

## Preprocessing for Reservoir Seismicity Location: Rotokawa Geothermal Field, New Zealand

Stephen Bannister<sup>1</sup>, Steve Sherburn<sup>1</sup>, Sandra Bourguignon<sup>1</sup>, Stefano Parolai<sup>2</sup>, Deborah Bowyer<sup>3</sup>

<sup>1</sup>GNS Science, New Zealand; <sup>2</sup>Helmholtz Centre Potsdam GFZ, Germany; <sup>3</sup>Mighty River Power, Hamilton, New Zealand

Email: [s.bannister@gns.cri.nz](mailto:s.bannister@gns.cri.nz)

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### ABSTRACT

We are investigating bulk seismic properties and fault structure in the Rotokawa geothermal field, New Zealand, by accurately locating and characterizing microseismicity recorded by temporary seismometer arrays, deployed in 2006 and 2008-2009. Analysis approaches used in microearthquake location at Rotokawa and other similar fields need to allow for high background noise levels, complex sub-surface geology, and the high attenuation of near-surface volcanic deposits often experienced in New Zealand. The location problem is exacerbated by high sub-surface temperatures, which currently negate the use of down-hole sensors for any length of time. Our focus in the analysis workflow is on increasing the signal-to-noise ratio of data recorded by surface seismometers, to enable higher accuracy for P- and S-wave arrival picks, dealing with data which occasionally has strongly polarized background noise. We can do so through the use of adaptive polarization and S-transform based filtering before slowness estimation, followed by rotation of 3-component data into ray coordinates (L-, T-, and Q-components) before S-wave picking. Waveform cross-correlation is then carried out on waveform data, before double-difference relocation of the microearthquakes, allowing for 3D heterogeneous velocity structure.

### 1. INTRODUCTION

Approaches used in microearthquake location analysis in high entropy geothermal fields such as found in New Zealand need to allow for high background noise levels, the complex sub-surface geology, and the high attenuation of near-surface volcanic deposits often experienced in New Zealand. The location problem is exacerbated by high sub-surface temperatures, which currently negate the use of down-hole sensors for any length of time. At Rotokawa geothermal reservoir our focus in the preliminary analysis workflow is on increasing the signal-to-noise ratio to enable higher accuracy for P- and S-wave arrival picks, dealing with data which occasionally has strongly polarized background noise.

We can do so through the use of adaptive polarization filtering before slowness estimation and the rotation of 3-component data into ray coordinates (L-, T-, and Q-components) before S-wave picking. One aim is to improve error quantification for slowness estimates, to strengthen the utility of fully non-linear global-search location algorithms for earthquake location, so allowing for highly heterogeneous velocity structure. In this paper we discuss noise characteristics of seismic data recorded at Rotokawa, and the utility of recent filtering approaches, such as the S-transform (Parolai, 2009), which assist with noise reduction before subsequent slowness estimation, arrival-time picking and location analysis is carried out.

### 2. ROTOKAWA RESERVOIR

The Rotokawa Geothermal Field is located in central North Island, New Zealand, north-east of Lake Taupo (Figure 1), a region of active crustal extension with a very high heat flow (Bibby et al, 1995). The field was discovered by exploratory drilling by the Department of Science and Industrial Research (DSIR) in the 1960's; geothermal generation of 27MWe began in 1997. Mighty River Power acquired interest in the field through the Rotokawa Joint Venture, a joint venture with the Tauhara North No. 2 Trust, a Maori trust, in 2000. Generation was subsequently expanded to 34 MWe in 2001, fed by 2 deep production wells (RK5 & RK9), with reinjection into a shallow thermal aquifer overlying the production reservoir (RK1, RK11 & RK12). A map of the field is presented in Figure 1.

A shift from shallow to deep reinjection was implemented in May 2005 to relieve shallow pressure within the field. Wells RK16, RK17 & RK18 were drilled from a single pad at the south-western margin of the reservoir, as determined by MT-TDEM geophysical surveys (Heise, et al, 2008). Whereas RK16 and RK18 encountered acceptable deep injectivity, RK17 encountered a high temperature (330°C) and highly permeable fault structure.

#### 2.1 Reservoir Seismicity (2005-2006)

Most of the naturally occurring earthquakes in the region outside of the reservoir are due to normal faulting along north-east trending faults (Hurst et al., 2002), occurring in spatiotemporally distinct swarms (Sherburn, 1992) along the central axis and eastern side of the region (Bryan et al., 1999). The maximum depth of the seismicity rarely exceeds 6-7 km beneath the region (Bryan et al, 1999), suggesting that the depth to the brittle-ductile transition in the region surrounding the reservoir is relatively shallow.

