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Delineation of Reservoir Structure by the Coherence Collapsing Relocation Technique of Microseismicity

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ABSTRACT

The authors have investigated a variation of the collapsing method that tries to bridge collapsing and multiplet analysis techniques utilizing the advantages of each of the methods. The collapsing method is a mapping method for relocating microseismicity that involves utilizing information from all the events in the data set. In the version of the collapsing method introduced here the idea of the coherence of the waveforms is also incorporated into the method (coherence collapsing). The new method aims to bridge absolute and relative mapping techniques, because this method has a nature to selectively relocate a group of multiplets to a point. The principle of the coherence collapsing method was developed from the concept of the original collapsing method, and parameters in the analysis are optimized from synthetic studies and from real data. The relocated events in simulation revealed that the coherence collapsing method has the ability to estimate absolute location of multiplets in a seismic cloud. This method was applied to a part of the seismic data set of the Soultz 1993, 2000 and 2003 stimulations and Australian 2003 stimulation in Cooper Basin. The relocation of events with high mutual coherency showed structures consistent with multiplet analysis suggesting the advantage of this method for semi-realtime mapping of the multiplets.

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 engineered geothermal systems which includes EGS, HDR, HWR and HFR. 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. To reduce the uncertainty caused by the velocity structure all the events in a data set are located together or jointly. The joint hypocenter determination method (JHD; Frohlich, 1979) has been developed in global seismology. 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” (referred to as original collapsing here). The original collapsing method always tries to collapse structures back to the simplest structure, i.e. a point structure. The collapsing method showed a good ability to delineate seismic structure and has been applied to global seismicity, volcanic seismicity and induced seismicity from engineered geothermal systems. 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. Asanuma et al. (2001) developed a variation of the collapsing method (here referred to as Ishimoto's collapsing) that aims to estimate original small-scale seismic structure by introducing principal component analysis of the locations as a pre-process of the original collapsing. Ishimoto's collapsing method can resolve smaller seismic structures although it is still based on a statistical process.

Some of the seismic events are known to have very similar waveforms although their origin times have wide separations. These events are called as “Multiplets” and highly precise relative mapping techniques or their location have been investigated (Moriya et al., 2002). In this methoid, the similarity of events are quantitatively evaluated in the frequency domain using coherence as a measure, and the relative time of arrival of P and S waves are precisely estimated in the frequency domain. The relative location of multiplets are estimated with a typical error of several metres. Typically planar/linear seismic structures with a size of several metres to several ten metres result, and they are highly correlated to the orientation of pre-existing fractures and to the tectonic stress state. Instead of the precise nature in relative location, the absolute location of multiplet cluster is not directly estimated in this method. The location by JHD is normally used to estimate the absolute location of multiplet cluster. New approach to estimate absolute location of the doublets/multiplet are underway. The multiplet analysis normally takes much longer time than the other absolute mapping methods, because some part of the analysis should be done manually to bring higher resolution and reliability. Hence methods to estimate absolute location of multiplets in semi-realtime basis has been desired.

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 analysing 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. This paper shows the principles behind this new variation of collapsing, results from simulation and application to field data collected at Soultz, France and Cooper Basin, Australia.

2. PRINCIPLES OF THE COHERENCE COLLAPSING METHOD

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 (out to a limit of 4.2 standard deviations), 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 neighbouring events, without any relationship to waveforms. However the multiplet analysis has already resolved that a part of dataset, which has higher mutual coherency, are relocated to a very small seismic structure. This suggests that it is reasonable to correlate the movement in the collapsing method to the similarity of events. Thus the concepts of the new version of the collapsing (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 (see Figure 1) 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.

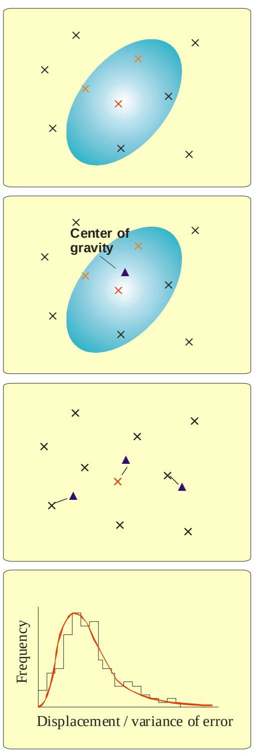

Figure 1: Principle of the coherence collapsing method

(1) draw a confidential ellipsoid with a size of 4.2 s.d. (initial confidence ellipsoid or search volume) for a target event

(2) search for multiplets within this initial confidence ellipsoid using coherence threshold of 0.68 (multiplet criterion)

(3) Using weighting function to enhance the multiplets, relocate the events following the procedure in the original collapsing

In the Ishimoto's Collapsing, the original seismic structure is estimated from the JHD locations. However the seismic structure obtained by the multiplet analysis is negligibly smaller than that in the JHD mapping, and it is reasonable to simply collapse events to a point in the coherence collapsing method.

