Current Status of Microseismic Monitoring Techniques for the Stimulation of HDR/HFR Reservoirs

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ABSTRACT

Microseismic monitoring has been used in Hot Dry/Fractured Rock (HDR/HFR) projects worldwide as one of the standard techniques to monitor stimulation. The authors have been investigating uper resolution mapping techniques of the microseismic events to obtain more reliable locations of the hypocenters and more detailed analyses of the response of the fracture system to the stimulation. In this paper, we illustrate the concept of coherence-based analysis and demonstrate results from stimulations carried out in the Cooper Basin and at Basel, Switzerland.

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

INTRODUCTION

It has been widely accepted that the microseismic mapping/imaging method is one of the few methods that can estimate the time/spatial distribution of reservoir growth in HDR/HWR/HFR Engineered Geothermal Systems (EGS). The mapping of the locations of the microseismicity is the most fundamental analysis process in the microseismic method and research aiming to improve the accuracy and reliability of this mapping has been carried out in a worldwide project which is referred to as 'TC/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 the 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 optimising relocation method which is referred to as the 'collapsing method'. This method has been used with success in a number of studies. However, because of the initial assumption that the original seismic structure is actually a point, the ability to resolve structures that are comparable to or smaller than the spatial confidence ellipsoid is not high in this original collapsing method.

In the population of recorded microseismic events from an EGS stimulation 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 of their locations have been investigated (Moriya et al., 2002).

The authors have been investigating a mapping method that tries to bridge collapsing and multiplet analysis techniques thereby utilising the advantages of each of the methods. The objective of this development is to offer similar information as is obtained from time intensive multiplet analysis but in the relatively shorter analysing time available with the JHD and collapsing methods. It is hoped that this new method will provide better locations and permit a more meaningful interpretation of the physical meaning of the seismic cloud of results. Because coherency among events is used as an input, we have named this variation of the collapsing method as 'Coherence Collapsing' (Asanuma et al., 2003).

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 capitalise on waveform similarity for precise estimation of differential travel times among events at each receiver. These differential times are then 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 the 'Double Differential method' (DD method) and is now one of the standard mapping techniques in global seismology.

In this paper, we discuss the potential of these newly developed coherence-based mapping techniques using data sets collected during the stimulation of Engineered Geothermal Systems.

COHERENCE COLLAPSING METHOD

Principles

In the Original Collapsing method of Jones and Stewart (1997), an event is selected as a target event and is then moved slightly toward the centre of gravity of all the events that are located within its confidence ellipsoid. This implicitly assumes that the original seismic structure was a point. The movement is normalised 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. This procedure is repeated for several generations until the distribution of normalised movements fits to the Chi distribution with three degrees of freedom.

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

- The events which have higher mutual coherency are relocated to a point (or to a very small structure); and
- The events with lower mutual coherency are relocated to reduce uncertainty of the whole seismic cloud.

The main procedure of the Coherence Collapsing method is based on that of the Original Collapsing method. The coherence of the events to the target event is again 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 a study of synthetic events and we currently use the 8th power of the coherency (Asanuma et al., 2003).

Application to the data set collected in the Cooper Basin.

The Coherence Collapsing method was applied to the microseismic data set collected during the stimulation of reservoirs in the Cooper Basin, Australia (Asanuma et al., 2004). The location of microseismic events determined by JHD, the original collapsing method, and the coherence collapsing method for the data sets from the simulation in 2003 are shown in Figure 1.

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 a sub-horizontal seismic cloud extending horizontally approximately 1,500 m from the injection well with thickness around 150 m (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 a single fracture with multiple slip, this result suggests the existence of a set of sub-horizontal fractures in this site.

