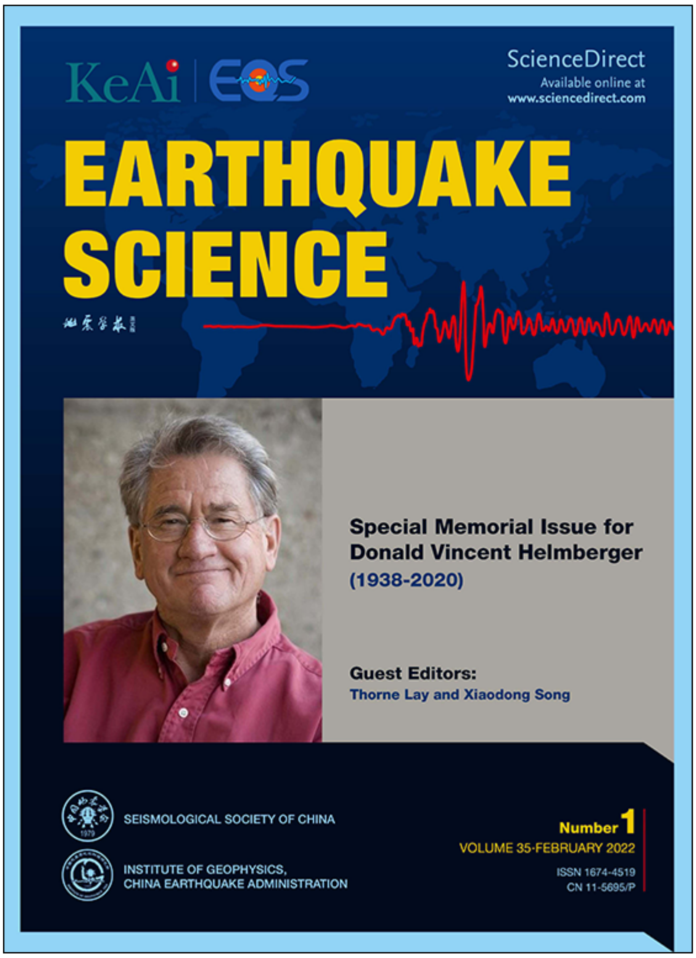
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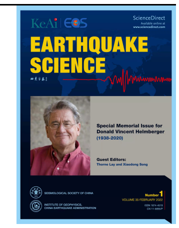

In Memoriam

Donald V. Helmberger the Mentor

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Don is certainly missed, by me, and by so many others. I particularly miss the constancy I derived by thinking of him down in Pasadena on the third floor of South Mudd, under the tree in his office, looking at waveforms. I have myriad memories with him, formed not just as a student at the Caltech Seismo Lab but over the two decades following. It is therefore a bit difficult to choose which I might use to paint a picture of the person I knew, the person who did more to shape me scientifically than anybody except my father, and the person for whom I felt such affection. Obviously, pure science, waveform modeling done purely for curiosity to tease out Earth's secrets, should take center stage, particularly for this venue, but Don was a rich tapestry of humanity and science, so I thought I might tell a few offbeat stories, interwoven with the work I did with him, to offer up my sense of him.

