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Progress Report for the Past One Year

(May 1, 1989 - April 30, 1990)

Introduction

This is a progress report for the past one year of research (year 3 of 5-year project) under the project titled "CSDP: Seismology of Continental Thermal Regime", in which we proposed to develop seismological interpretation theory and methods applicable to complex structures encountered in continental geothermal areas and apply them to several candidate sites for the Continental Scientific Drilling Project.

The past year has been extremely productive especially in the area of interpretation theory, including the following two major break-throughs. One is the derivation of an integral equation for time-dependent power spectra, which unified all the existing theories on seismic scattering (including the radiative transfer theory for total energy and single and multiple scattering theories based on the ray approach) and offers more complete and economical solutions to the problems of seismic scattering and attenuation. The other is the new formula for synthetic seismograms for layered media with irregular interfaces, combining the T-matrix method for an arbitrary shaped inclusion and the method of global generalized reflection/transmission coefficients for layered media. Both breakthroughs will enable us to deal with seismic observations in complex earth structures more efficiently and accurately. In the area of experimental studies, we discovered seismic guided waves trapped in the San Andreas fault near Parkfield, California.

In addition to the above research work, the P.I. has promoted the study of scattering and attenuation of seismic waves by organizing an international symposium as a part of the IASPEI meeting at Istanbul in August, 1989. The Proceedings of the symposium will be published as a special issue of the Physics of the Earth and Planetary Interior.

Adding the publications and presentations made in the past year to the list for the preceding years, the following table lists 37 papers published, submitted, or presented in the past three years of the present project.

List of Publications and Presentations in the Past Three Years

1. Koyanagi, R., Chouet, B., and K. Aki, The origin of volcanic tremors, Part I: Data from Hawaiian Volcano Observatory 1969-1985, U.S.G.S. Professional paper 1350, ed. R. W. Decker, T. L. Wright and P.H. Stauffer, 1221-1259, 1987.
2. Chouet, B., R. Koyanagi, and K. Aki, The origin of volcanic tremors, Part II: Theory and discussion, U.S.G.S. Professional Paper 1350, ed. R. W. Decker, T. L. Wright and P. H. Stauffer, 1259-1280, 1987.
3. Ferrazzini, V. and K. Aki, Slow waves trapped in a fluid-filled infinite crack: Implication for Volcanic Tremor, J. Geophys. Res., 92, 9215-9223, 1987.
4. Leary, P. C., Y. G. Li and K. Aki, Observation and modeling of fault zone fracture seismic anisotropy - I. P, SV and SH travel times, Geophys. J. R. astr. Soc., 91, 461-484, 1987.
5. Li, Y. G., P. C. Leary and K. Aki, Observation and modeling of fault zone fracture seismic anisotropy - II. P-wave polarization anomalies, Geophys. J. R. astr. Soc., 91, 485-492, 1987.
6. K. Aki, Impact of earthquake seismology on the geological community since the Benioff zone, The Centennial Bulletin of the Geological Society of America, 100, 625-629, 1988.
7. Li, Y. G., P. C. Leary and K. Aki, Fault zone trapped seismic waves, Bull. Seis. Soc. Am., in press, 1990.
8. Leary, P. C., D. M. Manov and Y. G. Li, A fiber optical borehole seismometer, Bull. Seis. Soc. Am., v. 80, no. 1, 218-225, 1990.
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10. Ferrazzini, V., K. Aki, B. Chouet, and M. Fehler, Very slow waves trapped in a fluid layer with application to the long period events. Hawaii Symposium on How Volcanoes work, abstract volume, Jan. 1987.
11. Roberts, P. M. and K. Aki, A study of the 2-D Seismic structure of the Valles Caldera, New Mexico using discrete wave-number modeling of observed teleseismic P-waves, EOS, 68, 1347, 1987.

