

ACTIVE SEISMICS TO DETERMINE RESERVOIR CHARACTERISTICS
OF A HOT DRY ROCK GEOTHERMAL SYSTEM.

A S P Green and R Baria

Camborne School of Mines Geothermal Energy Project
Rosemanowes Quarry, Penryn, Cornwall, England

ABSTRACT

Since 1981 three wells have been drilled to depths of between 2.0 and 2.6 km in the Carnmenellis granite, Cornwall, England in order to create a HDR geothermal system. These wells are separated by between 150 and 300 m and have been hydraulically connected by massive injections of both water and viscous gel (50 cpoise). Passive microseismic monitoring of the hydraulic stimulation and circulation experiments has been used since 1982 to determine the size and structure of the reservoir, and monitor its growth.

The active seismic survey techniques of cross-hole seismics and vertical seismic profiling (VSP) have been introduced to complement the passive microseismic monitoring in characterising the reservoir.

The cross-hole seismic surveys indicate that the microseismicity defines the area of joint dilation. The attenuation of high frequencies in the region of microseismicity suggests that the reservoir is composed of a complex zone of cracks rather than a single large fracture.

VSP surveys also show a good agreement between the the microseismically defined reservoir and seismic signal attenuation.

Recent improvements in hardware, computer processing and interpretation indicate that active seismics will play an increasingly important part in mapping and understanding geothermal reservoirs.

INTRODUCTION

The Camborne School of Mines (CSM) has been researching into hot dry rock (HDR) geothermal energy since the mid 1970's. The development of an HDR reservoir at 2 km depth has been underway since 1980. This has been designated Phase 2, Phase 1 being a 300 m system developed in the late 1970's. Phase 2 is split into Phase 2A and Phase 2B. Phase 2A comprised the drilling of two wells (RH11 and RH12) and the subsequent circulation of water between these two wells. Phase 2B commenced with the drilling of a third well (RH15) followed by the fracturing of this and the circulation of water between RH12 and RH15.

Several aspects of the project have been presented at previous Stanford Workshops (Batchelor 1986, Pine 1984). These details will not be repeated here.

Phase 2A work started in 1981 with the drilling of wells RH11 and RH12 in a Hercynian granite to true vertical depths (TVD) of 2038 m and 2058 m. The wells have a maximum deviation of 30° at the base and a closest approach of 150 m in the uncased sections. During 18 months of fracturing and circulation, 300 000 m³ of water was injected into the system and only 100 000 m³ recovered. In the period in which 200 000 m³ of water was lost 30 000 microseismic events were detected of which over 5000 were located. (Baria et al, 1985). The microseismic locations showed a systematic downward growth and suggest that this was where the lost water went (Pine and Batchelor 1984). This phase of the project was completed in 1983.

Phase 2B started in 1983 and involved the drilling of a third well.

Based on the analysis of the microseismic data a highly deviated third well (RH15) was drilled to a depth of 2653 m TVD, beneath RH11 and RH12 to intersect the region of seismicity. RH15 was drilled in 1984 with a gas (nitrogen) lift test run immediately. Flow logs run during the test showed that the only flowing zones were in regions where the well intersected microseismicity (Baria and Green 1986).

The hydraulic connection between RH15 and RH12 was still not adequate for a prolonged circulation to take place. A massive viscous injection of RH15 was designed to improve the hydraulic connection. The bottom 365 m of RH15 was sanded off so the hydraulic energy could be concentrated on a 146 m section of open well between the casing shoe and the top of sand. The injection took place on 4 July 1985 when 5500 m³ of viscous gel (50 cpoise) was pumped into RH15 over an 8 hour period at an average flow rate of 198.2 l/s. This was followed by 200 m³ of water. The peak wellhead pressure was 15 MPa during the viscous injection and 16.3 MPa during the water injection.

A total of 270 microseismic events were detected during the test of which 202 were located (Baria and Green 1986). The majority of the seismicity was detected during the first 2 hours, after which the event rate declined. The seismicity was located in a vertical tubular structure approximately 70 m by 70 m by 200 m encompassing a volume of 800 000 m³.

