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DOUBLE DIFFERENCE RELOCATION, DETERMINATION OF LOCAL AND DURATION MAGNITUDE OF MICROEARTHQUAKES IN THE "XYZ" GEOTHERMAL FIELD

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Abstract

During the fluid injection in the "XYZ" geothermal field from February 1998 until March 1998, 37 microearthquakes were recorded around this field. We have determined the locations of those microearthquakes using highly precision hypocenter double difference (HypoDD) earthquake location algorithm. We found that microearthquake hypocenters distribution, which were sparsely distributed around the injection wells, became tightly elongated distribution. We also calculated the local magnitude scale using those microearthquakes data and then calculated the relationship between local magnitude and signal duration to determined the duration magnitude scale. As the result, we calculated the value of geometric spreading parameter, *n*, 3.4064, and attenuation parameter, *k*, -0.3477, so the local magnitude scale for "XYZ" geothermal field is M_L = log A – 3.4064 log(r/17) + 0.3477(r-17) + 2. From the relationship between local magnitude and signal duration, we found : M_D = 2.2 log(duration) – 1.1. Finally, we have found the local magnitude duration of microearthquakes are -0.18<M_L<1.55 and -0.23 <M_D<0.94.

A. Introduction

Fluid injection in geothermal field can trigger induced microearthquakes due the change of pore pressure, temperature decrease, and volume change (Majer et al., 2002). Microseimicity can be used to reveal possible structure within geothermal reservoir and further analyses such as fluid migration and stress and starin changes (Holland, 2002; Miyazawa, 2008).

Determining hypocenter location is one of the most fundamental analysis in earthquake study. In many cases, hypocenter determinations are often resulting biases and displced from the true locations. Those biases posibbly lead to wrong further analyses. To overcome those problems, we could apply several improvements in seismic network design and crustal model, and also apply relative event location eg. double difference earthquake location (Foulger and Julian, 2011). In this research we have appllied double difference earthquake relocation using hypoDD software (Waldhauser and Ellsworth, 2000). The double difference relocation reduced travel time residuals root mean square (rms) from single event determination significantly. We also derived local and duration magnitude scale for "XYZ" geothermal field.

B. Methodology

Single Event Determination

Single event location of microearthquakes in this research were determined using Geiger Method which implemented least square optimization. Geiger method is linearization inverse problem which the first step is guessing the initial location and initial origin time (x_0, y_0, z_0, t_0) (Havskov and Ottemöller, 2010). In order to linearize the inverse problem, the true location of earthquake is assumed close to the initial location so travel-time residuals at the trial hypocenter are a linear function of thecorrection that have to make in hypocentral distance for each iteration.

The calculated arrival times at station *i*, t_i^{cal}, from initial location are

$$t_i^{cal} = t_i^{tra}(x_0, y_0, z_0, t_0, x_i, y_i, z_i, t_i) + t_0 \qquad (1)$$

with t_i^{tra} is calcluated travel time from intial hypocenter to station *i*. The residuals due to the error in trial error($\Delta x, \Delta y, \Delta z, \Delta t$) can be written :

$$r_i = \frac{\partial t_i^{tra}}{\partial x_i}\Delta x + \frac{\partial t_i^{tra}}{\partial y_i}\Delta y + \frac{\partial t_i^{tra}}{\partial z_i}\Delta z + \Delta t \qquad (2)$$

Equation (2) can be arranged in matrix form and solved using least square method, which the initial location and initial origin time are corrected using the result of least square method.

Double Difference Relocation Algorithm

Double difference algorithm (DD) is a development of Geiger Method with using absolut and/or differential travel time cross corellation of P and S wave (Waldhauser and Ellsworth, 2000). The principle of DD method is assuming that if each pair of earthquake has closer separation than hypocentral distance of each earthquake, then the waveforms and ray paths of both earthquakes will be similar. Thus the difference of two events can beattributed to the spatial offset function between the events.

Residual between travel time of two earthquakes, i and j, to obsevation station k is

$$dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal} \qquad (3)$$

wheret_k^i is travel time from hypocenter earthquake i to station k and t_k^j is travel time from hypocenter earthquake j to station k. The detail of mathematical operation were provided by Waldhauser and Ellsworth (2000).

