

Introduction

During the December 2004 annual meeting of the American Geophysical Union (AGU), Professor Keitii (Kei) Aki was awarded the Bowie Medal, which is the highest honor bestowed annually by the AGU. To celebrate this occasion, a scientific symposium in honor of Kei was organized by Yehuda Ben-Zion, Eystein Husebye, John McRaney, Haruo Sato, and Willie Lee under the title “Quantitative Seismology: Advances in Studies of Fine-scale Heterogeneities in a Deforming Earth”. Since Kei studied (and was instrumental in developing) most aspects of quantitative seismology, including source, propagation and site effects over the entire range of observed frequencies, it was difficult to pick a subset of topics that would form a reasonably focused scientific session. The title was finally chosen to reflect a set of problems that was central to Kei’s interests, while having a somewhat different focus than those of two earlier 2000 symposia that commemorated Kei’s retirements from academia.

The description of the 2004 AGU session in honor of Aki is as follows: *In the past 25 years, there have been tremendous advances in many aspects of quantitative seismology using physics-based approaches. New fronts were made possible by many factors: Large data sets with unprecedented resolution and bandwidth; innovative computational techniques; new theoretical models for seismic phenomena; and integrative research accounting for broad ranges of space and time scales. These advances were stimulated by many pioneering papers, and were aided strongly by the publication of the two-volume treatise “Quantitative Seismology: Theory and Methods” by Keiiti Aki and Paul Richards in 1980. This session will focus on integrative physics-based seismological studies, with an emphasis on the nature of fine-scale heterogeneities and earthquakes. Contributions from theory, observations, and applications are welcome.* The citation for the Bowie medal (Appendix 1) was given by Tom Jordan.

In contrast to the two earlier 2000 symposia honoring Kei Aki, which had only invited participants, the 2004 AGU meeting provided a venue that allowed anyone who wished to contribute or attend to do so. The special AGU session and a related follow-up banquet were highly successful, both in terms of covering current state-of-the-art research results and celebrating lasting fundamental contributions of Kei Aki. The scientific session received an overwhelming response of 85 contributions. These were given over four oral sessions which included an opening speech by Paul Richards (Appendix 2), an introduction and response by Kei at the beginning and the end of the oral sessions (Appendix 3), and 27 papers. The remaining 58 papers were presented in a poster session. Many participants wrote “tributes” to Kei, some of

which were read at the banquet. The tributes provide interesting windows into aspects of Kei's personal and scientific interactions with students and colleagues and are posted at <http://www.iris.edu/seismo/quakes/1964niigata/>.

The present volume has 13 papers on topics related to the theme of the special 2004 AGU session in honor of Kei, which is a small fraction of the 85 presentations that were given in the meeting. The papers belong generally to three broad categories: Studies related to dynamic earthquake rupture, studies associated with imaging of earthquake locations and structures using coherent (P and S) seismic phases, and studies associated with imaging source and structure properties using scattered (coda) seismic waves. In the first group of papers, CHEN and ZHANG provide analytical and numerical results on dynamic rupture along a dipping fault in a 3-D elastic half space, using a recently-developed boundary integral formulation that accounts for the free surface and numerical regularization of the associated singular integral kernels. The calculations show that waves reflected from the surface can affect significantly the rupture growth, especially at shallow depth. A resolution test suggests that the method provides accurate results with larger grid size than is required by some other computational methods of dynamic rupture. DOR *et al.* present detailed geological mapping of rock damage in the structure of several faults of the San Andreas system in southern California. The results show strong damage asymmetry across the faults that is correlated with available information on seismic velocity structures at seismogenic depth. The observations are compatible with theoretical results on dynamic rupture along material interfaces in the fault zone structures, with preferred propagation direction associated with the velocity structure.

In the second group of papers, RICHARDS *et al.* outline the double-difference technique for relative earthquake locations, using arrival-time data obtained by waveform cross correlations and catalog phase picks, and illustrate the method with applications to regions with different size and different density of seismicity and stations. They conclude that the double-difference method and accurate arrival-time data obtained by waveform cross correlations can improve considerably the precision of relative locations, and that routine application of the double-difference and waveform cross correlation techniques is now possible at local and regional scales. ZHANG and THURBER review a recently-developed double-difference tomography method for simultaneous derivation of earthquake locations and velocity structure, based on a mixture of absolute and more accurate differential arrival times. The material includes theory, implementations, and applications of the method to synthetic and observed data at several scales. The results indicate that double-difference tomography provides generally more accurate results than standard tomography. GOT *et al.* review an alternative treatment of double-difference tomography that incorporates probabilistic optimization of results, and discuss effects of various errors in data and model parameters. Application of the method to the structure of the Kilauea volcano in Hawaii resolves internal velocity variations, and comparison to results of several other algorithms suggests that the approach is advantageous for imaging

heterogeneous structures, especially when the data quality is not very high. GAUTIER *et al.* perform tomographic inversion of local earthquake arrival times for crustal structure and earthquake locations in the actively rifting Gulf of Corinth. The velocities image the rift basin and the hypocenters image a regional-scale detachment fault.