3. SIMULATION

We have made simulations to (a) investigate optimum weight from coherence, and (b) observe difference between JHD, original collapsing, and coherence collapsing. Figure-2 shows location of events in this study. The initial event locations are shown in (a), where 9 groups of multiplets with a linear distribution are assumed (sold circles). Each multiplet group consists of 11 events and coherency within a group is in a range of 0.7-1.0. The coherency among events in different multiplet groups are 0.2-0.5. The location of non-correlated events with lower mutual coherency of 0.2-0.5 are also put in this simulation (open circles in Figure 2(a)).

The initial location is then blurred by a spatial random noise with a standard deviation of 30 m to simulate mapping by by the JHD (Figure 2(b)), and it was used as an input to the various collapsing methods.

The results from the original collapsing and Ishimoto's collapsing are shown in (c) and (d). The output from the coherence collapsing are shown in (e) and (f) where squared coherence is used as a weight to calculate the centre of gravity of events in (e), and the eighth power of coherence is used in (f). It is clearly seen that the multiplet groups are relocated near the real location in Figure 2(f) where eighth power of coherence is used as a weighting function. The original collapsing and Ishimoto's collapsing shrinks the size of whole seismic cloud but no significant structure is related to coherency. Most of the seismic structure are estimated to be a linear in Ishimoto's collapsing and three layered structure of non-multiplet/multiplets/non-multiplets is appeared, although it is not very clear. It is seen from the comparison of (e) and (f) that the weighting on coherence highly changes the collapsed location in the coherence collapsing. We have made several simulations and concluded that eighth power of the coherence is the best to relocate multiplets to the real location and non-correlated events are collapsed as in the original collapsing method.

Figure 3 shows relocation of two groups of multiplets (Figure 3(a)) by the original collapsing (Figure 3(c)) and the coherence collapsing (Figure 3(d)) with a weight of eighth power of coherence. In this case, we assumed that two separated fractures, which has identical source mechanism, generate two groups of multiplets, and the coherency of events between the two groups is high. It is desirable that the relocated hypocenter of the multiplets make two point structure correlated to the original location. It is seen from Figure 3 (d) that the coherence collapsing method has higher ability to relocate two groups of multiplets event the source parameter has high similarity, although relocated two groups of multiplets shows linear structure bridging the original locations.

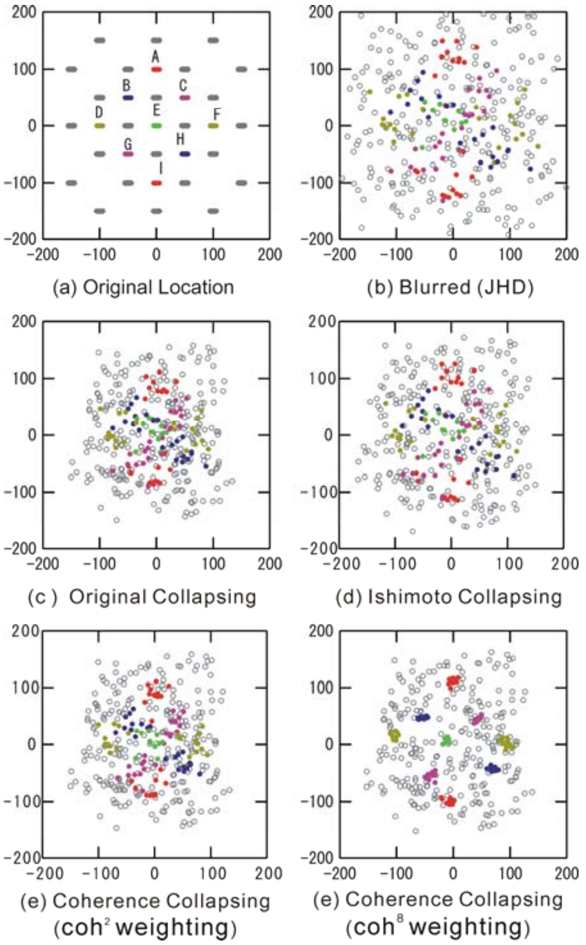

Figure 2: Similation of relocation of the multiplets by different variation of the collapsing method

