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Progress Report to U.S. Department of Energy:

STUDIES OF DIGITAL SEISMIC DATA OBTAINED IN
GEOTHERMAL AND VOLCANIC REGIONS

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Introduction

During the period 1 February, 1982 - 31 January, 1983, we have been funded by a grant from the Department of Energy, Office of Basic Science to study seismic data obtained in volcanic and geothermal regions. Much of our work has been in cooperation with Dr. Keiiti Aki, Dr. Bernard Chouet, Mr. Peter Roberts and Mr. Paul Mattaboni of the Massachusetts Institute of Technology. Using funds provided by this grant we have undertaken a number of studies and published or submitted for publication a number of papers describing our results. This document is a report of progress made using funds provided by the Department of Energy.

Work accomplished falls into three categories which will be discussed separately in this progress report. These categories include (1) Study of tremor waveforms recorded at Mount St. Helens during 1980. (2) Study of seismicity recorded during 1981 at Mount St. Helens during the period of time that we operated a network of digital seismic event recorders on Mount St. Helens. (3) An experiment carried out in the Jemez Mountains of New Mexico to monitor seismicity accompanying hydrofracturing experiments being carried out by the Hot Dry Rock Geothermal Energy Group of the Los Alamos National Laboratory. A final section of this report lists scientific papers and a list of talks that have resulted from the work funded by this grant.

Study of tremor waveforms recorded at Mount St. Helens during 1980.

A systematic study was made of ground motion recorded during volcanic tremor episodes accompanying two eruptions of Mount St. Helens during 1980. Complete details of the study can be found in the paper by Fehler (1982c) entitled "Observations of Volcanic Tremor at Mount St. Helens", which has been submitted for publication. A copy of this paper accompanies this progress report. Throughout this discussion this paper will be referred to as Fehler (1982c). Since the paper contains a complete discussion of methods of analysis and conclusions about tremor at Mount St. Helens, only a brief summary of the main conclusions of the study is presented here.

During the summer of 1980 we operated one three component digital event recorder in the vicinity of Mount St. Helens. The location of this instrument was an abandoned quarry called House Rock Quarry which is approximately 22 km southeast of the summit of Mount St. Helens. (A location map appears as Figure 2 in Fehler (1982c)). During the period that the instrument was in operation there were two explosive eruptions of Mount St. Helens that were accompanied by volcanic tremor. The digital event recorder successfully recorded many occurrences of tremor and other seismicity that accompanied these two eruptions. Study of the seismic waveforms recorded during these two eruptions yielded the following results: (1) The spectra of the tremor waveforms consisted of many peaks. Peaks at .9 and 1.1 Hz dominated spectra of all waveforms. (2) The relative amplitudes of the two peaks changed from event to event and often during an event which leads us to conclude that the unique waveform of volcanic tremor is due to a source effect, not a path effect. (3) The frequencies at which the dominant peaks in spectra occur do not change with signal amplitude. If the dominant frequencies are determined by the source volume, variations in the amplitude of the signal must be due

to variations in the force driving the source. Our finding that the dominant frequency does not change with amplitude is different from that of Aki and Koyanagi (1981) who studied deep tremor in Hawaii and found that the dominant frequency varies systematically with tremor amplitude. Tremor at Mount St. Helens thus does not follow the concept of dynamic similarity that Aki and Koyanagi (1981) found for deep tremor in Hawaii and Aki (1972) found for earthquakes. (4) The spectra of tremor are very similar to spectra of long period volcanic earthquakes recorded at the same location. This leads us to conclude that tremor is composed of a sequence of long period earthquakes that occur close enough together in time that individual events are indistinguishable. Koyanagi (personal communication) has recently observed a sequence of long period events occurring in Hawaii that began as discrete events that were well enough separated in time that individual events could be detected. As time progressed, Koyanagi observed that the events occurred closer together in time until individual events were indistinguishable and the seismic record could be regarded as consisting of volcanic tremor. These observations of Koyanagi further substantiate our conclusions regarding the relationship between tremor and long period seismic events at Mount St. Helens. (5) Amplitudes of ground motion during tremor episodes studied varied between $.11 \mu\text{m}$ and $4.7 \mu\text{m}$. Seismic moment rates calculated using the model of Aki et al (1977) varied between 6×10^{18} and 1×10^{20} dynes cm sec⁻¹ which are larger than values found by Aki et al (1977) who studies amplitudes of shallow volcanic tremor events recorded during the October, 1963 eruption of Kilauea volcano in Hawaii. We estimated the seismic moment rate of tremor accompanying the cataclysmic eruption of Mount St. Helens on May 18, 1980 and found it to be at least one order of magnitude larger than tremor recorded during the two eruptions for which digital data was studied. This large seismic moment rate

means that the total seismic moment associated with tremor accompanying one hour of the May 18 eruption is equivalent to the seismic moment of one magnitude 5 earthquake,