12. Leary, P. C. and Y. G. Li, Observation and modeling of fault-zone trapped Rayleigh modes, Oroville, CA. Annual meeting of Seis. Soc. Am., Honolulu, May, 1988.
13. Ferrazzini, V., K. Aki, B. Chouet and M. Fehler, Hydrofracture experiments at Fenton Hill, New Mexico; Implication for volcanic tremor, Annual meeting of Seis. Soc. Am., Honolulu, May, 1988.
14. Benites, R. and K. Aki, Seismic response of inhomogeneous layered media with irregular interfaces by Gaussian Beam Method, Annual meeting of Seis. Soc. Am., Honolulu, May, 1988.
15. Li, Y. G., P. C. Leary and K. Aki, VSP fracture study of Mohave desert and 3-D modeling by ray tracing, Annual Meeting of Seis. Soc. Am., Honolulu, May 1988.
16. Ferrazzini, V., B. Chouet, M. Fehler and K. Aki, Quantitative analysis of long-period events recorded during hydrofracture experiments at Fenton Hill, New Mexico, submitted to J. Geophys. Res., 1989.
17. Aki, K., State-of-the-art in Volcanic Seismology, Proc. International Workshop on Volcanic Seismology, Capri, Italy, Oct. 1988, in press.
18. Li, Y. G., P. C. Leary and K. Aki, A ray series approach to travel times and amplitudes in layered, heterogeneous anisotropic media. Third International Workshop on Seismic Anisotropy, Chapman conference on seismic anisotropy in the earth's crust, Berkeley, Calif., 1988.
19. Li, Y. G., Seismic wave propagation in anisotropic media with applications to defining fracture in the earth, Ph.D. thesis, University of Southern California, 262 pp., 1988.
20. Roberts, P. M., Seismic Q and velocity structure for the magma-hydrothermal system of the Valles caldera, New Mexico, Ph.D. thesis, Massachusetts Institute of Technology, 332 pp., 1989.
21. Li, Y. G., P. C. Leary and K. Aki, Ray series modeling of seismic wave travel times and amplitudes in three-dimensional heterogeneous anisotropic crystalline rock: Borehole vertical seismic profiling seismograms from the Mojave Desert, California, J. Geophys. Res., in press, 1990.
22. Zeng, Y., F. Su and K. Aki, Scattering wave energy propagation in a random medium with isotropic scatterers, EOS, 71, 559, 1990.
23. Su, F., K. Aki and N. N. Biswas, Discrimination of Quarry Blasts from earthquakes using the time-dependent power spectrum, EOS, 71, 566, 1990.
24. Chen, X. F., and K. Aki, Seismogram synthesis for multilayered media with irregular interfaces by global generalized reflection/transmission matrices method, EOS, 71, 567, 1990.

25. Mayeda, K., F. Su, and K. Aki, A comparative study on the seismic albedo from the hypocentral distance dependence of total seismic energy, EOS, 70, 1193, 1989.
26. Aki, K., K. Mayeda and J. Jackson, Tomographic back-projection of crustal coda Q in southern California, EOS, 70, 1194, 1989.
27. Benites, R. and K. Aki, Scattering of elastic waves in laterally heterogeneous media of some seismological interests, EOS, 70, 1201, 1989.
28. Chen, X. F. and K. Aki, Seismic mapping of deep discontinuity topography by the T-matrix method: Part I. SH problem, EOS, 70, 1231, 1989.
29. Chen, X. F. and K. Aki, Seismic mapping of deep discontinuity topography by the T-matrix method: Part II. Toroidal case, Seis. Res. Letters, 61, 28, 1990.
30. Li, Y. G. and P. Leary, Fault zone trapped waves observed in a near-fault borehole seismometer at Parkfield, CA., Seism. Res. Letters, 61, 45, 1990.
31. Mayeda, K., F. Su and K. Aki, Seismic albedo from the total seismic energy dependence on hypocentral distance in southern California, PEPI, in press, 1990.
32. Zeng, Y., F. Su and K. Aki, Scattering wave energy propagation in a medium with randomly distributed isotropic scatterers, Part I. Theory, submitted to J. Geophys. Res., 1990.
33. Li, Y. G., P. C. Leary, K. Aki and P. E. Malin, Seismic trapped modes in the Oroville and San Andreas fault zones, Science, in press, 1990.
34. Chen, X. F., Seismogram synthesis for multi-layered media with irregular interfaces by global generalized reflection/transmission matrices method, I. Theory for 2-D SH case, submitted to Bull. Seis. Soc. Am., 1990.
35. Chen, X. F., R. Benites and K. Aki, Seismic mapping of deep discontinuity topography by the T-matrix method, Part I. SH-problem, submitted to Wave Motion.
36. Aki, I., Summary of discussions on coda waves at the Istanbul IASPEI meeting, PEPI, in press, 1990.
37. McSweeney, T. J., N. N. Biswas, K. Mayeda and K. Aki, Scattering and anelastic attenuation of seismic energy in central and southcentral Alaska, PEPI, in press, 1990.

Summary of Results

Results contained in the 16 new papers published, submitted or presented in the past year (papers 22 through 37 in the above list), may be summarized under the following three headings.