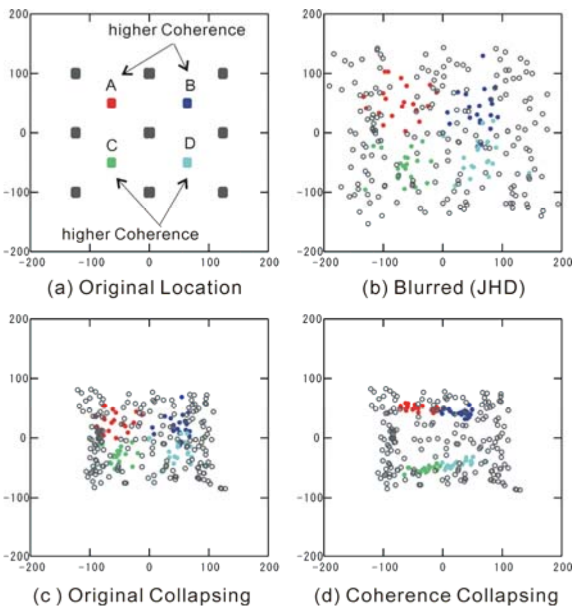

Figure 3: Similation to evaluate ability to relocate two groups multiplets by different variation of the collapsing method

4. APPLICATION TO FIELD DATA

The coherence collapsing method was applied to data set collected during the stimulation of HDR/HWR/HFR 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 1993, 2000 and 2003, and that from Cooper Basin in 2003 are shown in Figures 4 -7.

The extension process of a part of the shallow reservoir created at Soultz in 1993 has been interpreted by a 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 4. 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 HDR/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.

5. CONCLUSIONS

This paper described principles of the coherence collapsing method and its application to data collected at Soultz, France and Cooper Basin, Australia. A concept of similarity of waveforms is introduced to the original collapsing method which is a statistical optimization of the location using just a residual error, and seismic events are relocated to enhance the location of similar events. The simulation showed that this method has a good ability to estimate absolute location of the multiplet as well as collapse uncorrelated events. The coherence collapsing method was applied to data set collected during the 1993, 2000 and 2003 stimulations at Soultz and 2003 stimulation at Cooper Basin. This method provided more detailed seismic structure than the original collapsing, and interpretation of the reservoir extension are realized

The computer time for relocation in the coherence collapsing is much shorter than the multiplet analysis, most of the procedure is run automatically within one or two days. Although the resolution of seismic structures is slightly less than the multiplet analysis, the coherence collapsing can be used for on-site or flash reporting of seismicity. Because the multiplets are interpreted to be highly correlated to permeable zone in engineered geothermal systems, the simple and quick nature of the coherence collapsing method is effectively used for development of engineered geothermal systems.

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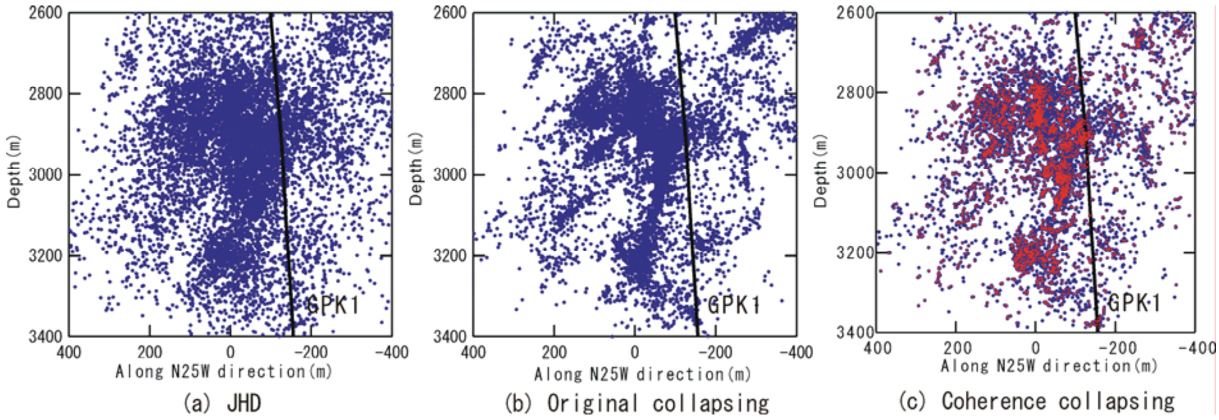