Don was, at his core, salt-of-the-earth, and he had a lot of sayings for a lot of situations. One I heard more than once, and which I think he was proud of, was "I grew up on a ranch and when something broke, you fixed it". The first I heard it was early on, just a few months into graduate school, when he wandered into my office. He'd been back-burner thinking, as was his wont, about some Mammoth Lakes waveforms I'd shown him and had started modeling. Rather than working diligently on my betterment through my science, he instead found me and my officemate pouring over a newly milled and acid-bathed aluminum head for my hideous late '70s Mazda hatchback car' that had previously died and which my roommate and I had decided, based on no evidence or prior experience, that we could fix. I recall kind of trying to hide the head from Don, since I was putatively modeling shallow caldera anisotropy in that office and it being very un-Caltech to have an engine head sitting on your office desk, but Don saw it nonetheless. To my surprise, rather than chew me out like I might have expected, he lit right into it. He poked at it, flopped it over, asked for a book to push down on and test the valve stems so he could see their seatings, peered into water jackets, etc. He asked a bunch of questions that clearly indicated he knew what he was talking about, and concluded we were right in our diagnosis. When I commented that he seemed to know a lot about engines, voila- "I grew up on a ranch and when something broke, you fixed it". It was wondrous to me, at my young age, squaring Don-the-Cagniard-de-Hoop-path-integral-through-complex-ray-parameter-space abstractician with Don-the-small-engine-repair-guy. But that was the thing with Don, the more you got to know him, the more layers you discovered there were to him.

Don was a gentle soul and to get him to yell at you, and I mean really let loose, took some doing. It happened

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precisely once, playing Don's version of American football, a game affectionately known as Helmberger Ball. The rules of this game, held on Saturday mornings, pretty much went as follows: Don always played quarterback, all Helmberger students were duly expected to show up to populate both teams, and Don's team always won. When I first arrived at the Seismo Lab, being a big American guy, Don assumed I could play football, when in fact I had never previously played, or even watched, a football game, so I was no good. But I was fast, as was he, and the incident of note happened when I failed to catch a pass inbound to me while Don was covering me. We both jumped into the air to catch the pass, I missed it in a way no receiver should ever miss, and it hit Don squarely on the middle finger and he went down howling. When he came up, cradling his hand, his middle finger was terribly broken, a step function right at the middle joint. I remember telling him we needed to take him to the ER, but he was looking at his hand, turning it over, this way and that, clearly in a lot of pain. Finally, he mumbled "It's not broken. Dislocated". And then, to my horror, he held his finger up right at me and said "Pull". Dismayed (to say the least), I said "Don you need to get to the ER and have that thing set." And then he let loose, and I mean he bellowed at the top of his lungs: "PULL!! GRAB IT AND PULL IT!!". So commanded, I took his finger in my hand, pulled hard, and there followed the grinding, rending-cartilage vibrations you get when you bend a chicken wing backwards to break it apart, followed by a pop, and suddenly the finger was straight. When something broke, you fixed it. At our regular meeting the following Monday, I could tell Don was deeply irritated with me. His finger was terribly swollen, black and blue, and duct-taped to an adjacent finger. Clearly, had not bothered with a doctor. When I asked how it was doing, he was obviously bitter, and muttered something along the lines of "It's fine. I don't see how you could possibly have missed that ball". Perhaps, but we were all back playing Helmberger Ball once the quarterback's finger healed up.

Don's waveform intuition, developed through modeling of countless datasets, was remarkable, arguably the singular best in the world, for the fifty or so years he was active. I learned early on the trick of bringing him new waveforms to hide the fact that I'd gotten little done since our last meeting. It was remarkable to just to watch him muse over new waveforms and tease out physical structure within the Earth with his simple raypath drawings that could explain the coarse attributes of whatever it was we were looking at. The Seismo Lab at that time was in an interesting state because TriNet, as the original broadband network was then called, had only recently been funded and the first Streckheisen STS-1s had been around only a couple years and were showing all sorts of amazing things. But it was tedious to get the data out of the archives. It seemed wise to me at the time to figure out how to write some routines that would automatically parse incoming NEIC emails for hypocentral information, extract the relevant TriNet waveforms, sort by distance into record section and zoom into any particular phase, and then print it out on paper, paper being the only format Don could use. Once I got it working, every NEIC email automatically triggered the production of a record section of some phase waiting on the printer. The record sections piled up, Don was in heaven, and this endeavor yielded a very fun time spent looking at all sorts of lateral variation within the deep earth. There was no real focus to it, we just looked at phases that varied rapidly across the network from whichever earthquakes Mother Nature threw our way, from regional to nearly antipodal. For a few months, anyways, after which at some point even Don had had enough and started pushing me to actually finish modeling and write up some of the many small projects I had started.

