Don L. Anderson

1933–2014

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
Thorne Lay

NATIONAL ACADEMY OF SCIENCES

DON LYNN **ANDERSON**

March 5, 1933–December 2, 2014

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By Thorne Lay

Don L. Anderson, the Eleanor and John R. McMillan Professor of Geophysics at the California Institute of Technology, was a geophysicist who made numerous seminal contributions to our understanding of Earth's origin, composition, structure and evolution. He pioneered applications of seismic anisotropy for global surface waves, contributed to discovering the seismic velocity discontinuities in the mantle's transition zone and initiated their mineralogical interpretation, established deep insights into seismic attenuation, co-authored the most widely used reference Earth structure model, helped to establish the field of global tomography, and re-opened inquiry into the nature of hotspot volcanism and mantle stratification. He contributed to initiatives that upgraded global and regional seismic instrumentation. He served as Director of the Caltech Seismological Laboratory for 22 years, overseeing a prolific scientific environment, distilling many advances into his masterpiece book *Theory of the Earth*. His enthusiasm for debate and his phenomenal editorial efforts raised the scientific standard of students and colleagues alike.

Don was a geophysicist of tremendous breadth, publishing about 325 peer-reviewed research papers between 1958 and 2014 in seismology, mineral physics, planetary science, tectonophysics, petrology and geochemistry. He had a remarkable familiarity with the literature across all these disciplines, keeping reprints sorted into a multitude of three-ring binders that he could access in an instant, uniquely positioning him to undertake the writing of his ambitious book, *The Theory of the Earth*, published in 1989. The title echoes James Hutton's 1788 paper and 1795 treatise that established the modern field of Geology, but Don brought to the topic an additional 200 years of enhanced understanding of physics, chemistry, and planetary context, incorporating many of his own contributions. Many graduate students who took Don's *Physics of the Earth's* Interior class at Caltech can recognize specific topics in his book that were class themes developed across several decades. His career was a life-long quest to understand the Earth as a planet and to have an impact across all disciplines by which the Earth is studied.

Early Life

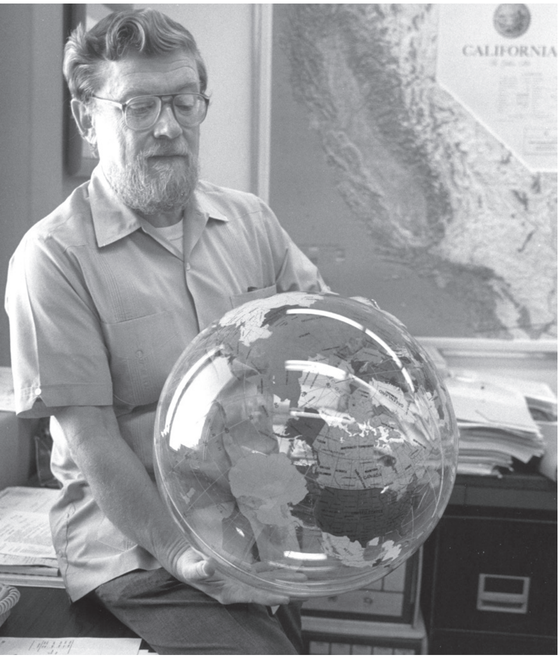
Don was born in Frederick, Maryland, the youngest of three siblings raised by a school teacher and an electrician. He attended high school at the Baltimore Polytechnic Institute, from which he graduated in 1950. He then pursued a B.S. in geology and geophysics at Rensselaer Polytechnic Institute, graduating with high honors in 1955. He worked for Chevron Oil Company for a year, involved in seismic exploration doodle-bugging in Montana, Wyoming, and California. He then fulfilled an ROTC obligation and served at the Air Force Cambridge Research Center, engaged in research on rheological properties of sea ice. This took him to Thule Air Base in northwestern Greenland, where his work had a practical emphasis on determining the thickness of ice needed to support emergency landings by aircraft.

