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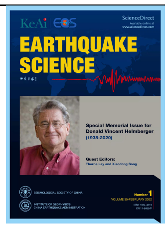


In Memoriam

# A graduate student experience with Professor Donald V. Helmberger

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A year after the passing of Don Helmberger, it is remarkable how memories of interactions with him over my entire professional career continue to spark affection and admiration. I arrived at Caltech in the summer of 1978 having had typically little exposure to seismology as an undergraduate. One of my academic advisors during my undergraduate program in Geomechanics (a joint program between Geology and Mechanical Engineering at the University of Rochester) was Geoff Davies, who had received his Ph.D. at Caltech working in mineral physics. Perhaps two-weeks-worth of seismology was covered in a survey of geophysics class that I had taken from Geoff, so the field was pretty much unknown to me. Geoff was actually not very encouraging about me possibly going to Caltech when I applied, but I was very keen to head south from the rough Rochester winters so I ignored him. I was a graduate student at the Caltech Seismological Laboratory from 1978 to 1983, and a postdoc there for 9 months longer before leaving for a faculty position at the University of Michigan. It was, nostalgically, a golden age in the Seismo Lab, affording my classmates (Tom Hearn, Marianne C. Walck, Terry C. Wallace, Mario Vassilliou) and myself the opportunity to interact daily with Don Helmberger, Hiroo Kanamori, Don Anderson, David Harkrider, Tom Ahrens, Clarence Allen, and Bernard Minster. Figure 1 shows the Seismo Lab crew sometime in the 1978–1979 academic year. What more could a graduate student ask for than to be surrounded by these creative geophysical pioneers along with more senior graduate students while seeking your own place in the world of seismology?

The immersive environment upon entry to the Seismo Lab was intoxicating; a true smorgasbord of topics was laid before us in twice daily Seismo Coffee Hour sessions (sometimes greatly exceeding the nominal 1-hour scheduled for each). Key seismological topics of the day were new applications of seismic waveform modeling to study earthquake sources and upper mantle triplication structure, modeling of long-period surface wave spectra for large earthquake faulting models, application of new frequency-dependent parameterizations of seismic attenuation, and seismic array analysis of the new digital regional seismic network (SCARLET) in Southern California. The program encouraged students to work on multiple projects with different faculty, and we were required to develop three research propositions to defend in an oral exam at the beginning of our second year. The open-door policy of the faculty enabled us to readily inquire about possible

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**Figure 1.** Photo of the faculty, research staff and graduate students in the Seismo Lab at Caltech in 1978-1979. Don Helmberger is sitting in the first row, second from the left. The author is sitting in the first row 7th from the left, yes, with no shoes on. From Caltech archives.

research projects (you did have to overcome the feeling that you were wasting the faculty's valuable work time), and I initiated efforts on body and surface waves from large earthquakes in the Solomon Islands with Hiroo Kanamori, lateral variation in upper mantle velocity structure and attenuation with Don Helmberger, analysis of the onset of P wave diffraction by the core using SCARLET, guided by senior students Rhett Butler and Larry Ruff, and frequency dependent reflectivity of PKiKP overseen by Don Anderson (OK, that never got published), along with a few additional aborted efforts that I barely remember.

With such different projects and advisors, it was a great opportunity to sample the diverse topics raised in coffee discussions and to feel like you were at the front edge of seismological research. Hiroo Kanamori is a tremendous teacher and patiently introduced me to his surface waves analysis codes and data processing as I undertook manual digitization of hundreds of WWSSN (World-Wide Standardized Seismograph Network; a global network of analog seismic stations deployed in the early 1960s; Peterson and Hutt, 2014) surface wave recordings for analyzing three large doublet events. Don Helmberger guided me to digitize many short-period and long-period P and SH body waveforms from deep earthquakes recorded across North American WWSSN and CSN (Canadian Seismograph Network) stations, seeking to constrain the systematic upper mantle variations in travel times and attenuation that account for the anomalous attributes of signals from nuclear tests at the Nevada Test Site (these were the days of the 1974 bilateral Threshold Test Ban Treaty which constrained underground nuclear tests by the U.S. and Soviet Union to less than 150 kt, so absolute amplitudes that are used for explosion yield estimates had to correctly account for upper mantle heterogeneity). All that digitizing (and the slow deterioration of the WWSSN analog network) made it a pleasure to work with digital data from SCARLET, but I gained an appreciation for how station gains and polarities could change even for digital recordings when sites were visited for maintenance. It was all intensely interesting and exciting to me, and these three topics were presented in my pre-oral exam (a trial-run presented to the graduate student group prior to the real oral exam before the faculty) (Figure 2). Somehow, I managed to pass my oral exam in October 1979, allowing me to continue on toward a Ph.D.