All of the work I did end up publishing with Don came out of this tinkering. One record section yielded a remarkable range discrepancy between SCSN short-period recordings versus broad-band TriNet recordings of the back-branch of the 410 triplication from a perfect southern Baja California, Mexico low magnitude 6 event that lit up all of California and produced an extraordinarily clean full-bowtie triplication (Figure 1; Melbourne and Helmberger, 1998). The back-branch frequency dependence allowed us to constrain the thickness of the discontinuity fairly precisely; Cagniard synthetics done with a 5-km thick discontinuity produced quite different waveforms than did a 15-km thick discontinuity, for instance, and the best-fitting synthetics required a composite discontinuity that caused destructive interference and effectively quenched the short-period arrival beyond about 13 degrees of distance.

Another anomalous record section yielded a project of modeling diffracted precursors to SS along the Pacific-North American plate boundary that were very sensitive to lithospheric thickness. SS is a maximum travel-time phase and modeling the interference of these precursors with rays was tedious. But eventually I switched to a Frequency-Waveform code written by Lupei Zhu which was also a complete solution (with diffraction), fast and clean to use even if you didn't get the raypath information, so determining the structure was largely trial-and-error. But it allowed us to map out the E-W edge of Pacific plate lithosphere along the California and Baja borderlands, which we could then compare to the long-term velocity