- I. Interpretation of space time-dependent seismic power spectra; unified theory and new observations from S. California and Alaska.
- II. Seismogram synthesis for scattering and attenuation in complex media; T-matrix, Boundary Integral methods.
- III. Seismic properties of fault zone; trapped mode and attenuation tomography.

Let us now summarize major results for each of the above three areas. Details of the results are given in the preprint form if they are referred to in the list of publications shown above as "submitted" or "in press". They are available from the P.I. upon request. Otherwise, the manuscript is currently in preparation.

I. Interpretation of Space-Time-Dependent Seismic Power Spectra.

One of the main tools we have been developing for the study of complex earth structures is the space-time-dependent seismic power spectra, namely the formation and evolution of the seismic energy envelope in time and space by propagation through the earth structures.

One such example is the temporal envelope of local S-wave coda and another example is the hypocentral distance dependence of total seismic energy. During the past year, we have obtained new important observational results, as well as a new integral equation which can unify all the existing theories on various aspects of the seismic power spectra. Our observational results contributed significantly to sharpen the outstanding controversy on the fundamentals of coda Q, and our new theory will offer an effective means for resolving the controversy.

New observational results.

Papers 25 and 31 in our publication list describe a remarkable observation on how the total seismic energy varies with the hypocentral distance in southern California. The total energy $E_{\text{obs}}(r, \omega)$ was obtained from the onset of S-waves to the end of local earthquake seismograms by correcting for the source effect by the coda method. Figure 1 shows the observed $E_{\text{obs}}(r, \omega)$ multiplied by $4\pi r^2$ for geometric spreading separately for four frequency bands centered at 1, 5, 3, 6 and 12 Hz.

The observed distance dependence of total energy is clearly independent of frequency for the above frequency range. This is consistent with the Q values in California determined from attenuation of strong ground motion spectra as well as coda decay.

The observed total energy vs. hypocentral distance in Fig. 1 is compared with the theoretical curves calculated by the method of Wu (1985) based on the Radiative Transfer theory. Fig. 1 shows theoretical curves for different choices of relative importance of scattering loss and intrinsic absorption in seismic attenuation, expressed in terms of seismic albedo, $B_0 = \eta_s / (\eta_s + \eta_a)$, where η_s and η_a are the scattering and absorption attenuation coefficients respectively.

The comparison of observed with theoretical curves in Fig. 1 leads us to a conclusion that the seismic albedo is very high in southern California, and the scattering loss dominates the attenuation. The resultant Q^{-1} value for scattering loss is comparable to the coda Q^{-1} , supporting the interpretation of coda decay by the single-scattering model.

A very similar result was obtained for the central Alaska in Paper 37 of our publication list. The observed distance dependence of total energy for central Alaska is shown in Fig. 2 for the frequency range from 6 to 16 Hz. The difference between these curves can be explained by a slight decrease of albedo from 0.95 to 0.90 in the frequency range from 6 to 16 Hz. These high albedos are comparable to those obtained in southern

Southern California Total Energy

Fig. 1.

Fig. 2.

California, and show that the scattering loss dominates seismic attenuation also in the central Alaska.

Another interesting new result from southern California is the comparison of temporal coda decay between different seismic sources, namely, quarry blasts and earthquakes as reported in Paper 23. We measured the slope of coda decay at different lapse times and for different frequencies, and found that they are identical between blasts and earthquakes if we compare them for lapse times greater than about 30 sec for frequencies 1.5 to 3 Hz (compare Fig. 3a and 3b) and for lapse times greater than about 20 sec for frequencies 6 to 12 Hz (compare Fig. 4a and 4b). This suggest that the composition of coda waves may be the same for sufficiently later lapse time whether the source is a blast at a very shallow depth or an earthquake at depths down to about 10 km. The difference in the early part of coda decay between blasts and earthquakes can be explained by the relative dominance of surface waves in the coda of a blast seismogram. The difference disappears for the later lapse time probably because surface waves are absorbed by the low Q near surface material, and only those scattered back from deeper high Q regions survive in the later coda. Thus, the comparison of coda waves from blasts and earthquakes supports the idea that coda waves from earthquakes are primarily back-scattered body waves.

Controversies on coda Q^{-1}

New observations described above add to a large body of observational evidence which supports the idea that coda Q^{-1} determined using the single-scattering model represents the total attenuation effect including the scattering loss.

Theoretical, numerical and laboratory results, on the other hand, conclusively show that the single-scattering model cannot apply to the lapse time greater than the mean free time, and coda Q^{-1} should be representing the intrinsic absorptive loss in most cases.

