutenberg lecturer by the American Geophysical Union in 2002 and received the AGU's Inge Lehmann Medal in 2004. Further work on finite-frequency effects was extended to surface-wave tomography and to the production of a catalogue of deep-mantle plumes.

By the middle of 2005 Tony had become afflicted by cancer of the esophagus. He continued to pursue research topics in a range of subjects and turned his attention to multitaper analysis on a sphere. His work with F. J. Simons (2008) on spherical Slepian functions represents a new contribution to spectral estimation on a sphere. During this period, Caltech selected Tony for its Distinguished Alumni Award.

In April 2007 the Seismological Society of America (SSA) selected Tony to receive the Harry Fielding Reid Medal, the highest honor of the society. William ("Bill") Ellsworth, SSA president, sent the medal to Princeton in the hope that Tony would receive it in the last days of his life. Unfortunately, on June 3, 2007, Tony died from complications arising from his cancer, one day before the arrival of the medal. It was awarded posthumously in 2008 at the annual SSA meeting (Appendix 2).

PROFESSIONAL SERVICE

During his career Tony served his profession in many ways, including:

National Science Foundation, Graduate Fellowship Review Panel, 1976

Associate editor, Geophysical Journal of the Royal Astronomical Society, 1977-1980

National Science Foundation, Earth Sciences Review Panel, 1982-1985

IRIS, Standing Committee on the Global Seismic Network, 1983-1985

Office of Technology Assessment, Advisory Panel on Seismic Verification, 1986-1987

National Science Foundation, Principal Young Investigator Awards Review Panel, 1986-1987

Visiting Committee, Department of Earth and Planetary Sciences, Harvard University, 1987-1993

International Union of Geodesy and Geophysics, Committee on Mathematical Geophysics, 1988-1992

National Science Foundation, Science and Technology Centers Review Panel, 1988

National Research Council, Committee on Seismology, 1989-1995

IT IS A PLEASURE TO ACKNOWLEDGE the contributions of Elisabeth H. Dahlen, Guust Nolet, Frederik Simons and Gerald Wasserburg. (The appendixes contain a letter from Elizabeth Dahlen, a presentation by Guust Nolet upon the posthumous award of the Reid medal, and an editorial from the *Geophysical Journal International.*)

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APPENDIX 1

Elisabeth H. Dahlen wrote to Freeman Gilbert on October 22, 2007, a few months after Tony's death. The following remarks are taken from her letter.

Tony's parents were schoolteachers in a one-room schoolhouse in Idaho. Mary taught the lower grades and Fritz the upper. Fritz was the son of German immigrants. His mother died at an early age and he and his two brothers were raised by his father. Mary grew up on a farm in Missouri and I can't remember how she got to Idaho but they met at school and fell deeply in love.

Tony was born on December 5, 1942 in American Falls, Idaho, while his father was in the navy. Because of the war, he did not see his father until he was three. At that time, they moved to Albuquerque, New Mexico so that Fritz could get a BA (he and Mary had both been teaching with a 2 year degree) from the University of New Mexico. Mary insisted on moving somewhere warm after her time in Idaho, so the family moved to Winslow, Arizona where they lived until they retired. Tony was an only child.

Winslow is a small town of about 10,000, 50 miles from Flagstaff. The main highway across the country, Route US 66, went right through the middle of town. It was also a crew change station for the Santa Fe Railroad. The town had a large population of Hopis and was considered the gateway to the Navajo country. The Navajos from the reservation sent their children to dormitories in Winslow so that they could attend school. The school system was far from stellar. Tony was the top student all the way through school. His father was eventually the superintendent of schools and his mother became the high school librarian. Tony's teachers always suspected his parents of doing his homework because it was so good. Tony particularly liked mechanical drawing and went far beyond the class. I think he loved calligraphy just as much though many years later.

Tony grew up hunting and fishing. He got his first hunting rifle at age nine. Family vacations were trips to different western states with a camper hitched to the car for hunting or fishing. Tony loved football and joined the high school team but was always on the bench. He also loved his ham radio. He coached a basketball team, delivered newspapers for a while, and had a very small-town experience.