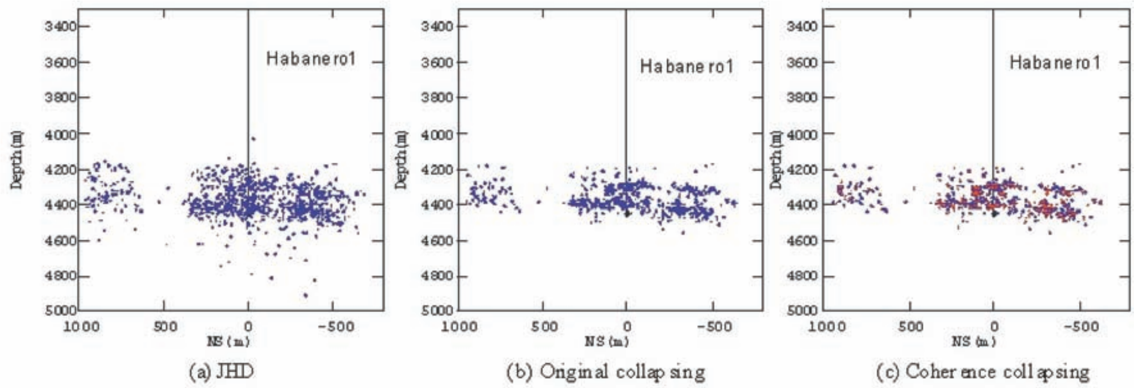

Figure 1. Relocation of the microseismic data collected at Cooper Basin in 2003 by Coherence-collapsing.

DOUBLE DIFFERENTIAL (DD) METHOD

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 method to estimate absolute location is lower than for relative location. The residual error after DD has been investigated by Kumano et al. (2006). It has been revealed that the orientation of the spatial distribution of the error is dependent on the geometry of the network in the same manner as JHD.

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 be longer than for other techniques in the 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 using cross spectra for the delay estimation (Moriya et al., 2002).

Application to data set collected at Cooper Basin and Basel

Because the number of events with higher similarity was large (>10,000) in the data collected in the Cooper Basin in 2003, we selected a part of the seismic cloud where more complex seismic/reservoir structure is expected from the analysis using 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 2(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.

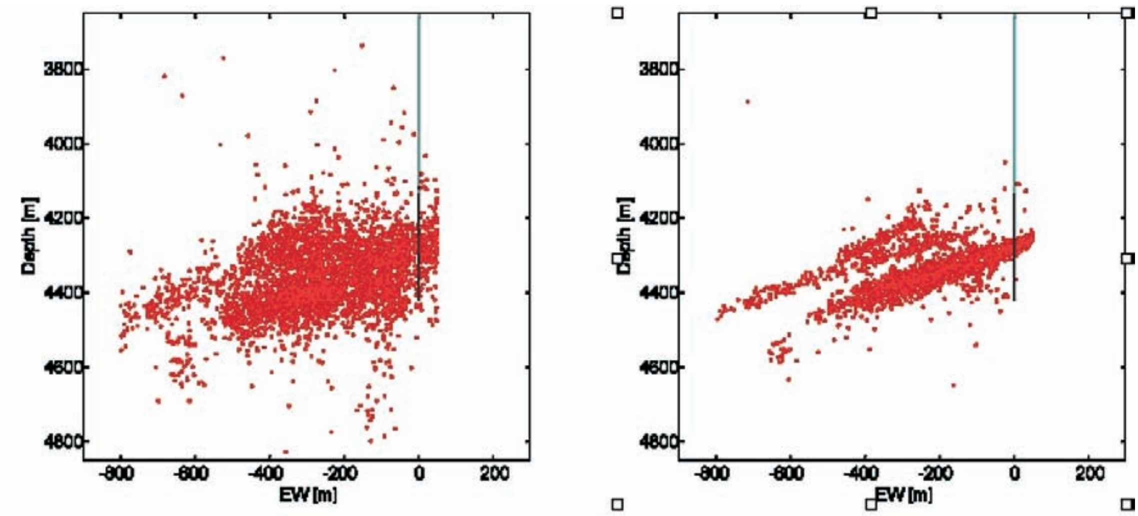

Figure 2. Relocation of the microseismic data collected at Cooper Basin in 2003 by DD, (a) JHD (left), (b) DD (right).

