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Analysis of induced microseismic events from HDR/EGS reservoirs by super resolution mapping techniques

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Abstract

Microseismic monitoring has been used in worldwide hot dry rock (HDR) and engineered geothermal systems (EGS) projects as one of the standard techniques to monitor stimulation. The authors have been investigating "super resolution mapping techniques" of the microseismic events to obtain more reliable location of the hypocenter. In this paper, we will show concept of Coherence Collapsing method and double differential (DD) method and application to data sets collected during the stimulation.

Keywords: Coherence Collapsing, double differential method, super resolution mapping

1. Introduction

It has been widely accepted that the microseismic mapping/imaging method is one of the few methods that can estimate time/spatial distribution of HDR, HWR, HFR, and EGS systems. The mapping of the locations of the microseismicity is the most fundamental analysis process in the microseismic method and studies for improvement of accuracy and reliability of mapping has been carried out in worldwide project which is referred to as "MTC/MURPHY International Collaborative Project" (Murphy et al., 2000).

Most of the mapping techniques are developed to estimate the "absolute" location of the hypocenter. Because of uncertainty in the velocity structure and observational errors in picking of arrivals, it is believed that the absolute locations typically have errors in the order of several tens of metres for microseismic locations in the case of seismic mapping of engineered geothermal systems. The joint hypocenter determination method (JHD; Frohlich, 1979) has been developed in global seismology to reduce the uncertainty caused by the velocity structure. The JHD is one of the standard methods for absolute mapping although it still has uncertainty mainly due to the error in picking. Jones and Stewart (1997) developed an optimizing relocation method which is referred to as the "collapsing method" (original collapsing method). However, because of the initial assumption that the original seismic structure is a point, the ability to resolve structures that are comparable to or smaller than the spatial confidence ellipsoid is not high in the original collapsing method.

Some of the seismic events are known to have very similar waveforms although their origin times have wide separations. These events are referred to as "Multiplets" and highly precise relative mapping techniques or their location have been investigated (Moriya et al., 2002).

The authors have been investigating a mapping method that tries to bridge collapsing and multiplet analysis techniques utilizing the advantages of each of the methods. The objective of the development of this version is to offer similar information as multiplet analysis in the comparable analyzing time as JHD or collapsing method. It is hoped that this new method will provide better locations and so a more meaningful interpretation of the physical meaning of the seismic cloud. Because coherency among events is used as input, we named this variation of the collapsing method as "Coherence Collapsing" (Asanuma et al., 2003).

On the other hand, a multiplet is assumed to arise from repeated shear slip on one fracture, because highly similar waveforms can only be produced through a combination of similar source mechanism and nearly identical source-to-receiver raypaths. We capitalize on waveform similarity for precise estimation of differential travel times among events at each receiver; these differential times are used as input into the relative location technique. Because raypaths are nearly identical among multiplet members, the relative location technique eliminates location errors introduced by velocity model inaccuracies over most of the path, providing improved accuracy for relative locations within the source region (Waldhauser et al., 2000). This technique is referred to as "double differential method" (DD method) and as considered to be one of the standard mapping techniques in the global seismology.

In this paper, the authors will discuss potential of these newly developed mapping techniques using data sets collected while stimulation of engineered geothermal systems and gas field.

2. Coherence Collapsing method

2.1 Principles

In the Original Collapsing method, an event is selected as a target event and it is moved slightly toward the centre of gravity of all the events that are located within its confidence ellipsoid, implicitly assuming that the original seismic structure was a point. The movement is normalized by the size of the spatial confidence ellipsoid. The process is repeated for all events in the data set and a new "generation" of locations is formed in this way. This procedure is repeated for several generations until the distribution of normalized movement fits to the Chi distribution with three degrees of freedom.