EARTHQUAKES ($f=1.5$)

Fig. 3A.

Fig. 3b.

Fig. 4a.

QUARRY BLASTS ($f=6.0$)

Fig. 4b.

Thus, we have a head-on collision between the observational result from the real earth and the model prediction. During the general assembly of IASPEI in Istanbul, Turkey, on 30 Aug. 1989, about 20 scientists interested in coda waves met and engaged in intensive discussions on the above outstanding dilemma.

A general consensus of the meeting was that the dilemma must be due to simplified assumptions used in prediction by theoretical, numerical and laboratory methods. For example, most predictions are made under the assumption that the distribution of scatterers and attenuators are statistically uniform. We recognized strong need for developing theories and methods applicable to more realistic models of earth structure.

Unified theory for space-time-dependent seismic power spectra.

Coming back from the IASPEI meeting, the P.I. drew the attention of his students to the above dilemma and emphasized the need for a new effective theoretical approach. Papers 22 and 32 in our list of publications are the response to this urging. We found a new integral equation for the space-time-dependent seismic power spectra, from which all the earlier equations were derived as special cases. The equation can be easily extended to the case of more realistic models of earth structure.

The basic equation is given for the seismic energy density $E(r, t)$ at a point r and time t . Considering the source at $r=r_0$, and the incident wave energy density $E_{in}(t)$ at the source, we find

$$E(r, t) = E_{in}(t - \frac{|r-r_0|}{v}) \frac{e^{-\eta|r-r_0|}}{4\pi|r-r_0|^2} + \int_V \eta_s E(r_1, t - \frac{|r_1-r|}{v}) \frac{e^{-\eta|r_1-r|}}{4\pi|r_1-r|^2} dV_1 \quad (1)$$

where $\eta = \eta_s + \eta_a$, η_s is the scattering coefficient which equals to the product of scatter cross-section and the scatterer number density, η_a is the absorption coefficient, and v is the wave speed.

In the past, the time dependence of $E(r, t)$ for a fixed recording site r was studied by the use of single-scattering model (Aki and Chouet (1975), and Sato (1977)) or multiple-scattering models (Kopnichev (1977) and Gao et al. (1983a,b)). The space-dependence of $E(r, t)$, on the other hand, was studied by Wu (1985) starting with the Radiative Transfer theory. We can show that these two separate approaches are equivalent to each other and both can be derived from our equation (1).

First, by integrating equation (1) with respect to time, we can find the equation used by Wu (1985) for calculating the total energy vs. distance curves such as those shown in Fig. 1. Secondly, the iterative solution of equation (1) gives us a general solution for temporal variation of $E(r, t)$ as Neumann series expansion characterized by a power of the scattering coefficient. The first term of this series gives the first-order scattering formula obtained by Sato (1977). For the source and receiver coincident case, our solution gives the corrected version of high-order formulas obtained by Gao et al. (1983b).

Equation (1) can be solved using a Fourier transform technique to obtain a compact integral solution for the temporal variation in scattered wave energy decay which includes all multiple scattering contributions.

Equation (1) can be extended to the case in which the scattering coefficient η_s varies from place to place, by replacing η_s by $\eta_s(r_1)$, and $\exp \{-\eta|r-r_0|\}$ by $\exp \{-\int \eta(\xi) d\xi\}$ in the integrand. Thus, our new equation may offer an effective tool needed for resolving our outstanding dilemma mentioned earlier.

The plan for proceeding along this line of work in the next year is described later.

II. Seismogram Synthesis for Scattering and Attenuation in Complex Media

The study of scattering and attenuation of seismic waves described in the preceding section is based on the energy conservation principle. In order to fully understand the phenomena, however, the complete synthesis of seismograms by solving the wave equation is needed.

During the past year, we made a considerable progress in this area. First, we were able to solve the wave scattering due to many scatterers (up to 50) distributed arbitrarily in a homogeneous full space or half space for SH waves, by the Boundary Integral method. This lead to a preliminary result on the frequency dependence of scattering Q^{-1} which agrees with the result obtained by the Born Approximation (Sato, 1982), but disagrees with the result by the finite difference method (Frankel and Clayton, 1986).

Second, we developed a new method for mapping the topography of an inclusion using scattered seismic waves by the T-matrix method. The SH wave problem for near circular shapes and the toroidal motion problem for spherical shapes have been studied.