The hydraulic connection between RH15 and RH12 (Phase 2B) was much better than that of the old RH11/RH12 system (Phase 2A). The hydraulic impedance reduced from about 1.9 MPa/l/s (RH11/RH12) to about 1.0 MPa/l/s (RH12/RH15) and the water losses in circulation reduced from 70% to 20%. The impedance has subsequently reduced to 0.6 MPa/l/s.

It has been generally assumed that regions of seismicity define the areas of enhanced permeability. There has been some support for this from the comparison of the flow zones in RH15 and the Phase 2A microseismicity described above. However it is not clear whether there are aseismic areas where fluid flow and increased permeability also occur.

Active seismic surveys provide a means of determining the relationship between the hydraulic reservoir and the microseismic reservoir. The two techniques employed were cross-hole seismic surveys and large offset vertical seismic profiling (VSP).

Both types of surveys were performed in all three wells before and after the Phase 2B viscous injections. The collected data set is large and it is only proposed to examine a small part in this paper.

The VSP data collected after Phase 2A but before the Phase 2B viscous injection will be examined to determine the effect of the Phase 2A circulation.

The cross-hole data collected immediately before (pre-stimulation) and after (post-stimulation) the Phase 2B viscous injection will be compared to assess the effect of the injection.

VERTICAL SEISMIC PROFILES

Vertical seismic profiles were performed on all three wells (RH11, RH12 and RH15) after the fracturing and circulation between RH11 and RH12 (Phase 2A). These surveys were designed to image the Phase 2A reservoir and provide a base for surveys carried out later, after the Phase 2B viscous injection.

The surveys were large offset (2.4 km) surveys using 250 gm of explosive in a water filled quarry as a source. The receiver was a hydrophone with recordings taken every 2.5 m interval in the open hole sections (Figure 1).

The amplitude, velocity and frequency of a seismic wavelet are all sensitive to changing

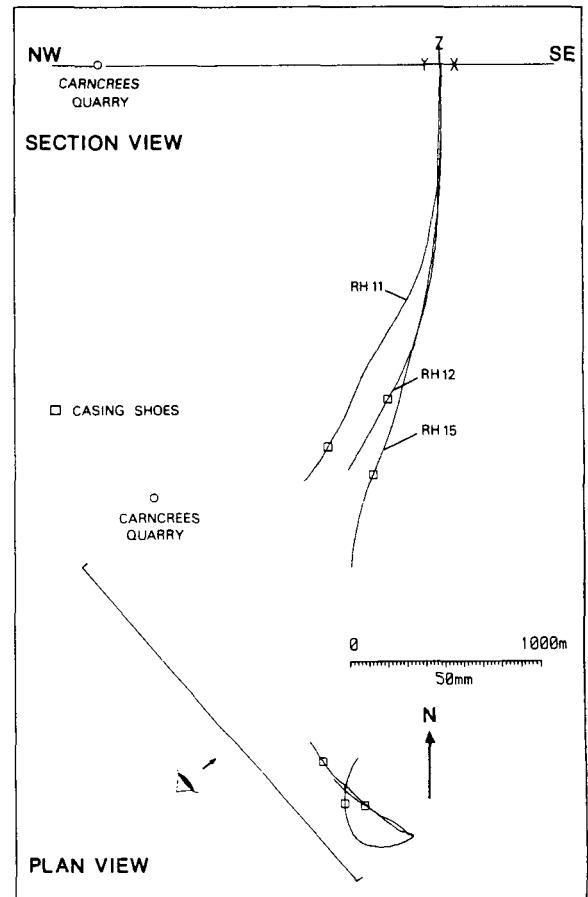


Figure 1. The locations of the three wells and the VSP source.

rock properties. The amplitude is a particular sensitive parameter, however a source with a consistent signature is necessary and borehole effects need to be taken into account.

The explosive source proved to have a very consistent source signature and the large distance from source to receiver meant that the ray angle to the borehole was similar for all hydrophone positions.

