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SEISMOLOGICAL INVESTIGATION OF CRACK FORMATION IN HYDRAULIC ROCK FRACTURING EXPERIMENTS AND IN NATURAL GEOTHERMAL ENVIRONMENTS

Progress Report
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Abstract

We have been developing new seismological methods for determining the structure of a geothermal energy source region by the use of data from both active and passive experiments. We have published technical papers on four topics, namely: a field experiment at Kilauea Iki, source models of volcanic tremors, microearthquake source spectra, and a numerical study of elastic wave diffraction by fluid-filled cracks. In addition, we have submitted for publication papers on a statistical synthesis of source mechanism of seismic events in Kilauea Iki and the observation of a temporal variation in the attenuation of earthquake coda in central California.

During the period covered by the present progress report, we worked on the following subjects: (1) interpretation of seismic data from the LASL Hot Dry Rock system; (2) analysis of volcanic tremor data from the U.S.G.S. Hawaiian seismic network; (3) frequency dependence and three-dimensional distribution of seismic attenuation in central Japan; (4) experimental study of seismic scattering by a penny-shaped crack; (5) development of a microprocessor system for the treatment of the data from digital event recorders.

Scope of Investigations

We are using a variety of seismic methods to determine the structure of geothermal energy source regions such as magma reservoirs and conduits in a volcano or hydrofractured cracks in a hot dry rock geothermal system. Our approach has been based on laboratory and field experiments as well as on data available to us from the U.S.G.S. Hawaiian Seismic Network and the Hot Dry Rock Geothermal Group of the Los Alamos Scientific Laboratories.

In one set of experiments, we use an ultrasonic source and study the scattered waves in the near-field of a heterogeneity upon which the primary waves are incident. Laboratory experiments have been performed on small scale models using a block of epoxy in which a penny-shaped crack was made that can be filled with a fluid. The ultrasonic source and receivers are set over the surface of the block and records of the signals are obtained in the absence of a crack and under both conditions of an empty or fluid-filled crack. The difference in the seismograms obtained prior to and after introduction of the crack give the wave field scattered from the crack. The image of the crack is recovered from the differential seismogram by use of a holographic technique (downward continuation of the wave front).

Data from another set of active experiments performed at the Fenton Hill site by the LASL Geothermal Energy Group is now being studied. We are investigating travel time anomalies of waves that have sampled the geothermal source region and which may be associated with regions of high permeability.

Preliminary analysis of seismic data from the U.S.G.S. Kilauea Network has been made using the mathematical model of volcanic tremors proposed by Aki et al. (1977).

A new method is being developed to determine the three-dimensional distribution of seismic attenuation as a possible indicator of anomalous regions (high temperature, high crack density, etc.) within the earth's crust.

The principal investigator has published a paper on the diffraction of elastic waves by a fluid-filled crack and another paper on a field experiment at Kilauea Iki. He supervised M. Fehler's computational work on the interaction of seismic waves with a fluid layer as well as his analysis of the data from the LASL experiment, J. Scheimer's ultrasonic laboratory experiment, C. Jaupart's analysis of volcanic tremor data and P. Mattaboni's work on instrumentation. The co-investigator published a paper on microearthquake source spectra and finished papers on a statistical synthesis of source mechanism of seismic events in Kilauea Iki and on the observation of a temporal variation in the attenuation of earthquake coda. The Kilauea Iki results were presented at the Spring AGU meeting in Miami, Florida.

Preprints of the two papers submitted for publication have been sent to D.O.E. under separate cover and will not be described here. In the following, we shall briefly summarize the work in progress.

Interpretation of seismic data from the Fenton Hill Hot Dry Rock System.

A significant portion of attention this year has been devoted to assisting in interpretation of seismic data collected by the Hot Dry Rock Geothermal Energy group of the Los Alamos Scientific Laboratory. The data under study was collected while performing the so called "Dresser Atlas experiment" during the month of October, 1977.

The Dresser Atlas experiment was performed at the Fenton Hill Geothermal energy project site near Los Alamos, New Mexico. The main purpose of the experiment was to try to determine physical properties of the rock in the geothermal reservoir, look for changes caused by pressurizing the reservoir and to attempt to relate the observations to the flow characteristics of the geothermal system. One instrument used in the experiment consisted of a piezoelectric seismic source with a peak frequency of approximately 12 KHz as well as a piezoelectric receiver located 12 feet away from the seismic source. This instrument was lowered into the EE-1 wellbore. A second instrument, consisting of only a seismic receiver, was lowered into the GT-2 wellbore. The most useful data was obtained when the receiver in the GT-2 was stationary and the source instrument in EE-1 was moved along the wellbore sweeping out angles of approximately 45^0 above and below the horizontal plane containing the receiver in GT-2. The

