Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Automatic Wave Picking Technique for Multi-Component Microseismicity and It's Practical Application to on Site Analysis in HDR Development

Nobukazu Soma[1*], Takashi Takehara[1], Hiroshi Asanuma[2], Hiroaki Niitsuma[2], Roy Baria[3], Sophie Michelet[3], and Doone Wyborn[4]

1) National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8569, Japan

2) Graduate School of Environmental Studies, Tohoku University, Sendai 980-8579, Japan

3) EEIG “Heat Mining”, 67250 Kutzenhausen, France

4) Geodynamics Limited, Queensland 4064, Australia

* n.soma@aist.go.jp

Keywords: microseismicity, HDR, on site analysis

ABSTRACT

A more reliable automatic picking technique has been developed and tested during onsite analyses of microseismicity in practical Hot Dry Rock developments. The technique imitates human procedures by a combination of various signal processing techniques. A trial using laboratory data and past field waveforms from the Soultz HDR project in 2000 indicated good reliability as the source locations were very similar to those based on manual picking. By using the technique, about 12,000 events were successfully located during onsite analysis both at Soultz and Australia in 2003. The observed reliability of the source locations suggests that in the future this technique may be used for more precise onsite analysis as more complex techniques can be applied using the automatic picking of the P- and S-wave arrivals.

INTRODUCTION

Measurement of geothermal reservoir is one of essential task and various techniques are used for it. Microseismic monitoring is relatively simple, easy and low cost, and commonly used in both Hot Dry Rock (HDR) and hydrothermal geothermal development. It is useful for understanding the extent of the reservoir area because the position of the events seems to correspond to fractured area . Recently, various techniques to extract more detailed information from the microseismic cloud have been developed. For example, as parts of the MTC (More Than Cloud) international collaborative project, multiplet analysis of Moriya et al. (1995) permits the definition of detailed structure and the collapsing method (Jones and Stewart, 1997) reveals potential major structures within the microseismic cloud. We can also see surrounding sub-vertical structures, such as a fault system, by the Acoustic Emission reflection method (Soma and Niitsuma, 1997, Soma et al., 2002).

However, these techniques have not been applied during onsite analysis because all the techniques need accurate P- and S-wave arrival times from large data sets which have not generally been available. Manual picking is the most reliable method but it is extraordinarily time consuming work. There have been many studies of automated analysis and in seismology it is already used in practical earthquake location. In HDR development, we usually need both P- and S-wave arrivals because the seismic network consists of relatively few downhole observation points. Furthermore, applicability to more complex waveforms is necessary for the recent HDR developments because deeper development makes a not ideal observation condition causing influence of attenuation, transformation, multi-pass, etc. Therefore, the software used in seismology and previous HDR studies may not be optimum. This has hindered the application of advanced analysis such as MTC techniques during onsite analysis.

The research team in the MTC/MURPHY international collaborative project conducted onsite microseismic monitoring at the Soultz HDR site in summer 2000 (Asanuma et al., 2001). At that time, we made very reliable onsite analysis using manual wave observation, but only 756 events, which is 2 % of the total recorded wave files, could be analyzed. The rate of the analyzed event was regarded not enough even for statistical meaning. After a few months, the locations of about 7500 events were found by manual processing in the laboratory, which is 18 % of the total recorded wave files.

In this paper, we describe an automatic wave picking technique in which the flow of human processing is imitated by several signal processing techniques. First, the concept and method of the technique are described, and then the results of a trial using waveforms in the laboratory and observed at the Soultz HDR site in 2000 are shown. Finally, the application to the onsite analysis in actual HDR development sites, at Soultz and Australia, are reported.

THE CONCEPT OF THE AUTOMATIC TIME PICKING TECHNIQUE

For practical applications, reliable source locations are essential as the interpretation of the microseismicity is a very important contribution to decisions regarding the hydraulic injection, which is an irreversible process. Therefore we think the most important aspect of the automatic picking is the reliability, analysis speed is a secondary consideration. We have developed an algorithm which imitates human processing by a combination of several signal processing techniques. Although the complexity of this algorithm makes it slower than some other methods, we feel this limitation will become insignificant with increasing CPU speeds.

The following manual picking procedures are imitated by the automatic picker. (i) The approximate positions of the P- and S-waves are evaluated by observation of the whole waveform. (ii) A potential P-wave arrival point is selected by detailed observation considering wave energy and characteristics of the waveform. (iii) A discontinuous point is selected as the P-wave arrival point. (iv) For the S-wave, orthogonality of the wave direction between P- and possible S-wave is evaluated and a potential S-wave arrival is determined. (vi) Detailed observation enables a discontinuity of the waveform to be selected as the S-wave arrival. (vii) For all stations, (i)~(vi) are repeated. (viii) The relative timings among all the stations are checked with priority given to the P-wave arrivals. The automatic picking algorithm imitates these processes using several signal processing techniques.