In order to compare the VSP results with the microseismic data a stimulation index was determined from the event locations. This is based on the number of events within 50 m of a straight line raypath between each shot and receiver position (CSM 1986, Hearn 1986). The distance of 50 m was based on the accuracy of the locations.

Seismograms with the stimulation index and first arrival amplitude curves for RH12 and RH15 are shown in Figures 2 and 3. The amplitude of the first arrival was determined from the signal envelope (Farnbach 1975).

The data for RH12 (Figure 2) can be divided into two groups; (i) above and (ii) below a measured depth (MD) of 2000 m. The data above

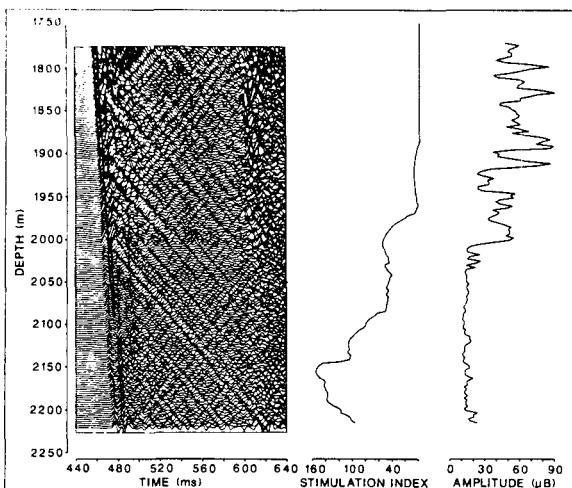


Figure 2. VSP results for well RH12.

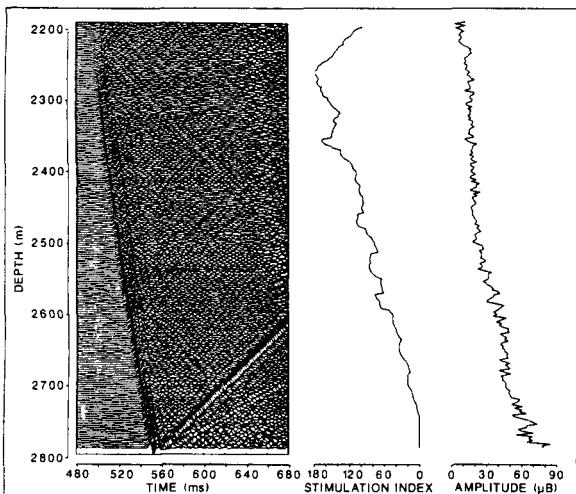


Figure 3. VSP results for well RH15.

2000 m MD show high amplitudes but with large variations, while the data below 2000 m MD shows only low amplitudes. The stimulation index shows that above 2000 m MD the rays passed through zones of low microseismicity but below 2000 m MD the rays pass through zones of high microseismicity. There is a good correlation between the attenuation and stimulation index. The variation in amplitude above 2000 m MD is probably caused by fractures close to the borehole wall.

Figure 3 contains the data for the VSP survey in RH15. The results show a smooth increase in the first arrival amplitude with depth consistent with gradual decrease in the stimulation index.

The good correlation between the amplitude and stimulation index support the view that the microseismicity represents regions of stimulated rock and that aseismic areas have remained largely unaffected by the Phase 2A fracturing and circulation.

CROSS-HOLE SEISMIC SURVEY

The cross-hole seismic method, whereby seismic signals are transmitted between wells, has been in use for a number of years (Fehler 1982, McCann et al, 1986). The advantage over surface methods is that it avoids the weathered surface rocks which attenuate the high frequencies and reduce resolution.

The difficulties that have prevented its widespread application are the design of reliable and easy to use downhole sources and receivers. The CSM HDR project has designed and manufactured its own source and receiver. The source is a detonator tool holding up to 12 detonators. The receiver a high pressure marine hydrophone used both as a single unit and as part of a three hydrophone string.

The pre-stimulation survey was performed in May 1985, four months after the completion of RH15 and 2 months before the Phase 2B viscous injection. A total of 71 shots were fired with the detonator tool in RH15, the single hydrophone in RH12 and the three hydrophone string in RH11 (Figure 4).

