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Identifying Structures in Clouds of Induced Microseismic Events

Michael Fehler, Leigh House, and W. Scott Phillips, Los Alamos National Laboratory*

Summary

A method for finding improved relative locations of microearthquakes accompanying fluid production and injection is presented. The method is based on the assumption that the microearthquake locations are more clustered than found when events are located using conventional techniques. By allowing the rms misfit between measured arrival times and predicted arrival times to increase if events move closer together, we find that there is more structure in the pattern of seismic locations. The method is demonstrated using a dataset of microearthquakes induced by hydraulic fracturing. We find that structures found using relative arrival times of events having similar waveforms to find improved relative locations of events can also be recovered using the new inversion method but without the laborious repicking procedure. The method provides improved relative locations and hence, an improved image of the structure within the seismic zone that may allow for a better relation between microearthquake locations and zones of increased fluid permeability to be found.

Introduction

Microearthquakes induced by hydraulic fracturing and fluid production are often studied to find information about the fracture structure of rock in reservoir regions (Albright and Hanold, 1976; Vinegar et al., 1991; Withers and Rieven, 1996). While the locations of the microearthquakes provide indirect evidence for the presence of fluids in the rock, it is desirable to use the locations to obtain more information about the presence of fractures. An initial attempt at finding the locations of fractures from the locations of the microearthquakes was the development of the Three Point Method by Fehler et al. (1987), which is a statistical method for identifying planes that microearhquakes cluster along. These planes are interpreted as fracture planes and the orientations of the planes have been compared with *in situ* stress fields (Fehler, 1989). More recently, relative locations of events having similar waveforms have been determined and it has been found that these events often fall along planar trends that are inferred to be fracture planes (Moriya et al., 1994; Phillips et al., 1997).

Another approach for finding structure within the cloud of seismic events is the so-called collapsing approach of Jones and Stewart (1997). In this method, the locations of events found using a joint hypocenter determination (JHD) method are moved within their 95% confidence ellipsoids in a direction towards the center of mass of the events within the ellipsoid. The argument for moving the events is that they can be reasonably well located anywhere within the ellipsoid with little change in the rms misfit to the arrival-time data that are inverted to find the event location. Jones and Stewart (1997) find that structures are found within the seismic cloud after the events have been moved. In one stunning example, they show that the seismicity of Rubal volcano clearly falls along two structures that define the ring fractures for the volcano. The uncollapsed locations show no evidence for the ring fracture structures.

In this paper, we will demonstrate an approach for collapsing that can be incorporated into the location-inversion algorithm. We find that there is little change in the misfit to the arrival-time data used to locate the microearthquakes. We will show that the alignments of events found by Phillips et al. (1997), from picking relative arrival times of events having similar waveforms, can be recovered using raw picks and the new analysis method. The agreement between the collapsing results and those of Phillips et al. (1997) lends credibility to the collapsing method as finding significant structures within the seismic zone that cannot be found in locations determined using JHD.

Approach

We begin with the JHD method outlined in Block et al. (1994). This method is a procedure for simultaneously locating all microearthquakes and finding relative station residuals that provide a best fit to all arrival-time data for all events. The method is similar to the tomography method outlined in Block et al. (1994) except that all media velocities are held constant. In the conventional JHD approach, we perform an inversion to find the event locations (x,y,z), event origin times, and station corrections for both P and S waves that minimize $\Sigma(RMS)$ where RMS is the rms traveltime for each event; e.g. the difference between the measured and predicted arrival times. In the collapsing approach, we choose a sphere around each event having radius r and find the location of the center of mass of all events within that sphere. We then modify the function that is minimized in the inversion for each event in the joint hypocenter inversion to be

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$\Sigma(RMS)+\lambda\Sigma\{|x_i-x_{ixm}|+|y_i-y_{ixm}|+|z_i-z_{ixm}|\}$ where x_i is the x-coordinate of the location of event i, x_{icm} is the x coordinate of the center of mass of events within the sphere around event i, etc. In this procedure, there are two free parameters, the radius of the sphere, and the multiplier, λ. We choose these two parameters using test data.