SIGNAL PROCESSING IN THE AUTOMATIC PICKING TECHNIQUE

The technique includes several signal processing methods, such as energy variation analysis, autoregressive model (AR model), phase angle index analysis of wavelet transform, and wave direction analysis in time-frequency domain using wavelet transform.

For the approximate evaluation of P- or S-wave arrivals, energy variation is evaluated. The root mean square amplitudes are calculated for two sequential moving time windows and the ratio is evaluated. Around the P- or S-wave arrival, the value generally increases sharply.

The locally stationary AR model technique can extract a discontinuity based on a statistical character of the waveform, which is commonly used in seismology (Shirai and Tokuhiro, 1979, Morita and Hamaguchi, 1984). When the observed signal is regarded as a time series $\{y_1, \ldots, y_N\}$, the basic equation of the AR model is

$$y_n = \sum_{i=1}^{m} a_i y_{n-1} + v_n \quad , \qquad (1)$$

where y_n: n-th value of time series, n: integer ($1<n<N$), m: order, a_i: AR coefficient, v_n: gauss noise.

This model represents the current signal from observation of the past signal and Gaussian noise. To find the best fit model, a criteria called AIC (Akaike's Information Criteria), denoted as,

AIC=-2(maximum log-likehood)+2(number of parameter) (2)

is minimized. To clarify the separation between noise and seismic waveform, we use AIC for the two windows. The point where the AIC is minimized determines the optimal separation of the two windows and this is interpreted as the phase onset. This technique is very useful to detect the most likely point of the wave arrival.

The phase angle index analysis of the wavelet transform with Gabor function can precisely detect a discontinuity in the waveform (Kawahara, 1991, Niitsuma et al., 1994), which is used to determine accurate wave arrival points around the potential wave arrivals. Continuous wavelet transform is written as

$$WT(b,a) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{a}} h^*\left(\frac{t'-b}{a}\right) f(t)\,dt \qquad (3)$$

where a: scale, b: shift, $h(t)$: analyzing wavelet, *: complex conjugate.

Here, the Gabor function, $h(t) = e^{j\omega t} e^{-\frac{t^2}{2}}$, is used as an analyzing wavelet which has minimum uncertainty for time and frequency. The phase angle index is the integration of the phase of the wavelet coefficient. This index has an extremum for the point of discontinuity in the waveform because the phase usually becomes the same at that point. This technique is used for fine adjustment of the detected arrival points.

To avoid misreading the S-wave arrival, orthogonality of the S-wave against P-wave is evaluated by covariance matrix in the time-frequency domain using wavelet transform (Soma et al., 2002). The matrix is

$$\mathbf{S}_{\mathbf{WT}}(b,a) = \begin{pmatrix} W_{xx}(b,a) & W_{xy}(b,a) & W_{xz}(b,a) \\ W_{yx}(b,a) & W_{yy}(b,a) & W_{yz}(b,a) \\ W_{zx}(b,a) & W_{zy}(b,a) & W_{zz}(b,a) \end{pmatrix} \quad , \qquad (4)$$

where $W_{ij}(b, a)=W_i(b, a)W_j^*(b, a)$, a is the frequency (scale), b is the time (shift), $W_i(b, a)$ is the wavelet coefficient of the ith component, and * indicates the complex conjugate.

Here, we use Mayer's analyzing wavelet because we need an orthogonal wavelet transformation. By analyzing the eigenvectors of (4) we can evaluate the 3D direction of the detected waveform.

Through a combination of these signal processing techniques, we developed an automatic wave picking method similar to human processing. The flowchart of the automatic picking technique is shown in Figure 1.