In order to develop an enhanced geothermal reservoir as part of the Deep Heat Mining project at Basel (Switzerland) a hydraulic stimulation program was conducted in deep geothermal well Basel 1 during December 2006. This EGS project is financed by Geopower Basel AG. The stimulation was operated and monitored for microseismic activity by Geothermal Explorers Ltd. More than 13,000 microseismic events were observed during the stimulation and afterwards. Hypocenters of approximately 2,900 events were located onsite. During subsequent analysis, we analyzed microseismic multiplet events that exhibit similar waveforms to those among the located events. Seventy percent of the located events comprise multiplets which may be assigned to over 100 distinct multiplet clusters. We estimated relative hypocenters for 1,635 of the multiplet events using a double differential hypocenter location technique (Asanuma et al., *in press*). Figure 3 shows the hypocenter distribution determined by the DD technique. Each multiplet cluster has dimensions of several tens to hundreds of meters and delineates a planar or linear structure having vertical inclination and predominant strike in two directions: N25W or N50W. Although the tectonic stress state has not been clearly investigated near this site, it has been reported that the tectonic stress at the Soultz Hot-Dry-Rock geothermal field, also located within the Rhine Graben, exhibits a maximum horizontal stress of NW-SE, consistent with local tectonic activity around the graben (Baria et al., 2000). We thus conclude that the orientation of multiplet clusters in the Basel field arises from local tectonic stresses.