Local Magnitude and Duration Magnitude

Local Magnitude

For a set of P earthquakes recorded by N stations, A_{ij} is maximum displacement of jth recorded by ith station, r_{ij} is hypocentral distance, M_j is local magnitude and S_i, then (Langston et al., 1998)

$$\log A_{ij} + 2 = -n log\left(\frac{r_{ij}}{17}\right) - K(r_{ij} - 17) + M_j - S_i$$

$$i = 1, N, \qquad j = 1, P \qquad (4)$$

In this research we used generalized inverse solution (Pujol, 2003). Equation (5) can be modified into matrix form :

$$\mathbf{W}_j \mathbf{a}_j = \mathbf{W}_j \mathbf{B}_j \mathbf{x}_j - \mathbf{W}_j \mathbf{s}; j = 1, P. \qquad (6)$$

where $\mathbf{a}_j$ is amplitude matrix, $\mathbf{B}_j$ consists parameter that related with hypocentral distance, $\mathbf{x}_j$ consists geometric spreading, attenuation parameter, and local magnitude, $\mathbf{s}$is station corrections matrix, and$\mathbf{W}_j$ is N x N diagonal weigthing matrix with entries is 1 or 0, depending on whether the coressponding station is used or not.

The first step of this magnitude inversion, we calculated station correction using adopted method from Joint Hypocentral Distance which apply singular valude decomposition. More details information about mathematics expression are provided by Pujol (2000, 2003). Once the station corrections are found, we could solve equation (10), through several modification and least-square operation (see Pujol, 2003).

Duration Magnitude

Lee et al. (1972) established an empirical formula for estimating magnitudes of local earthquakes recorded by the USGS Central California Microearthquake Network using signal durations. There are several defenitions about total signal duration, but in this research we defiened τ as total duration from the P-wave onset to the end of the coda i.e., where the signal disappears in the seismic noise of equal frequency (Bormann et al., 2002).We applied the linear regression to determined the relationship between logarithm of signal duration and local magnitude.

C. Data Processing and Results

Single Event Determinations

We determined the single event locations using Geiger Adaptive Damping using fortran code (Nishi, 2005). In this code, Geiger Method is applied to the arrival times of P and/or S wave to calculate location and origin time of microearthquakes. The result of single event determination and travel time tesidual rms can be seen in Figure 1 and 2.

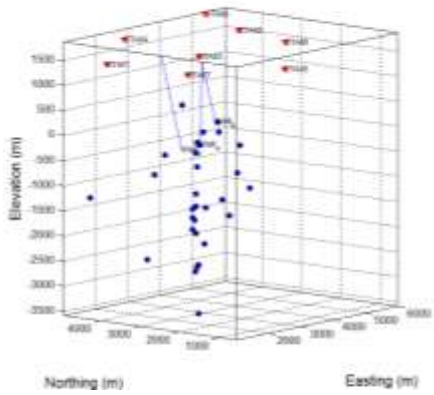

Figure 1. 3D section of 37 Microearthquake hypocenters located using Single Event Determination (red reverse triangles are recording stations, blue lines are injection wells, and blue circles are microearthquake hypocenters).

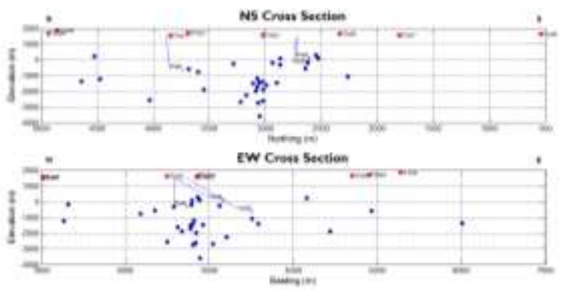

Figure 2. NS Cross Section (top) and EW Cross Section (bottom) of 37 Microearthquake hypocenters located using Single Event

Determination (red reverse triangles are recording stations, blue lines are injection wells, and blue circles are microearthquake hypocenters).

Double Difference Relocations

Considering the distribution of hypocenters resulting from single event determination, we removed 5 outlier microearthquakes. Those outlier microearthquakes that distributed sparsely and quite far from geothermal field could possibly affect the relocation result. Thus, we relocated only 32 microearthquakes using hypoDD software. The result of HypoDD can be seen in Figure 3 and 4.