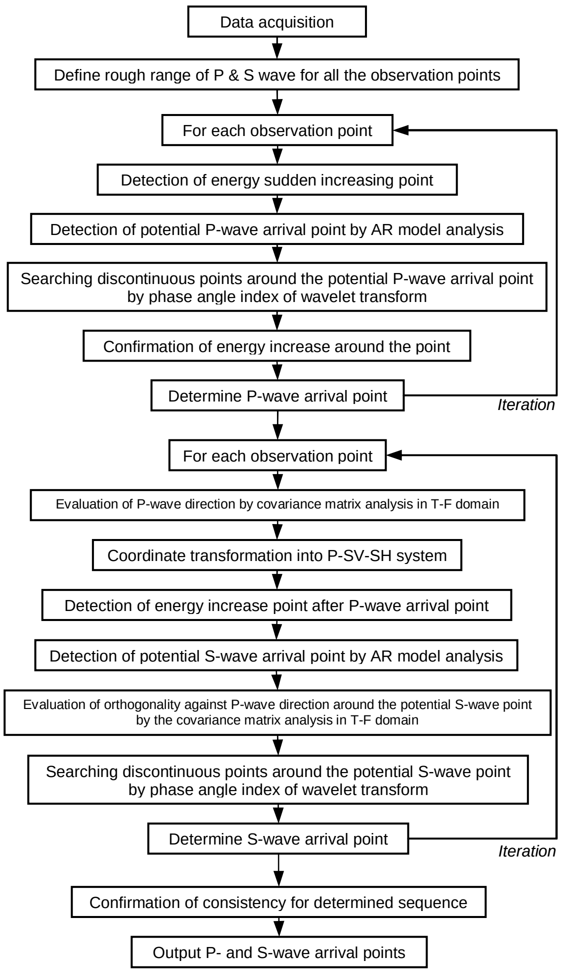

Figure 1: Flow of the developed automatic picking technique.

TRIAL OF THE AUTOMATIC TIME PICKING

We have tested the performance of the automatic picking technique using waveforms obtained from the Soultz HDR site in 2000 (Dyer, 2000, Asanuma et al., 2001).

Before applying the technique to field microseismic data, we confirmed the performance of the basic algorithm using acoustic emission (AE) data from laboratory experiments. Hydraulic fracturing tests were performed under 2 axial stress conditions using 20 cm cube blocks of granite and sandstone (Takehara et al., 2003). The AE waveforms were recorded with 10 AE sensors. The example of comparison of AE distribution between using automatic and manual time picking is shown in Figure 2. We could use only P-wave because of characteristic of the AE sensor. We were able to obtain the location of an artificial fracture from the AE source distribution using the automatic picking technique. Since there was a limitation of working time, we could not analyze all the AE events although we spent nearly one month. Total number of the located AE by the automatic picking resulted much more than manual processing, because processing speed enable to look over all the AE waveform. The analysis speed was at least 16~33 times faster than that of picking by eye.

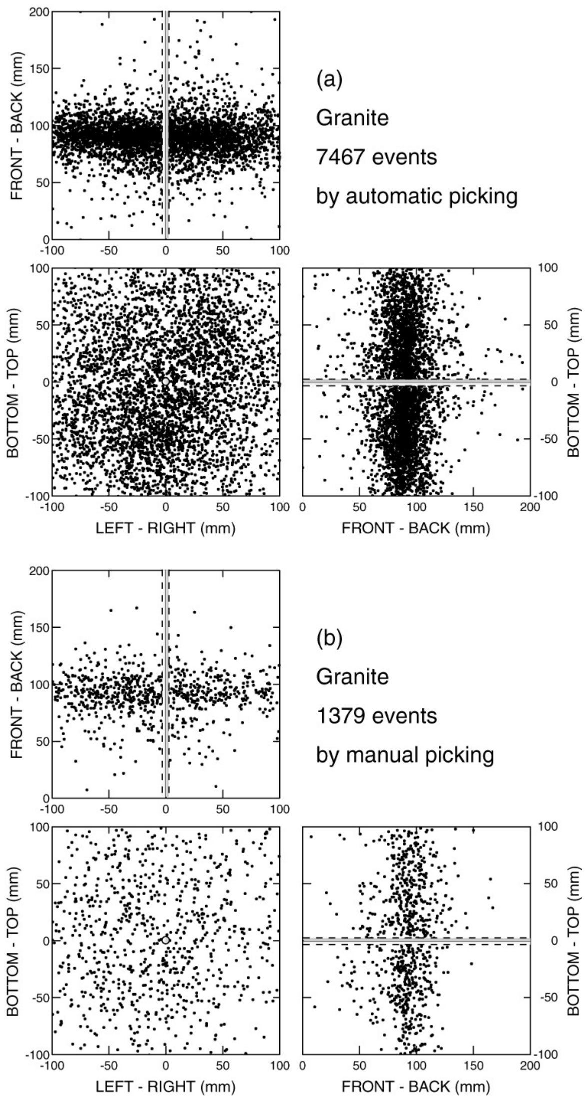

Figure 2: Results of trial of automatic picking using AE waveforms from a laboratory hydraulic injection experiment on a granite rock sample. AE location by automatic picking: (a) and by manual picking (b).