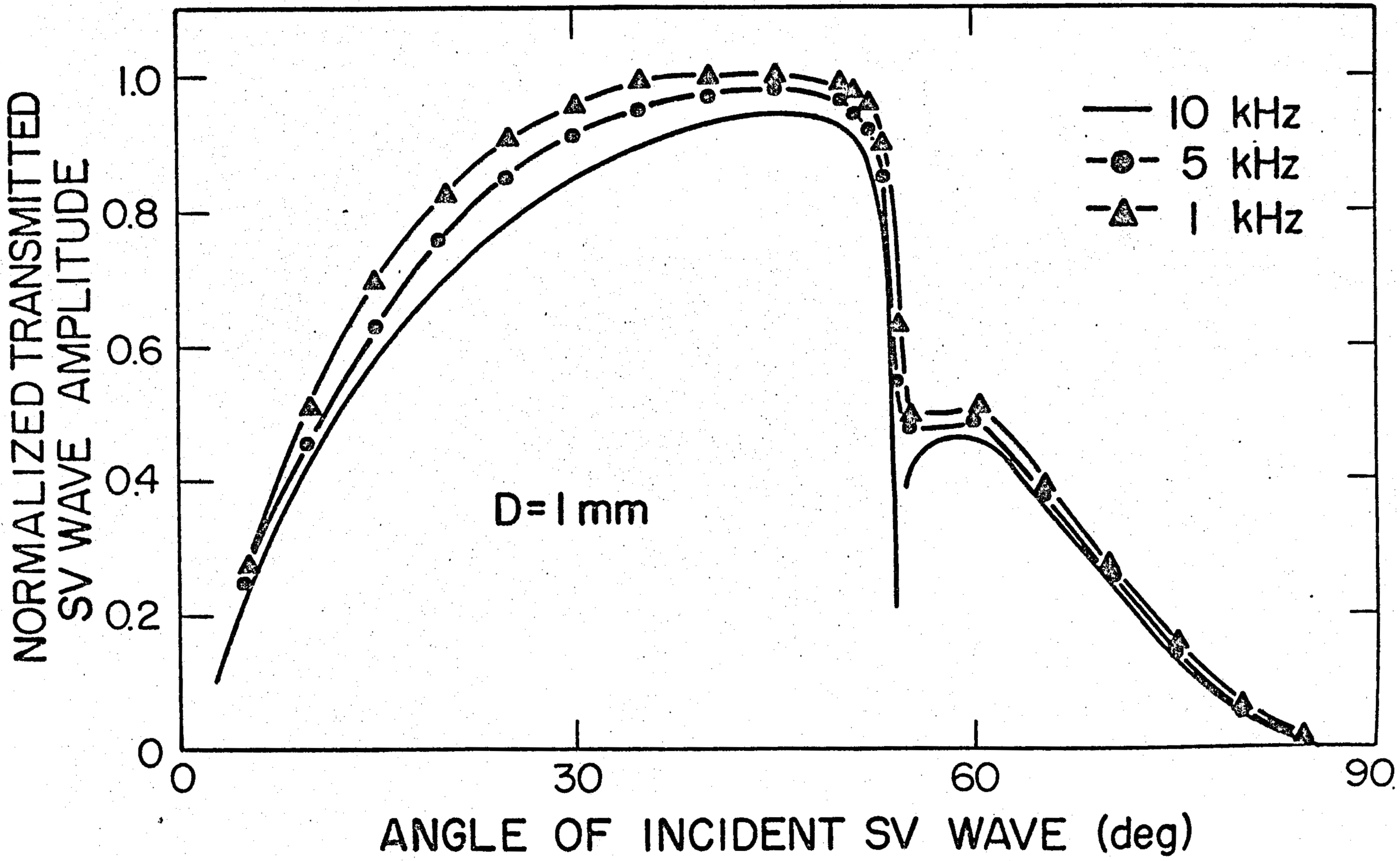

NORMALIZED TRANSMITTED
SV WAVE AMPLITUDE
1.0
0.8
0.6
0.4
0.2
0
0
30
60
90
ANGLE OF INCIDENT SV WAVE (deg)
10 kHz
5 kHz
1 kHz
D=1 mm

Fig. 1

source was fired at a rate of five times per second. During the first day of the two-day experiment both wellheads were open at the surface so that the water pressure in the geothermal source rock between GT-2 and EE-1 was equal to the pressure of the water column in the wellbores. On the second day of the experiment, the GT-2 wellhead was sealed off and water was pumped into the EE-1 wellhead under a pressure of approximately 105 bars.

The original objective in performing the Dresser Atlas experiment was to try to observe the effects of a thin fluid filled fracture on seismic waves. To aid in interpreting the results of the experiment, the interaction of seismic waves with a plane fluid filled (finite viscosity) fracture was studied. A computer program was produced which computes the amplitudes of waves reflected by and transmitted through a fluid-filled fracture as a function of angle of incidence of a plain P, SV or SH wave. Amplitudes were computed for fracture thickness and incident wave wavelengths thought to be appropriate for conditions <u>in situ</u> at Fenton Hill. A typical example of the results obtained is shown in Figure 1 which shows the amplitude of SV waves reflected from a layer of water of thickness 1 mm as a function of the angle of the incident plane SV wave. The results of these computations were presented at the Fall meeting of the American Geophysical Union held in San Francisco, California in December, 1977.

In order to directly study physical properties of the geothermal source rock, we decided to analyze first arrival times for waves traveling from the seismic source in EE-1 to the receiver in GT-2. Since thousands of seismograms were recorded during execution of the Dresser Atlas experiment, we decided it would be most efficient if a computer algorithm were developed to pick arrival times of the first P arrival at the receiver. The first arrival is chosen by its signal to noise ratio, frequency content, and direction of first motion. Some of the arrivals picked by the computer were checked with plots of the actual seismograms.