While I continued to work on projects with Hiroo Kanamori, elaborating on his ideas of slip heterogeneities in large earthquakes as framed in the Asperity Model, and working on novel digital recordings for the 1980 Mt. St. Helens eruption and the 1980 Eureka (Gorda Plate) earthquake, my research focus was increasingly under the supervision of Don Helmberger. There were several reasons for this; great earthquake occurrence dropped off

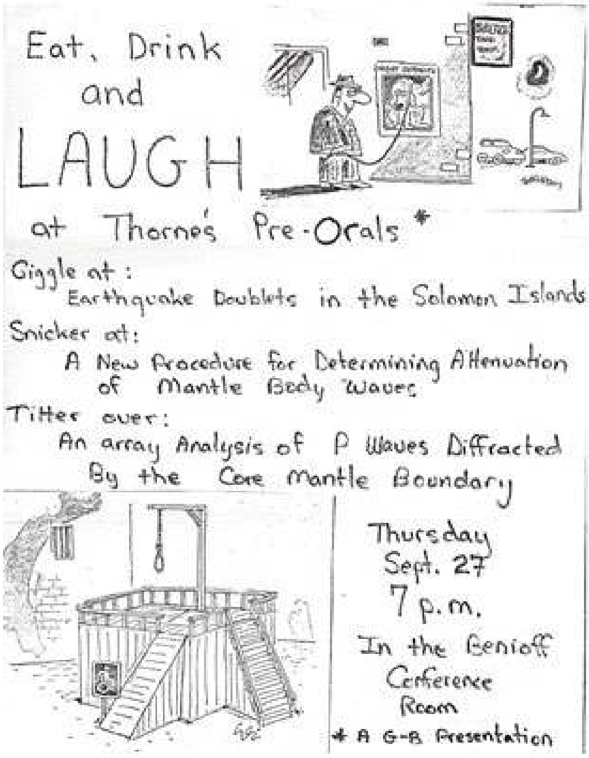


**Figure 2.** Copy of the announcement posted for my pre-oral exam on September 27, 1979. Presenting to fellow grad students proved much more stressful than the subsequent exam with the faculty; I think the system was intentionally designed that way to burn-off your nervousness prior to the real exam.

during the early 1980s just as I was becoming positioned to analyze their signals, while more senior students like Jeff Givens were working with Hiroo to rapidly advance efficient digital waveform analysis, so the technical side was covered. Also, I had found observational work particularly rewarding as it offered somewhat more frequent surprises; the large data set I had accumulated with Don was revealing travel time and amplitude behaviors (Lay and Helmberger, 1981, 1983a) that were not readily accounted for by the upper mantle variations that we had set out to document. One of the pleasures of looking at a *lot* of data with Don was that I realized he did not have all the answers in advance (unlike Hiroo, who seemingly always knew exactly where a project was going), and there was a sense of mutual discovery.

I began to appreciate that lower mantle structure has three-dimensional heterogeneities (Lay, 1983), only hinted at in the first-generation global tomography images that were beginning to appear, with effects that were readily apparent in the simple waveforms from deep events. Here I learned a profound lesson from Don; the Earth has myriad ways to make a seismic waveform complex (source rupture complexity, slab structure, receiver structure, instrument response, etc.), but if you observe a 'simple' waveform, it is not likely to be a fortuitous outcome of complex interference. Such simple waveforms thus indicate a clean path for which minor features can be reliably interpreted as Earth structure. This is a perspective now suppressed by automatic processing of large data sets, which is a loss. Using Don's generalized ray theory codes for 1-dimensional velocity structures, reproduction of simple waveforms by modifying radial structure had been making great progress in application to regional *Pnl* waveforms and upper mantle discontinuities. Don's one class provided deep understanding of the generalized ray theory method that he had developed based on the Cagniard-de Hoop solution. It was a great class and I sometimes sat in repeat offerings; I still teach a similar class that uses Don's lecture notes (and the nicely typed-up version from Tom Heaton's thesis).