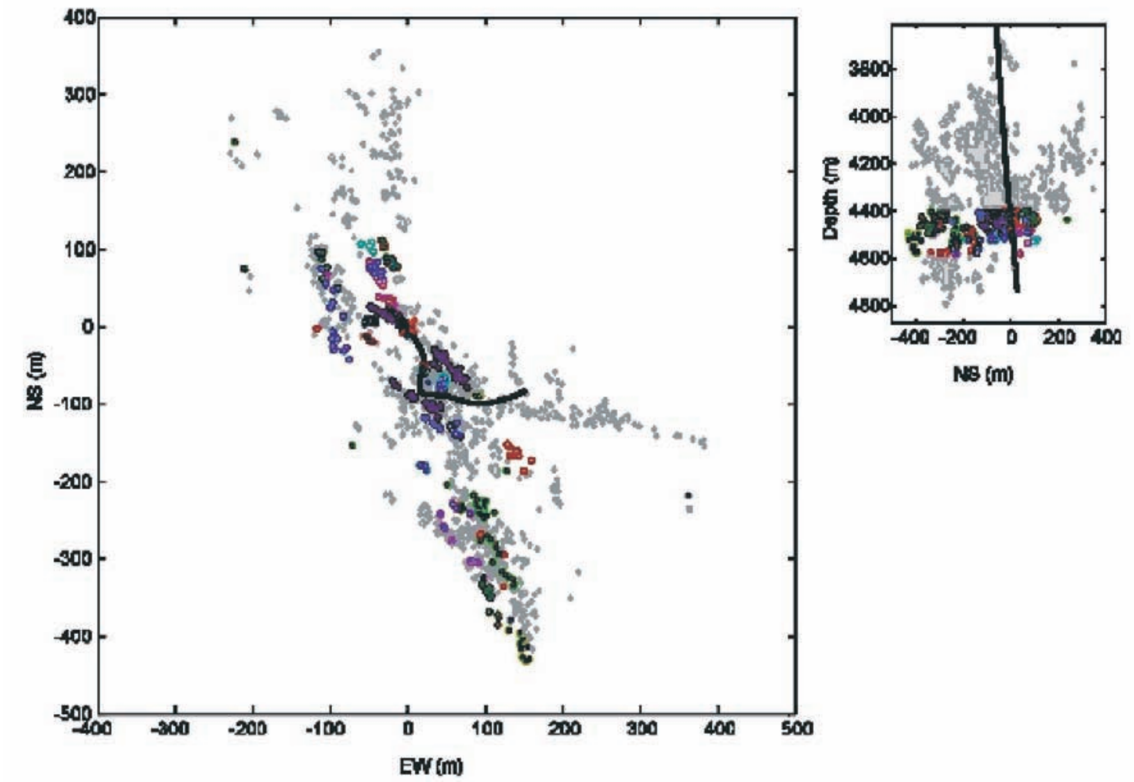

Figure 3. Location of microseismic multiplets at Basel. Hypocenters were re-located by DD.

OTHER TECHNIQUES

In the Cooper Basin case, source distribution determined by the DD technique indicates that the reservoir structure consists of sub-parallel, planar clusters. However, we could not estimate the more detailed structure inside each of these clusters because the thickness of each cluster is only of the order of tens of metres.

Waveform similarity is related to similarity of both the source mechanism and travel path. Similar waveforms can be assumed to be radiated from repeated, consistent shear slip on a fracture, which results in a similar focal mechanism. Therefore, we can discuss the complexity of the fracture system within clusters by examining the spatial distribution of multiplets, which are defined by their waveform similarity. By using the coherence function as a measure of waveform similarity, we examined the multiplets and associate the coherency among member events with the source locations. Figure 4 shows the spatial distribution of microseismic sources (Kumano et al., 2006). In this figure, the varied color of source locations indicates the coherency between the events and a reference event, indicated by a square. We can see that coherency is lower between different clusters than within the same cluster. Moreover, within a single cluster the coherence function varies smoothly with distance from the reference event and there is no discontinuity of the spatial variation of coherency. These results suggest that the fracture system within each seismic cluster is very simple and may be a single fracture plane.

If the collected data has a wideband nature and contains information of the corner frequency f_c , the similarity of the waveform is correlated to the f_c , which is determined by the size of the ruptured area (source radius), and the hypocentral distance, as well as the focal mechanism. Vertical projections of the distributions of multiplet hypocenters for Basel data are shown in Figure 5, where the colour of the circles correlates to each multiplet group, the size of the circles indicates the

