GEOPHYSICAL RESEARCH LETTERS, VOL. 13, NO. 1, PAGES 149-152, FEBRUARY 1986

OBSERVATIONS OF LONG PERIOD EARTHQUAKES ACCOMPANYING HYDRAULIC FRACTURING

Dorthe Bame[1] and Michael Fehler

Earth and Space Sciences Division, Los Alamos National Laboratory

Abstract. Waveforms of most seismic events accompanying hydraulic fracturing have been reported to contain clear P and S waves and have fault plane solutions consistent with shear displacement across a fault. This observation is surprising since classical hydraulic fracturing theory predicts the creation of a tensile opening of a cavity in response to fluid pressure. Very small long period events, similar to long period earthquakes observed at volcanoes, were found to occur during four hydraulic fracturing experiments carried out at Fenton Hill, New Mexico. Since the long period earthquakes occur in the same region as the shear type events, it is concluded that the unusual character of the long period earthquake waveforms is due to a source effect and not a path effect. The occurrence of long period earthquakes during hydraulic fracturing could indicate tensile fracturing. Many waveforms of these events are identical, which implies that these events represent repeated activation of a given source. A proposed source for these long period events is the sudden opening of a channel that connects two cracks filled with fluid at different pressures. The sizes of the two cracks differ, which causes two or more peaks to appear in the spectra, each peak being associated with one physical dimension of each crack. From the frequencies at which spectral peaks occur, crack lengths are estimated to be between 3 and 20m.

Introduction

Microseismic events induced during hydraulic fracturing experiments carried out in low permeability crystalline rocks have been observed and used to monitor the growth of the fracture system. The majority of microseismic signals occurring during fracturing experiments are shear events [Pearson, 1981; House et al., 1985] with corner frequencies in the range of 80 - 800 Hz. Compared with other observations and a model of McGarr [1976], the cumulative seismic moment of these shear events accounts only for a small portion of the seismic moment expected for the volume of water injected during an experiment which suggests that some other mechanism, such as tensile fracturing, is occurring [Murphy and Fehler, 1984].

For many years, volcanologists have observed long period (LP) seismic events and tremor near volcanoes. LP events have been interpreted as being due to oscillations in magma chambers [Crosson and Bame, 1985; Shimozuru, 1961], oscillations in fluid conduits along which magma is transported [Ferrick et. al., 1983; Chouet, 1985] and tensile openings (e.g., jacking) of fluid-filled cracks [Aki et. al., 1977, Chouet and Julian, 1985]. Since hydraulic fracturing involves the injection of fluid into rock in much the same way that movement of magma beneath a volcano does, LP events occurring during hydraulic fracturing experiments may indicate that one of the above mechanisms is occurring.

Method

To identify potential long period events, data recorded by a seismic sensor located in wellbore EE-1 during two hydraulic fracturing experiments (termed 2018 and 2023) conducted at the Hot Dry Rock geothermal energy site at Fenton Hill, New Mexico were studied in detail. In addition, we briefly looked at data from two other experiments, called 2012 and 2032. Figure 1 shows the injection intervals for the four hydraulic fracturing experiments, the location of the triaxial geophone package in well EE-1 and the geometry of the wells EE-2 and EE-3 that were used for the fracture experiments. Preliminary studies of the data showed that very small signals were recorded that were different from the shear events that were previously reported by Pearson [1981]. The small

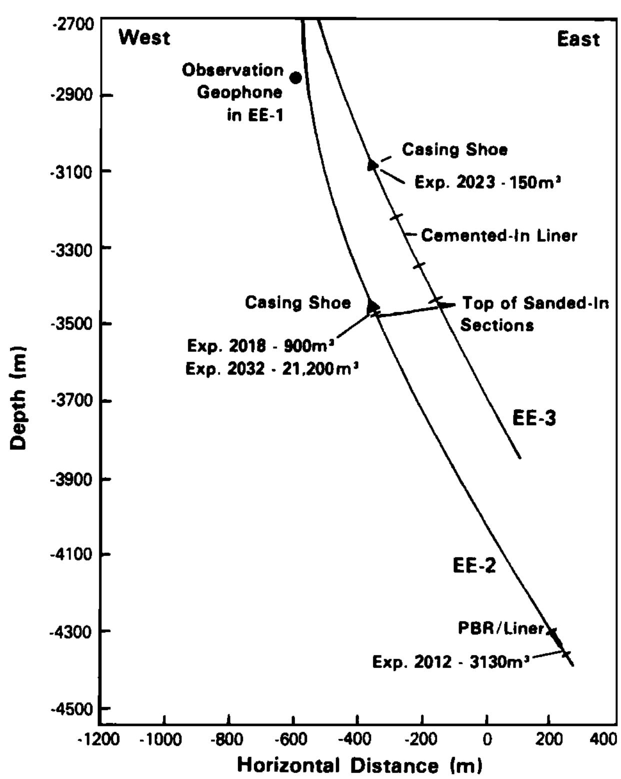

Figure 1. East-West vertical cross section map showing locations of hydraulic fracturing experiments studied and volume of fluid injected during each experiment. The location of the three component borehole seismometer used to detect events is shown.