The shooting in RH15 was started at the bottom. As the shot positions progressed up RH15 the hydrophones were kept stationary until the source and hydrophone in RH12 were at the same vertical depth. The hydrophone and source were then pulled up together to perform a horizontal scan. The three hydrophone string in RH11 was kept stationary throughout the survey.

During the survey there was no wellhead pressure at RH15 or RH11 and only a small pressure on RH12 (0.2 MPa).

The post-stimulation survey was performed in November 1985, 6 months after the Phase 2B viscous injection. The deeper 59 shots of the pre-stimulation survey were repeated, a shortage of detonators preventing all the shots being repeated.

The wellhead pressure and injection flow rate at RH12 were maintained at over 6 MPa and 9 l/s for most of the period of the survey, so that the reservoir would be inflated. RH15 was shut in and maintained a wellhead pressure of between 6 and 7 MPa. RH11 was vented between 0.5 and 2 l/s.

As we have seen the amplitude was observed to be a sensitive measure of the rock properties in the VSP surveys. However the effect of the borehole wall on both the source and receiver in the cross-hole survey make it difficult to extract the part of the attenuation that is caused by joint dilation. The velocity and frequency variations have proved to be less ambiguous to interpret.

Figures 5 and 6 show the pre- and post-stimulation seismograms from the bottom hydrophone in RH11. The first arrivals have been

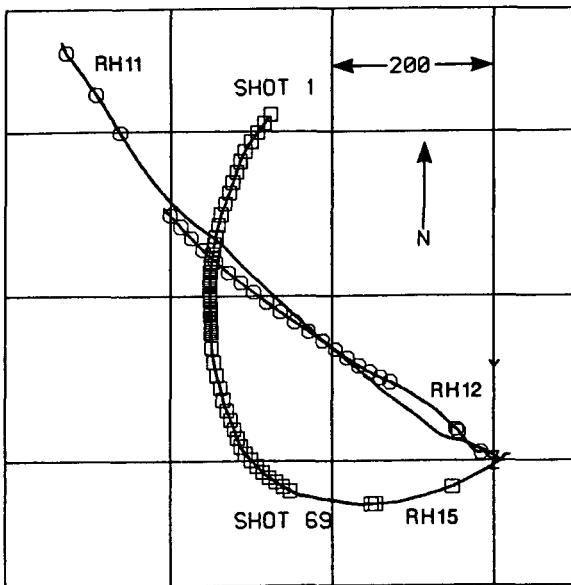
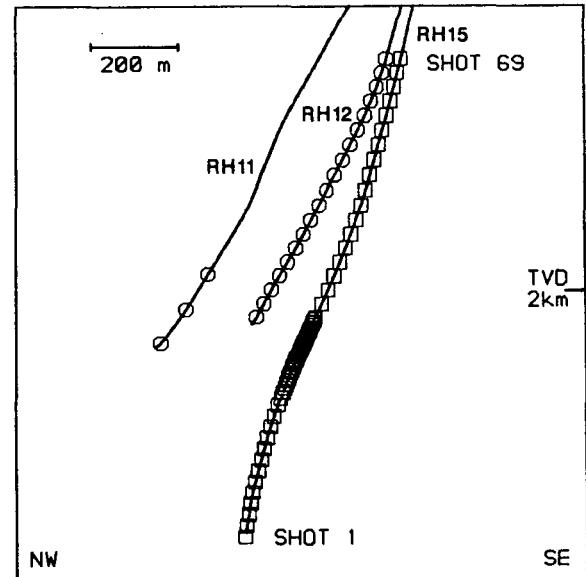


Figure 4. Source and receiver locations for the cross-hole seismic survey.

aligned and the amplitudes normalised for ease of display. Figures 7 and 8 show the frequency spectra for the same seismograms. It is clear that the energy in the 3 to 4 kHz band has been severely attenuated in the post-stimulation survey for shots shallower



than 2480 m (shot 12) in RH15.

