Pure appl. geophys. 160 (2003) 439–444
0033 – 4553/03/040439–6



Pure and Applied Geophysics

# Seismic Motion, Lithospheric Structures, Earthquake and Volcanic Sources: The Keiiti Aki Volume

## Introduction

On March 16–18, 2000, the Department of Earth Science at the University of Southern California held a scientific meeting to honor the retirement of Professor Keiiti (Kei) Aki from academia. The meeting was attended by over 75 former students, postdoctoral fellows, close scientific associates and friends of Kei, representing universities, government agencies, and industry from the United States, Japan, China, France, New Zealand, England, Mexico, and Brazil. The scientific program consisted of 18 long review presentations and 12 additional short talks on theoretical and applied problems concerning earthquakes, faults, volcanoes, wave propagation, and engineering seismology. The 13 papers in this special volume are based on the long review talks given in the meeting and they provide examples of the broad range of topics that were pioneered, developed, and promoted by Aki over the last four decades.

Keiiti Aki was born on March 3, 1930, in Yokohama Japan to a family of engineers with a 100-year tradition of education and openness to the west. His grandfather was involved in construction of about 100 ports in Japan. After the 1923 great Tokyo earthquake he was in charge of rebuilding the port of Yokohama. He then built a house on top of a hill overlooking the port where Kei was later born. The house was burned in World War II but was rebuild. Kei's father was even more accomplished. He was a professor of hydrology at the University of Tokyo, a chairman of a national advisory committee to the Japanese government on utilization of natural resources, appeared often on television, worked together with Americans on various projects, and wrote scores of books. When it was time for Kei to attend university he wanted to study geophysics rather than continue the family tradition in engineering. His father agreed because he considered geophysics to be an important scientific field. The rest is history from which geophysics has greatly benefited. However, engineering did not lose! As is clear from Kei's career, he maintained an active interest in many engineering problems, and assisted in the development of an interface between seismology and earthquake engineering.

Kei obtained B.Sc. and Ph.D. degrees in geophysics from the University of Tokyo in 1952 and 1958. His Ph.D. dissertation under the supervision of Chuji Tsuboi was on space and time spectra in stationary stochastic waves with a special reference to microtremors. He was a postdoctoral fellow with Hewitt Dix and Frank Press at Caltech in the early 1960s and then an Associate Professor in the Earthquake Research Institute of the University of Tokyo from 1963 to 1966. When Frank Press left Caltech to head the MIT Department of Earth and Planetary Sciences, Aki was invited to join the MIT faculty where he began in 1966 his (U.S.) academic career as a Professor of Geophysics. In 1984, Kei moved to USC where he became the first W. M. Keck Foundation Professor of Earth Sciences, a position he held until his retirement in 2000. While at USC, Kei was largely responsible for the establishment of the Southern California Earthquake Center and he served as the first Science Director of the center.

Aki's scientific achievements cover source, path and site effects over the entire range of frequencies observed until about 1990. During the 1960 meeting of the IUGG in Helsinki, Kei was extremely impressed when theoretical spectral peaks of free oscillations predicted by Chaim Pekeris and observed peaks by three independent groups all matched. He was also very impressed by a dispersion analysis of Frank Press using seismic records from California generated by sources in the Pacific. These studies convinced Kei that it is possible to use deterministic methods for quantitative analysis of earthquakes, and inspired him to work on long-period seismology. That led to his fundamental 1966 paper on the seismic moment. Shortly after that paper was published, four talented young geophysicists developed important applications to the seismic moment: Hiroo Kanamori applied it to study of large earthquakes, Jim Brune related moment to plate tectonics, Boris Kostrov extended the concept to regional strain, and Adam Dziewonski developed systematic moment tensor inversion. With these and other seismologists working on long-period seismology, Kei decided to shift his focus to short-period seismology, a decision that eventually led him to return to California in 1984.

Kei's studies on high frequency waves include fundamental works on scaling laws of seismic spectra, scattering theory, analysis of coda waves, strong ground motion, seismic tomography, and frequency-dependent attenuation. Kei's group was instrumental in developing numerical methods for calculating seismic radiation from earthquake and volcanic sources, and imaging geophysical structures on different scales. Many of these works opened up new fields for seismologists and they played important roles in making quantitative seismology a mature science. One sign of a mature science is the existence of a standard comprehensive and rigorous textbook. This of course was provided in 1980 by the superb 2-volume book *Quantitative Seismology* of Aki and Richards. Another sign of a mature science is applications to various subjects. The papers in this special volume provide windows into such applications.