First arrivals for seismograms from four steps of the Dresser Atlas experiment were picked. For each step, the receiver was fixed in a given position in GT-2 and the source moved along the EE-1 wellbore. Data was gathered for each step for both the pressurized and unpressurized conditions. Table 1 lists, for each step, the depth of the receiver, as well as the source depths where data collection began and ended. Depths are given in feet to correspond with Los Alamos descriptions of the experiment. Selsyn depth is depth measured on a meter at Fenton Hill and true depth is vertical depth measured from 8700 feet above mean sea level. It should be noted that there is a difference of approximately 16 feet in the center depth between the pressurized and unpressurized data. This is due to an error that occurred during the pressurized part of the experiment.

Table 1. Results of least squares fits to first arrival data

		Selsyn		True					Selsyn		True		
	Step	Receiver Depth	Center Depth	Receiver Depth	Center Depth	vel. km/sec	wellbore spacing (meters)	γ	Data begins at depth	Data ends at depth	Data begins at depth	Data ends at depth	Number of Readings
Unpressurized	2	8547	8515	8485	8485	5.91	28.8	1.03	8485	8551	8455	8521	1100
	30	8632	8595	8570	8565	5.83	24.6	1.51	8645	8547	8615	8517	1500
	7	8704	8666	8641	8635	5.85	22.2	.82	8612	8684	8581	8653	1100
	16	8915	8874	8850	8843	5.82	16.0	1.64	8833	8915	8802	8884	1200
Pressurized	2	8547	8500	8485	8469	5.83	28.8	1.22	8465	8534	8435	8504	1100
	30	8632	8580	8570	8549	5.71	24.6	2.68	8636	8538	8606	8508	1500
	7	8704	8653	8641	8622	5.86	22.2	1.27	8601	8673	8570	8642	1100
	16	8915	8858	8850	8827	5.71	16.0	2.29	8841	8916	8810	8885	1200

Arrival times were plotted as a function of position of seismic source along the EE-1 wellbore. Assuming that the travel medium is homogeneous and isotropic the arrival time vs. position data should fall along a hyperbola described by

$$v^2t^2 = (x - x_0)^2 + d^2$$

where v is the medium velocity, t the travel time from source to receiver, x the position of source along the EE-1 wellbore, x_0 the location of the source when it is closest to the receiver and d is the distance between source and receiver when the source is located at $x = x_0$. A damped least squares linear inversion routine was developed to find the best hyperbola to fit the data. We assume that the value of d must be the same for both the pressurized and unpressurized conditions but that the velocity is different for the two cases. In this way we simultaneously fit hyperbolae to pressurized and unpressurized arrival time data to find two velocities, two values of x_o and one value of minimum source receiver spacing. The results of the least squares inversion are shown in Table 1. The results show that there is a small but consistent decrease in velocity when the geothermal system is pressurized. This decrease in velocity is consistent with the concept of effective pressure in rock mechanics (Brace, Pore Pressure in Geophysics, AGU Monograph 16, 265 (1972)) whereby the net effect of increasing the pressure of a fluid in a rock is to decrease the effective stress acting on the cracks, resulting in a lower rock velocity.

Figures 2 and 3 show the arrival time data picked from seismograms in step 30 for the unpressurized (Figure 2), and pressurized (Figure 3) cases. Each triangle represents one first arrival pick. The continuous line represents the least squares fit hyperbola. The vertical axis is scaled in digitized units which are equal to 82 times time in milliseconds. Regions where the hyperbola deviates from the dataare assumed to show where some sort of rock heterogeneity exists. We found that, in all cases, the fit of the hyperbola to the data was better for the unpressurized than for the pressurized data. The quantity γ in Table 1 is a quantitative value describing the fit. The larger values of γ for the pressurized cases indicate that the rock is more heterogeneous than in the unpressurized case. The increase in heterogeneity may be due to an increase in porosity brought about by pressurizing the system.

Figure 4 shows two seismograms recorded from step 2 for unpressurized conditions (a) and pressurized conditions (b). The locations of source and receiver were virtually the same while recording both seismograms. The seismogram recorded for the unpressurized case exhibits a clear first arrival wave packet consisting of five or six periods of motion. The remaining portion of the seismogram is of very small amplitude. In Figure 4b we see that the seismogram for the pressurized case is much more complicated in character. There is an emergent first arrival followed by a very complicated looking signal. This