Serendipitously, we gradually noticed that minor features in simple waveforms (Figure 3) had systematic variations with distance from the deep sources, and we sought to understand the origin of these features. This required familiarization with lots of waveforms (another profound lesson I learned from Don was to look at many waveforms carefully so that you could recognize anything unexpected), and we spent a lot of time looking at data (with Don intermittently staring out of his office windows for mysterious interludes). Through this I acquired my skill and enthusiasm for analyzing body waveforms directly from Don.

It became clear that the unexplained signals we were observing originated from the lower mantle. Don had previously worked on structure above the core-mantle boundary (CMB) when Brian Mitchell visited Caltech on sabbatical in the early 1970s. They produced an exotic model with very high shear velocity increases in a thin layer above the CMB to account for waveform differences between ScSH and ScSV (horizontally and vertically polarized reflections of *S* waves from the CMB) (Mitchell and Helmberger, 1973). Some recent array studies had proposed that a P velocity increase occurred about 170 km above the CMB based on subtle waveform interference effects (Wright and Lyons, 1980), but the prevailing perspective of the lower mantle elastic velocity structure was that it had smooth radial variations all the way down to the lowermost mantle where thermal boundary layer effects produce reduced velocity gradients and increased lateral heterogeneity in the so-called D" region overlying the CMB. I had greatly augmented the data considered by Mitchell and Helmberger (1973), and the waveform feature they had discovered was clearly supported and could be modeled as they suggested (Lay and Helmberger,

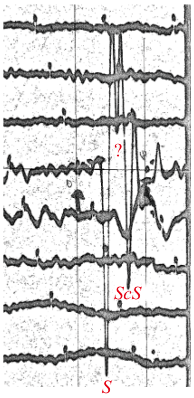


**Figure 3.** Segment of the recording for a deep earthquake below the Sea of Okhotsk on the EW component of the long-period WWSSN instrument (15-100 Sprengnether) at SCP, which operated with a gain of 1500 at 15 s period. The analog record was on a rotating drum that covered one hour per row, with tick marks every minute. The ground shaking shows the impulsive S and ScS arrivals, with an unexplained pulse in between that captured our attention. These signals had to be manually digitized and the horizontal components were digitally rotated to isolate the transverse (SH) component of the signal. I still have copies of several thousand seismograms like this that were used in my work with Don.

1983b), but this most likely involved anisotropic structure of D" rather thin high velocity layers, as was modeled much later (Garnero and Lay, 1997). Our focus was on the unexpected arrivals between direct S and the core reflection ScS like that in Figure 3, which are not accounted for by standard Earth models such as PREM or the JB model. Guided by Don's experience in modeling upper mantle triplications, we introduced a sharp velocity jump of 2% to 3% at the top of the D" region, about 250–300 km above the CMB, with synthetic seismograms being computed using one of his 1D generalized ray theory codes (BOUNCE) accounting for the timing and amplitude of the extra arrivals (Figure 4) as the result of triplication of the wavefront. A triplication results in three arrivals at some distances: some energy turns above the discontinuity, some reflects off it, and some turns below the discontinuity. This was the discovery of the D" seismic shear velocity discontinuity (Lay and Helmberger, 1983c, d), and it became a focus of my Ph.D. thesis and of much work with students over the next decade. It is probably fair to say that it spurred interest in D" structure, as related research subsequently expanded greatly. About 20 years later it was established that a phase change in (Mg,Fe)$SiO_3$ magnesium-silicate perovskite (Bridgmanite) in relatively low temperature mantle downwelling regions can plausibly account for the depth, strength and lateral variation of this seismic velocity discontinuity.