Third, we found another new method which will be particularly effective for complex structures found in many geothermal areas. This method combines the T-matrix method for wave scattering from inclusions with the generalized reflection/transmission matrix method for layered media. This method is exact and is applicable to discontinuities of arbitrary geometries. This is a definite improvement over the Aki-Larner method used by Roberts (Papers 11 and 20 in our publication list) for the study of the magma system under the Valles caldera using teleseismic P wave-form.

Scattering Loss in media with Randomly Distributed Cavities.

R. Benites, a non-resident MIT PhD candidate working at USC on this project, is near to completion of his Ph.D. thesis. Fig. 5a illustrates a typical problem studied in the thesis. There are 50 circular scatterers (cylindrical form in the SH problem) distributed in a rectangular region of a homogeneous full or half space. He calculates the scattering of SH waves of the Ricker type vertically incident from below using the method described in Paper 14 of our publication list. The result and seismic motions observed along the upper boundary A-A' of the rectangular region are shown in Fig. 5b for the case of characteristic wave length x_c of incident Ricker-type wave is 8 times the radius of the circular scatterer. Fig. 5c and 5d show the same synthetic motions for $x_c = 3.15a$ and $2a$, respectively. The

Fig. 5.

c

d

Fig. 5.
(Continued)

accuracy of these synthetic seismograms has been tested by checking the residual mismatch of stress field across the boundary, as well as through identification of individual arrivals in terms of multiply reflected and diffracted ray paths for the case of smaller number of scatterers.

Synthetic seismograms, as shown above, generated for the medium of randomly distributed scatterers can be used to determine the attenuation coefficient of primary waves propagating through such a medium. By numerically filtering, by a band-pass filter centered at frequency ω , primary waves before entering and after leaving the scattering zone, we calculated the Q^{-1} value from the ratio of $A_1(\omega)$ (after leaving) to $A_0(\omega)$ (before entering) by the following equation.

$$\frac{A_1(\omega)}{A_0(\omega)} = \exp\left(-\frac{\omega h}{2\beta Q}\right) \quad (2)$$

where h is the thickness of the scattering zone and β is the wave velocity.

The resultant Q^{-1} as a function of wave number k , showed a peak around $ka \approx 1$, where a is the radius of the circular scatterer. The decrease of Q^{-1} toward smaller k or longer wavelength is due to the well understood Rayleigh scattering. The decrease toward greater k or shorter wavelength has been somewhat controversial. The analytic solution obtained by the Born approximation for random media characterized by various autocorrelation functions usually showed this decrease. So did the result obtained by Kikuchi (1981) by the T-matrix method for a medium with randomly distributed cracks.

On the other hand, the finite difference method applied to random media by Frankel and Clayton (1986) failed to show this trend. Since the decrease in Q^{-1} with increasing wave number (or frequency) has been commonly observed for frequencies higher than about 1 Hz for waves travelling in the lithosphere of tectonic activity, the above discrepancy among different theoretical results has been a major concern among lithospheric seismologists. Our result gives an additional support to the decrease of Q^{-1} with frequency.

Seismic Mapping of Deep Discontinuity Topography by the T-matrix Method.

In this area of our research, we consider a problem of idealized geometry, namely, a homogeneous inclusion bounded by a surface S buried in a different but homogeneous unbounded elastic medium. We found that the T-matrix method of Waterman (1969, 1976) can be applied to this problem to obtain an elegant exact solution for the forward problem, and an explicit solution for the inverse problem (determining the shape of S from observed scattered waves) if we restrict the shape to be not too far deviated from the circular or spherical.

We are interested in this idealized problem because it may offer understanding of the fundamentals of inverse problem on what and how we can recover from observed scattered waves about the geometry of a subsurface body.

So far, the problem of SH waves was solved, and we have a well-defined inverse problem for the Fourier coefficients of the deviation from the circular shape in the form of a linear equation, where all the constants can be found from the forward solution for the case of unperturbed circular inclusion.

Currently, the problem of toroidal motions is being studied, and the inverse problem for the spherical harmonics coefficients of the deviation from the spherical shape has also been written in the form of a linear equation.

We plan to use these results to address some of the generic problems to be encountered in determining the geometry of subsurface body from seismic observations made on the earth's surface. For example, we can use them to find how much we can learn about the part of the boundary of the inclusion on the other side when our observations cannot completely enclose the inclusion. We can also address such questions as how the limited frequency range of observed scattered waves, and the distance between the subsurface body and the observer affect the information recoverable about its geometry.

Seismogram Synthesis for Multi-layered Media with Irregular Interfaces by Global Generalized Reflection/Transmission Matrix Method.