In 1958 he relocated to Pasadena to become a graduate student at the California Institute of Technology, living in a trailer with his wife, Nancy, and two children, Lynn and Lee. His thesis work, rather loosely supervised by Frank Press, focused on seismic anisotropy, the property that causes elastic waves to travel through rocks with different velocities depending on wave direction and sense of particle motion. His 1962 Ph.D. thesis established the basis for understanding the discrepancy in velocity structures inferred from Rayleigh and Love waves when inadequate isotropic theory was assumed. He sustained an interest in seismic anisotropy for decades, and prompted its first-time incorporation into a reference Earth structure many years later. His improved theory for understanding surface wave dispersion revealed large-scale patterns of distinct structure beneath oceans and continents, extending far deeper than had been thought to be the case, and provided indications of structural complexities in the mantle transition zone at depths from 400 to 700 km. This prompted his career-spanning efforts in compositional and mineralogical models for mantle structure. He developed an interest in temperature-dependent partial melting and anelasticity and began to explore their effects on

Associate Professor of Geophysics in the Kresge Seismological Laboratory at Caltech in March, 1968. (Caltech Archives) surface waves and body waves experimentally and theoretically in what was to become another long-term interest culminating in the first-time incorporation of anelasticity and its frequency-dependent effects on seismic velocities into a reference Earth structure. In 1963 he became a faculty member at Caltech, where he was to pursue his entire research career.

Director of the Seismological Laboratory

Don became the fourth director of the Caltech Seismological Laboratory in 1967 (following Frank Press's departure for MIT in 1965) and held that position for 22 years. Under his leadership the Seismo Lab became the world's foremost program in global seismology, pioneering quantitative investigations of deep Earth structure and earthquake rupture processes. Don regularly presided over the twice-daily coffee break 'hours' where many ideas and discoveries were spawned and he worked hard to protect the relative autonomy of the seismology group,



Don with the world in hands.

From 1965 to 1970, the accumulating seismic data from stations of the World Wide Standardized Seismographic Network (WWSSN) and regional arrays such as Tonto Forest led to the discovery of seismic velocity discontinuities in the transition zone, clarifying early inferences from the study of surface wave dispersion. These features were the most significant advances in deep Earth structure since the 1940s, and Don participated in both their observational detection and in their interpretation using phase equilibria for pressure-induced phase transitions in major mantle minerals such as olivine. He ensured that the Seismo Lab had active research in mineral physics, recognizing the critical symbiotic relationship between seismology and high-pressure experiments for interpreting the deep interior. While not an experimentalist himself, he drew upon burgeoning mineral physics findings to explore scenarios for the physical state of the interior. Don also tapped into evolving ideas of planetary accretion to place constraints on the composition and evolution of the Earth. This led to Don's active engagement with NASA on the lunar program and to his leadership as principal investigator of the seismological component of the Viking missions to Mars. He contributed early papers on the composition and origin of the Moon, Mars, and Venus, recognizing that this planetary context held key insights into the Earth itself.

In the 1970s, several major undertakings by Don laid the foundation for a new global reference Earth model. One was the systematic application of geophysical inverse theory to formulate the problem of solving for earth structure models from free oscillation, surface wave dispersion, and body wave travel time observations. Another was deep analysis of anelasticity effects on seismic waves, clarifying the dispersive effects of attenuation and resolving discrepancies between earth structures obtained from short period body wave travel times and long period surface waves or free oscillations. In a suite of collaborative papers with colleagues and students, the mysteries of anelastic properties of the mantle and core were resolved, setting the stage for Don's collaboration with Adam Dziewonski to construct the Preliminary Reference Earth Model (PREM), which commenced in 1977 and culminated in 1981. Drawing upon a large data set of body wave travel times, free oscillation periods, and seismic wave attenuation measurements, PREM provides a one-dimensional radial structure of elastic material properties and density throughout the Earth, but unlike earlier Earth models, it included radial anisotropy in the upper 220 km and depth dependent attenuation with accompanying velocity dispersion of shear and compressional wave speeds. This model has found vast applications in seismology, geodynamics, and mineral physics for decades, and is providing the foundation for current efforts to advance toward a fully three-dimensional reference Earth model. The development of PREM was cited when Don and Adam were awarded the Crafoord Prize in 1998 in Sweden.