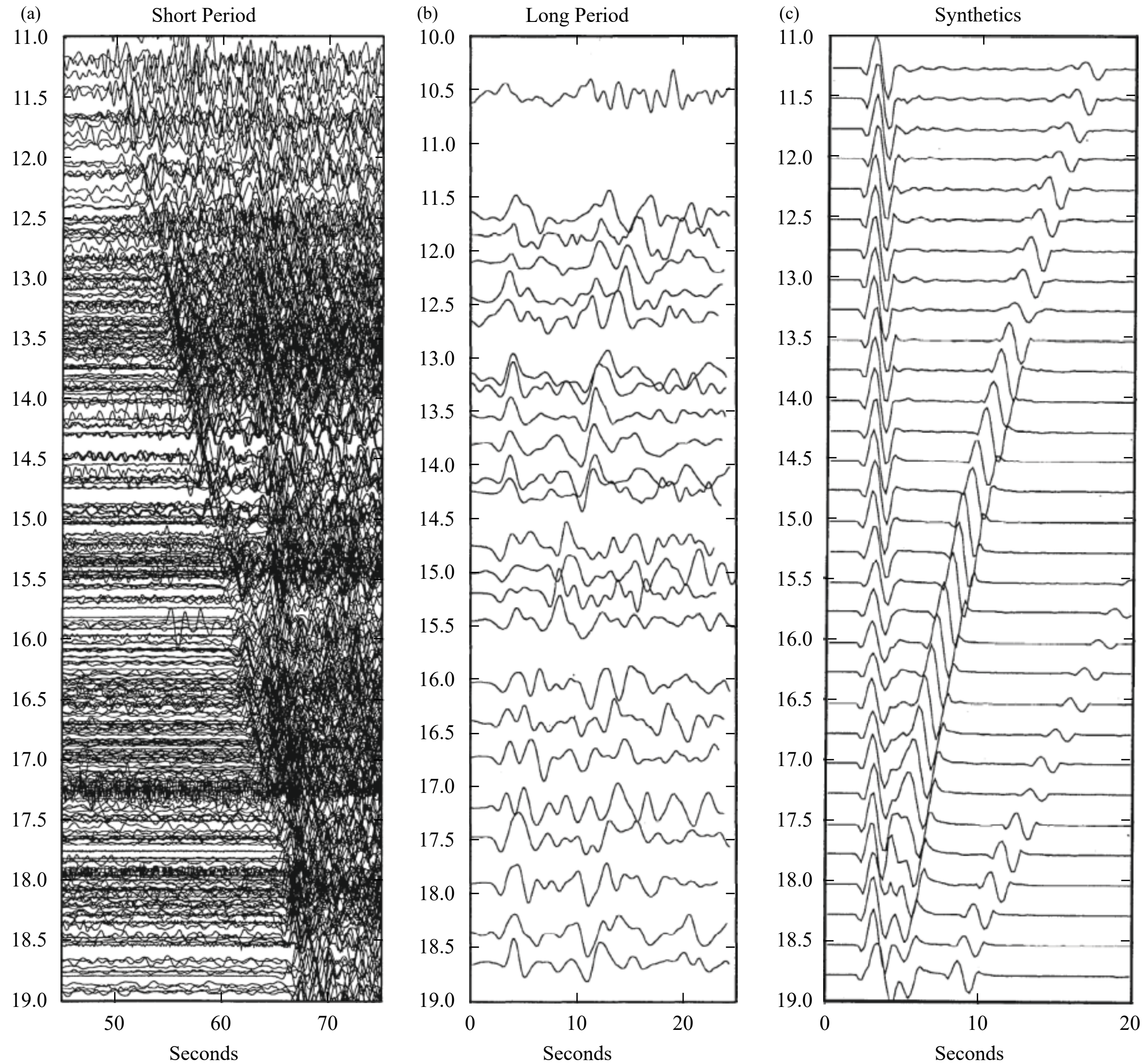

Figure 1. Fine structure of the 410 km discontinuity, from Melbourne and Helmberger (1998). (a) Short-period vertical data plotted with reduction velocity of 10.5 km/s. The 394 traces shown in this array are 1-Hz lowpass ltred and normalized to the maximum amplitude in the windown shown. The 410 reection is clearly visible out to near 13 degrees, where it rapidly disappears. (b) Long-period recordings show 410 reection to ~11 degrees. (c) Best-fitting Cagniard synthetics yield a composite 410 discontinuity in which a 3% velocity increase is overlain by an additional 3.5% increase spread over 14 km radial distance.

field that had recently come out of the new continuous GPS networks all over California (Figures 2 and 3; Melbourne and Helmberger, 2001). For all of the continental dynamics theories that are still argued over today, from our work, it sure looked like the steady-state strain rates along the California plate boundary, as measured with then-new continuous GPS networks, simply mirror the whole lithospheric thickness of the Pacific plate, what Don always called "the 800-lb gorilla of earth plate tectonics". The idea that the thickness of the whole lithosphere, rather than dynamics attributed California's overlying crust, which seems to be passively carried at a rate proportional to the thickness of the underlying mantle lithosphere, was controversial then and remains so today.

A third related project showed conclusively that the transition zone under the East Pacific Rise has no idea there's a spreading center above it (Figure 4; Melbourne and Helmberger, 2002). With the full development of California broad-band networks and the high earthquake productivity of the southern East Pacific Rise, we could map out transition zone structure and depth under and away from the spreading center itself, and I remember how fascinated Don was that I could find no systematic variation with distance away from the rise. Given the sensitivity of how the multiple branches of the triplication interfered to produce the observed waveforms, interference