Figures 3 and 4 are examples of P-and S-wave points in the waveforms from the Soultz HDR site. Here, we compare the results of automatic picking with the manual picking performed by Tohoku University. We also compared the automatic picks with picks using only the AR model on the Z- and X-component. In Figure 3, the automatic and manual P wave picks agree. The S-wave automatic pick, Figure 4, is also very close to the manual pick. The AR method provides a close fit to the manual P wave pick but it is clearly less reliable at picking the S wave than the automatic picking algorithm.

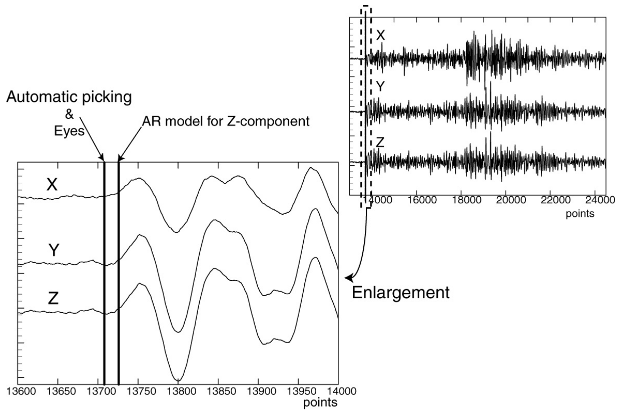

Figure 3: An example of P-wave picking by the automatic picking technique. Example waveform was recorded at Soultz in 2000.

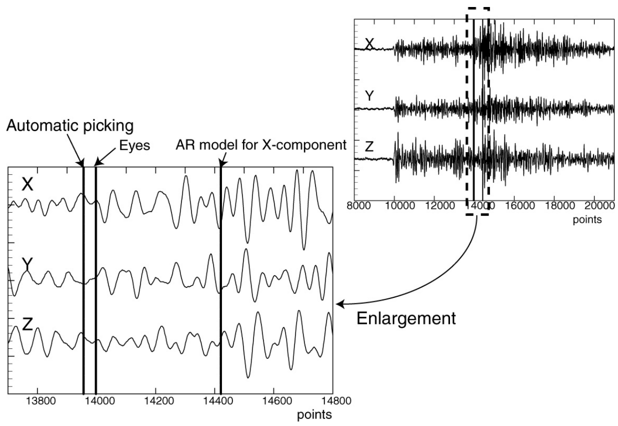

Figure 4: An example of S-wave picking by the automatic picking technique. Example waveform was recorded at Soultz in 2000.

The locations of 2470 events (from 3724 recorded events) obtained with the automatic picking technique are compared with 7565 manually picked events in Figure 5. For the trial, we did not process all the recorded files due to limited computer resources. The velocity model used here is a uniform velocity model which was used during the onsite analysis in 2000. The software for the source location is the same in both distributions, therefore the location differences should be a reflection of the picking technique alone. In Figure 5, the overall event distribution is almost consistent between the automatic and manually processed locations, although the number of events is less for automatic picking. The linear outer boundary of the seismic cloud is also reproduced by the automatic picking technique. The dispersion effects in results using automatic picking can be effectively reduced in a practical onsite analysis when we make a kind of threshold filter for such as number of picked sensor and RMS error for the calculation of location. The accuracy of automatic picking seems to be reasonable for practical onsite analysis. The calculation speed of the automatic picking was 50 events per hour for the Soultz 2000 data which consisted of 12 channels of 60,000 words each using an Alpha 21264 667MHz computer. This is already about 10 times faster than that of the onsite manual picking in 2000. The speed may be improved very much if the data length was shorter and faster CPU could be used.