In the third group of papers, SNIEDER reviews theoretical concepts governing changes of coda waves due to small localized perturbations in the medium properties or source location, and describes how to estimate the resulting mean and variance of the travel-time perturbations. CAMPILLO reviews theoretical results on properties of coda waves in asymptotic multiple-scattering regime, and how to construct Green functions from coda waves and ambient seismic noise. The results are illustrated with applications of imaging velocity structures in Alaska and California. WEGLER *et al.* use the theory of radiative transfer to model the transport of seismic energy in 2-D and 3-D acoustic random media. The theory accounts correctly for the direct wave front, envelope broadening caused by multiple forward scattering, and late coda caused by multiple wide-angle scattering. However, for very heterogeneous media the radiative transfer results differ from those of the full wave equation. ZENG develops a set of scattered wave energy equations that include scattered surface waves and conversions of body waves to surface wave scattering. Numerical results show that scattered wave energy can be approximated well by body-wave scattering at earlier times and short distances, but at large distances scattered surface waves dominate the scattered body waves at surface stations.

MAEDA *et al.* find that the direct and scattered fundamental-mode Rayleigh waves are dominant in the earlier part of each coda envelope, however higher modes become dominant at lapse times later than 20,000–35,000 sec. The authors conclude that higher mode waves are uniformly distributed at large lapse time because of large velocity dispersion and/or scattering, and they dominate over the fundamental mode waves because of smaller attenuation in the lower mantle. PENG and BEN-ZION analyze evolving properties of coda waves generated by clusters of repeating earthquakes in the overlapping aftershock zones of the 1999 Izmit and Duzce earthquakes on the North Anatolian fault. The results show abrupt co-mainshock reduction of seismic velocities in the shallow crust, followed by gradual logarithmic-like recoveries. The decay rates of the repeating events in individual clusters are compatible with the Omori's power law relation for regional aftershocks. NISHIGAMI estimates a 3-D distribution of relative scattering coefficients in the source region of the 2004 Mid-Niigata Prefecture earthquake using inversion analysis of coda envelopes. An area with weaker scattering is found along the mainshock fault plane that appears to be related with the large slip area during the mainshock rupture. Hypocenters of the mainshock and major large aftershocks with M 5–6 tend to be located close to stronger scattering areas.

While editing this volume in honor of Kei Aki, we were greatly saddened (along with many others) to receive the news that Kei passed away on May 17, 2005. Several obituaries to Kei were already published and a few others are in preparation. A brief material in memory of Kei prepared by us is given at the end of this volume, followed by Kei's publication list.

Acknowledgments

We thank Shamita Das, Eystein Husebye, Tom Jordan, John McRaney, Paul Richards, Haruo Sato and the many other participants in the symposium and banquet for making the activities successful. We are grateful to the referees of the papers for critical reviews that improved the scientific quality of the volume. These include Brad Aagaard, Rasool Anoshehpour, Niren Biswas, Michel Campillo, Judi Chester, Bob Crosson, Mamado Diallo, Eric Dunham, Mike Fehler, Phillipe Geubelle, Jean-Luc Got, Jeanne Hardebeck, Egill Hauksson, Michael Korn, Harold Magistrale, Martin Mai, Kevin Mayeda, Hisashi Nakahara, Zhigang Peng, Malcolm Sambridge, Haruo Sato, Peter Shearer, Roel Snieder, Paul Richards, Stephanie Ross, Justin Rubinstein, Toshiro Tanimoto, Cliff Thurber, Uli Wegler, Cecily Wolfe, and Yuehua Zeng.

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Appendix 1: Citation for Kei Aki, 2004 Recipient of the Bowie Medal by Thomas H. Jordan

Kei Aki's scientific research has expanded the frontiers of seismology for fifty years. He pioneered the electronic processing of seismic data to infer earth structure and properties of the earthquake source. Much of what we know about large earthquakes follows from his work. He was the first to measure seismic moment (for the 1964 Niigata earthquake); Aki moment has since replaced Richter magnitude as the fundamental measure of earthquake size. He discovered the fundamental scaling laws for seismic spectra and interpreted these laws in terms of physical models, such as the barrier theory of heterogeneous rupture. This work contributed significantly to both the basic understanding of the rupture process and the practical understanding of strong ground motions.