[1]Now at Sandia National Laboratory

Paper Number 5L6753

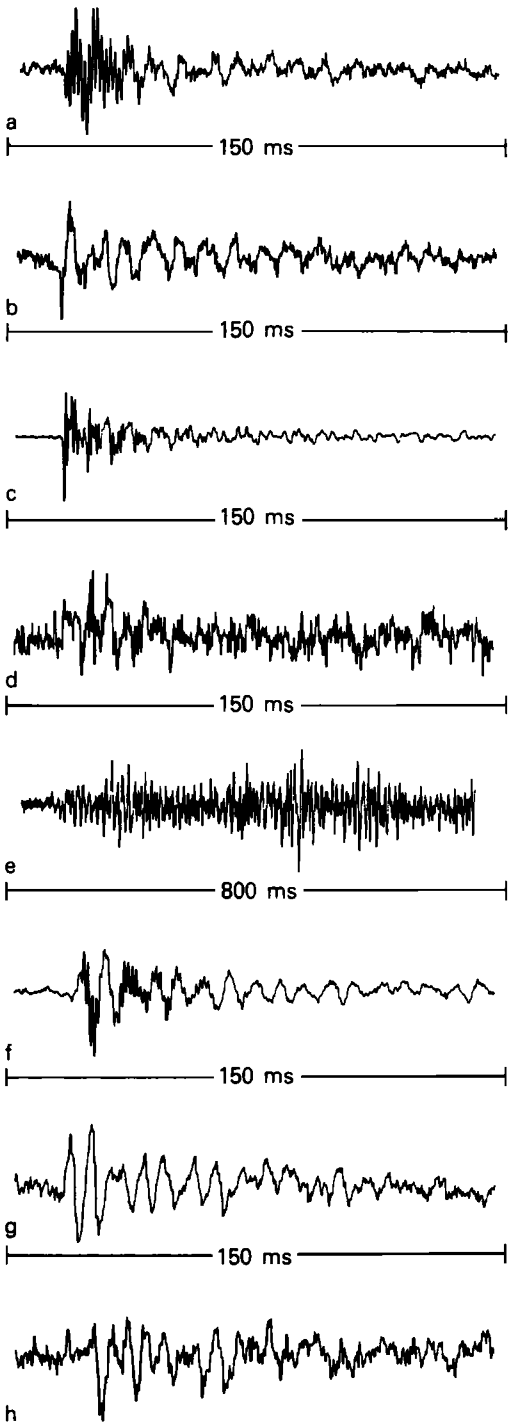

Figure 2. Vertical component waveforms of typical LP events. The first five events are from experiment 2018: (a) Family A, (b) Family P, (c) Family C, (d) Family H, (e) Family T. The rest of the events are from experiment 2023: (f) Family A, (g) Family B, (h) Family D.

signals were dominated by low frequencies (100-300 Hz) and generally lacked a second (S) arrival. These signals are called long period due to their similarity to long period signals observed at volcanoes [Minikami, 1974]. The term "long period" is used to differentiate these events from the shear events accompanying hydraulic fracturing, which have corner frequencies in the range of 80-800 Hz. Both shear and long period events accompanying hydraulic fracturing are very small in amplitude and short in duration when compared to their tectonic and volcanic counterparts. Seismic events were found to occur sporadically at the beginning of an experiment and the rate at which events occurred increased to between five and ten per minute later in the experiment. The first events to occur in each experiment were long period. After approximately two hours into an experiment, most of the events recorded contained clear P and S arrivals and appeared to have a wide range of frequencies and, hence, are considered to be shear events.

Many long period events with nearly identical waveforms were observed and these were grouped into earthquake families [Hamaguchi and Hasegawa, 1975]. In experiment 2018 there were periods during which certain families dominated. Events in other families, however, occurred indiscriminately throughout the early part of the experiment.