The same pattern is apparent for recordings on the other hydrophones in RH11. The recordings on the hydrophone in RH12 show attenuation of the high frequency energy for all shots.

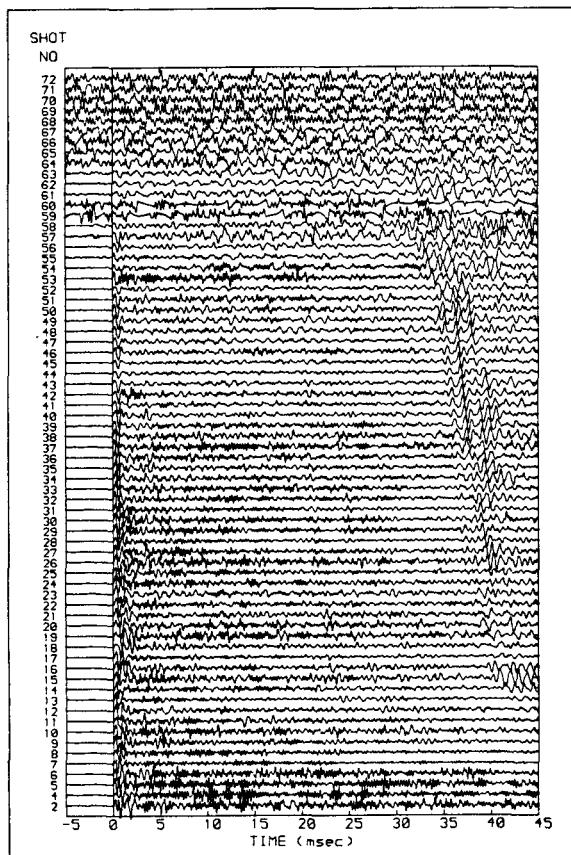


Figure 5. Pre-stimulation cross-hole seismogram for the bottom hydrophone in RH11.

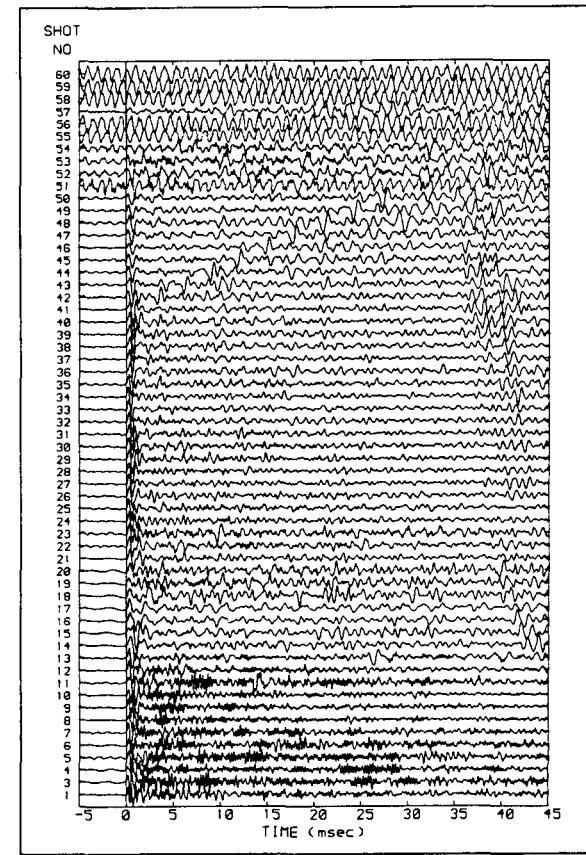


Figure 6. Post-stimulation cross-hole seismogram for the bottom hydrophone in RH11.