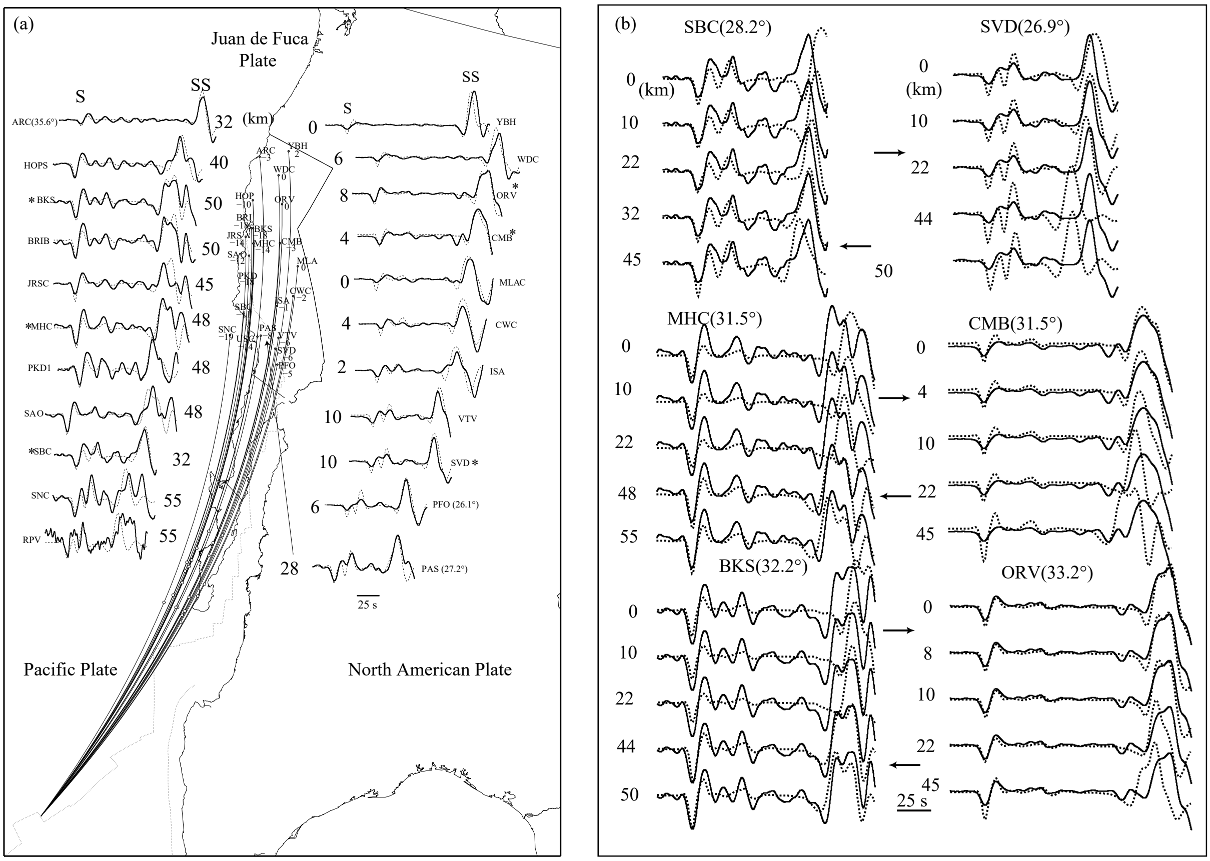

Figure 2. Mapping the Edge of the Pacific Plate Lithosphere, from Melbourne and Helmberger (2001). (a) Observed (solid) and calculated (dashed) shear body waveforms recorded along Pacific-North American plate boundary, with corresponding lid thickness printed beside each trace. Westernmost raypaths uniformly require substantially thicker lithospheric lid structure, averaging 50 km, while eastern paths require thin or no lithospheric lid structure, consistent with known Basin and Range upper mantle shear structure. S2-S travel time anomalies relative to TNA (Grand and Helmberger, 1984) in seconds are shown below station name. FK synthetics are computed for 1D average lithospheric lid thicknesses indicated adjacent to waveform traces. (b) Infuence of Lithospheric lid thickness on S2-S travel times and S2 waveforms. Varying lid thickness between 0 and 50 km produces over 20 seconds change in S2-S travel time, and strongly alters S2 pulse shape. Each shear wave seismogram is repeated 5 times, and overlaid with synthetics with a single 1D model in which the thickness of the high velocity lid (v_S=4.55 km/s versus v_S=4.4 km/s, non-lid) varies according to thickness printed to left of data trace. Lid thickness providing minimal synthetic-data mist is identied with arrow.

we could readily replicate in synthetics, Don felt it would be hard to ever come up with a more robust constraint on transition zone variability under the East Pacific Rise than these well-modeled record sections presented.