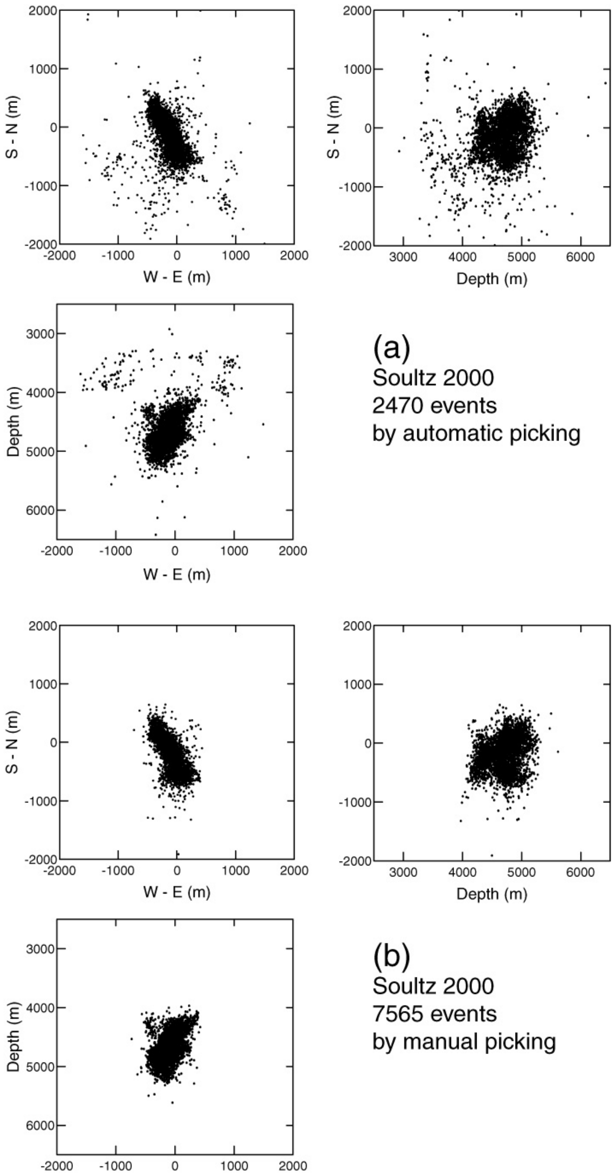

Figure 5: Comparison of source location using the proposed automatic picking technique:(a), and that based on manual picking:(b). Past microseismic data sets acquired at Soultz HDR site in 2000 are used.

APPLICATION TO THE ONSITE ANALYSIS AT THE SOULTZ HDR SITE IN 2003

The European deep geothermal energy programme using HDR technology has been conducted at Soultz-sous-Forêts, in France (Figure 6) since 1987, supported mainly by the EU, France and Germany (Baria et al., 1995). Presently, the program is working towards the production of electric power for commercial power in future, and developing depth has moved around 5 km (Baria et al., 2000).

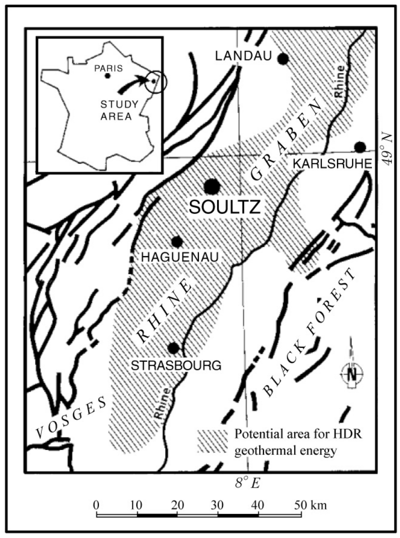

Figure 6: Location of Soultz HDR site

Here we introduce results of the practical application to the GPK3 stimulation at the Soultz HDR site in 2003 (Baria et al., 2004). Details of the onsite AE monitoring and analysis were given in Asanuma et al., 2004. From two weeks observation 86,985 triggers were obtained.

An example of the picked points in the waveform using the proposed automatic method is shown in Figure 7. During the onsite analysis we generally used P-wave picks from all five sensors, 4550, 4601, OPS4, GPK1, EPS1 and S-wave picks from four sensors, 4550, 4601, OPS4, EPS1, since the condition of the GPK1 sensor was not good for 3D particle motion analysis. In the figure, both P- and S-waves are picked at a similar position to the manual observations.

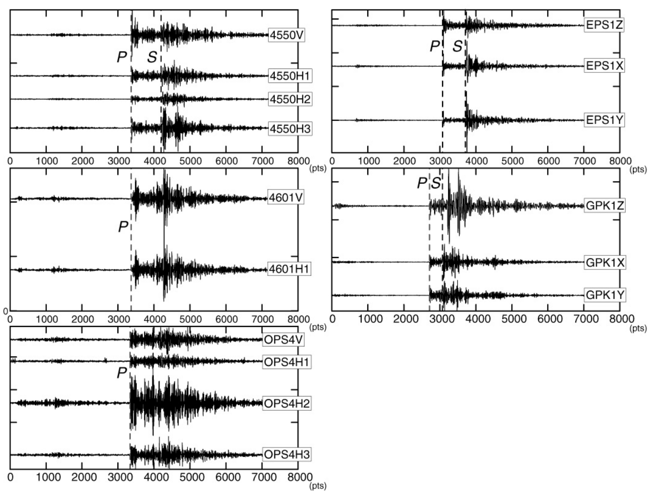

Figure 7: An example of the automatic wave picking during onsite analysis at Soultz in 2003.