As an advisor, Don was very encouraging of meeting

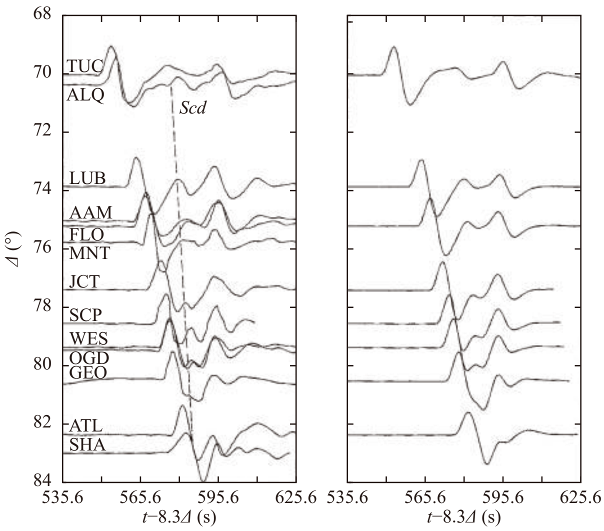


**Figure 4.** Profile of digitized WWSSN SH component recordings for the 29 January 1971 event (left panel) showing the systematic move-out with increasing epicentral distance, Δ, for the extra arrival between S and ScS seen in Figure 3, which we labeled Scd. Generalized ray theory synthetics for a model with a 2.75% shear velocity discontinuity at the top of the D" layer are shown on the right, matching the primary features of the observed signals. From Lay and Helmberger (1983d).

attendance, and prompted me to attend my first Air Force Research conferences, my first international meeting, which was for Mathematical Geophysics, along with other domestic meetings. He always checked to see if a meeting had been enjoyable; he particularly enjoyed international meetings with some attendant extra excursions, and I embraced that practice throughout my career. Don also sustained the Seismo Lab football games on Saturdays and he clearly enjoyed displaying his athletic skills, which outpaced most of the graduate students. These personal touches stuck with you, making you feel like a part of both the local and external scientific communities.

In the last year or two while I was a graduate student and throughout my postdoc appointment, I was a seismological consultant with Woodward Clyde Consultants, for which Don had established a Pasadena research office with funding primarily derived from the Air Force. This involved work using Don's codes ASERIES and BOUNCE to model P wave recordings for underground nuclear tests. Together with Larry Burdick, one of Don's former Ph.D. students, we developed a relative waveform equalization procedure (Intercorrelation) to estimate explosion source time functions, depths, and yields using teleseismic data (Lay et al., 1984a), and to model near-field strong motion recordings for source functions of large explosions along with absolute attenuation operators that matched the far-field observed amplitudes and waveforms (Burdick et al., 1984). Terry and I worked with Don on tectonic release from nuclear explosions using sP arrivals at regional distances and teleseismic amplitude patterns (Lay et al., 1984c). My one joint collaboration with Don and David Harkrider determined broadband source functions for the Amchitka nuclear tests using body and surface wave observations (Lay et al., 1984b); that was my last work while at Caltech.

Over the ensuing years, I had the opportunity to work with Don a bit on the 2004 Sumatra-Andaman earthquake, and in a review of the post-perovskite phase change interpretation of the D” discontinuity after he was elected to the National Academy of Sciences. I also had many visits to Caltech in which we chatted about waveforms and the impressive discoveries he was making with later generations of graduate students. His enthusiasm remained unabated and his advances in core, deep mantle, upper mantle, and earthquake source modeling were breathtaking. We also intersected at many meetings and sometimes enjoyed field trips (Figure 5), where he did his best to get some of his current and former students in trouble (with grizzly bears!). He somehow nominated me to join him in service on the Air Force Technical Applications (AFTAC) Seismic Review Panel, which advises the nuclear test monitoring operations of the government. As a result, we also met three times a year at AFTAC in Florida or in Pinedale, Wyoming, with day-long meetings in windowless rooms, after which Don was always up for a long walk on a beach or in the woods. Mostly we talked about seismic waves on those walks, as always, sharing a wonderful comaraderie born of mutual enthusiasm for the joys of extracting information from seismograms. I will always remember and miss those conversations with my mentor.

**Figure 5.** A side excursion to Denali Park, after a Seismological Society of America meeting in Anchorage in 1984. Don is elevating himself above Thorne Lay and Steve Grand, while Heidi Houston relaxes. This excursion was memorable as our group left the bus into the park (illegally) so we could walk across the tundra to see Denali better. Of course, there were grizzly bears, and Don just had to try to get their attention. Photo by John Vidale.

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