new_proc
r 2316 1.923 53.215 769

66.318 1433

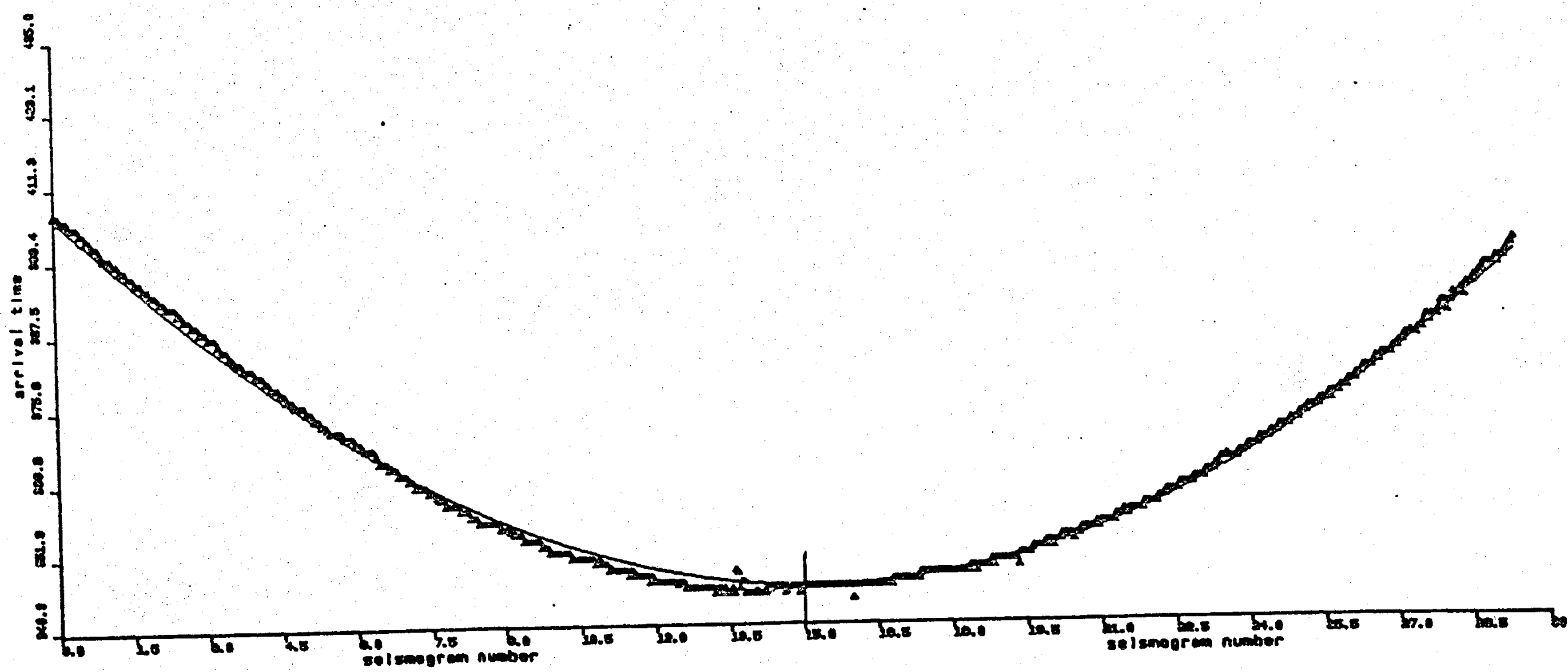


Fig. 2

new_proc

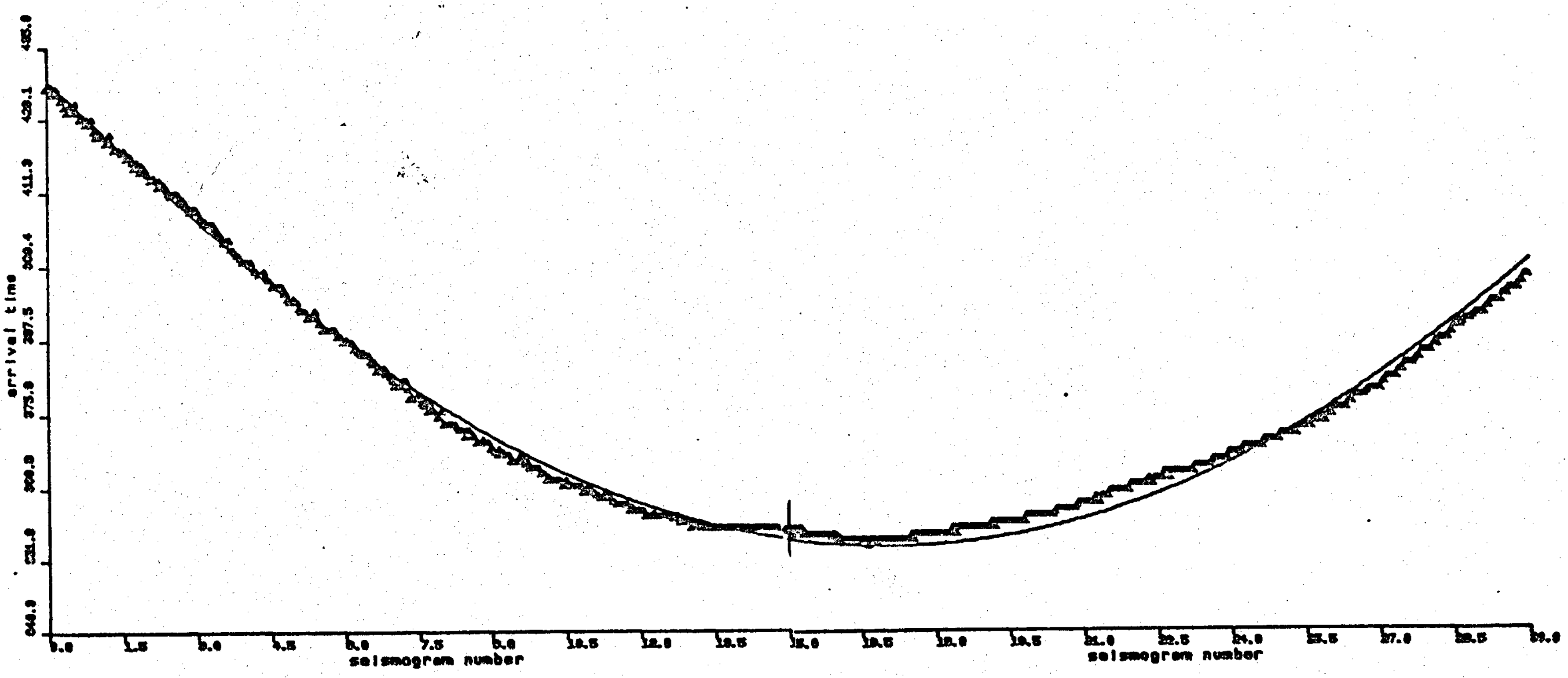


Fig. 3

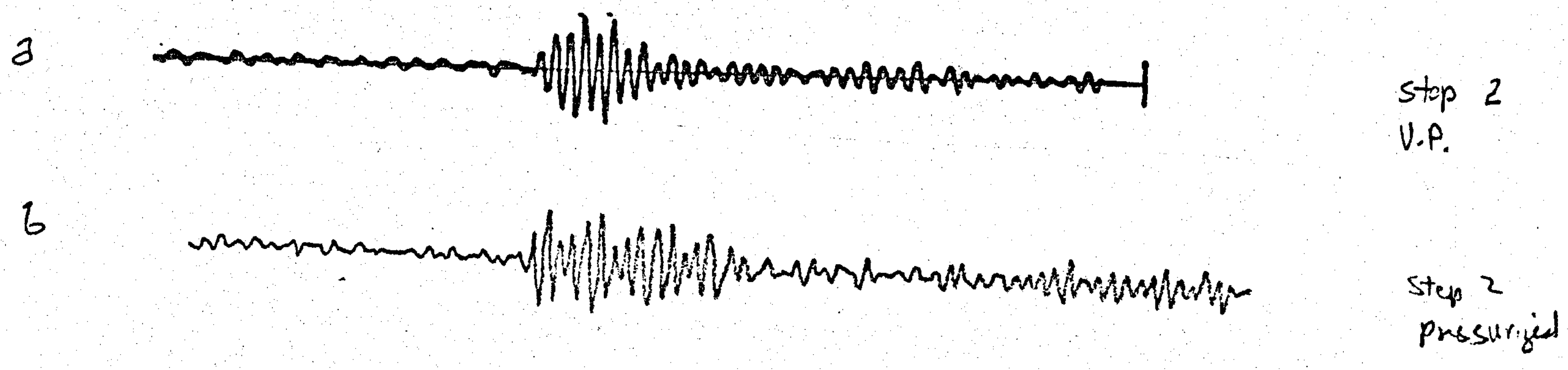


Fig. 4

suggests that the seismic wave is very strongly scattered in traversing the pressurized medium. We attempted to quantify the scattering process by using the random media theory of Chernov. (Chernov, Wave Propagation in a Random Medium, 1960). We found, however, that the scattering of waves between source and receiver is too strong for the assumptions made by Chernov to be valid.

Analysis of volcanic tremor data from the U.S.G.S. Hawaiian Seismic Network

Claude Jaupart, a graduate student, analyzed eight events which occurred in the vicinity of the Kilauea volcano during periods of quiescence in volcano activity in May 1975, March 1976 and May 1976. These events can be separated into two groups according to the location of the hypocenters. The first group includes events located at depths of 6 to 13 km directly beneath Kilauea caldera and the second consists of events located at depths near 40 km south of Kilauea. The parameters of the eight events are listed in chronological order in Table 2. Five of these events (events 1, 2, 4, 5, and 8) can be classified as tremors and three (events 3, 6, and 7) can be classified as earthquakes on the basis of their characteristics. Seismograms from earthquake-type events have a relatively short duration (on the order of 10 sec) and their frequency content changes from station to station due to attenuation effects. Events of the tremortype, on the other hand, are longer in duration and have a distinct dominant frequency which is constant throughout a record and is independent of station location. Fourier spectra exhibit spectral peaks at 7-7.5 Hz for events 1 and 2, 4.3-7 Hz for events 4 and 5, and 2.6 Hz for event 8.

It is significant to observe the two kinds of events for the deep source region south of Kilauea, which is presently not very well known. In fact, there are many similarities with the well known shallow seismic zone beneath Kilauea. This zone lies in the vicinity of the low-velocity layer located at a depth near 6 km, which has been interpreted as the primary magma chamber associated with Kilauea.