When he applied to college his parents pulled down the World Almanac and looked for colleges with the name “technology” in them. He also applied to a few other schools, Princeton being one. Ironically, he got in every school to which he applied with full scholarship except for Princeton which simply admitted him. That was like a rejection since he did not have the money to attend. In the end he got an Alfred Sloan fellowship that paid the costs. Tony went off to college intending to help the US keep up with the Russians (it was right after Sputnik).

At Caltech he changed a lot. His peers had been better prepared and were far more worldly than he. He was worried he would flunk out so at first he didn’t do any extracurricular activities. Eventually he found his way and began to feel comfortable. He realized he did not want to be an engineer and was drawn to geophysics because he loved physics and he loved the outdoors. There was a particular professor at Caltech who had an influence on him; I believe his name was Jerry Wasserburg. His friends at Caltech were also very different from what he was used to.

Tony took every opportunity to learn new things. He took the great books humanities courses, art history, and world history. In his later years, he would spend a lot of time reading history and fiction for pleasure. His interests were always very broad.

He selected IGPP for grad school because of you and George. He packed up his belongings and sent them by bus. He rode his bike to San Diego but soon thereafter his parents bought him a VW. Bike riding was another love. It really didn’t start until the year we were in Boulder (after 2 years at Princeton). But after that it continued throughout his life. He mostly rode alone but enjoyed the time Jeroen Tromp used to ride with him. He also took up photography while in grad school but it only lasted a few years.

In La Jolla, he lived with Bob Stewart and after that with Jon Berger, and then with me in Del Mar. The summer after his first year he went to Costa Rica on FLIP (the Scripps Floating Instrument Platform) and then traveled up through Mexico. He played volleyball every day at noon. He took lots of math courses throughout his five years. Even when he got to Princeton he continued to sit in on Martin Kruskal's math course.

APPENDIX 2

SEISMOLOGICAL SOCIETY OF AMERICA
HARRY FIELDING REID MEDAL
PRESENTED POSTHUMOUSLY BY GUUST NOLET, APRIL 17, 2008

Tony Dahlen, who should really have been here to receive the Reid medal, died last June in Princeton, NJ, after having battled cancer for two years. Many of you knew Tony personally, quite a few of you worked at some time with Tony, and the session today shows that Tony's spirit is still very much alive.

Through his seminal research on topics as far apart as the Earth's rotation and the growth of mountains in convergent margins, and certainly through his standard textbook with Jeroen Tromp on theoretical global seismology, he exerted a strong influence on geophysics, and on seismology in particular.

Tony was born in 1942 in Idaho while his father served in the US Navy. After the end of the war, the family moved to Winslow, Arizona, where he grew up in the shadow of Meteor Crater. He often told me how he spent hours searching for fossils and meteor fragments in the desert. But he combined this interest in geology with a passion for mathematics and physics, and a scholarship brought him first to Caltech, and then to UC San Diego.

The newly established university was still cutting its teeth at the time. But the Scripps Institution of Oceanography, on the same campus in La Jolla, had already become one of the major US geoscience laboratories in the wake of the Second World War and this institution was where the geosciences were hosted. It was an exciting time in particular for global seismology, which influenced Tony's choice of research topic. The huge earthquakes in Chile of 1960 and in Alaska of 1964 had visibly excited the lowest eigenvibrations of the Earth.

For his PhD thesis, Tony tracked the problem of the coupling of modes that were split by the Earth's rotation and its elliptical shape. This work laid the foundation for his development of the splitting of modes due to lateral heterogeneity, which culminated in 1979 in a joint paper with John Woodhouse that can be seen as the beginning of low-frequency tomography.

In that same decade he also made important contributions to dislocation theory, incorporating pre-stress, rotation and self-gravitation into the theoretical framework and culminating in his 1977 paper on the energy balance of earthquakes. With Martin Smith he developed a linearized perturbation theory for wave velocities in an anisotropic Earth which today forms the most practical means for imaging the flow directions in the Earth's mantle, and also with Martin he studied the Earth's viscous response to stresses using the damping of the Chandler wobble.

In the 1980's Tony worked with Dan Davis and John Suppe on the mechanics of fold-and-thrust belts and accretionary wedges. He showed how the seismicity and folding 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, and he calculated the energy balance of such a system for western Taiwan.