As mentioned earlier, the structure of magma-system under the Valles caldera was studied by Roberts (Papers 11 & 20 in our publication list) by the application of the Aki-Larner method to the teleseismic P wave form data. The applicability of the Aki-Larner method is restricted to an irregular interface with a gentle slope because of the well known Rayleigh ansatz problem. The method described here completely eliminates the problem by the use of the T-matrix method for the region where the Rayleigh ansatz problem arises. This method can be seen as either an extension of the T-matrix method for an inclusion to multi-layered media by introducing the global generalized reflection/transmission matrices, or an extension of the generalized reflection/transmission coefficient method for horizontally layered case (Kennett (1974), Luco and Apesl (1983) to an irregular layered case by incorporating the T-matrix method. This method provides an efficient scheme to synthesize seismograms in multi-layered media with irregular interfaces due to an arbitrary source as depicted in Fig. 6.

Details of our new method are described in paper 34 of our publication list. In this summary, we shall skip all the equations and show only a flow diagram for computing the synthetic seismogram in Fig. 7. Some of the key terms in this flow diagram are illustrated in Fig. 8 and Fig. 9. These figures would serve to convey a rough idea about the procedure.

We plan to apply this new method to the data from the Valles caldera in order to revise the earlier result of Roberts obtained by the Aki-Larner method.

Fig. 6.

Fig. 7.

Fig. 8.

(b)

Fig. 9.

III. Seismic Properties of Fault Zones

In many geothermal sites, fault zones control the paths of geothermal fluid such as vapor and hot water. The seismic identification of fault zones has become one of the major targets of geothermal research in Japan.

Under the present project, we studied seismic anisotropy of a fault zone (Papers 4, 5, 18 and 19 in our publication list) and guided waves trapped in a fault zone (Papers 7, 12, 21).

Fault Zone Trapped Mode

During the past year, we extended our study to include the borehole data collected close to the San Andreas fault near Parkfield. Papers 30 and 33 in our publication list describe the clear evidence for guided waves trapped in a low velocity zone along the fault. Paper 33 (accepted for publication in Science) summarizes the discovery of trapped modes in a fault zone as follows.

Three-component borehole seismic profiling of the recently active Oroville, CA, normal fault and microseismic event recording with a near-fault three-component borehole seismometer on the San Andreas fault at Parkfield, Ca, have shown numerous instances of pronounced dispersive wave trains following the shear wave arrivals. We believe that these are the first-observations of fault zone trapped seismic modes. Parkfield earthquakes exciting trapped modes have been located as deep as 10 km, as shallow as 4km, and extend 12 km along the fault on either side of the recording station. Modeling selected Oroville and Parkfield wave forms as the fundamental and first higher trapped SH modes of a narrow low velocity layer, we find at Oroville an 18 meter wide fault with shear velocity 1 km/s and at Parkfield a 100 to 150 meter wide fault gouge of shear velocity 1.1 to 1.8 km/s. We suggest that these low velocity layers are the fault rupture planes on which earthquakes occur.

In order to demonstrate the above statement in a more tangible form, let us show some of the observed waveform of the trapped mode. Fig. 10 shows downhole digital seismic network stations (triangles) in the Parkfield area and microearthquake epicenter (dots). A and B mark the location of events exciting fault zone trapped waves recorded at station Middle Mountain. The depths of events A and B are 10 km and 5 km respectively.

At the top of Fig. 11, vertical component seismograms of event A recorded at station Middle Mountain are shown. Waves marked as I and II are first higher and fundamental modes respectively. The second trace shows the corresponding computed wave forms for a low velocity zone with 100 meter width and shear velocity 1.4 km/s. The trapped waves from the same event were recorded neither at stations Frolich (FR) nor at Eades (ED), because of the larger distance from the fault zone.

Seismograms of four events occurring close to the point B in fig. 10 recorded at Middle Mountain are shown as top four traces (B, C, D, and E) of Fig. 12. The corresponding computed wave form is shown as the trace F. In this case, trapped mode marked by III includes overlapping fundamental and first higher modes.

The traces G and H are seismograms recorded at Middle Mountain for events near point B, but outside the narrow low velocity zone. They show very little indication of trapped modes.

Thus, observation of trapped mode can give a very precise definition of the geometry as well as material property of a fault zone. The field experiment to detect the trapped mode may require a shallow (~200m) borehole, but does not require a dense array of seismographs as in conventional reflection/refraction methods.