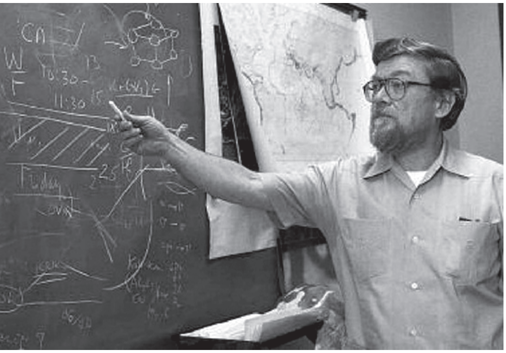
Don and Adam Dziewonski receiving the Crafoord Prize at the Royal Swedish Academy of Science in 1998.

Being located in Southern California, the Seismolab had a natural role in earthquake reporting and research, and Don helped to foster this by bringing Hiroo Kanamori and Don Helmberger to the faculty. They produced a revolution in seismology by introducing quantitative waveform modeling and inversion approaches for surface waves and body waves. While Don's primary interests were decidedly in planetary scale processes rather than earthquakes, he intermittently participated in important collaborative studies of earthquake source processes with Hiroo and with some students, typically prompted by data and ideas discussed in coffee break. In his capacity as Director, he ensured that the Caltech seismic stations and the regional earthquake monitoring network operated in collaboration with the USGS were progressively upgraded and maintained at the leading edge of technology for seismic operations. This enabled many research applications and earthquake monitoring contributions that are not directly reflected in Don's publications.

Observing the progressive decline of the WWSSN system, Don brought his influence to bear in building a community-wide initiative to upgrade the global seismic network with broadband, high dynamic range instrumentation that had been developed in the mid-1970s. This led to the establishment of the Incorporated Research Institutions for Seismology (IRIS), with the National Science Foundation and U.S. Geological Survey supporting establishment of a modern Global Seismic Network, which continues to provide superb data today for earthquake and Earth structure investigations. Don's role in bringing about the improved global seismological system was specifically acknowledged when he was awarded the National Medal of Science in 1998.

Don receiving the National Medal of Science from President Clinton in 1998.

Don resisted being swept along by conventional dogmas, in part because his exceptional breadth gave him familiarity with the limitations of observations and assumptions that often precariously perch existing paradigms on a house of cards. These weaknesses are often difficult to perceive from the perspective of stove-piped disciplines. He repeatedly invoked arguments from physics and thermodynamics, reinforced by common sense, to advocate for mineralogical and compositional scenarios for the Earth involving chemical stratification of the planet resulting from early differentiation. He sustained a conviction that the upper mantle and transition zone, down to about 800 km depth, presently convect separately from the lower mantle. Strong mantle stratification had long been embraced by geochemists to account for long-lived reservoirs of distinct isotopic



Don at the chalk board.
(Caltech archives.)

material, but this notion was progressively being challenged from about 1977 on by seismological evidence for significant interchange of upper and lower mantle materials and by geodynamical simulations supporting the viability of whole mantle mixing that could still preserving chemical heterogeneities.

Don proposed that Earth's transition zone is not peridotitic, as conventionally assumed, but is composed of piclogite, a pyroxene and garnet-rich rock. He argued that down-welling slabs of former oceanic lithosphere deflect and accumulate in the transition zone, rather than penetrating into the lower mantle. Seismological tests of deep slab penetration, petrological models, and comparisons of phase equilibria and elasticity with the PREM velocity structure were among many lines of argument that he explored with students and postdocs. The emergence of three-dimensional models of seismic velocities in the interior, the result of analysis of expanding digital broadband seismic body wave and surface wave data sets, provided fodder for Don's exploration of upper mantle evolution models. He was engaged with postdocs in developing some of the first seismic tomography models, using spherical harmonic expansions of the heterogeneity free of a priori shallow structure based parameterizations that had constrained regionalized models before the early 1980s. The underlying thermal and compositional variations that cause the lateral variations in seismic velocities were explored in his book Theory of the Earth in 1989 and became the focus of many of his papers over the next 25 years.