In order to study details of the seismic waveforms, all three components of motion - vertical, and both horizontals - of a number of events from each family were digitized. Spectra of the entire LP waveforms were calculated and corrected for the electronic response of the instrument and recording equipment. Spectra from events in each family were nearly identical. In addition, spectra from some families were similar; these families were grouped together and are called a class (see Table 1). The grouping of earthquake waveforms into families and classes is made only for the purpose of this empirical study.

Data

The long period events from experiment 2018 were divided into eight families and five classes.

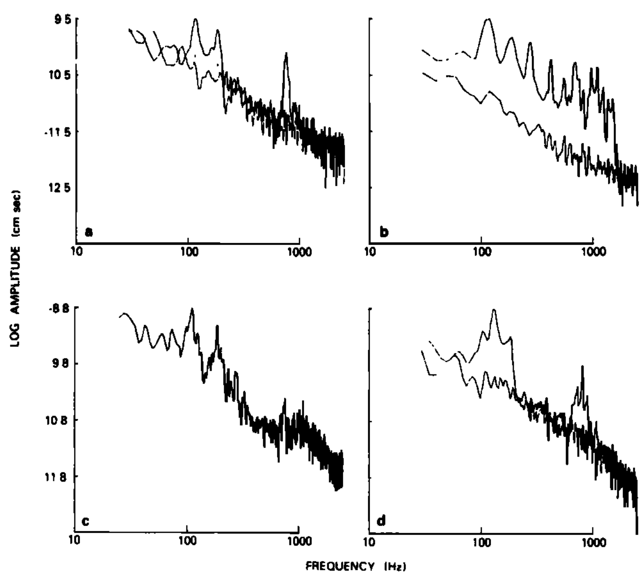

Figure 3. Vertical component spectra of events in Figure 2: (a) Family A, Spectral Class 1, experiment 2018; (b) Family C, Spectral Class 3, experiment 2018; (c) Family T, Spectral Class 5, experiment 2018; (d) Family A, Spectral Class 1, experiment 2023. Dots denote the peaks referred to in text. Lower spectrum in each a, b, and e are spectra of noise preceeding the event.

TABLE 1
SPECTRAL PROPERTIES OF VERTICAL COMPONENT WAVEFORMS OF LONG PERIOD EARTHQUAKES

SPECTRAL CLASS	WAVEFORM FAMILIES	PEAK FREQUENCIES (Hz)
Exp. 2018		
1	A	112, 150, 180, 745
2	B	115, 185, 268, 415
3	C,D,E,G	112, 185, 268, 550
4	H	Many <400
5	T	110, 185, 750
Exp. 2023		
1	A,F	130, 800
2	B	130
3	C,D,E,I,J	110,130,180,850

The events in experiment 2023 were divided into nine families and three classes. Figure 2 shows vertical component waveforms of representative LP earthquakes. Spectra of some events are shown in Figure 3. Table 1 lists the families that make up each spectral class, and the frequencies at which prominent peaks in the spectra of the vertical component waveforms occur. Some of the characteristics of the waveforms and their spectra will now be discussed.

Experiment 2018

Most LP events from Experiment 2018 are characterized by a waveform that is a superposition of a high frequency component and a lower frequency component as shown in Figure 2a. The almost monochromatic high frequency portion of the waveform is dominant. As seen in Figure 3a, there are two major peaks in the spectrum of the vertical component. Other examples of LP events for Experiment 2018 are shown in Figure 2(b-e).

Some events recorded during Experiment 2018 have characteristics similar to volcanic tremor. These events have emergent onsets and vary from one to four seconds in length. Figure 2e shows a 800 ms portion of one of these events. The spectra of these events were the same no matter which portion of the waveform was chosen for analysis. The spectra contain two large peaks at about 110 and 185 Hz (Figure 3c). There is also a bread peak close to 750 Hz.

Experiment 2023

The LP events that occurred most often during Experiment 2023 were similar to those that occurred most often during Experiment 2018, except that the high frequency component was not as strong during Experiment 2023. The spectra of the two sets of events are also similar except for a slight shift in the frequencies at which peaks occur and the occurrence of secondary peaks on both sides of the two major peaks of 2023 spectra. Some of the events lacked the high frequency component altogether (Figure 2g) although the low frequency component of the waveforms of these events look very similar to those containing the high frequency component.