The movement of events in the Original Collapsing is determined only by residual and location of neighboring events, without any relationship to waveforms. However the multiplet analysis has already resolved that a part of dataset, which has higher mutual coherency, is relocated to a very small seismic structure. This suggests that it is reasonable to correlate the movement in the Original Collapsing method to the similarity of events. Thus the concepts of the Coherent Collapsing are,

a) The events which has higher mutual coherency are relocated to a point (or to very small structure), and

b) The events with lower mutual coherency are relocated to reduce uncertainty of whole seismic cloud.

The main procedure of the Coherence Collapsing is based on that of the Original Collapsing. The coherence of the events to the target event is used as a weight coefficient in the calculation of the centre of gravity. It is reasonable to use the coherence to multiply the weighting factor as we expect these events to come from small scale structures, however the optimum weight is unknown. We decided to determine the optimum weight using synthetic study and currently using 8th power of the coherency (Asanuma et al., 2003).

2.2 Application to data set collected at Soutlz and Cooper Basin.

The Coherence Collapsing method was applied to data set collected during the stimulation of reservoirs at Soultz, France (Baria et al., 2000, Asanuma et al, 2002, 2004) and Cooper Basin, Australia (Asanuma et al., 2004). The location of microseismic events by JHD, the original collapsing, and the coherence collapsing for data sets from simulations at Soultz in 2003, and that from Cooper Basin in 2003 are shown in Figures 1 and 2.

The extension process of a part of the shallow reservoir created at Soultz in 1993 has been interpreted by an integrated analysis of microseismicity, logging data and hydraulic record (Niitsuma et al., 2002). The seismic location in this part of the reservoir is magnified in Figure 3. The location of the highly coherent seismicity was in good agreement with that from the multiplet analysis (Moriya et al., 2002). The location of events with higher coherency shows sub-vertical linear seismic structure, which is interpreted as a firstly stimulated pre-existing fractured zone. The data from Soultz in 2000 and 2003 are collected during the creation of deep reservoir, which has more hydraulically "closed" nature than the shallow one (Asanuma et al., 2002, 2004). The location of events with higher coherence is more widely/uniformly distributed than the shallower reservoir suggesting the lower density and higher stiffness of the pre-existing fractures in the Soultz deep reservoir.

Because of the horizontal maximum stress and sub-horizontal pre-existing fractures, it is expected that a horizontal over-pressured fracture, which was not plugged in the drilling, and its subset fractures are stimulated in the Cooper Basin HFR Project, Australia. The location of microseismic events in the fracture initiation tests and main stimulation in 2003 showed sub-horizontal seismic cloud extending horizontally approximately 1500m from the injection well with thickness around 150m (Asanuma et al., 2004). The coherence collapsing method, applied to this dataset, showed several sub-horizontal seismic structures. Because it is accepted that multiplets are correlated to single fracture with multiple slip, this result suggests the existence of a set of sub-horizontal fractures in this site.

3. DD method

3.1 Principles

The DD method is a precise relative location technique (Waldhauser et al., 2000) using relative time of arrival for a group of events. A double differential equation from the relative delays is solved to obtain the absolute location of the microseismic events. Because relative time of arrival is used as an input, it is believed that the ability of the DD to estimate absolute location is lower that for relative location.

There are several methods to estimate the relative time of arrival among a set of events. Cross spectra and coherence can bring the most accurate information on the delay and similarity of the events, although processing time may longer than the other techniques in time domain. Because the DD method can be used as a pre-processing of the multiplet analysis to estimate orientation and behavior of each fracture, the authors have been