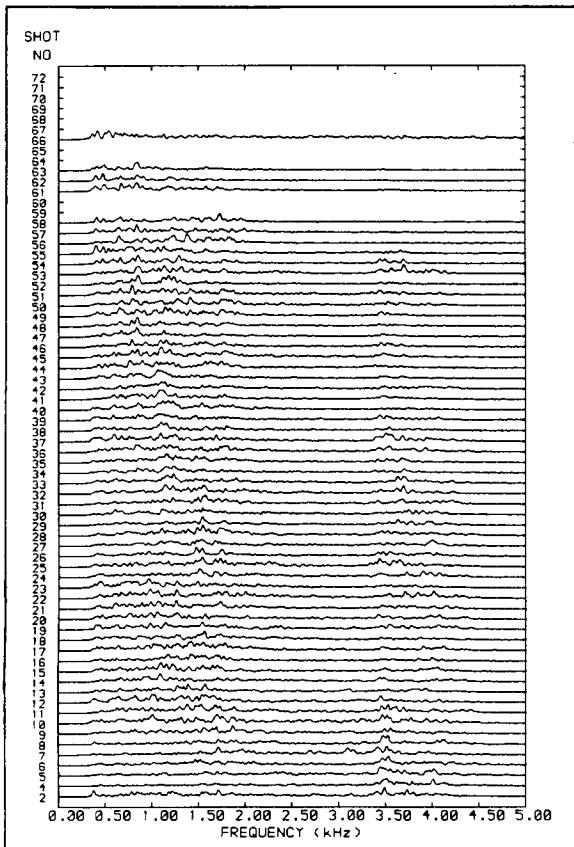


Figure 7. Frequency spectra of pre-stimulation cross-hole seismogram in Figure 5.

Figure 9 shows the difference in compressional wave velocity between the pre and post-stimulation survey for the middle (hydrophone 2) and bottom (hydrophone 3) in RH11 and the hydrophone in RH12 (hydrophone 4). The top hydrophone in RH11 did not occupy the same position for both surveys, so a direct comparison cannot be made.

Figure 9 shows that for shot depths in RH15 shallower than 2500 m (shot 10) the compressional wave velocity recorded by the hydrophones in RH11 has been reduced by up to 0.05 km/s. The velocity recorded by the hydrophone in RH12 is reduced by as much as 0.07 km/s for all shots.

The attenuation of the high frequencies and the reduction of the compressional wave velocity can be understood if the ray paths for the surveys are superimposed upon the Phase 2B microseismicity generated during the viscous injection (Figures 10 and 11).

Figure 10 shows the ray paths for explosive shots in RH15 to the bottom hydrophone in RH11. The 10 rays from the deepest shots do not cross the microseismicity. It is these rays that show no attenuation of high frequency energy or velocity reduction. It can be shown that this is not due to a change

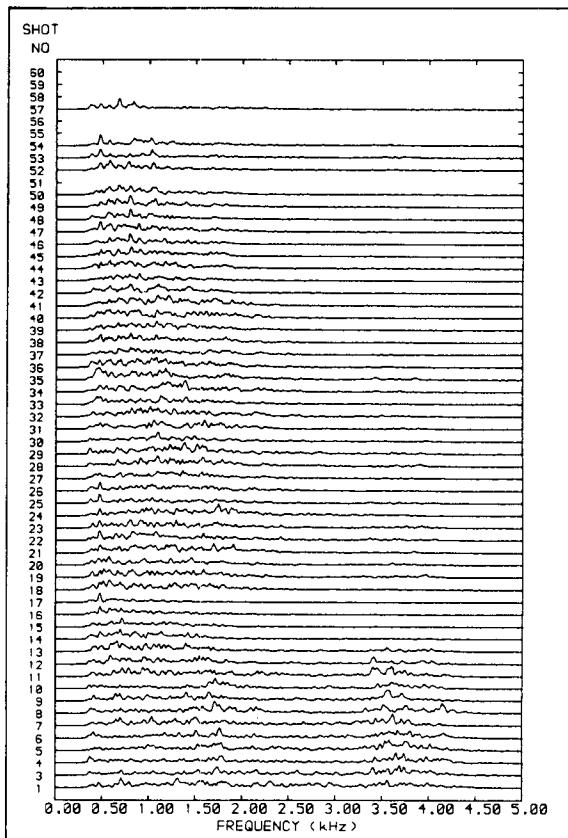


Figure 8. Frequency spectra of post-stimulation cross-hole seismogram - Figure 6.

in the shot characteristic by inspection of the ray paths to the hydrophone in RH12 (Figure 11). All the ray paths cross the microseismic cloud and all shots in the cross-hole survey show frequency attenuation and velocity reduction.