Coda Q^{-1} Tomography

Another promising method for seismic identification of a fault zone is the coda Q^{-1} tomography reported in Paper 26 of our publication list. In this paper, we assumed that the coda Q^{-1} determined from the lapse time window ending at t represents a volume

Fig. 10.

Fig. 11.

Fig. 12.

average of Q^{-1} of S waves within a spherical region with radius $t/(2\beta)$, where β is the shear wave velocity.

A direct support of the above assumption was obtained in the Ph.D thesis of Peng (1989) who found that the zero-crossing distance of spatial autocorrelation function of the coda Q^{-1} determined for different lapse time windows is proportional to the time of closing window in agreement with the above assumption.

Encouraged by Peng's result, we decided to undertake a tomographic inversion of coda Q^{-1} data. The usual tomographic inversion uses the traveltime data which is an integral of slowness along a line (ray path). The coda Q^{-1} , on the other hand, represents an integral of Q^{-1} of S waves over a volume. The inversion procedure for this case is described in Paper 26.

We used the data collected for the study of distance dependence of total seismic energy (Papers 25 and 31) for southern California, and applied the inversion procedure assuming a block structure each with unknown Q^{-1} parameter. The resultant Q^{-1} distribution is smoothed and shown in Fig. 13 and 14 in map view for two depth ranges 5-10 km and 10 to 15 km respectively. The Q value shows minimum in an area where the San Andreas fault and the Banning fault run parallel and high values away from the fault zone.

Proposed Research for the Next Year

Important breakthroughs in interpretation theory, as well as exciting discoveries from observations reported in the above Summary of Results, point to several promising directions to pursue in the next year. In addition to natural extensions of these past studies, we also have new opportunities to test some of our newly developed methods. For example, recent seismic activities in the Long Valley may offer an opportunity to apply the coda Q^{-1} tomography method to define the anomalous region where geothermal fluid may be penetrating.

PENNINSULAR RANGES

8-MAY-90 14:55:16

NONE

TOMO1.DEF

Fig. 13.

LONGITUDE (deg. West)

PENNINSULAR RANGES

8-MAY-90 14:55:16

TOMO1.DEF NONE

Fig. 14.

Let us now describe our proposed plan for research in the next year.

(1) Revising the Structure Under the Valles Caldera

As mentioned in the Summary of Results, we have developed a new method for calculating synthetic seismogram for layered media with irregular interfaces, which eliminated the limitation (Rayleigh Ansatz error) of the Aki-Larner method (Aki and Larner, 1970). As a first application of this new powerful tool, we shall revisit the teleseismic data collected by P. Roberts using an array of digital seismographs deployed in the Valles caldera, and revise the seismic velocity and attenuation structure derived by Roberts (Paper 20 in our publication list) using the Aki-Larner method. This task will be carried out by X. F. Chen and V. Ferrazzini under the supervision of the P.I.

(2) 2-D Structure Models for the Fault Zone Trapped Mode.

We shall use the new tool also to reinterpret the observations on the fault zone trapped mode using more realistic 2-D models, instead of the 1-D model that has been used for the synthetic seismograms shown in the Summary of Results (Paper 33 of our publication list). This task will be carried out by X. F. Chen and Y. G. Li under the supervision of the P.I. and P. C. Leary

(3) Inversion Scattering Problem for the Geometry of Subsurface Solution Body.

The elegant solution of inverse scattering problem for the geometry of subsurface inclusion described in the Summary of Results (Paper 28, 29 and 35 in our publication list) will be used to address basic issues generic to the inverse problem. For example, our formal solution given in an explicit form facilitate to answer such fundamental questions as how (a) the lack of observations below the subsurface body, (b) the limitation in observed frequency range, and (c) the distance from the receiver to the boundary surface affect the quality of the inverse solution.

The task proposed above will be carried out by X. F. Chen and M. Al-fares under the supervision of the P.I.

(4) Resolving the Coda Q^{-1} Dilemma

As described in the Summary of Results, we have a first-order dilemma about the seismic scattering and attenuation in lithosphere, that is "field observations support the single scattering model in many ways, while simulations by computer and scale model based on homogeneous random media do not." The only way to resolve the dilemma is to develop an efficient method of simulation for more realistic earth models with non-uniform distribution of scatterers and absorbers. The new integral equation described in the Summary of Results is expected to be useful for this purpose.

We shall solve the integral equation for various cases in which scatterers are localized along a relatively thin horizontal sheet (brittle layer) and/or vertical sheet (fault). We shall also consider the cases in which absorption is varying from place to place. We shall compare these theoretical predictions with various observations from the regional network in central and southern California on the space-time-dependent seismic power spectra, including coda Q^{-1} , strong motion attenuation, and the hypocentral distance dependence of total seismic energy. This task will be carried out by Y. Zeng and F. Su under the supervision of the P.I.