Study of Seismic Data Recorded during 1981 at Mount St. Helens

During the period May - October, 1981 we operated, with the cooperation of the Massachusetts Institute of Technology and the United States Geological Survey, a nine station array of digital seismic event recorders in the vicinity of Mount St. Helens in Washington State. The purpose of operating this array, the array configuration and some preliminary results of analysis of data collected by the array are described in a paper by Fehler and Chouet titled "Operation of a digital seismic network on Mount St. Helens volcano and observations of long period seismic events that originate under the volcano", which will be referred to as Fehler and Chouet (1982). This paper has recently been accepted for publication in Geophysical Research Letters. The information contained in this paper will be only briefly summarized in this progress report since a copy of the paper accompanies this report.

During the time that our array of digital event recorders was in operation on Mount St. Helens we obtained many excellent recordings of seismic events occurring under the volcano. Figure 1 shows typical earthquake records obtained at a number of the stations. (Station locations on Mount St. Helens are shown in Figure 1 of Fehler and Chouet (1982)). Figure 2 shows records of ground motion obtained during a type of event that we refer to as a long period seismic event. Contrasting waveforms shown in Figures 1 and 2 leads to the conclusion that the waveform of the long period event contains little high frequency component. Figure 3 shows spectra calculated from signals for the event shown in Figure 1. The spectra are characterized by a flat region at low frequencies and a high frequency roll off. Spectra shown in Figure 3 are similar to spectra of earthquakes in other tectonic regions. Figure 4 shows spectra of signals recorded at three stations for the long period event shown in Figure 2. The spectra shown in Figure 4 all contain peaks at

Figure 1. Typical vertical component waveforms of short period earthquakes recorded by digital seismic array at Mount St. Helens. The station name is given below each trace. For a map of station locations see Figure 1 of Fehler and Chouet (1982). Amplitudes of waveforms at various stations are not plotted on a common scale.

Figure 2. Typical vertical component waveforms of long period earthquakes at Mount St. Helens. Amplitudes not to scale.

3×10^{-5}

3×10^{-8}

Amplitude in
cm. - sec.

3×10^{-5}

3×10^{-8}

Amplitude in
cm. - sec.

Figure 3. Spectra of waveforms shown in Figure 1.

6×10^{-4}

6×10^{-7}

Amplitude in
cm. - sec.

SRW

Frequency in Hz.

9×10^{-4}

Amplitude
in cm.-sec.

9×10^{-7}

NWD

Figure 4. Spectra of waveforms shown
in Figure 2.

Frequency in Hz.

approximately 1.2 Hz. These peaks are at nearly the same frequency for all three stations. We have calculated spectra of waveforms of many long period seismic events. We find that nearly all of the spectra contain dominant peaks in the frequency range between 1.2 and 2.3 Hz. There is no systematic variation of dominant frequency with amplitude for all signals studied to date. This lack of change of dominant frequency with signal amplitude is similar to the results mentioned in the previous section on volcanic tremor at Mount St. Helens. This provides further evidence for the relationship between long period seismic events and volcanic tremor at Mount St. Helens as put forth in the previous section.

We have attempted to locate some of the long period seismic events recorded by our digital seismic array. Our initial attempt was made using the program Hypoinverse (Klein, 1978). In order to obtain better constraints on locations we have supplemented arrival time data for first arrivals recorded by instruments in our array with arrival times recorded by the University of Washington regional seismic network. We have found that event hypocenters fall in a distributed region under Mount St. Helens at depths of less than 5 km. We note the following problems with locations using the program Hypoinverse; (1) The program locates only one event at a time and computes station residuals (misfit of observed arrival time to computed arrival time for the determined hypocentral coordinates). This has the disadvantage that there can be no comparison of relative event locations since station residuals often vary dramatically from event to event. Since it is desirable to search for changes in event locations as an eruption nears and for differences in locations of short and long period events it is best if relative event locations can be determined. (2) The velocity structure of Mount St. Helens is poorly known. Event locations calculated using Hypoinverse may change

dramatically if the velocity structure input into the program is changed.