Several microearthquake seismic surveys have been run at Rotokawa – in 2005, 2006, and 2008-2009; the first to determine the level of seismicity associated with deep injection, the second to map seismicity to determine the pathways of injection returns, and the current 2008-09 survey, still being undertaken, to monitor changes in seismicity associated with changes in injection and field management. In 2005 a seismometer was deployed near to deep injectors at the start-up of deep injection, to ascertain whether enhanced seismicity accompanies deep injection at Rotokawa. More than 350 microearthquakes were recorded within 2.5 kilometres of the injectors, as determined by "S-P" times, suggesting sufficient induced microearthquake activity to warrant deployment of a microearthquake array. Subsequently, in 2006, a temporary, 10 station array was deployed from 4 April to 9 August 2006 during a long term flow test of RK17, combined with an injection tracer test of injectors RK16 and RK18. More than 225 events were recorded by this 2006 array, which were subsequently detected and relocated using double-difference relocation techniques (Bannister et al., 2008). The event locations indicated a spatial relationship between the seismicity and

inferred faults near and beneath a producer well, indicating that fluid pressure changes and/or injection-induced cooling triggered seismicity on the deeper fault structure (Bannister et al, 2008).

## 2.2 The 2008-2009 Array

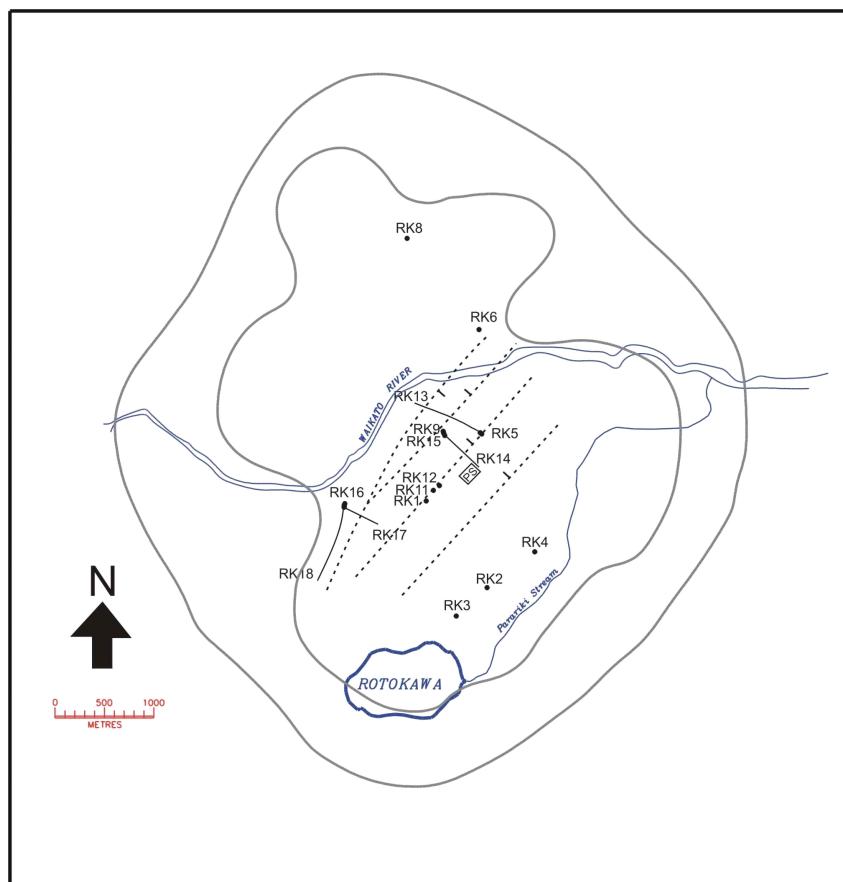
A seismic array currently operating (2008-2009) is now monitoring changes in the seismicity associated with changes in the location of the injection and production wells. More than 500 events have been recorded and located so far, with the new locations showing distinct temporal and spatial changes which are correlated with the water re-injection. The array uses Nanometrics Taurus recorders, coupled with Lennartz LE-3Dlite seismometers (up to October 2008, subsequently using 4-Hz I/O geophones). The seismometers are buried about 50 cm deep in the top soil and sense three-components of ground motion. The Taurus recorders digitize ground motion at a rate of 200 samples per second and write data to a 8 Gb card which is changed every four weeks. Data are read from the smart card and subsequently converted into day-length mini-seed files ready for further processing. The new array was designed to surround the reinjection wells, although land-use, geology, and location of man-made noise sources place considerable constraints on where seismographs can be operated. The northeast part of the geothermal field is pine plantation and therefore unsuitable for seismograph sites in all but the calmest weather conditions. The southeast part of the geothermal field has hot ground at the

surface, and is unsafe for access. The Rotokawa power station is a significant source of man-made ground noise, as are surrounding highways which have heavy truck traffic.