All the tremors coming from the deep source have the same first motion pattern at the nearest stations, i.e. an outward directed first arrival. There is one exception: event 2, dated from May 1975, where the first motion is downward instead. This may perhaps be explained by considering the general activity of the volcano, as studied by Koyanagi _et al_. (1975, 1976). In 1975, inflation was reported to continue at moderate rates for many months, interrupted occasionally by brief episodes of rapidly fluctuating deflations and inflations. From February to June 1976, a continuous weak inflation was observed. Although the information available to us is scanty, it is tempting to link event 2 with a period of deflation, and all the other tremors with a period of inflation in 1975 and the sustained inflation observed in 1976.

The series of events studied allows us to answer an important question about the origin of volcanic tremors. The characteristic peak structure of a tremor spectrum can be attributed either to a source effect or a path effect. In our case, we can rule out the path effect because: (1) the oscillatory motion has a constant frequency throughout the whole record, (2) this peak frequency is constant from station to station, (3) it changes with time, and (4) the same features are not observed for earthquake-type events coming from the same source region. Observation (4) is exemplified by event 3 which originated in the same region as events 2, 4, and 5 and has distinctly different displacements.

We link the observed tremors with magma movements before and after the November 29, 1975, Kalapana earthquake, which are demonstrated by the inflation and deflation of the Kilauea summit. The processes involved in magma transport are still largely unknown, and the few models which have been proposed generally do not give quantitative estimates of the various parameters involved. For our purpose, however, it is only necessary to define a seismologically consistent model. We have found that the characteristics of the records discussed are not due to path effects and this imposes a

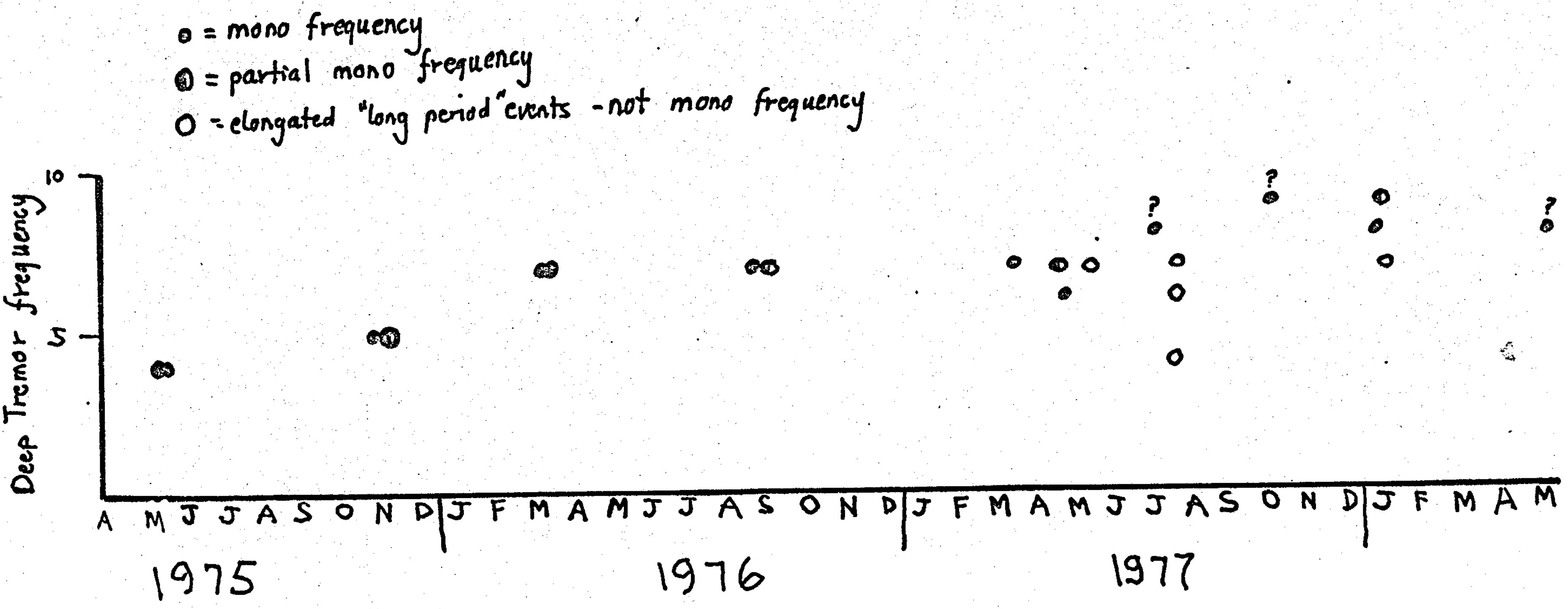
TABLE 2

The hypocenters of the eight events analyzed in this study

Event	Date	Origin time	Latitude	Longitude	Depth	NR	RMS	ERH	ERZ
1	5/26/75	18 26 33.79	19 7.40	155 24.00	39.00	10	0.07	3.3	6.0
2	5/30/75	07 02 10.00	19 13.75	155 16.97	40.00	13	0.05	1.0	1.7
3	3/23/76	16 16 18.75	19 14.43	155 17.85	38.28	11	0.02	1.1	1.7
4	3/24/76	07 31 46.32	19 14.22	155 19.76	40.00	11	0.02	1.1	0.8
5	3/30/76	22 37 21.35	19 12.21	155 17.00	40.00	9	0.03	1.3	2.2
6	5/17/76	17 59 16.67	19 24.14	155 15.70	7.00	9	0.18	1.3	2.3
7	5/29/76	19 27 51.16	19 24.82	155 16.73	13.00	11	0.04	0.5	0.6
8	6/12/76	04 02 9.31	19 22.32	155 16.17	6.02	6	0.10	1.7	2.2