Figure 4: Microseismic events from stimulation at Soultz in 1993

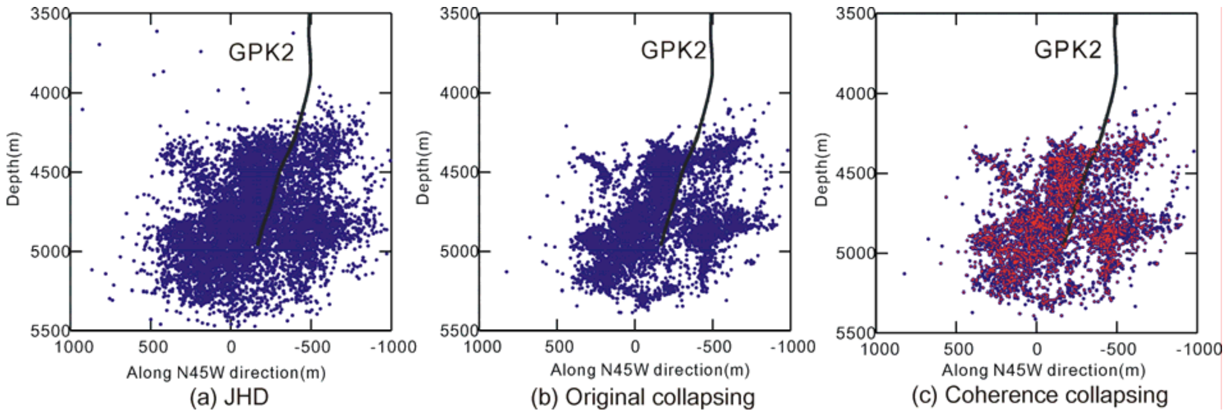

Figure 5: Microseismic events from stimulation at Soultz in 2000

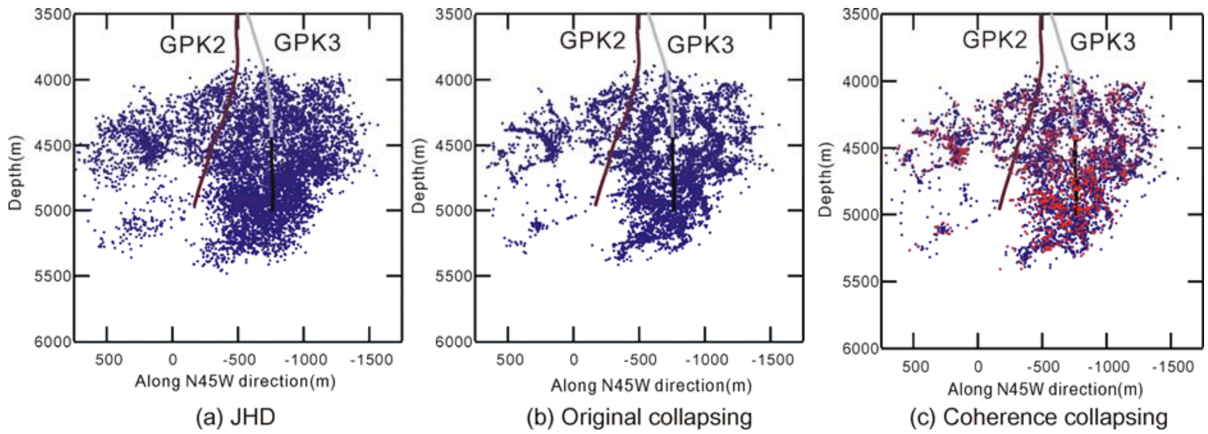

Figure 6: Microseismic events from stimulation at Soultz in 2003

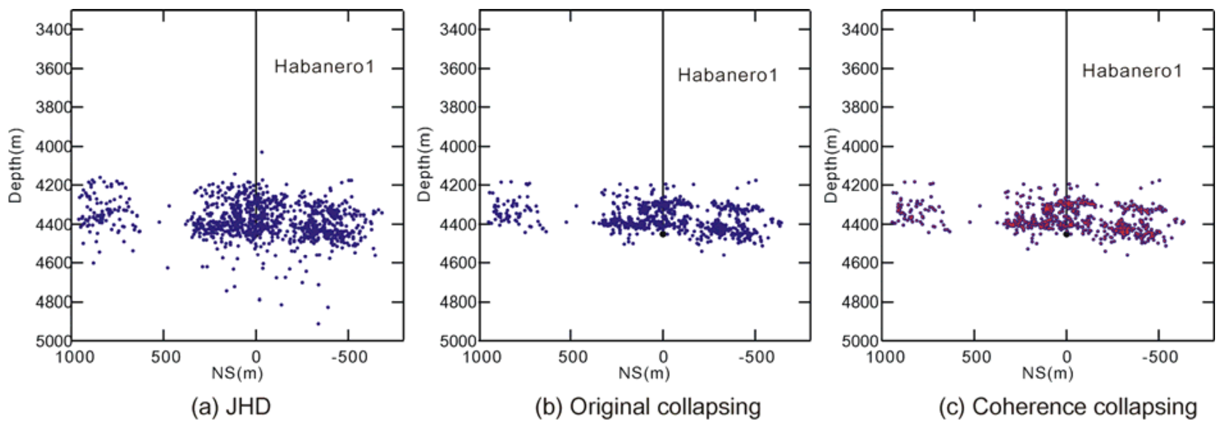

Figure 7: Microseismic events from stimulation at Cooper Basin in 23