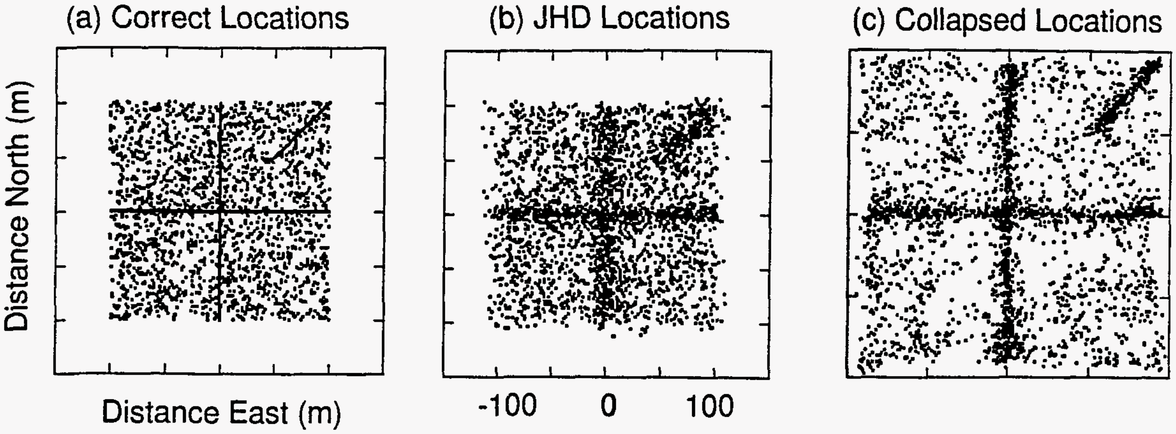

Figure 1. Test of the collapsing method. (a) Synthetic data. (b) Locations found using JHD with noisy data. (c) Locations found using collapsing method with noisy data.

Figure 1 shows an example of application of the method to test data. For this test, a total of 3000 events were located within the region of study. The events were chosen so that 400 of them fell along the east-west trending plane, 400 along the north-south trending plane, 200 along the NE-SW trending plane, and 2000 were scattered randomly within the zone. Traveltimes were calculated for all events and noise was added to the traveltimes. Figure 1a shows the locations used to generate the traveltimes. Figure 1b shows the locations determined using JHD on the noisy data. The three planes with events can bee seen but they are not clear. Figure 1c shows the events determined using the collapsing approach with $\lambda=1$ and radius of 30 m. The collapsing approach clearly shows the alignments of events more clearly than can be seen in the JHD locations.

Application to Real Data

To test the collapsing approach with real data, we choose data from the Fenton Hill Hot Dry Rock Geothermal Energy project. Locations of these events have been discussed by House (1987), Fehler et al. (1987), Fehler (1989), and Block et al. (1994). We investigate a dataset consisting of approximately 10000 of the best located events (quality a and b of House,