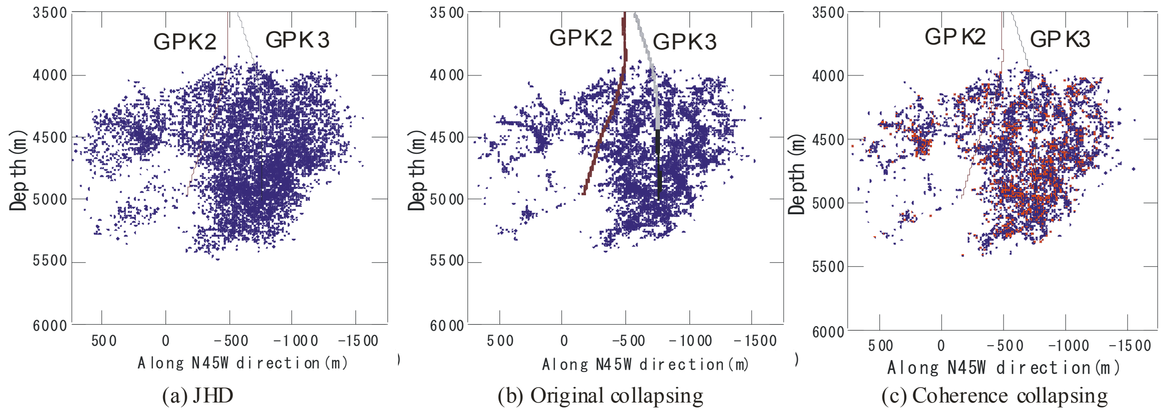


Figure. 1. Relocation of the microseismic data collected at Soultz in 2003.

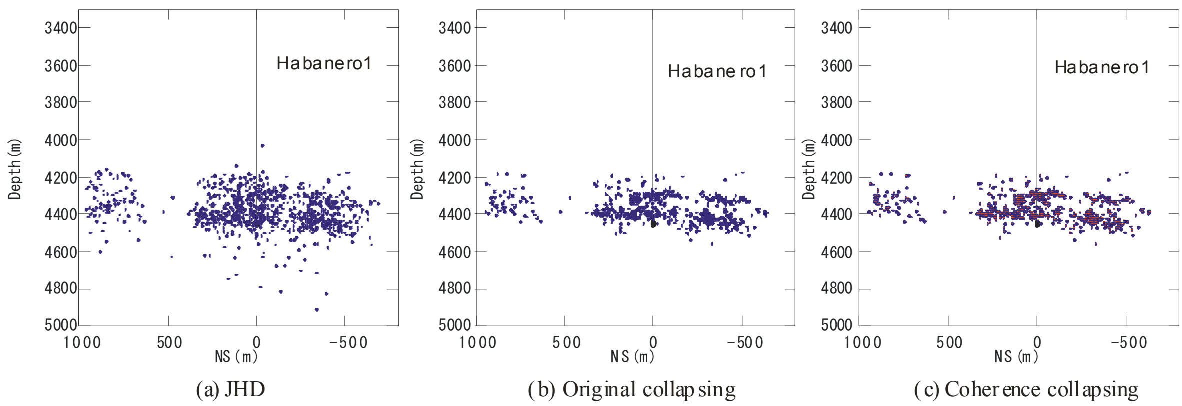


Figure. 2. Relocation of the microseismic data collected at Cooper Basin in 2003.