The microseismic events detected during Phase-2B were caused by shearing of natural joints within the granite (Baria and Green 1986). Shearing causes dilation of the joints and during pressurization of the system more fluid is stored in these joints. It is this joint dilation which is responsible for the high frequency attenuation and reduction in velocity.

The close correspondence between the microseismicity and the cross-hole data indicates that the regions of microseismicity have enhanced permeability and that furthermore the aseismic regions do not.

CONCLUSION

Cross-hole seismic and VSP surveys have shown that variations in the amplitude, frequency and velocity of a seismic signal can be used to define regions of enhanced permeability. These surveys indicate that reservoir growth during the hydraulic stimulation as monitored

by the generated microseismicity does represent regions of increased permeability. There is little evidence of aseismic reservoir growth.

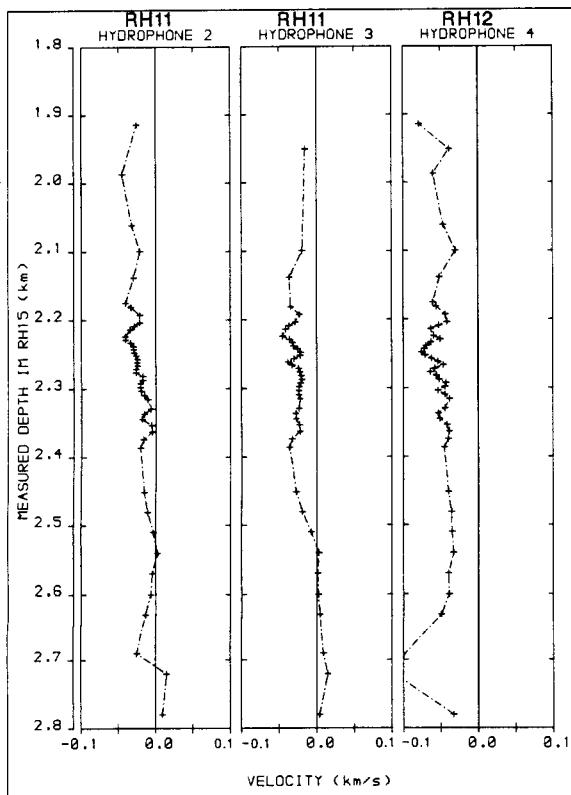


Figure 9. Difference in velocity for pre- and post-stimulation cross-hole surveys.

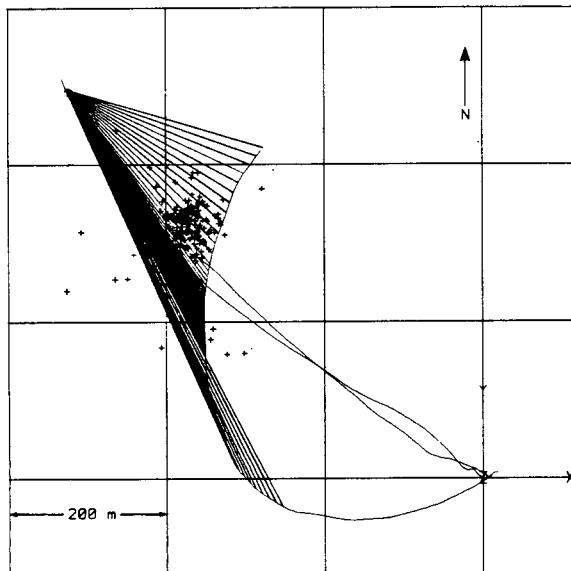


Figure 10. Raypaths from the shot in RH15 to the bottom hydrophone in RH11 (H3) with the seismicity generated during the Phase 2B viscous injection of well RH15.