These were just three of the projects that I saw through to publication with Don, but I was always struck by the fact that the three were just three among dozens that I could have chosen from those automated record sections spat out like clockwork with every NEIC email. At some point, perhaps in my 5th year at Caltech, something clicked and I decided that I had done enough and that it was time to move on. I more or less announced this to Don one day, he didn't disagree, and that was that.

One of the gut instincts I took away from my work with him is that, at a 10 second period at least, the deep earth is a real mess and clean figures and simple velocity profiles really belie the complexity therein. There are many crazy structures, and, presumably processes, at work, whose signatures all blend together and become invisible in waveforms at longer periods or are smeared out or missed entirely by tomographic inversion. Don really gave me the freedom and liberty to pretty much pursue what I was interested in, and only if I pushed his patience too far, for instance by disappearing to climb mountains in Alaska, did he gently reign me in, in his way. But he was remarkably gracious and generous to a fault. For instance, my work with him was interrupted in the middle because I was serendipitously given an *M*8 earthquake that ruptured just offshore a GPS network that Joann Stock (also at Caltech) had built in Jalisco that I had partaken in as a

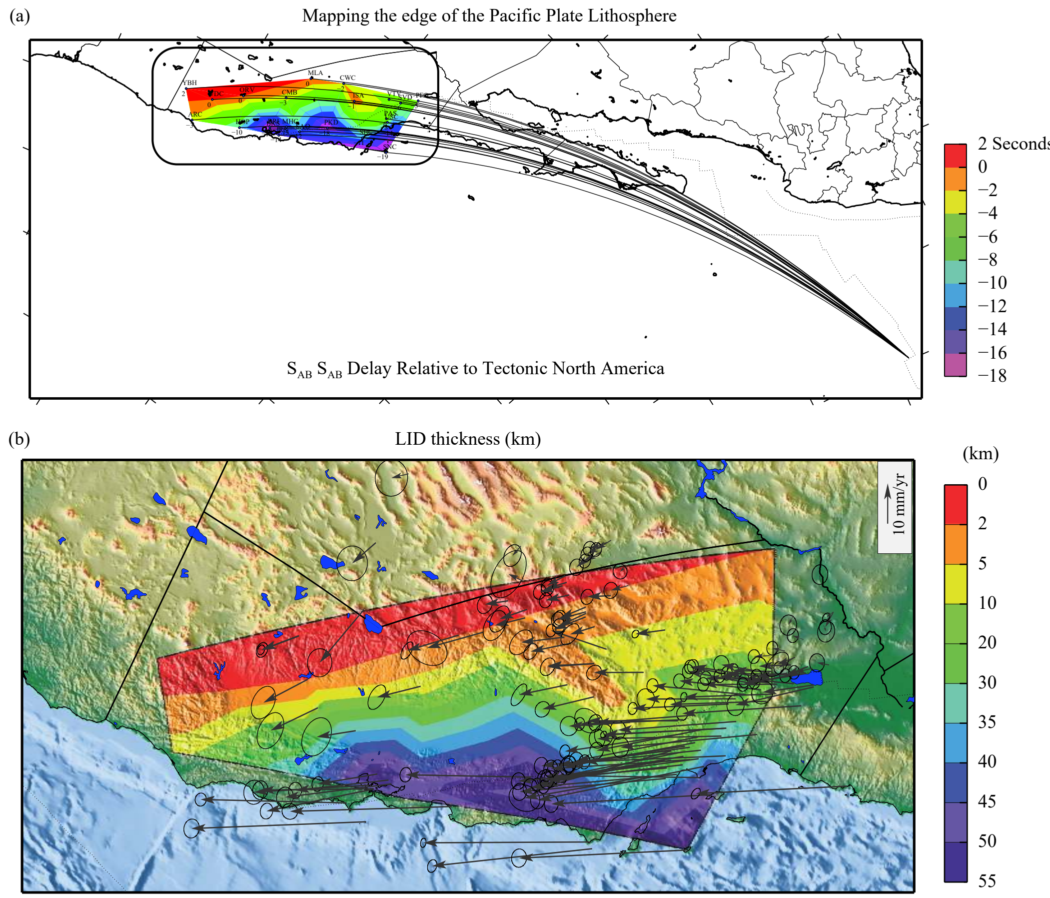

Figure 3. Mapping the Edge of the Pacific Plate Lithosphere, from Melbourne and Helmberger (2001). (a) Contoured delay in accrued SS (AB branch) arrival times relative to the Tectonic North America model of Grand and Helmberger (1984) for waveforms propagating along the Pacific Plate edge from the source at the East Pacific Rise. Inset square corresponds to bottom panel. (b) Contoured seismic lithosphere thicknesses beneath North American continental margin derived from broadband S2 waveforms and S2-S travel times. Lithospheric lid thicknesses range systematically from 55 km along margin coastal paths (Peninsular Baja-Western California), typical of Miocene-aged oceanic