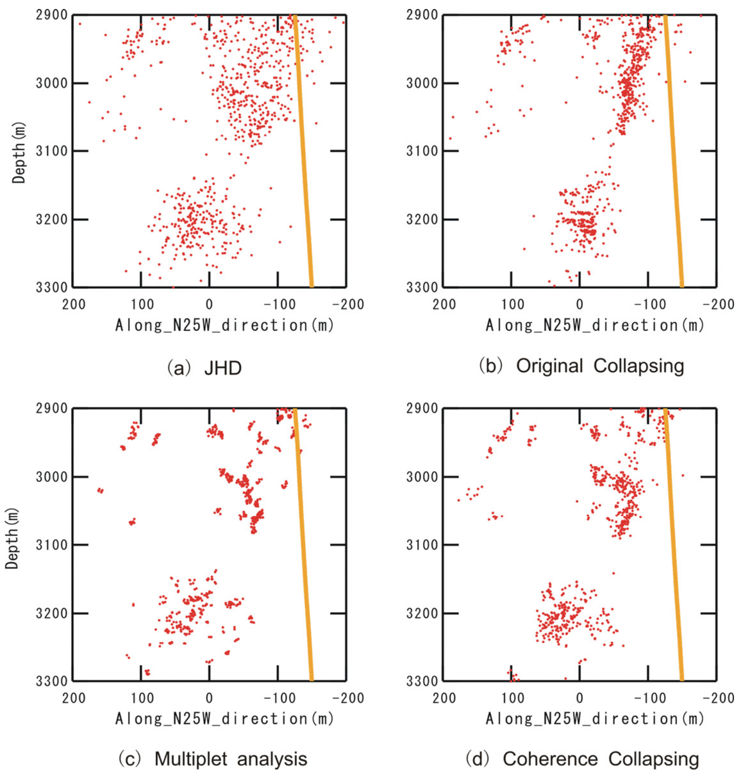


Figure. 3. Relocation of the microseismic data collected at Soultz in 1993.

using the cross spectra for the delay estimation (Moriya et al., 2002).

3.2 *Application to data set collected at Cooper Basin and Yufutsu Gas field.*

Because number of the events with higher similarity was large (>10,000) in the data collected at Cooper Basin in 2003, we selected a part of the seismic cloud where more complex seismic/reservoir structure is expected from the conventional single event location (SED) technique. A total of 3,687 events were located using SED. Approximately 30% of the located events did not have adequate signal to enable determination of waveform similarity. We discuss here the remaining 70%, whose source locations we adjusted using the DD method (Kumano et al., 2006). Figure 4(b) shows the result of DD re-location in the western part of the microseismic cloud. The re-located hypocenters illuminate sub-horizontal, quasi-parallel, planar clusters that dip ~15° toward the West. The thickness of each cluster is less than 50 m, and the horizontal extent is as great as 100 m. The location of the same data set by the Coherence Collapsing is shown in Figure 4(c). The locations from the DD and the Coherence Collapsing method show detailed reservoir structure which was not delineated by the conventional SED method.

At Yufutsu gas field, Hokkaido, Japan, natural gas lies within a reservoir composed of naturally pre-existing fractures distributed in granitic basement and the upper conglomerate formations. 14 boreholes have been drilled into the reservoir, and FMI logging has been conducted at ten of them. The FMI images suggest that the boreholes with large gas production penetrate fractures with large apertures and that smaller fractures are not contributing significantly to gas production.

A hydraulic stimulation was conducted at one of the boreholes, in May, 2005. 5,628 m^3 of sea water was injected during 3 stages (1st step injection, the main injection, and 2nd step injection) for a week. The injection interval was from 4078mMD (Measured Depth) to 4220mMD in a conglomerate formation. We have monitored microseismic events using 4 downhole detectors at depths around 3100-3600m (Kumano et al., 2006)

Figure5 (b) shows the source distribution for events re-located using DD. In this figure, events are reclassified into multiplet clusters using a coherence criterion of 0.8, and each cluster is represented by a different color. Sub-parallel streaks represent each multiplet; these appear to be dipping to the SW with inclinations between 40 to 60 degrees.

To examine the reliability of the source distribution determined by DD we numerically calculated travel times using virtual source locations distributed on a sphere of radius 10 m around the feed point. The result indicates that DD technique cannot improve the source location in the direction that is consistent with direction of the streaks.

The geometry of the network is nearly planar; its normal is consistent with the direction of our multiplet streaks. Thus, we conclude that the source ‘streaks’ produced in this study using the DD method are artifacts arising from the planar geometry of the sensor network.