Preliminary studies of two other experiments, 2012 and 2032, (Figure 1) indicate that LP events accompanying these two experiments are similar to those seen in 2018 and 2023. Experiment 2032 differs from the other three experiments in that it took place in a portion of the reservoir that had already been fractured. The major difference in the LP seismic signals from this experiment is the absence of a high frequency component that was previously superimposed on the low frequency signal.

Discussion

At this time, no well accepted model exists to explain long period earthquakes observed during hydraulic fracturing. However, we can draw upon models of long period volcanic earthquakes and volcanic tremor to guide our interpretation of the data presented above. Since the waveforms of all events in a family of earthquakes appear to be nearly identical, we must conclude that all events within a family occur at the same location within the Hot Dry Rock reservoir. Events with nearly identical waveforms have been reported at Volcano Usu in Japan [Takeo, 1983] and interpreted to be due to repeated activation of one fault.

Since long period earthquakes that accompany hydraulic fracturing are very small, we have not detected one event at enough stations to allow us to determine the location of the event. We can, however, assume that at least some of the events are located very near to the point of injection of water into the rock since the permeability of the rock is very low and long period earthquakes begin almost immediately after injection begins. Since shear earthquakes have been found to occur near the injection point, and to completely surround it [House et al., 1985], the path between many shear events and the receiver must be nearly identical to that for some, if not all, of the long period events. We can thus rule out the path affect as being the dominant cause of the unique character of long period earthquakes.

Since the long period events occur almost immediately after fluid injection begins, it is unreasonable to attribute their source to be due to fluid oscillations in a fluid flow conduit in the rock. Since the granitic rock into which fluid is being injected has very low permeability [Pearson, 1981], it is reasonable to conclude that the source of the long period events is the tensile opening of a crack driven by the fluid pressure.

Most investigators also conclude that the unique character of the waveforms recorded at volcanoes during long period earthquakes and tremor is due to a source effect, not a path effect [Aki and Kayanagi, 1981; Fehler and Chouet, 1982]. Fehler [1983] has argued that tremor is composed of a sequence of long period earthquakes that occur close enough together in time that individual events are indistinguishable. Numerous attempts have been made to interpret the peaks observed in spectra of LP volcanic earthquakes and tremor in terms of the geometry of the source region. A model that is particularly appropriate for the present situation is that of Aki et. al., [1977] in which injected fluid propagates along a tensile crack which extents due to increase in fluid pressure in the crack. Alternatively, a closed channel connecting two open fluid filled cracks may suddenly open, allowing fluid to be transported between cracks containing fluid at different pressures. Once fluid transport has occurred, the pressure in the high pressure crack drops, allowing the channel to close until pressure builds up again as more fluid is injected. This process repeats itself until the pressure in the low pressure crack increases enough to keep the channel permanently open. The size of the cracks on each side of the channel may be estimated from the spectral peak frequencies. Aki et. al., [1977] modeled a simple case in which two open cracks of equal length L, are separated by a narrow channel of width ΔL. In this case, the spectral peak occurred at a frequency of approximately $.8\beta/2L$ where β is the S-wave velocity of the rock. If the channel closes almost immediately after it opens, there will be two spectral peaks with frequencies given by $.8\beta/L$. For example, for events studied with peak frequencies of 130 and 800 Hz in a material with S-wave velocity 3.5 km/sec, the characteristic lengths would be 20m and 3m respectively. The long period earthquakes can be interpreted as being more directly associated with tensile jacking and probably occur only in a region where there are gradients in fluid pressure. Since these small earthquakes probably occur in direct response to fluid pressure they may be the most important clue regarding tensile fracturing when high pressure fluid is injected into rock. At this time, our model for these earthquakes is necessarily crude because of its geometrical simplicity. In addition, the calculation of far field spectra using a model that incorporates the fluid motion inside the tensile fracture, such as discussed by Chouet and Julian (1985), may yield more reliable estimates of source size.

Acknowledgements. The data analyzed in this paper were collected with the assistance of Bert Dennis, Evon Stephani, Everett Horton and Jerry Kolar. We benefited greatly from technical discussions and critical reviews of the manuscript by Leigh House, Hugh Murphy, Kei Aki and Scott Phillips. This work was funded by the U.S. Deprtment of Energy and the governments of the Federal Republic of Germany and Japan. We also greatfully acknowledge Greg Nunz, who found the money in an otherwise tight budget to support this work.

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D. Bame, MS5323A, Sandia National Laboratory, P.O. Box 5800, Albuquerque, NM 87185.

M. Fehler, MSJ979, Los Alamos National Laboratory, Los Alamos, NM 87545.

(Received November 12, 1985;
Accepted November 27, 1985)