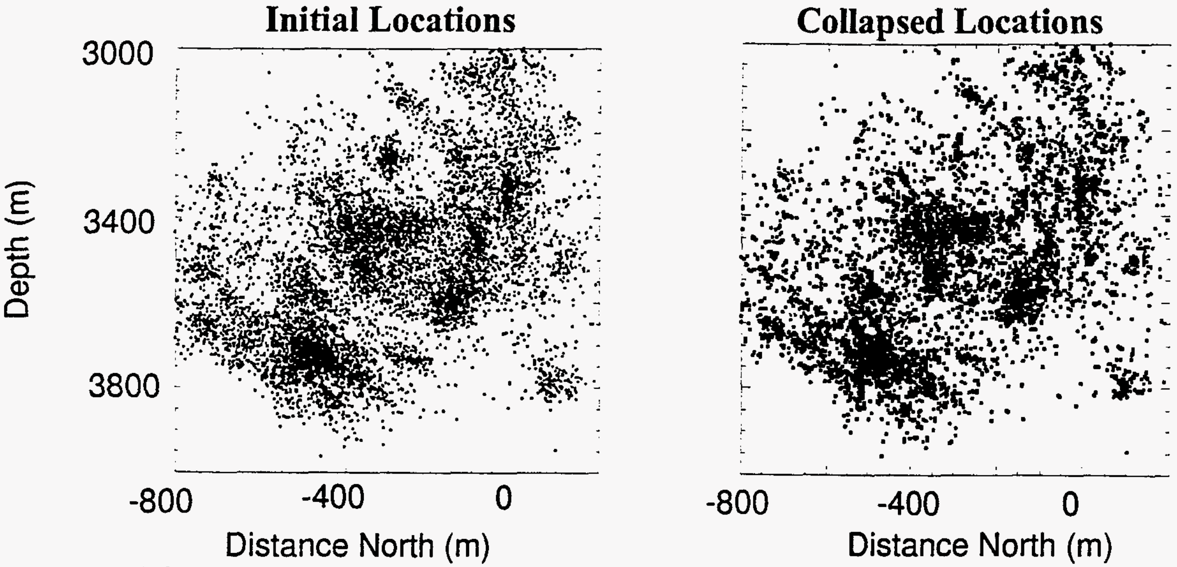

Figure 2. North-South vertical cross sections through the locations found using a single event location technique (a), left, and using the collapsing method (b), right.

1987). Arrival times from P and S waves recorded at four borehole seismometers were used to locate the events. Figure 2 shows North-South vertical cross-sections of the event locations. Figure 2a shows the raw locations determined using a single-event technique. Figure 2b shows the locations found using the collapsing method. The location pattern found using the collapsing approach shows more structure than can be seen in the raw event locations.

To investigate the structure within the seismic zone in more detail, we show plan view maps of locations within a cube having dimensions of 400 m on a side in Figure 3. The region shown is a region identified by Phillips et al. (1997) as having a large number of microearthquakes with similar waveforms. Figure 3a shows single-event locations found for all the events within the cube. Figure 3b shows the locations found with JHD using the same set of arrival time data as used in Figure 3a. JHD generally provides improved relative locations and Figure 3b shows more structure than does Figure 3a although no clear pattern can be found. Figure 3c shows the locations found using the collapsing approach with the same raw arrival times used in Figures 3a and 3b. The collapsed locations show significantly more structure than found using single event or JHD locations. Phillips et al. (1997) repicked arrival times focusing on the similarity of the waveforms to find precise relative arrival times of the events. They then relocated the events using a single-event location technique and found that the events with similar waveforms fell along planar features. They identified more than one feature within the box. Figure 3d shows all the events they located using the relative picking procedure. The number of events shown in Figure 3d is smaller than in 3a, 3b, and 3c since 3d shows only events having similar waveforms. Figure 3e shows events from 3d that have the same polarity. This figure clearly shows the linear trend of the earthquakes having similar waveforms. Phillips et al. (1997) discussed the implications of structures like shown in Figure 3e for fluid flow in the reservoir region. Comparing Figures 5c with 5d and 5e, we see that the collapsing technique has recovered features similar to those found using precise relative picking of events. The difference in absolute locations of the planar features found by the two methods is not surprising since the two methods provide improved relative locations but do not improve absolute locations.