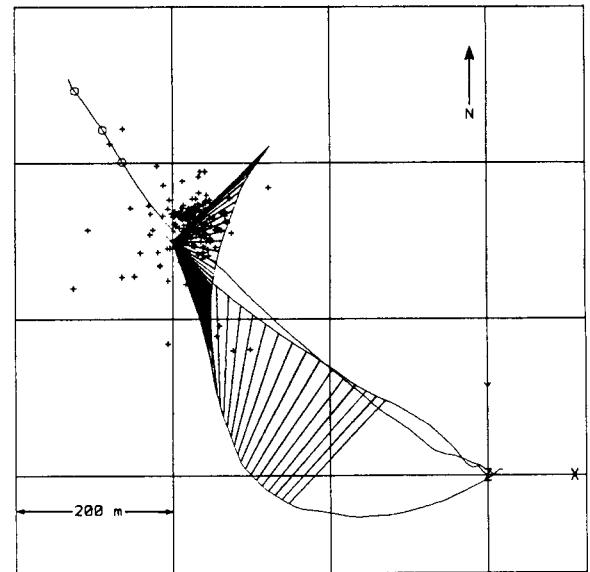


Figure 11. Raypath from the shot is RH15 to the hydrophone is RH12 (H4) with the seismicity generated during the Phase 2D viscous injection of well RH15.

Relatively simple analysis has shown that the active seismic surveys can play an important part in defining the shape of the reservoir and improving the interpretation of the microseismicity. The interpretation of active seismic data can be improved by the use of tomographic inversion algorithms. However the highly deviated nature of the wells makes the usual two dimensional approximation difficult to implement. To collect the large amounts of data that a full three-dimensional inversion would demand requires the development of new tools. Particularly important is a fast recycling downhole source with a consistent source signature. The CSM HDR project is developing such a source for use not only at 2 km but also in any future 6 km system.

ACKNOWLEDGEMENTS

This work was carried out under the contract to the European Economic Community and the United Kingdom Department of Energy contract numbers EG-D-2-003-UK(N), E/5A/CON/125/960 and E 5A/CON/137/1593. The support and encouragement of the staff of these organisations and the project is gratefully acknowledged.

REFERENCES

Baria R, Hearn K and Batchelor, (1985). The monitoring of induced seismicity during the hydraulic stimulation of the potential hot dry rock geothermal reservoir. In 4th conf on acoustic emission/microseismic activity in geological structures and materials, Penn State Univ, Oct 1985.

Baria R and Green A S P. (1986) Seismicity induced during a viscous stimulation at the

Camborne School of mines hot dry rock geo-thermal energy project in Cornwall, England. In Progress in acoustic emission III, proc 8 int acoustic emission symp., Tokyo, Japan, Oct 21-24, 1986.

Batchelor A S. (1986) Reservoir behaviour in a stimulated hot dry rock system. In 11th workshop on geothermal reservoir engineering, Stanford University, California, Jan 1986.

Camborne School of Mines Geothermal Energy Project. Vertical seismic profiling results. Phase 2 report, 1986, (in prep).

Farnbach J S. (1975) The complex envelope in seismic signal analysis. Bull seismol Soc of Am, Vol 65, No 4, pp 951-962.

Fehler M. (1982) Using dual-well seismic measurements to infer the mechanical properties of a hot dry rock geothermal system. J geophys Res, Vol 87, pp 5485-5494.

Hearn K. (1986) Application of surface to borehole seismic surveys to delineate a hot dry rock geothermal reservoir. In Society of professional well log analysts 10th European formation evaluation symposium, Aberdeen, 22-25 April, 1986.

McCann D M, Baria R, Jackson P and Green A S P. (1986) Applications of cross-hole seismic methods in site investigation surveys. Geophysics, Vol 51, No 4, pp 914-929.

Pine R J. (1984) Pressure transient analysis for large scale hydraulic injections in the Carnmenellis granite, England. In 9th workshop on geothermal reservoir engineering, Stanford University, California, Dec 1983.

Pine R J and Batchelor A S (1984), Downward migration of shearing in jointed rock during hydraulic injections. International Journal of Rock Mechanics Mining Sciences and Geo-mechanical Abstracts. Vol 21, No 5, pp 249-263.