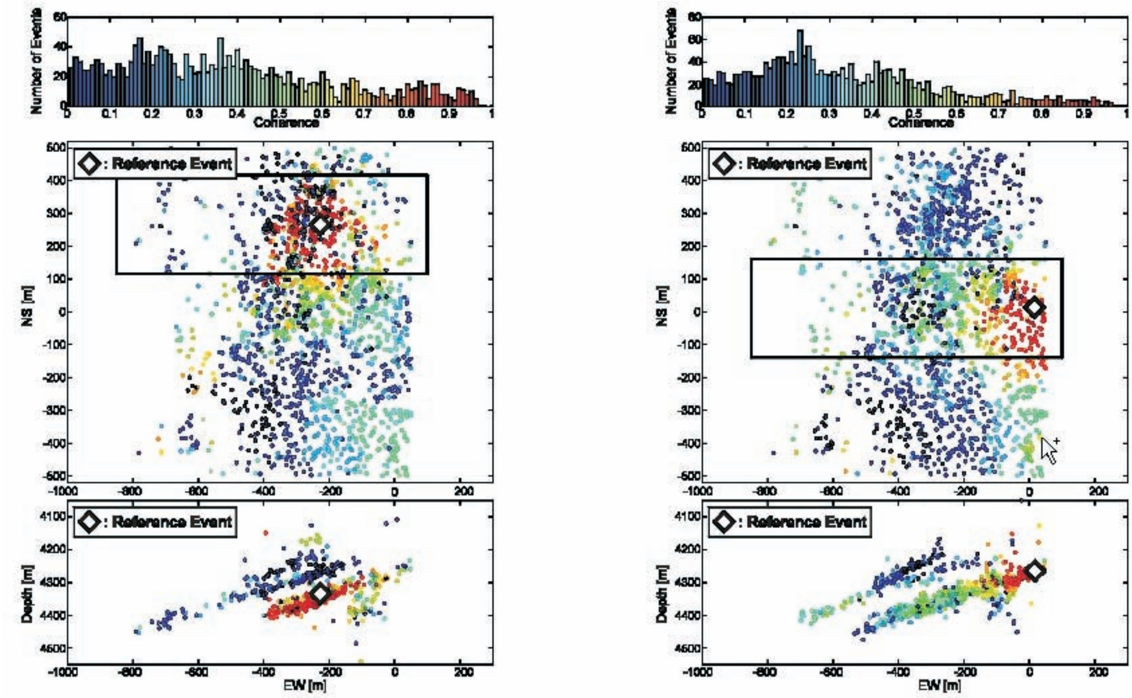

Figure 4. Spatial distribution of coherence relative to a reference event (square) for a data set collected at Cooper Basin.

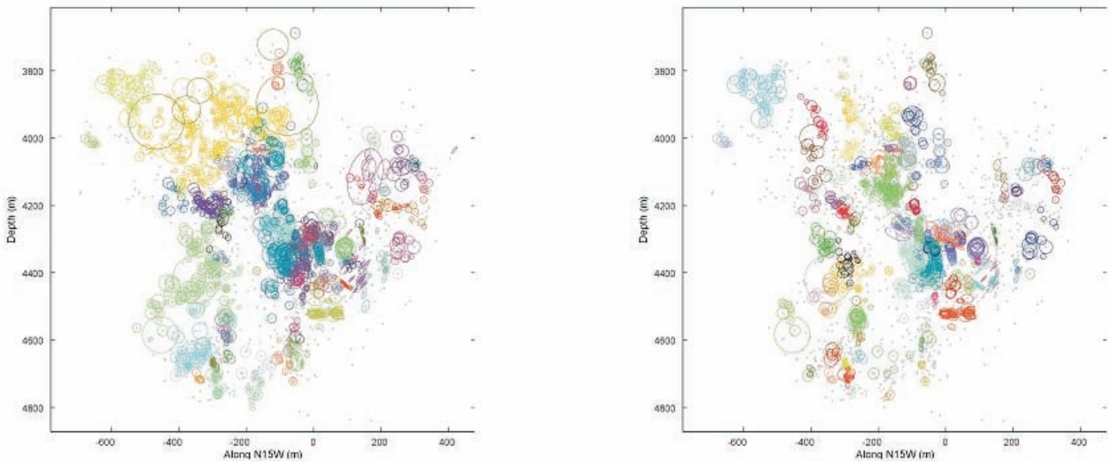

Figure 5. Location of multiplet by different criteria for Basel dataset, (a) lower frequency (left), (b) higher frequency (right).

estimated source radius, and grey dots show the hypocenters of uncorrelated (single) events. Figure 5(a) shows the hypocenter distribution of multiplets identified in lower frequency and Figure 5(b) is for higher frequency. The multiplets identified in the lower frequency domain show large sub-vertical seismic structures up to 400 m and heterogeneous source radii (10-100 m), while the multiplets identified in the high frequency domain show smaller sub-vertical seismic structures less than 200 m and their source radii are more homogeneous. It is also noticeable that large multiplet clusters in the south part of the seismic cloud identified in lower frequency are found to be sub-clustered into smaller clusters by applying the identification in higher frequency (Asanuma et al., *in press*). It is interpreted that a mechanism involving an identical direction of shear slip on single or sub-parallel macroscopic pre-existing fractures may be responsible for the multiplets identified in the low frequency analysis, while the multiplets identified in high frequency correlate to repeating slip of a part of the fracture system mainly around the feed point and the gradual rupture of one small-scale fracture.