The Origin time is the Hawaiian Standard Time,
Latitude in degrees and minutes of North Latitude,
Longitude in degrees and minutes of West Longitude,
Depth is the depth of focus in km,

NR is the number of P-arrivals used for solution,
RMS is the root mean square error of time residuals in seconds,
ERH and ERZ are the standard error of the epicenter in km.



o = mono frequency
◍ = partial mono frequency
O - elongated "long period" events - not mono frequency
Deep Tremor frequency
10
5
?
?
?
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M
1975
1976
1977

Fig. 5

strong constraint on the source mechanism. As the peak frequency is independent of station location, it must be the frequency with which the source itself oscillates. Whichever model is preferred, it is clear that this frequency is a function of source dimensions. Using the Aki <u>et al</u>. (1977) model, for example, we find the radius of crack containing magma to be a few hundred meters for the source of the deep tremors.

We sent our preliminary results on the deep tremors to Dr. R. Y. Koyanagi of the U.S.G.S. Hawaii Volcano Observatory. In response to our communication, he sent us a figure (Figure 5) showing the periods of tremor as a function of time which confirmed our findings. Surprisingly, the periods of the deep tremors appear to have changed from 4 to 8 Hz during the period 1975-78. The change appears to be related to eruptive episodes. The largest increase in frequency has occurred at the time of occurence of the M = 7.2 earthquake which was accompanied by large deformation.

In terms of the model of Aki <u>et al</u>., the increase in frequency corresponds to the reduced crack size implying that the deep magma pocket lost its contents at the time of activity at shallow depths. A more systematic study of deep tremors may reveal the mechanical process associated with the magma transport, and may give important information on the future supply of magma.

References

Aki, K., M. Fehler and S. Das, Source mechanism of volcanic tremor: fluid-driven crack models and their application to the 1963 Kilauea eruption, J. Volcanol. Geotherm. Res., 2, 259-287, 1977.

Koyanagi, R., K. Meagher, F. Klein and A. Okamura, Hawaiian Volcano Observatory, Summary 1975, U.S.G.S..report, 1975.

Koyanagi, R., K. Meagher, F. Klein and F. Punuvai, Hawaiian Volcano Observatory, Summary 1976, U.S.G.S. report, 1976.

Frequency dependence and three-dimensional distribution of seismic attenuation in central Japan

A new method was developed by the principal investigator to study the detailed three-dimensional distribution of seismic attenuation property in the earth's crust and upper mantle. The method is applicable to the area where microearthquakes are occurring, and is currently applied to the Kanto region in central Japan, where numerous earthquakes are occurring at depths ranging from 0 to 150 km. The method is based on the equalization of S-wave spectral amplitudes for the source effect using the coda spectral amplitudes (Aki and Chouet, 1975). The equalization is possible because of the insensitivity of coda to the distance and on the nature of direct wave path. The equalized S-wave amplitudes are used to find the frequency dependence of quality factor Q in the range from 1 to 24 Hz, and to determine the three-dimensional distribution of Q in the earth's crust and upper mantle under the Kanto region.

So far, 460 earthquakes were analyzed with extremely interesting results. First, Q increases with frequency proportional to the square root of frequency from 1 to 24 Hz. Combining the results from long-period surface wave attenuation, we find that the resultant frequency dependence of Q for the range from 0.04 to 24 Hz may be interpreted as due to the thermoelastic effect for the grain size of about 1 mm. This interpretation, however, may not be the only one which can explain observation. We are currently investigating other possible interpretations.

The three-dimensional distribution of Q for 24 Hz showed a remarkable correlation with the plate configuration expected under the Kanto region, which overlies a triple junction between the Eurasian, Pacific and Philippine Sea plates. Moreover, it revealed that Q is not uniform in a plate, but shows a layered structure within a plate. For example, the upper half of the Philippine sea plate shows low Q as compared to the lower half. This result is reasonable because of the presence of volcanic zones on the Philippine Sea plate.

Our discoveries on the frequency dependence and the three-dimensional distribution of Q are both very fundamental to the structure and tectonics of earth's crust and upper mantle. We are continuing the collection of more data from the Kanto region, to firmly establish our findings.

Reference

Aki, D. and B. Chouet, Origin of coda waves: Source, attenuation, and scattering effects, J. Geophys. Res. 80, 3322 - 3342, 1975.

Experimental study of seismic scattering by a penny-shaped crack

Ultrasonic model seismology was applied by Jim Scheimer to a study of scattering of P-waves by a dry and a fluid filled crack. Three experiments were conducted, the first of which provided background information on the model medium and served to develop experimental techniques. The data from the other two experiments were used to test the applicability of a number of seismic techniques to the determination of the crack's size, orientation, and location by studying the scattered signal.

The technique of wavefront reconstruction was used to analyze a data set consisting of first arrival times and amplitudes of the combined incident and scattered wavefields. The amplitude distribution of the reconstructed wavefronts at various depths in the model showed that the signal scattered by the dry crack resembles that radiated by the sudden opening of a tensile crack, though the sense of the motion is reversed.