Using the automatic picking technique, we have located 12,435 events during the GPK3 stimulation, which is about 15 % of all the triggers (Figure 8). For this analysis, we used the same velocity model as in 2000. The locations look reasonably reliable with a good agreement with the assumed injection point and past tendency of the reservoir. The linear outer boundary of the seismic cloud was already detected in the depth slices. Subsequent manual checking of the stimulation events confirmed the overall event distribution obtained using the automatic picking technique on-site, apart from some movement due to a revised velocity model.

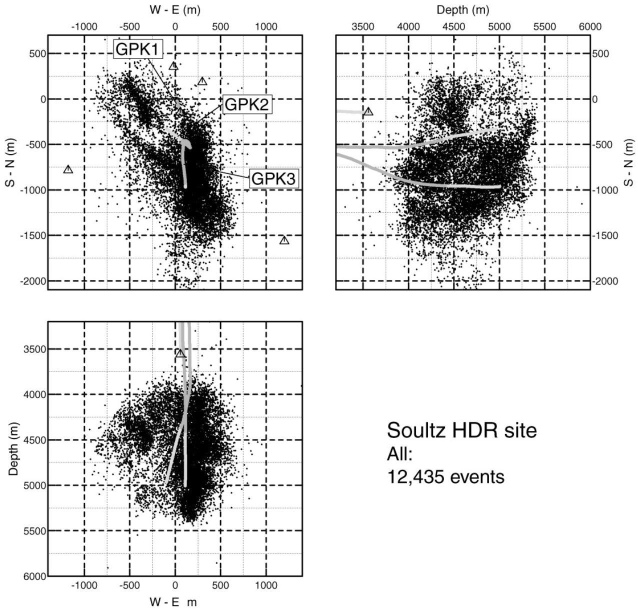

Figure 8: Reservoir mapping during onsite analysis at Soultz by using automatic picking technique

APPLICATION TO THE ONSITE ANALYSIS AT THE AUSTRALIAN HDR SITE IN 2003

We have also applied the developed automatic picking technique to onsite analysis at the Australian HDR project in 2003 (Soma et al., 2004). The Australian HDR project is locates north-east of South Australia, in the Cooper Basin about 10km south of the town of Innamincka (Figure 9), and is attempting to develop one of the largest HDR resources known. The project has been operated by Geodynamics Limited since early 2003. In 2003 winter, microseismic monitoring during a large scale stimulation of injection well Habanero-1 was conducted in cooperation between Japanese MTC team (Tohoku University, Central Research Institute of Electric Industries: CRIEPI, Japan Petroleum Exploration Co., Ltd.: JAPEX, National Institute of Advanced Industrial Science and Technology: AIST) and Geodynamics.

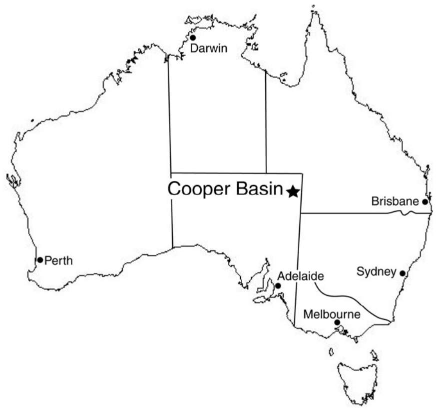

Figure 9: Location of Australian HDR site at Cooper Basin.

Plan view of the site showing associated seismic monitoring wells is shown in Figure 10. The Injection well is Habanero-1 which is 4421 m deep, and there are eight seismic stations where downhole 3-axis geophones were seated in the borehole. Because we could not obtain reliable S-wave velocity model before the stimulation, we decided to use only good P-wave arrivals for the onsite analysis in order to reduce uncertainty. Automatic picking also only worked for the P-wave arrivals.

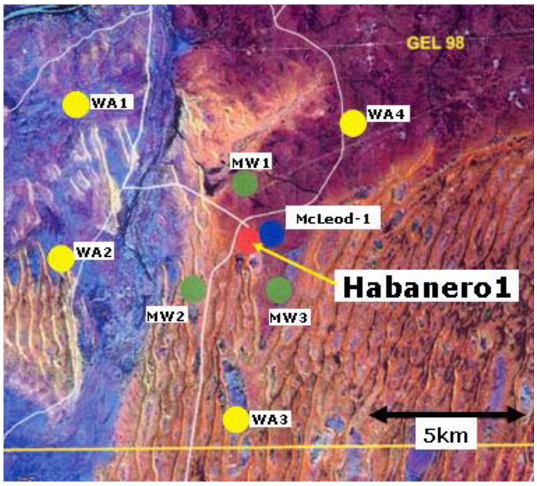

Figure 10: Plan view of the Australian HDR site.