lithosphere and similar to that observed beneath eastern Pacific, to effectively 0 km along Eastern California-Eastern peninsular Baja paths, typical of Basin and Range upper mantle. Intraplate dextral strain, indicated by geodetic GPS measurements conducted across thick lithospheric lid regions, is substantially lower than interplate dextral strain, indicated by measurements taken across regions of.

first-year orals project. We were able to easily measure the coseismic deformation, but we were also able to image all sorts of transient creep events propagating around the plate interface following the mainshock. The creep events both triggered and were triggered by aftershocks, and the fact that we could image these was all very new in 1995. Don never hesitated when I told him I'd like to work on this gift-from-god-and-Joann-Stock; he knew I was totally motivated by the science and that was enough for him so he was very supportive. Two years and three papers later when I came back into his office to resume my work with him, it was like I had never left and we picked up where we had left off. That's unusual in science these days and testament to Don's love of science and his recognition that paths forward on the cutting edge are often tangled and take strange turns.

I'm going to stop now only because, while there are many more stories I could relate, I feel I've only scratched the surface of my time with Don. I was shocked to learn he had passed since I did not see it coming. I sat at my desk processing the news for a minute or two, and then walked down the hall to tell Craig Scrivner, another former Helmberger student with whom I work (PhD, 1998), who was equally stunned. We knew Don was 80ish, but he personified human time-invariance and I had just seen him at the SCEC meeting a few months earlier, where he seemed the same Don as ever. I suppose at great age a sudden departure can be preferable in some ways to a drawn-out decline, but I would have liked some warning so I could have made an effort to track him down and say, more than anything, thanks. Thanks for the tutelage, for the role model of kindness and generosity and extraordinary but