(3) The program has no facility to account for differences in station elevations. Since elevations of our stations differed by as much as 1.0 km there could be substantial differences in arrival times at stations that are caused only by elevation differences between stations. (4) Most of the hypocentral determinations computed by program Hypoinverse had the property that event origin times were later than first arrival times at station BCR located in the crater of the volcano. In fact, the program most often threw out the arrival time at station BCR during the iteration procedure to compute an event location. Throwing out data from BCR has the undesirable property that the data from the station nearest to the epicenter is not used in the hypocenter determination. The early arrival at BCR relative to other stations is not completely understood at this time. One possible explanation for the early arrival is that there may be a high velocity body located beneath the station BCR. Ultimately, any of the problems mentioned above in 1 - 3 may be causing an event mislocation. Aki (personal communication) has performed ray tracing on hypothetical structures in an attempt to better understand the early arrival at station BCR. He concluded that one possible explanation is that the crater is underlain by high velocity material that advances arrival times to the station inside the crater. His model for velocity structure is similar to one found by Hayakawa et al (1957) at the volcano Showa-Shinzan in Japan. One prediction made by the Aki model is that waveforms from deep events will have small amplitude on the crater station relative to stations outside the crater since rays from deep events will be bent away from the crater by the high velocity zone. An event may go undetected by the crater instrument if the signal level were too small to trigger the event detection circuitry. Malone (personal communication) has noted that most high frequency events occur at

greater depth beneath Mount St. Helens than do long period seismic events. Our data show that high frequency events are recorded equally well inside and outside the crater. Preliminary analysis of arrival times of the high frequency events recorded by our digital seismic array show that the high frequency events recorded at BCR had shallow hypocenters. Thus, the occurrence of strong signals in the crater from high frequency events does not invalidate the Aki model. Instead we conclude that many high frequency events occur at shallow depth beneath Mount St. Helens. These events may be so small that they go undetected by the rather sparse University of Washington Seismic Network at Mount St. Helens.

In order to overcome some of the difficulties with program Hypoinverse mentioned above, we are currently developing a program to simultaneously locate many earthquakes beneath Mount St. Helens and obtain one station correction that is common to all events.

Particle motion plots of three components of motion for some long period seismic events have been made. We find that particle motion of waveforms from these events is dominantly horizontal.

Seismic Studies of the Valles Caldera, New Mexico

During the first half of 1982, the Hot Dry Rock Geothermal Energy Group of the Los Alamos National Laboratory (LANL) performed a series of hydraulic fracturing experiments intended to create a hydraulic fracture between the recently drilled holes EE-2 and EE-3. The experiment was set up so that water injected into hole EE-2 entered the rock formation at a depth of approximately 4570 meters (15,000 feet). Previous fracturing experiments, conducted in the original geothermal system consisting of holes EE-1 and GT-2 had been accompanied by sequences of small earthquakes whose magnitudes never exceeded -1. Signals from these small earthquakes were never observed at the surface but were recorded only by seismometers placed in one of the boreholes. The hydraulic fracturing experiments carried out in 1982 induced earthquakes as large as magnitude 1. These larger earthquakes were observed at surface seismic stations at distances as large as 30 km from the source. Robert Potter of LANL suggested that it would be beneficial to increase the seismic station density in the vicinity of the geothermal site in order to obtain more information about the earthquakes being generated. In consultation with Keiiti Aki of the Massachusetts Institute of Technology, (M.I.T.), it was decided to deploy six three component digital event recorders in the vicinity of the Jemez mountains at distances of less than 30 km from the LANL geothermal site. The purpose of this project was to study the shallow structure of the Valles caldera complex in order to determine whether or not there is evidence for a shallow magma body under the recently active volcano. We also hoped to obtain high quality digital recordings of the events so that source parameters of the earthquakes calculated from spectra of signals recorded at the surface could be compared with source parameters calculated from spectra of signals recorded by borehole seismometers. In addition, we hoped that data from our six instruments would

compliment that from the LANL network to enable a more accurate focal mechanism determination. Since the LANL seismic network consists of relatively few stations at distances between 5 and 30 km from the Fenton Hill geothermal site, it is difficult to obtain a well constrained focal mechanism from the LANL network data. Investigators from LANL were most interested in precise determination of the focal mechanism because of its usefulness for predicting in situ stress orientation.