(5) Defining the Region of Possible Geothermal Fluid Penetration in Long Valley by the Coda Q^{-1} tomography.

We are encouraged by recent exciting discovery by L. S. Gao (personal communication) at the material science laboratory of the University of Paris about the change in coda Q^{-1} associated with the penetration of liquid metal into aluminum. He demonstrated by this discovery that the coda method is the most sensitive and reliable method for measuring the attenuation of waves in a high Q body. This is exactly what the P.I. and his colleagues have been demonstrating in the actual field for the attenuation of seismic waves in lithosphere for many years.

For example, Peng *et al.* (1987) found a change in coda Q^{-1} in the Long Valley caldera by about 20% at the time of the Round Valley earthquake of November 23, 1984. Recently, Langbein (1989) reported a change in deformation rate measured by a two-color geodimeter in the Long Valley caldera coincident with the occurrence of the Round Valley earthquake. The change is such that the high Q^{-1} (high attenuation) corresponds to the high rate of deformation.

Recently, D. Hill of U.S.G.S. reported at a meeting of the California Earthquake Prediction Evaluation Council that the deformation rate in the Long Valley has increased drastically in the past several months. We proposed to find if a similar change is taking place for coda Q^{-1} . If it is taking place, we plan to delineate the region of change by the tomography method described in the Summary of Results. The result may define the region where geothermal fluid may be penetrating. This task will be carried out by K. Mayeda under the supervision of the P.I. and P. C. Leary.

(6) Observational and Theoretical Study of Resonance in Magmatic Systems.

The narrowly peaked spectral structure of volcanic tremors, long-period events and gas-piston events have been well established observationally as discussed in papers 13 and 16 in our publication list.

Recently, Biswas *et al.* (1990) studied T-phase from earthquakes in California and Alaska observed by the seismograph network across the Island of Hawaii, and found that an anomalous amplification occurred for stations allocated along the East Rift Zone. The amplification occurred in the form of narrow peaks in spectra, some of which are common to all earthquakes. Since the East Rift zone is currently active and is believed to be filled with magma, we suspect that the peaked spectral structure may indicate the resonance of magmatic system. Peaks are indeed in the same range of frequency as those observed for volcanic tremors, long-period events and gas-piston events.

We propose to undertake more systematic comparison of site amplification effects between 9 stations near an active magma system and another away from it for various seismic sources.

We shall also compare theoretical responses of a magma system to seismic sources in and near the system and those to distant ones. For this purpose, we can make an effective use of our new synthetic seismogram for layered media with irregular interfaces (Papers 24 and 34 in our publication list). This task will be carried out by S. Koyanagi and V. Ferrazzini under the supervision of the P.I.

VSP Experiments

Our VSP equipment (thumper, sonde, field computers) is being maintained and we will perform additional experiments during the year as opportunities develop. This work is led by P.C. Leary with the assistance of technicians and students.

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BIOGRAPHICAL SKETCH KEIITI AKI

Keiiti Aki is W. M. Keck Foundation Professor of Geological Sciences in the Department of Geological Sciences at the University of Southern California (USC). He moved to USC in 1984 from MIT where he was R. R. Schrock Professor of Earth and Planetary Sciences in the Department of Earth and Planetary Sciences. His research activity has covered a broad area of seismology including earthquake source mechanism, attenuation, strong motion prediction, earthquake prediction, three-dimensional seismic imaging, volcanic tremor, and hydraulic fracturing. His current interests are centered around the synthesis of various seismological investigations on structures and processes in seismic and volcanic areas. Professor Aki is a member of the National Academy of Sciences, and a fellow of the American Academy of Arts and Sciences. He is also honorary foreign fellow of the European Union of Geosciences. He received the society medal from the Seismological Society of America.

He is chairman of the subcommittee on Earthquake Studies of the Advisory Committee to U. S. Geological Survey, members of the National Earthquake Prediction Evaluation Council, the California Earthquake Prediction Evaluation Council, and the Review Group for DOE's Continental Scientific Drilling Project.

He coauthored books titled "Quantitative Seismology: Theory and Methods", and "Orogeny". The following is a selected list of his publications:

- (with A. Jin) Spatial and temporal correlation between coda Q and seismicity in China, *Bull. Seis. Soc. Am.*, 78, 741-769, 1988.
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