Differential seismograms were made between signals recorded for the case of the empty crack and the case of the crack filled with water. Since it can be shown for the elastic parameters of the model studied that the model containing a water-filled crack is equivalent to the homogeneous solid, this technique isolated the signal due just to the presence of the crack. These differential seismograms showed that the waveform of the scattered signal was indistinguishable from that of incident wave, but inverted. A kinematic model of scattering by a penny-shaped crack was developed based on elastic solutions for the opening and closing of a tensile crack, using the stress field of the incident P-wave as the loading function on the crack face. The tensile crack was replaced with a Haskell-type model, where the rise time of the displacement discontinuity was given by the rise-time of the first cycle of the incident wave, and the final displacement was derived in terms of the maximum amplitude of the incident wave. Using this model a scale factor relating the ratio of the amplitudes of the scattered and incident signals to the size of the crack and the wavelength of the insonifying radiation was calculated from the following relation:

$$\left| \frac{U^P(\omega)}{W_{z_1}(\omega)} \right| = 0.125 \frac{a}{R} \sqrt{\frac{a}{\lambda}}\, C$$

where the quantity on the left is the ratio of the amplitude, $U^P(\omega)$, of the scattered wave to that of, $W_{z_1}(\omega)$, of the incident wave at a given frequency, a = 1.27 cm is the radius of the crack, $\lambda = 0.05$ cm is the wavelength of the insonifying radiation, R is the distance to the observation point from the center of the crack, and C is the scale factor calculated from the observed data. We found that for our model the scale factor was 7.3, from which we could estimate the opening of the crack caused by the P waves propagating along the crack to be ~1.5 times the peak to peak displacement of the incident P waves, for this model.

We conclude that these techniques can be of value in inferring the parameters of cracks in the earth made by artificial hydraulic fracturing for geothermal and other purposes as well as those in volcanic areas made naturally by excess pressure in magma, following the methodology we have developed. Further, we conclude that the method would benefit from additional study. Specifically, different model geometries and crack size to wavelength ratios could be studied. We believe our success demonstrates that a most promising way to continue these studies would be to use model seismology. We believe our success in using model seismology demonstrates its viability as a research tool, and that the technique is worthy of serious reconsideration.

Seismic software development

We have developed a system of programs which collectively read digital tapes of our event-recorders and perform various functions on that data. They are capable of displaying, editing, reformating, and performing an FFT or PSD on the data.

A program written in Basic controls a machine program which reads the data tapes into memory via a parallel interface. All redundant time information is removed to allow for efficient storage on disk. Once the data is on disk, another program extracts portions of the data to be displayed on a video monitor for editing or analysis.

A cursor positioned by command from the key board indicates the exact time of any particular data point, this function may be used to identify arrival times, remove a bad data point, or duplicate the starting point of an FFT or PSD. All programs are designed to run on the OSI Challenger II Microcomputer complete with 48K of memory, the 440 video board and the 430 super I/O board.

We are also in the process of developing a low power microcomputer system to gather data in remote areas where power is not available. The minimum requirements of the system are to collect raw data on tape. We would also like to do some data reduction in the field. Presently we have a bread board system utilizing the dataset 6100 microprocessor.

List of Publications and Presentations

1. Aki, D., Fehler, M. and S. Das, Source mechanism of volcanic tremor: fluid-driven crack models and their application to the 1963 Kilauea eruption, J. Vol. Geotherm. Res., 2, 259-287, 1977.
2. Aki, K., Chouet, B., Fehler, M., Zandt, G., Koyanagi, R., Colp, J. and R.G. Hay, Seismic properties of a shallow magma reservoir in Kilauea Iki by active and passive experiments, J. Geophys. Res., 83, 2273-2282, 1978.
3. Chouet, B., Aki, K. and M. Tsujiura, Regional variation of the scaling law of earthquake source spectra, Bull. Seism. Soc. Am., 68, 49-79, 1978.
4. Chouet, B., Statistical synthesis of source-mechanism of seismic events in the cooling lava lake of Kilauea Iki, Hawaii, submitted to J. Geophys. Res., 1978.
5. Chouet, B., Seismic activity in Kilauea Iki, Hawaii, EOS Trans. AGU, 59, 317, 1978.
6. Chouet, B., Temporal variation in the attenuation of earthquake coda near Stone Canyon, California, submitted to Geophys. Res. Let., 1978.
7. Fehler, M., Transmission and Reflection of P and S waves by a viscoelastic fluid layer, EOS Trans. AGU, 58, 1192, 1977.
8. Scheimer, J.F., Experimental study of seismic scattering by a penny-shaped crack. Ph.D. Thesis. Dept. of Earth and Planetary Sciences, MIT, 1978.

PROPOSED TECHNICAL SCOPE

We shall continue to collect and analyze data from the U.S.G.S. Hawaiian Seismic Network and the LASL Hot Dry Rock experiments. We shall also pursue the development of our event recorder as well as the associated software for the treatment of the digital seismic data. Interpretation methods will be developed to handle the generation, transmission, and scattering of seismic waves in various geothermal systems.