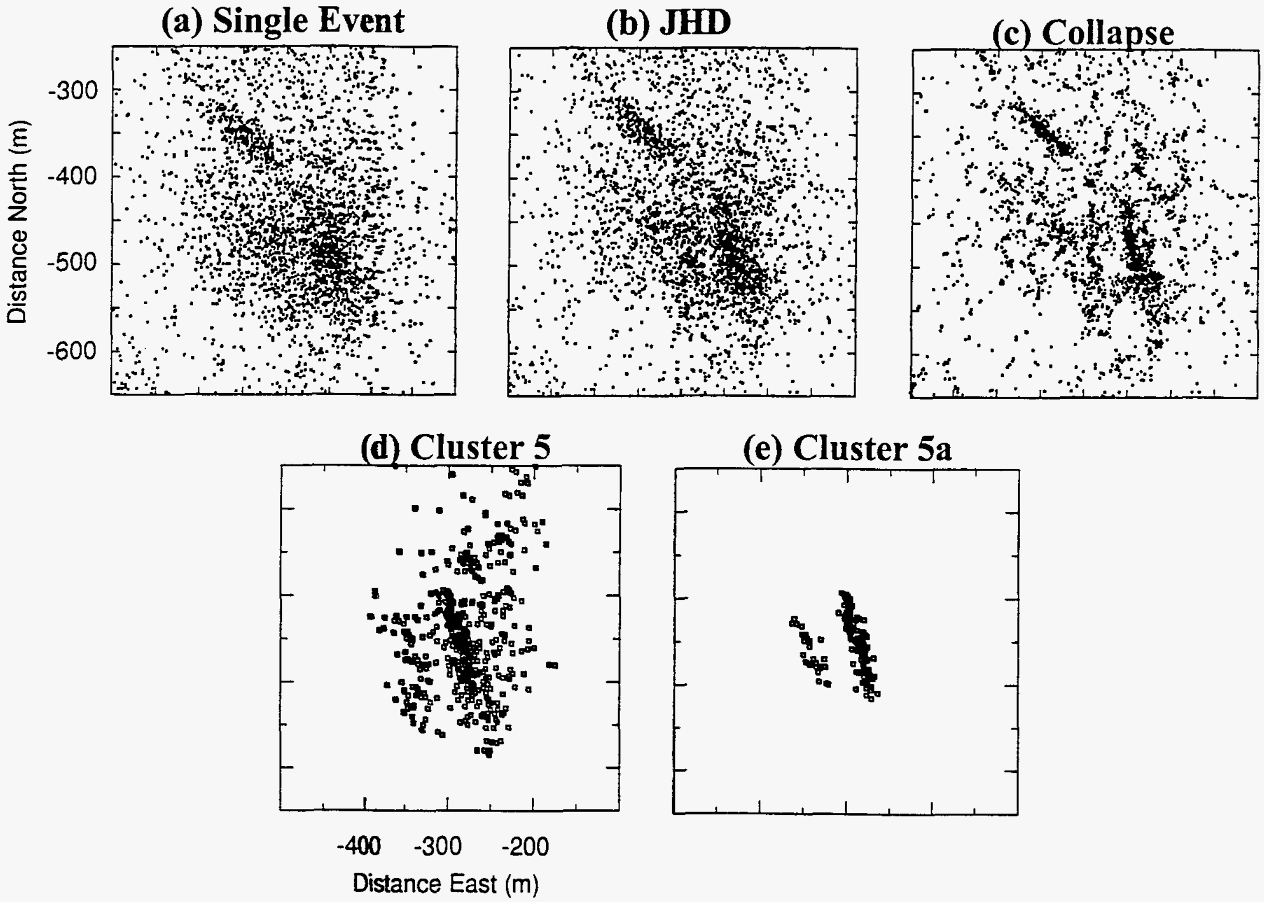

Figure 3. Locations within a cube having dimensions of 400 m on a side. (a) locations from single event location method. (b) JHD locations (c) locations from collapsing method (d) relative locations for events having similar waveforms found using relative arrival times picked from the waveforms (e) portion of the data shown in part (d).

Conclusions

We have illustrated a method for obtaining improved relative locations of microearthquakes within the cloud of seismicity induced by fluid injection or production. We have shown that the results are consistent with those found using a much more laborious method, repicking relative arrival times of events having similar waveforms. The new method has the capability of finding more structure in the seismic cloud than can be found by detailed analysis of events having similar waveforms since data from all events can be analyzed using the new method. It may also provide an important constraint for finding the structure of the reservoir regions using tomography with microearthquakes as sources.

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