In Figure 11, an example of the automatic picking for the waveform obtained at the Australian HDR site is shown. We see good agreement of picked time with those expected by manual picking even if the signal condition was not ideal. In most cases the auto picking correctly picked and the picked points of P-wave are almost identical to those by manual pick.

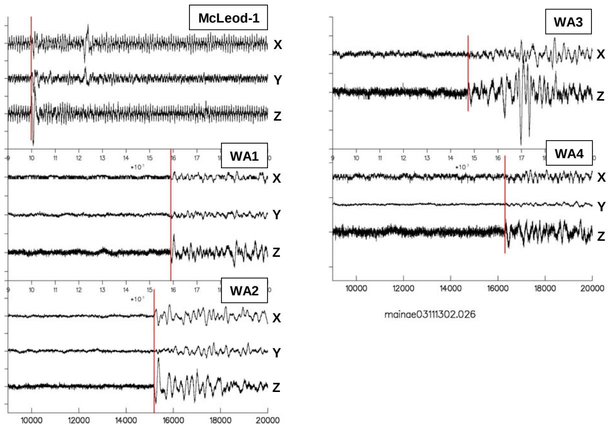

Figure 11: Example of the auto picking. Red bar shows picked P-wave arrival point for each detector.

A total of 11,725 events were located by applying automatic picking during onsite analysis. They were reported as various figures, technical reports, and 3D movies, and they were referred to the pumping operations. We made manual confirmation of the picked point as much as time allowed, in order to avoid serious mistake because only P-wave could be used and the number of stations was not ideal. Generally, automatic picking did not show serious errors, but often it could not analyze one or two stations due to a low signal-to-noise ratio affected by such as traffic noise. We obtained a structural source distribution at the site as shown in Figure 12. Since the regional tectonic stress is regarded to be a highly compressive, we expected horizontally extensive plainer shape of artificial reservoir.

We could see that the growing artificial reservoir corresponded to the expected plainer shape during onsite analysis. We analyzed event history, source migration, rough magnitude estimation, etc. as well as source location owing to the reliable and reasonably fast analysis by the developed automatic picking technique.

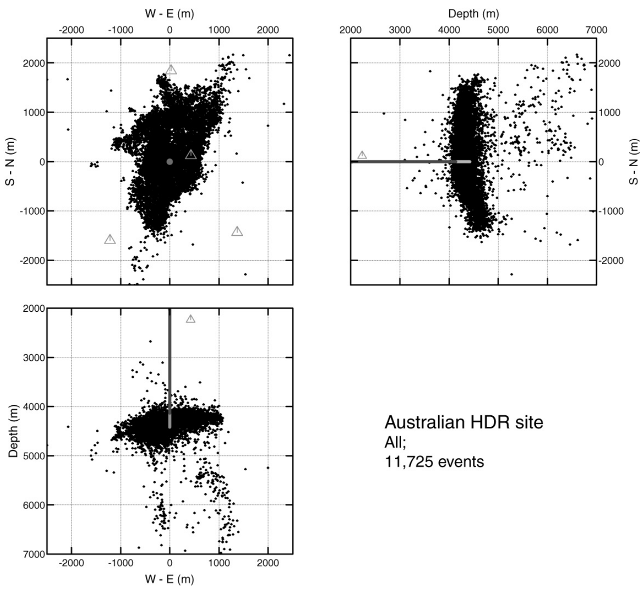

Figure 12: Reservoir mapping during onsite analysis at the Australian site by using automatic picking technique.

CONCLUSION

We have developed an automatic picking technique for microsesimic waveforms. The technique has been demonstrated at two practical HDR development site to obtain reliable, near real-time reservoir mapping. The performance of the technique has been checked by applying it to rock experiments in the laboratory and past microseismic data from the Soultz HDR site observed in 2000. The technique was used in onsite analysis at the Soultz HDR site and the Australian HDR site in 2003, and reliability and analyzing speed were demonstrated.

The automatic picking technique consists of several signal processing techniques which imitate human processing. From the trial using waveforms from laboratory experiments and the Soultz HDR site in 2000, the source distribution with automatic picking was almost the same as that by manual picking, thereby demonstrating the reliability of the method.

We show results of the practical application in onsite analysis during hydraulic stimulation at the Soultz HDR site and the Australian HDR site in 2003. At Soultz, we obtained 12,435 source locations, which is about 15 % of the total recorded triggers. It is close to the rate of manual processing done in 2000 which was about 18 % of the total recorded triggers. Therefore, analyzing speed of the automatic picking technique seems to be reasonable even if we use the current type of personal computer. At the Australian HDR site, we also successfully located 11,725 events, and the overall distribution agreed with the reservoir proportion expected by regional stress states. Owing to the reliable nearly real-time source location, further analyses such as event history, source migration, rough magnitude estimation, were also available during the onsite analysis. This information was practically used to guide the injection program.