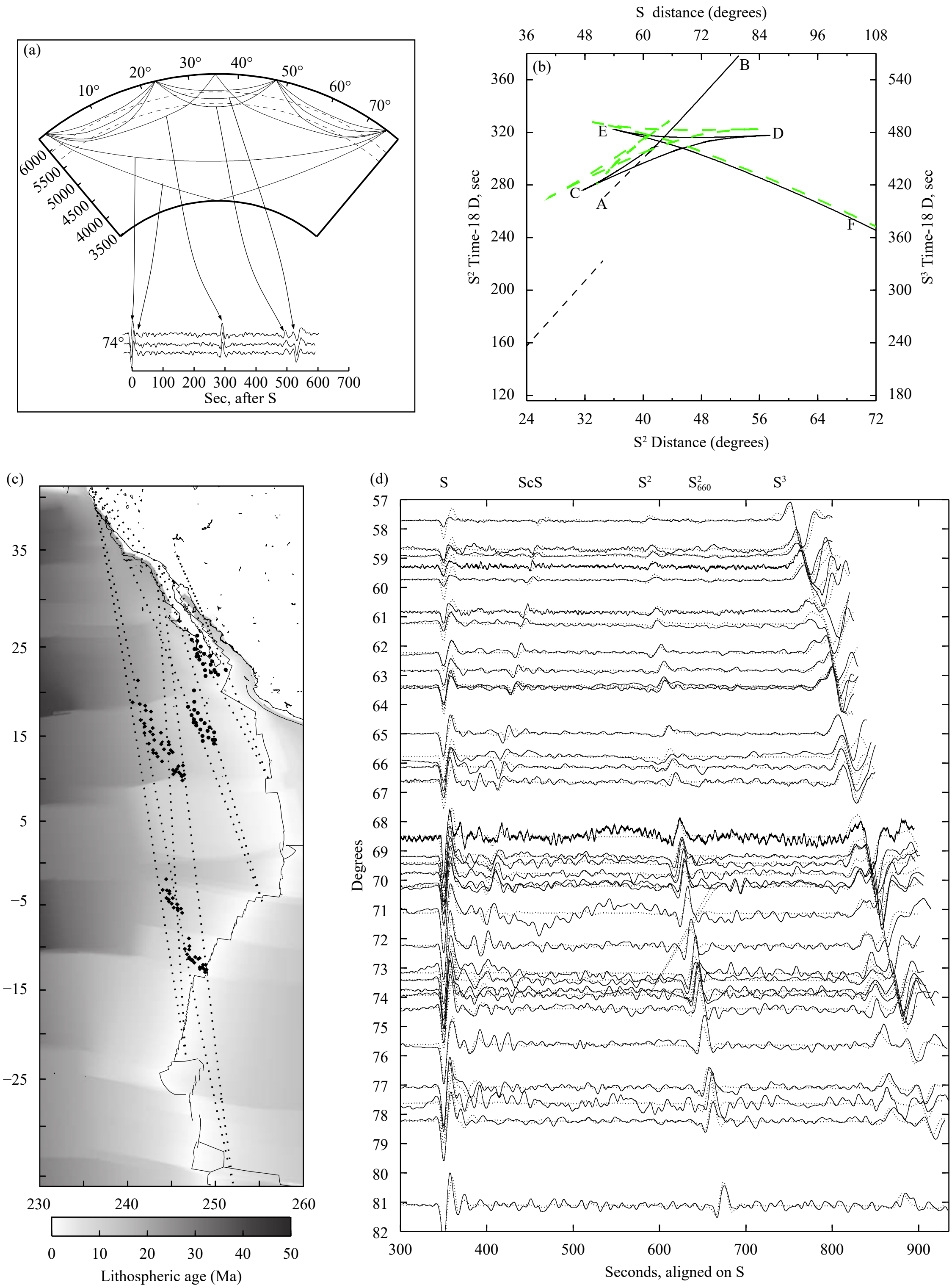

Figure 4. Transition Zone Variability Beneath East Pacific Rise, from Melbourne and Helmberger (2002). (a) Generalized ray paths showing discrete phases of the upper mantle triplication of multiple (in this case, triple) S. Doubled and tripled time separation of triplicated S2 and S3 subphases, respectively, facilitate their slowness identication and synthetic replication relative to S. (b) Triplication plots for the TNA model with (solid) and without (thick dashed) a lid. (c) Crustal age map indicating the position of four events used to constrain lateral variation in mantle structure. Shading density indicates plate age. (d) Modeled waveforms containing S, ScS, S2, and triplicated S3, aligned on S. No systematic misfit in subphases of the S3 triplication is observed.

quiet productivity, and thanks for giving so much to so many of us. So I'll say it here, instead: Thanks, Don.

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