He elucidated the scattering and attenuation processes that govern the propagation of high-frequency seismic waves, from which he derived new methods for measuring earthquake size, scattering distributions, and intrinsic attenuation parameters. He demonstrated, for instance, that the intrinsic attenuation must decrease at high frequencies. He developed many novel approaches for describing aspects of seismic waves, including free-oscillation splitting, Gaussian beams, and boundary integral methods. In each case, he and his students successfully used these techniques to extract new types of information from seismograms.

He pioneered travel-time tomography as a means to study lithospheric structure beneath dense seismic arrays, publishing seminal papers almost a decade ahead of its widespread application to global seismology. He established new seismological perspectives on volcanic processes, including the relationship of seismicity and harmonic tremor to magma injection and eruption. He detected fault-zone guided waves and used their propagation characteristics to constrain the width and elasticity of the damage zones around faults.

As impressive as this abbreviated list might sound (more topics could easily be added), it fails to communicate Kei's true impact within the geoscience community. He literally wrote the book: *Quantitative Seismology*, which he co-authored with Paul Richards in 1980, is the most influential textbook and reference manual in the history of the field. As a teacher and mentor, he trained many bright students in his quest to understand the active Earth, producing over 50 Ph.D.'s who now occupy key positions in seismology worldwide. His success in guiding young scientists stems in part from the depth of his understanding, but also from his remarkable personal qualities—charm, wit, and a deep respect for the harmony and poetry of the natural world.

Kei's quiet leadership in seismology has demonstrated the subtlety and power of unselfish cooperation in research. He has held many positions—president of the Seismology Section of AGU, president of the Seismological Society of America, chair of the NAS Committee on Seismology—but his greatest leadership achievement was the creation of the Southern California Earthquake Center in 1991. As its founding director, Kei articulated a vision for SCEC in which the investigations by disciplinary working groups would be woven together into a system-level “master model” for earthquake hazard and risk in Southern California. The master-model concept led to many advances in seismic hazard analysis, such as the incorporation of GPS data into long-term earthquake forecasting, and it continues to guide the growing SCEC collaboration.

Some scientists loom so large in their fields that we must mark their impact with special honors. Kei Aki, the 2004 recipient of the Bowie Medal, is one of our giants!

*Appendix 2: Introductory Remarks by Paul Richards, at the Aki Symposium,
8 am Dec. 13, 2004*

We shall shortly begin our scientific sessions on the subject of “Quantitative Seismology: Fine-scale Heterogeneities in a Deforming Earth,” and it is remarkable that 85 papers are included in these sessions, which therefore extend over two days.

The principal organization was done by Willie Lee, with some help from Yehuda Ben-Zion, Eystein Husebye, John McRaney, Haruo Sato, and Ru-Shan Wu — certainly not be by me — and it is very clear from the list of speakers and poster presenters that many of us have a close association, as a colleague or co-author or student, with Professor Keiiti Aki.

It is a great pleasure to be with him here, at the AGU meeting which later this week will recognize his accomplishments formally with the award of the Bowie Medal.

In geophysics, we understand that planet Earth is our laboratory. But few of us have seen our laboratory, and worked with it from so many perspectives, as Kei Aki.

For thirty years he lived in Japan, where he made the decision to pursue geophysics in 1949 and where he received his Bachelor's and Ph.D. degrees from the University of Tokyo. In 1960 he began his work in the United States with a post-doc appointment at Caltech. After a brief return to the University of Tokyo, he took up a professorship in M.I.T at the instigation of Frank Press.

For 18 years at M.I.T., where he had 36 Ph.D. students, he developed major new ideas on surface waves (interpreted via moment tensors), on source scaling, on tomography, on coda, on strong ground motions, on volcano seismology, and much besides.

In about 1984, I remember the excitement of Ta-Liang Teng, telling me that "Kei Aki is coming to California," and Kei himself telling me that he wanted to live in a place where earthquakes are recognized as a common experience.

In California, at the University of Southern California for 14 years where he had many more Ph.D. students, Kei promoted integration of scientific information about earthquakes and its public transfer, as the founding science director of the Southern California Earthquake Center. At the Center, for example, input from earthquake geologists was used together with the fault model of quantitative seismology, to generate output useful for earthquake engineers. In this work, the concept of seismic moment, which Kei had introduced with his classic paper in 1966 on the Niigata earthquake of 1964, was central to unifying information from plate tectonics, geology, geodesy, and historical and instrumental seismology. The public transfer of the integrated information was made in the form of probabilistic estimates of earthquake hazards.

Since 2000 Kei has been based in Réunion Island, living a life that few of us can imagine, accumulating seismological observations of an active volcano, from very close up. He travels the world — his laboratory — as a scientist who still is fascinated by the phenomena our planet exhibits — such as volcanoes that send out infrasound and seismic signals. They are influenced by the solid Earth, by the liquid magma, and by the atmosphere. Solid, fluid, gas. All three media contribute to signals recorded from volcanoes.