4. Summary

As described in this paper, coherence of the microseismic events is one of the parameters of importance to understand structure and extension process of stimulated zone. In this paper we introduced two mapping methods which uses information on coherency. The Coherence Collapsing method uses absolute picking of each event and a table of coherency among all the events. These inputs can be prepared in semi-realtime basis, and CPU time for the determination of the hypocenters is as small as that for JHD and original

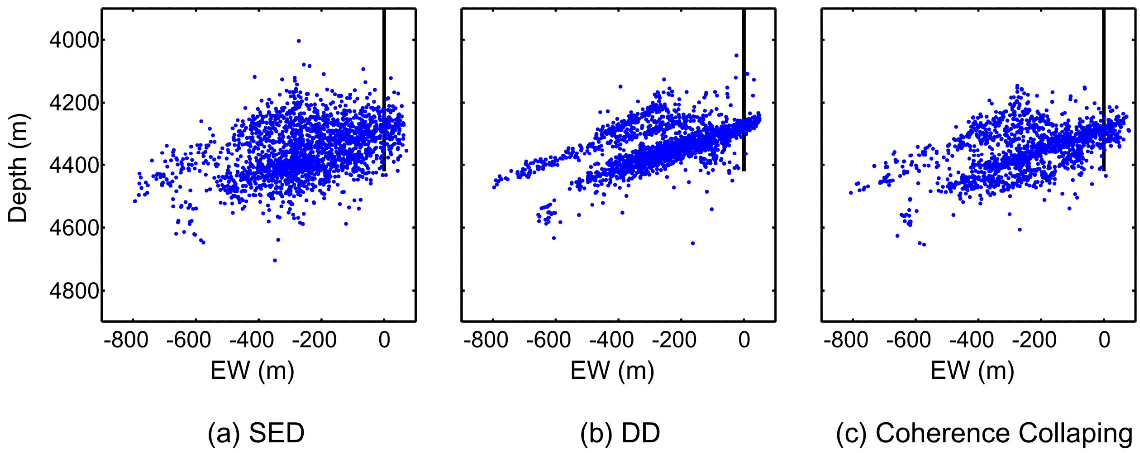
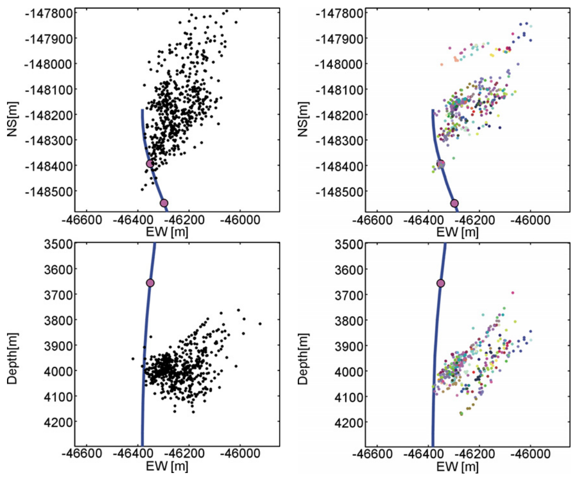


Figure. 4. Location of the microseismic data collected at Cooper Bain in 2003 by the SED, the DD, and the Coherence Collapsing.



(a) SED (b) DD

Fig.5 Comparison of source location

collapsing. The Coherence Collapsing method has an ability to provide absolute location of the multiplet groups but can not resolve seicmic structure of each multiplet groups. This means that orientation and stress state of the fracture with multiple slip can not be estimated. On the other hand, the DD has ability to precisely estimate relative location of the multiplets. However this method does not have realtime nature because of complex process to estimate relative time of arrivals. As shown in this paper, the distribution of the multiplets may be affected by the arrangement of the stations especially in the case of downhole sparse network. The absolute location by the DD is normally less reliable than relative locations.

Considering above mentioned advantages and disadvantages, we are currently using Coherence Collapsing method in realtime or semi-realtime monitoring as well as identification and clustering of mutiplet groups. After clustering the multiplets, precise relative picking is made to some groups of multiplets and DD is used to determine seismic structure of multiplets.

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