The automatic picking technique enables us to make reliable, and nearly real-time onsite analysis using a small number of multi-component seismic detectors, at reasonably low cost. Obtaining reliable source locations in nearly real time offers the possibility of applying various detailed analysis techniques, such as multiplet analysis, collapsing technique and reflection analysis on-site as well.

ACKNOWLEDGMENTS

Development of auto-picking software was supported by the Industrial Technology Research Grant Program in 2000 from the New Energy and Industrial Technology Development Organization (NEDO) of Japan. We would like to thank EEIG “Heat Mining” for providing the data from the European HDR site at Soultz-sous-Forêts, which is supported mainly by the European Commission, BMWI (Germany), ADEME (France) and the EEIG. We would also like to thank Ben Dyer (Semore Seismic), Jonathan Nicholls, Jörg Baumgärtner (EEIG, BESTEC GmbH) and others who made it possible for us to participate and acquire the seismic data at Soultz. Authors thanks also to the many people who took part in the on site mapping at the Australian HDR site from Tohoku University, CRIEPI, JAPEX, Geodynamics, and others. We also thank Geodynamics for kindly providing many data, information and figures.

REFERENCES

Asanuma, H., Mochizuki, S., Nakazato, K., Soma, N., Niitsuma, H. and Baria, R., 2001, Data acquisition and analysis of microseismicity from simulation of deep reservoir at Soultz by the MTC/MURPHY international collaborative project, GRC Transactions, 25, 161-166.

Asanuma, H., Izumi, T., Kumano, Y., Soma, N., Niitsuma, H. and Baria, R., 2004, Data acquisition and analysis of microseismicity from stimulation at Soultz in 2003 by Tohoku University and AIST, Japan, GRC Transactions, 28. (submitted)

Baria, R., Michelet, S., Baumgaertner, J., Dyer, B., Gerard, A., Nicholls, J., Hettkamp, T., Teza, D., Soma, N., Asanuma, H., J. Garnish, J. and Megel, T., 2004, Microseismic monitoring of the world’s largest potential HDR reservoir, Proc. 29th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, 194-201.

Dyer, B., 2000, Seismic field report to EEIG, Soultz GPK2 stimulation June/July 2000, Seismic monitoring.

Jones, R. H. and Stewart, R., 1997, A method for determining significant structures in a cloud of earthquakes, J. Geophys. Res., 102, 8245-8254.

Kawahara, H., 1991, Wavelet transform in acoustic signal processing, The Technical Report of The Institute of Electronics, Information and Communication Engineers, EA91-37. (in Japanese)

Morita, Y. and Hamaguchi, H, 1984, Automatic detection of onset time of seismic waves and its confidence interval using autoregressive model fitting, Zisin (Journal of the seismological society of Japan), 2, 37, 281-293. (in Japanese)

Moriya, H. and Niitsuma, H., 1995, Characterization of Subsurface Crack System by Combining Triaxial Doublets Analysis and Focal Mechanism Analysis, Geothermal Science & Technology, 123-145.

Niitsuma, H., Tsuyuki, K. and Asanuma, H., 1994, Discrimination of split shear waves by wavelet transform, Canadian Journal of Exploration Geophysics, 29, 106-113.

Shirai, K. and Tokuhiro, I., 1979, Detection of seismic wave onsets, Zisin (Journal of the seismological society of Japan), 2, 32, 141-148. (in Japanese)

Soma, N. and Niitsuma, H., 1997, Identification of structures within the deep geothermal reservoir of the Kakkonda field (Japan) by a reflection method using acoustic emission as a wave source, Geothermics, 26,1 43-64.

Soma, N., Niitsuma, H. and Baria, R., 2002, Reflection technique in time-frequency domain using multicomponent acoustic emission signals and application to geothermal reservoirs, Geophysics, 67-3, 928-938.

Soma, N., Asanuma, H., Kaieda, H., Tezuka, K., Wyborn, D., and Niitsuma, H., 2004, On site mapping of microseismicity at cooper basin, Australia HDR project by the Japanese team, Proceedings Twenty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, 240-245

Takehara, T., Soma, N., Tosha, T. and Yamaguchi, T., 2003, Experimental study on artificial fracture opening behavior by laboratory hydraulic fracturing test, Proc. 3rd International Symposium on ROCK STRESS, 133-137.