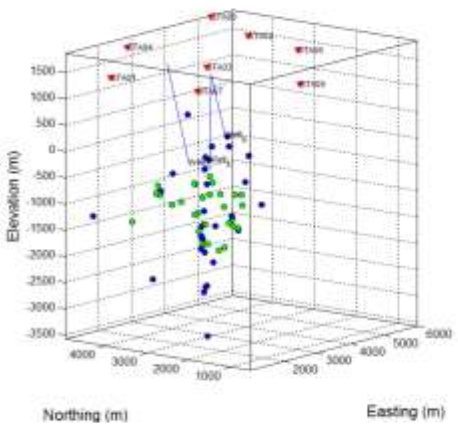

Figure 3. Hiocpenter microearthquake from SED method (blue circle) and DD relocations method (green circle)

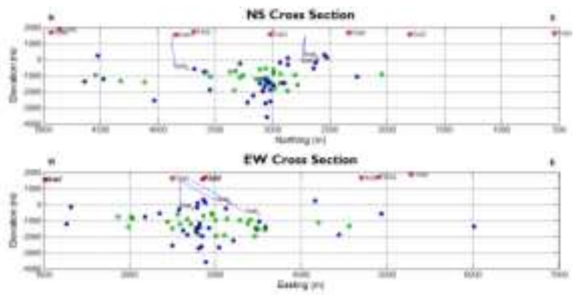

Figure 4. NS Cross Section (top) and EW Cross Section (bottom)of microearthquakes using SED (blue circle) and DD relocations methods (green circle).

In hypoDD result, the total rms error reduced from 0.1055 s to 0.0001 s. Rms reduction indicates that location become more accurate. We found that the hypocenters distribution became tighter than single event determination result. In further analysis, the double-difference result can be used along with geological data to illuminate estimated fractures in geothermal field.

Local Magnitudes and Duration Magnitudes

<u>*Local Magnitudes*</u>

We have tested the algorithm both in synthetic and real data. In real data, we obtained n = 3.4064 and k = -0.3477. The local magnitudes are between -0.1818 and 1.5502. Therfore the local magnitude scale for "XYZ" geothermal field is

$$M_j = \log A_{ij} + 3.4064 log\left(\frac{r_{ij}}{17}\right) - 0.1818(r_{ij} - 17) + S_i \quad (5)$$

We found that the station corrections varied from -0.3524 to 0.28 and total of the station corrections were 0.0001. According to Pujol (2003), the total station correction will be automatically equal to 0, because station correction is a minimum-length solution. In our case, it was probably caused by data condition.

<u>*Duration Magnitudes*</u>

We applied linear regression between log duration and local magnitude (figure 5), and obtain

$$M_d = 2.2 \log(Duration) - 1.1 \quad (7)$$

The duration magnitudes range are between -0.23 and 0.94.

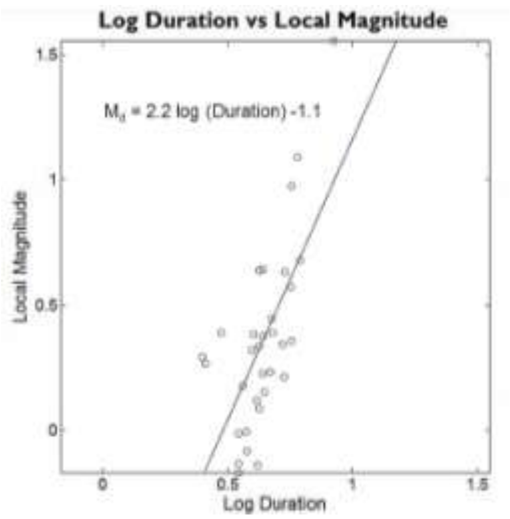

Figure 5. Plotting log durations vs local magnitudes of microearthquakes and linear regression result.

The duration magnitude is more practical in routine processing, since the displacement for local magnitude needs to be read in Wood-Anderson seismogram event though can be approximate using filtering (Havskov and Ottemöller, 2010). Understanding the behavior of the induced seismicity magnitude would have importance for constraining a hazard of damaging induced earthquakes (Shapiro et al., 2011)

Conclusions

We have determined the location of microearthquakes in "XYZ" geothermal field during the fluid injection using geiger method. Then we relocated the location using highly precission double difference earthquake location algorithm. From the double difference result, we found that error rms become greatly reduce. This indicates that location become more accurate than initial location from geiger method. The distribution of hypocenters became tighter, and can possibly be used in further analysis to reveal fracture estimation in "XYZ" geothermal filed. We also derived local and duration magnitude scale for this area. Both local and duration magnitude can be used for hazard assessment in geothermal field.

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