The first four papers deal with wave propagation techniques. Bouchon reviews the discrete wavenumber method of Bouchon and Aki (1977) for calculating Green functions for elastodynamic problems with irregular interfaces and finite sources. The method assumes spatial periodicity of the structure and source, extending earlier works of Rayleigh (1907) and Aki and Larner (1970) with a similar assumption on the structure. Using spectral representation and Fourier transform, the discrete wavenumber technique calculates seismic radiation as a superposition of plane waves. The method provides a simple yet powerful technique for computing realistic seismograms in a variety of applications. Computational schemes based on a spectral kernel function and wavenumber integration, like the discrete wavenumber and generalized reflection/transmission coefficient methods, converge very slowly when the spatial coordinates of the source and receiver in the direction that is transformed to the Fourier domain are similar. Zhang, Chen and Chang describe in the second paper an efficient remedy to this problem, using a peak and trough averaging of the oscillating kernel in the wavenumber domain integration. The technique is illustrated with examples associated with horizontally-layered structures.

In the third paper, Nowack covers the formulation, applications, and recent extensions of the Gaussian beam method for calculating synthetic seismograms in heterogeneous media. Following Popov (1981) and others, the method replaces rays (which are singular at caustics) with Gaussian beams. This allows a stable calculation of high-frequency elastic wavefield in various important cases. Additional types of beams and various implementation procedures are also discussed. Wu reviews in paper four the theoretical background, classical methods, and new techniques for wave propagation in heterogeneous media based on perturbation approaches. The review includes the Born, Rytov and De Wolf approximations, the phase-screen method for one-way propagation of elastic disturbances (neglecting reverberations and standing waves) implemented partially in the spatial and partially in the wavenumber domains, and several new generalized phase-screen methods. Applications of the new methods to seismic imaging are discussed and illustrated with 2-D and 3-D examples.

The well-known deterministic phases in seismograms, like *P* and *S* body waves, are followed by a decaying envelope of scattered waves. In a pioneering 1969 paper, Aki observed – without the benefit of modern broadband data and digital computers – some of the key properties of the seismic phases in that envelope which he called coda waves. Fehler and Sato review in the fifth paper analysis techniques, models, and applications of coda waves. The latter include imaging of crustal heterogeneities, scattering and attenuation of high-frequency waves, determination of site amplification factors, and more. Papers six to eight give results related to the seismic source. Madariaga clarifies conceptual and numerical subtleties associated with motion generated by a propagating rupture on a reverse dipping fault. The full solution has contributions from the rupture front and $P$, $S$, and surface wavefronts. The free surface modifies the frequency content of the solution as compared with full space results (in addition to adding surface waves). When the rupture does not reach the surface, the sum of all contributions gives finite motion although individual terms have singularities. When the rupture breaks the surface, a singularity at the surface-breaking tip remains in the full solution. Stable numerical calculations require regularization of the singularities. For shallow faulting, the rupture front produces strongly asymmetric disturbances across the fault with large motion in the hanging wall but not at the foot wall. In paper seven, Das reviews studies of dynamic rupture in the fracture mechanics and earthquake communities. The review is centered on her numerical works done first with Aki and then with Kostrov, and is focused on a discrete planar fault with possible strength/stress heterogeneities in a homogeneous isotropic medium. Simulation results include short rise time of earthquake slip, intersonic propagation, and spatially discontinuous ruptures. The discussion highlights important connections between material properties, rupture behavior, and radiated seismic fields, and the difficulty of inferring from available seismic data reliable information concerning properties and behavior at the earthquake source.

In paper eight, Papageorgiou discusses the specific barrier model of Papageorgiou and Aki (1983) and its use for calculations of strong ground motion. The model replaces the classical five-parameter (length and width of the fault, rupture velocity, final slip, and rise time) homogeneous kinematic framework of Haskell (1964, 1966, 1969) with a heterogeneous planar fault consisting of circular cracks separated by unbreakable barriers. Each circular crack fails at a random time following the passage of a uniformly propagating rupture front and sustains at failure a prescribed local stress drop. The model thus has a mixture of kinematic, dynamic, deterministic and stochastic ingredients. Calculations of seismic radiation involve specifying (or inverting for) six parameters, with the barrier interval, local stress drop, and maximum frequency replacing the final slip and rise time in the Haskell model. The interpretation of small-scale parameter values obtained by fitting model calculations to strong ground motion data remained controversial. Engineers typically simulate high frequency seismic waves with stochastic models. Boore gives in the ninth paper a comprehensive review of a stochastic method for ground motion calculations. The method combines a functional description of amplitude spectrum having contributions from source, path and site effects with random phase, using parameter choices related to the earthquake size and source-receiver distance. Detailed explanations and calculated examples illustrate the components needed to synthesize ground motion in a variety of seismological and engineering forms.