The 1000-page textbook 'Theoretical Global Seismology' marks the culmination point of three decades of research by Tony and others in the field of low frequency seismology. By the time the book came out, Tony had shifted his attention to body waves, which can provide a sharper tomographic resolution. The theory of seismic body waves had barely evolved since the beginning of the twentieth century. He worked with

Princeton students and colleagues on the properties of P and S waves at finite frequency, rejecting the classical paradigm of seismic waves propagating as narrow rays as in (infinite frequency) optics, and using paraxial theory to provide an efficient computational strategy.

I feel very fortunate to have worked with Tony at this time. He was a giant as a scientist, but as a person he was courteous, unassuming and generous towards students and colleagues alike. Had he been here, he would certainly have belittled his own accomplishments and stressed those of others. But he was elated when Raffaella Montelli showed that she could resolve plumes in the lower mantle with his new theory, and he would have been proud to see the progress being made at today's session in his honour.

Tony's untimely death is still too near. His family, Elisabeth and Alex, have preferred to stay home for this occasion which is a celebration, but which of course also revives memories of happier times when he was still around. Those who have worked with him have the luxury of seeing his work live on. We think it is most appropriate if the Reid medal is carried to Princeton by the younger generation of Tony's collaborators who are here: Tarje Nissen-Meyer, Frederik Simons, Yue Tian, Li Zhao.

APPENDIX 3

EDITORIAL BY C. J. EBINGER
GEOPHYSICAL JOURNAL INTERNATIONAL
FRANCIS ANTHONY DAHLEN JR.
GEOPHYS. J. INT. 174(2008):773

The current issue contains the last paper by F. A. Dahlen. Tony, as he was known, served our journal as an associate Editor from 1977 to 1980, when it was still the Geophysical Journal of the Royal Astronomical Society. His 64th paper in the journal was submitted in his 64th year, but Tony passed away June 3 2007, before its completion.

Over the course of his distinguished career, starting with his two-part *The normal modes of a rotating, elliptical Earth* (Dahlen 1968, 1969), Tony continued publishing seminal contributions to theoretical geophysics—at a rate of one or two papers per year in this journal alone.

Initially primarily concerned with the free oscillations of the Earth, his work eventually came to encompass all of theoretical global seismology—the title of his monumental 1998 textbook written on the subject (Dahlen & Tromp 1998), including normal-mode theory, Earth rotation, the earthquake source, body waves and surface waves. In addition, he made lasting contributions to the mechanics and thermodynamics of brittle frictional mountain building. Among his numerous contributions in the last decade were paradigm-shifting papers in a series on 'finite-frequency sensitivity kernels'.

While these 'banana-doughnuts', as they became widely known, emerged as the topic du jour in geophysical circles, Tony had set his sights on solving a problem of a quite different nature: the analysis of noisy data distributed over incomplete portions of a spherical surface.

As paraphrased from the paper in this issue (Dahlen & Simons 2008), as often arises in the (geo)physical sciences, we do not have access to, or may simply not be interested in, the values or properties of data outside some particular subregion of the sphere. As it turns out, noise-contaminated spherical data on mere portions of the sphere are best studied using so-called 'spherical Slepian functions' (Simons et al. 2006). These were named after David Slepian, the mathematician whose authoritative work on the eigenfunctions of the one-dimensional Dirichlet kernel (Slepian 1983) led to the widely used 'multitaper method' of time series analysis (e.g. Percival & Walden 1993).

Two different statistical problems that arise in this context are (i) how to find the best estimate of signal given such data, and (ii) how to construct from such data the best estimate of the power spectral density of the signal. A treatment of the first problem was published in this journal two years ago (Simons & Dahlen 2006); the second forms the subject of the paper in this issue (Dahlen & Simons 2008). Applications of the theory include disciplines as diverse as geodesy, geomagnetics, planetary science and global seismology, as well as, further afield, astronomy, cosmology, helioseismology, and medical imaging.

Tony collected all of the important awards in seismology and geophysics, and was a member of the United States National Academy of Sciences—but he always seemed most happy doing science, and helping others do theirs. He was a wonderful advisor and mentor to his students and post-docs and an incredibly generous colleague and collaborator. We at the Geophysical Journal feel privileged to have known this remarkable man.

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