It has been reported that origin time and distance from the injection point of the multiplets are highly correlated to the flow rate and wellhead/downhole pressure (Asanuma et al., *in press*). This kind of information can also be effectively used to interpret the stimulation process and reservoir characteristics.

SUMMARY

As described in this paper, the coherence of the microseismic events is one of the parameters of importance in understanding the structure and extension process of the stimulated zone. In this paper we introduced two mapping methods which use 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 on a semi-realtime basis, and the CPU time for the determination of the hypocenters is as small as that for JHD and original collapsing. The Coherence Collapsing method has an ability to provide absolute location of the multiplet groups but it cannot resolve the seismic structure within each multiplet group. This means that the orientation and stress state of the multiple slipping fractures cannot be estimated. On the other hand, the DD method has the ability to precisely estimate the relative location of the multiplets. However this method does not have realtime capabilities because of the complex processing required to estimate the 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 a sparse

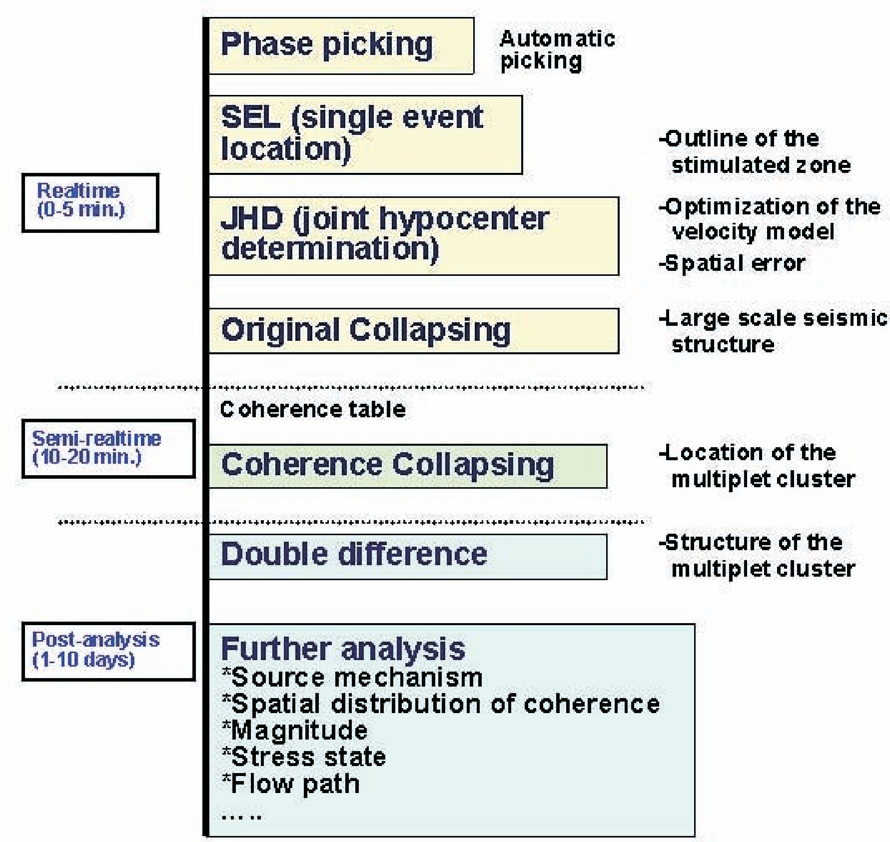

Figure 6. A flow chart of microseismic processing in the authors group.

downhole network. The absolute location by the DD method is normally less reliable than the relative locations.

Considering the abovementioned advantages and disadvantages, a flow chart of microseismic analysis in our group is shown in Figure 6. The re-location by Coherence collapsing can be done on-site in semi-realtime (~20 min.) by updating the coherence-table among the events. This enables the results to be used to help plan the continuing stimulation program. The DD re-location and the other analysis can be made as a post-analysis and provide information for more detailed interpretation and understanding of the reservoir that has been created.

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