With the assistance of Peter Roberts of M.I.T. and financial assistance from Keiiti Aki six seismic stations were installed around the Valles caldera in mid July, 1982. The instruments are identical to the ones used around Mt. St. Helens by the principal investigator in 1981 and described briefly in the two papers about Mt. St. Helens that were authored by the principal investigator (Fehler, 1982c; Fehler and Chouet, 1982). The locations of the six stations are shown in Figure 5. Also shown in the figure are the locations of the Hot Dry Rock geothermal site at Fenton Hill and the location of the Nacimiento uplift which is a region of relatively high earthquake activity as reported in earthquake catalogs produced by seismologists at LANL (Cash et al, 1982). If an earthquake occurring on the Nacimiento uplift were recorded by our instruments we could obtain information about deeper structure under the caldera than would be possible by using signals generated only at Fenton Hill.

Unfortunately, the LANL pumping experiment that we set up to monitor was plagued by delays due to equipment failure. When the pumping finally began, fluid pressures were kept lower than desired because of a weak equipment component in the downhole system. The weak component finally failed after twelve hours of pumping and the experiment was abruptly terminated. No earthquakes of sufficient size to be observed at the surface were generated. During the period of time that our array was monitoring seismicity, one regional earthquake

Figure 5. Map showing locations of digital seismic event detectors during seismic experiment in the Jemez Mountains, New Mexico during July, 1982.

Figure 6. Waveforms recorded during seismic experiment in the Jemez Mountains. Amplitudes at various stations are not plotted on a common scale.

did occur that was well recorded. The event occurred approximately 200 km northwest of the Jemez mountains. Figure 2 shows copies of three components of motion recorded by two stations (FEN and RMN) and two components of motion recorded by station CMN.

Scientific Communication

Six papers describing work funded by this grant have been published or submitted for publication by the principal investigator during the past year. Copies of these papers are included with this progress report. Papers that have been published or accepted for publication include:

Fehler, M., 1981, Changes in P wave velocity during operation of a hot dry rock geothermal system, J. Geophys. Res., 86, 2925-2928.

Aki, K., Fehler, M. et al., 1982, Interpretation of Seismic Data from Hydraulic Fracturing Experiments at the Fenton Hill, New Mexico, Hot Dry Rock Geothermal Site, J. Geophys. Res., 87, No. B2, 936-944.

Fehler, M., 1982, Interaction of Seismic Waves with a Viscous Liquid Layer, Bull. Seism. Soc. Am., 72, 55-72.

Fehler, M., 1982, Using dual well seismic measurements to infer the mechanical properties of a hot dry rock geothermal system, J. Geophys. Res., 87, 5485-5494.

Fehler, M. and B. Chouet, 1982, Operation of a digital seismic network on Mt. St. Helens volcano and observations of long period seismic events that originate under the volcano, Geophysical Research Letters, accepted for publication.

The following paper has been submitted and is currently in a review process:

Fehler, M., 1982, Observations of volcanic tremor at Mt. St. Helens Volcano.

In addition, the principal investigator presented talks on results of studies on Mount St. Helens data at the following meetings:

U.S. Geological Survey, informal gathering of scientists performing studies on Mount St. Helens, April 1, 1982.

Seismological Society of America, Annual Meeting, Anaheim, California, April, 1982.

Scripps Institution of Oceanography, Seminar, April, 1982.

The following papers and talks describe work of interest to investigators of Geothermal Energy but are the result of work performed prior to the funding of this grant.

Albright, J.N., P.M. Halleck and M. Fehler, Subsurface subsidence damage monitoring: Seismic tomography and microgravimetry, Proceedings of Workshop on Surface Subsidence due to Underground Mining, Nov. 30 - Dec. 2, 1981, Sponsored by U. of West Virginia, U.S. Dept of Energy, U.S. Bureau of Mines, 198-205.

Fehler, M. and C. Pearson, Cross-Hole seismic surveys: Applications for studying subsurface fracture systems at a Hot Dry Rock geothermal site, submitted for publication, 1982.

Pearson, C., M. Fehler and J.N. Albright, Changes in compressional and shear wave velocities and dynamic moduli during operation of a Hot Dry Rock geothermal system, submitted for publication, 1982.

Fehler, M., R. Turpening, C. Blackway and M. Mullen, Detection of a hydrofrac with shear wave vertical seismic profiles, talk to be presented at Society of Exploration Geophysicists Annual Meeting in October, 1982.

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