The final four papers of the special volume treat faults, volcanoes, and other lithospheric structures. Ben-Zion and Sammis discuss in paper ten conceptual frameworks and data on properties of earthquake fault zones. A wide variety of field, laboratory, and modeling results suggest that fault zones are formed as highly disordered structures characterized by strain hardening rheology and low mechanical efficiency. With increasing slip they appear to evolve toward strain weakening rheology, geometrical regularity and high mechanical efficiency. If this hypothesis is correct, it may be used to organize numerous geological and geophysical observations. The information available at present regarding the character of faults is, however, limited and the above hypothesis should be tested with future studies. In paper eleven, Thurber reviews teleseismic and local earthquake tomography, starting with the landmark 1976–1977 papers of Aki and coworkers on these topics and concluding with recent developments and applications. The discussed examples include tomographic imaging of sections of the San Andreas fault and the Valles caldera. Advances in computer power, 3-D ray-tracing techniques, inversion methods, and data availability (primarily through the establishment of IRIS and PASSCAL in the United States and similar initiatives in other countries) have led to significant improvements in the imaging capability of seismic tomography. This trend is likely to continue.

Chouet provides in paper twelve an extensive review of volcano seismology including theory, seismic observations, and lab data on source processes and structural properties. The physics of volcanic systems involves dynamic interactions between solid, liquid, and gas phases, and in that respect is more complex than the physics of tectonic earthquakes associated primarily with a solid state. Related to this, the diversity of volcanic sources and radiated seismic waves is larger than their counterparts in earthquake seismology and include, in addition to regular earthquakes and related waves, also tremor and long period events and waves. The latter types of waves are indicative of the eruption potential of volcanoes so quantitative predictive seismology is, perhaps paradoxically, more developed at present for volcanic activity than for tectonic earthquakes. Aki *et al.* (1977) developed the first quantitative description of volcanic tremor and long period events based on a fluid-driven crack model that is still in use today with some modifications. The pioneering tomographic 1976–1977 papers of Aki *et al.* provided the basis for imaging volcanic structures. After introducing these contributions, Chouet describes the state-of-the-art in volcano seismology using examples from his works with colleagues on tomographic imaging of the Kilauea volcano, source properties of tremor and long period events, and experiments with expanding gas-liquid flows. In the last paper of the volume, Zandt, Leidig, Chmielowski, Baumont and Yuan employ receiver functions to obtain a model of crustal stratigraphy and anisotropy in the Altiplano-Puna volcanic complex in the central Andes. The receiver functions provide information on impedance contrast interfaces by identifying P-to-S converted phases in seismograms. The method is especially useful for imaging narrow low velocity zones that have large impedance contrasts but produce small signals for tomographic studies. From teleseismic and local receiver functions, Zandt *et al.* infer on the existence of a thin sill-like regional magma body at a depth of about 20 km and overlying anisotropy in their study area.

*Acknowledgments*

Resources and facilities for the March 16–18, 2000, meeting were provided by the University of Southern California through the efforts of Tom Henyey, Charlie Sammis and Leon Teng. The administrative assistance of Sally Henyey, John McRaney, Michelle Smith and Shelly Werner made the meeting efficient and enjoyable. I thank the referees of the papers for critical reviews that improved the scientific quality of the volume. These include John Anderson, Rafael Benites, David Boore, Michel Bouchon, Michel Campillo, Bernard Chouet, Donna Eberhart-Phillips, Art Frankel, Hiroo Kanamori, Hitoshi Kawakatsu, Hiroshi Kawase, Brian Kennett, Geoff King, Peter Leary, Raul Madariaga, Chris Marone, Steve Martel, Bob Nowack, David Okaya, Tom Parsons, Jim Rice, Paul Richards, Francisco Sanchez-Sesma, Teruo Yamashita, Kiyoshi Yomogida, Yuehua Zeng, and Ru-Shan Wu.

Yehuda Ben-Zion
Department of Earth Sciences
University of Southern California
Los Angeles, CA, 90089-0740
U.S.A