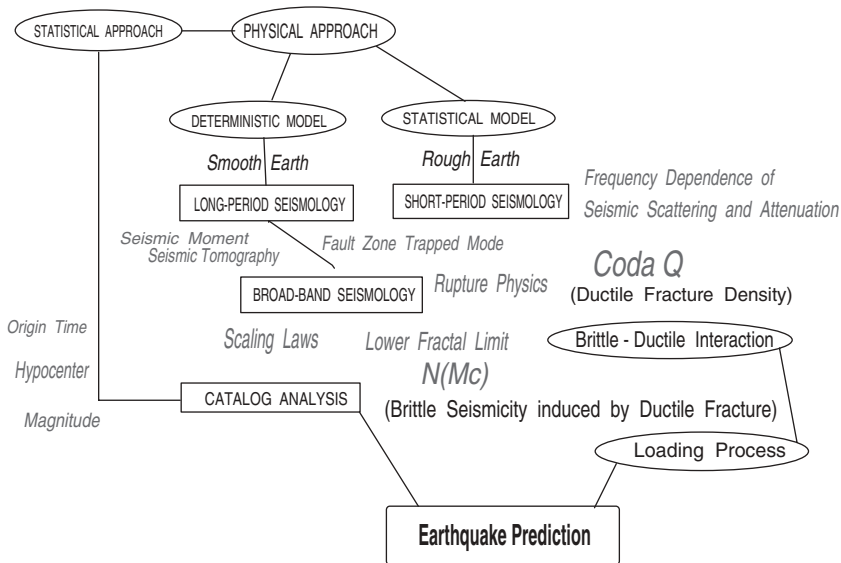
And today, in December 2004, he is with us here, in San Francisco. It has been a long and fantastic journey, full of remarkable accomplishments. Kei, we welcome you and invite your comments on the session about to begin, and the perspectives you have developed over many years.

Appendix 3: Introduction and Response by Keiiti Aki

Thank you, Paul, for your kind words.

Ladies and gentlemen:

I am Aki of Aki and Richards. Last time I attended an AGU meeting was 10 years ago, and I am very happy to have an opportunity to speak here again. The principal organizer of this symposium, Willie Lee, who is unfortunately absent today because of illness, asked me to summarize my work in the past 50 years as an introduction to the symposium.



The first slide shown above summarizes my 50 years' work. It starts with earthquake prediction and ends with earthquake prediction. My first paper written in English, published in the Japanese Journal JPE in 1954, and my last paper (so far) published in EPS, the successor of JPE, in 2004, are both on earthquake prediction.

The first paper is based on statistical approach and was motivated by Norbert Wiener's "Cybernetics" published in 1948, which was the first scientific book I read seriously. After applying his prediction method to the earthquake catalog data (t, x, y, z , and M), I realized that the data available then were poor and Wiener's method based on the view of the world as a stationary linear system was too simplistic to incorporate the physics of earthquake.

So, I decided to take a physical approach to go beyond the catalog data. I took two paths; deterministic modeling and stochastic modeling. The deterministic approach required simple models of earth structures and earthquake processes and

was only possible for long-period waves because short-period waves suffer from complex details of structures and processes. It started as “Long Period Seismology,” producing useful concepts such as the seismic moment. It has grown to “Broad-Band Seismology” in which the upper limit of the applicable frequency range has been pushed upward steadily.

Nevertheless, the approach is basically eliminating high-frequency waves that suffer from small-scale heterogeneities. The initially smooth Earth model remains smooth because of the elimination of high-frequency waves from the data.

On the other hand, the stochastic modeling approach accepts the existence of small-scale heterogeneities and tries to find their statistical properties. It cannot define the heterogeneities specifically in time and space, but can demonstrate their existence.

In this symposium we have Raul Madariaga as an invited speaker for the deterministic approach, and Michel Campillo for the stochastic approach.

I mentioned at the beginning about my latest paper published in EPS. This paper describes my current view of earthquake and volcano precursors reached after 50 years’ of travel along deterministic and stochastic modeling paths. I now see some light at the end of tunnel, and I like to encourage you to take multiple paths to achieve your goal.

Thank you for your attention.

Comments at the End of the Symposium

You all agree that it was a great symposium with uniformly excellent papers. Needless to say, I am very much pleased and impressed by new developments as well as over-all maturity attained in Seismology. It makes a great contrast to one of the first western AGU meetings I attended in 1962. It was held in the beautiful Stanford campus and the seismology session was chaired by Leon Knopoff. It was attended by half a dozen people; only the speakers were there.

I like to thank Willie Lee, Yehuda Ben-Zion, Eystein Husebye, Haruo Sato and John McRaney for organizing the symposium.

Thank you all for your participation.



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