Later Days of Plume Revisionism

Debate continues today regarding the fate of downwelling oceanic lithosphere, with progressively improving tomographic imaging supporting the occurrence of deflection and accumulation of some slabs in the transition zone, but also at least partial penetration of some into the upper few hundred kilometers of the lower mantle. Large-scale patterns of deep three-dimensional variations are commonly attributed to long-term whole-mantle mixing of slab accumulations, which Don always took issue with.

In the years after his tenure as Seismo Lab Director (he retired in 1992, but remained active in research for the rest of his life), Don tended to focus on the complementary topic of upwelling hot material feeding into long-enduring volcanic hotspots. The notion that deep-seated thermal plumes of material rising from an internal boundary layer, commonly assumed to be above the core-mantle boundary, as advanced by W. Jason Morgan, has long been invoked as an additional argument for whole-mantle convection. Don argued that hotspot volcanism can instead be accounted for by chemical and thermal processes in the upper mantle, and he produced many articles addressing this question, along with contributing extensively to the website mantleplumes.org in collaboration with Gillian Foulger, to challenge the mantle plume paradigm. Notions of massive lithospheric tears, small-scale convection along margins of thick lithosphere, and top-driven dynamics of the shallow mantle, or "perisphere", were advanced in his later papers. Critics abound and Don's ideas remain controversial, but final answers are not yet clearly in hand. Possibly, the ultimate resolution will be some complex mix of end-members, as appears to be the case for subducting slabs, but his re-opening of the discussion and the vigorous exchange that ensued have benefitted the science without question.

The plume debate has sometimes been rather heated, but intellectual debate was always a passion of Don's. He could evolve his own ideas as new evidence came forward, even as he adhered to a pretty consistent world-vision of strong mantle stratification for many decades. Don always enjoyed being challenged and had a famous twinkle in his eyes during and after debates. His extraordinary breadth of knowledge made him a formidable debate adversary, as many have come to know. To the frustration of some, he did sometimes lapse into argument by assertion and exercised special selection of observations to support his case. He also did not validate many dynamical assertions by rigorous geodynamic calculations. But, for provoking discussion of ideas and shaking the foundations of whole mantle convection paradigms, he was unparalleled.

Don and Nancy on their 50th wedding anniversary.

Don contributed generously to the broad scientific community throughout his career. He served as president of the American Geophysical Union from 1988 to 1990, and chaired the Tectonophysics section and several AGU Honors committees. He also served on a huge number of committees advising NASA, NSF, the U.S. Geological Survey, the National Academy of Sciences, and the National Research Council. He mentored a number of students and colleagues, generously giving detailed reviews of manuscripts and providing many references to the literature with no expectation of co-authorship. His selection for the 1991 William Bowie Medal of the American Geophysical Union was a perfectly fitting tribute to his generous spirit of scientific collaboration.

Don L. Anderson died from cancer in Cambria, California on December 2, 2014, at the age of 81.

HONORS AND AWARDS

James B. Macelwane Medal of the American Geophysical Union, 1966

Apollo Achievement Award of the National Aeronautics and Space Administration, 1969

Fellow of the American Academy of Arts and Sciences, 1972

Newcomb Cleveland Prize of the American Association for the Advancement of Science (Viking Mission Scientists), 1977

NASA Exceptional Scientific Achievement Medal, 1977

Member of the National Academy of Sciences, 1982

Honorary Foreign Fellow of the European Union of Geosciences, 1985

Emil Wiechert Medal of the German Geophysical Society, 1986

Arthur L. Day Medal of the Geological Society of America, 1987

Gold Medal of the Royal Astronomical Society, 1988

Fellow of the American Association for the Advancement of Science, 1988

Member of the American Philosophical Society, 199

William Bowie Medal of the American Geophysical Union, 1991

Guggenheim Fellow, 1998

National Medal of Science, 1998

The Crafoord Prize of the Royal Swedish Academy of Sciences, 1998

Gutenberg Lecture, American Geophysical Union, 1999

Honorary doctorate from Rensselaer Polytechnic Institute, 2000

Distinguished Alumni Award, Baltimore Polytechnic Institute, 2001

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Don L. Anderson's published papers from 1958-1999 are available at: http://www.mantleplumes.org/DLA.html

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