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The Era of Computational Seismology (Beno Gutenberg Medal Lecture)

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The quality of tomographic images of the Earth's interior and earthquake source models is closely tied to our ability to efficiently and accurately simulate 3D seismic wave propagation. For decades seismologists have used asymptotic, approximate methods to address the *forward problem* in seismology, namely, given a seismic source and a 3D Earth model, accurately simulate the associated wave motions. In recent years, modern numerical methods and parallel computers have facilitated fully 3D simulations of seismic wave propagation at unprecedented resolution and accuracy, heralding the age of *computational seismology*. The current focus is on harnessing the power of these sophisticated forward modeling tools to enhance the quality of images of the Earth's interior and the earthquake rupture process, that is, to address the *inverse problem*.

Traditional tomographic methods utilize traveltime and dispersion information obtained by comparing data with simulations, and interpret such measurements based on ray theory or other approximate methods. Because of the limitations of these approximate techniques, only certain parts of seismograms can be used, and initial models are generally restricted to be layered or spherically symmetric. With modern numerical modeling tools we are now going well beyond classical tomography, using fully 3D initial models and utilizing as much information contained in seismograms as possible. The ultimate goal is broad band *full waveform inversion* utilizing entire seismograms. Surprisingly, one tomographic iteration may be performed based on just two numerical simulations for each earthquake: one calculation for the current model and a second 'adjoint' calculation that uses time-reversed signals at the receivers as simultaneous, fictitious sources.

Seismic imaging based on adjoint methods assimilates seismographic information into 3D models of elastic (seismic wavespeeds) and anelastic (quality factors) structure. These methods fully account for the physics of wave excitation, propagation, and interaction by numerically solving the inhomogeneous equations of motion for a heterogeneous anelastic solid. Such methods require the execution of complex workflows, involving extensive pre- and post-processing of observed and simulated seismograms. After successful applications of *adjoint tomography* in southern California and Europe, we are currently moving toward adjoint tomography of the entire planet. The objective is to image Earth's global interior based on full waveform inversion, thereby facilitating a deeper understanding of its physics and chemistry. To start with, we selected 255 earthquakes and gathered data from global seismographic networks. Our strategy is to invert for crust and mantle structure jointly, thereby avoiding any bias introduced into upper-mantle images due to commonly used 'crustal corrections'. Our ultimate aim is to harness more than 6,000 magnitude 5-7 earthquakes digitally recorded over the past 20 years.