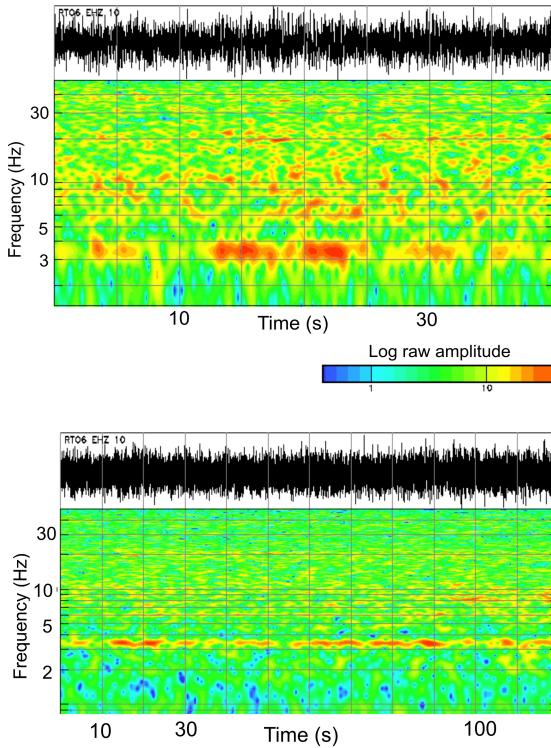
## 3. BACKGROUND NOISE CHARACTERISTICS

Microearthquake monitoring arrays in hydrocarbon reservoirs routinely use downhole seismometers to successfully detect events associated with fracturing (e.g. Phillips et al., 2002). The use of such downhole receivers can significantly reduce the effect of surface-related noise. However, in contrast to hydrocarbon reservoirs, the high temperatures encountered in high entropy geothermal reservoirs such as Rotokawa do not allow standard downhole receivers to be used; temperatures are as high as 120 degrees just at 50 metres depth, while the temperature is more than 280C at 500 m depth in some areas of the reservoir (Bowyer and Holt, 2010). New developments in high-temperature seismometers are expected to be useful in the future, but still only for wells in the cooler periphery of the field.

Spectral analysis of the background noise over different time scales, shown for Figure 2 for one seismograph station, indicates that there is intermittent noise at 3.5 Hz likely associated with the industrial noise from the geothermal power plant, which is located within the array boundaries.



**Figure 1: Rotokawa reservoir, indicating the relative locations of wells. Light dashed lines indicate interpreted subsurface faults.**

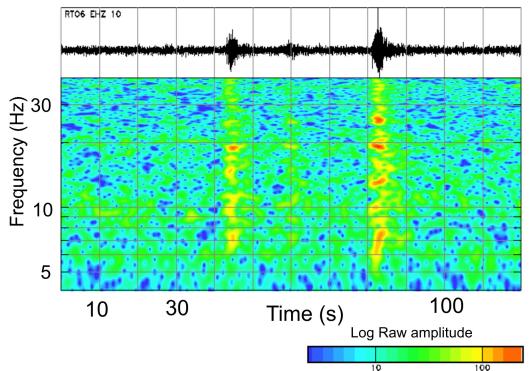


**Figure 2:** Example of the noise spectra for (a) 40-seconds, and (b) 120 seconds, showing the dominance of transient 3.5 Hz background noise, as well as intermittent energy at 6-10 Hz, and 20 Hz. Colour scale is as for Figure 2a. This seismograph station is 700 metres from the geothermal power plant.

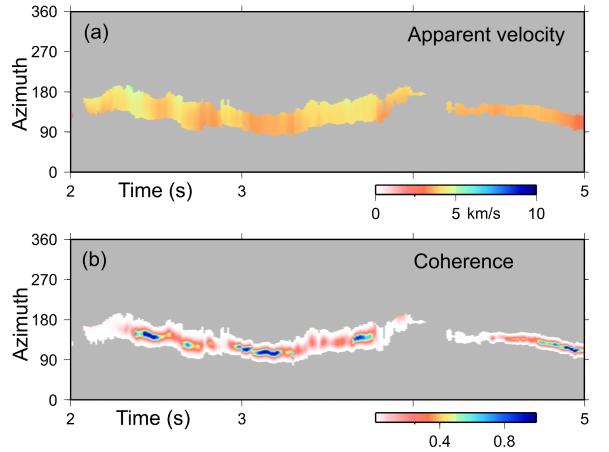
Similar examination of the spectral content of recorded microearthquakes show energy at between 5 and 30 Hz (Figure 3), although the higher frequencies are only observed at seismograph stations within 2-3 km of the events. We can examine the noise properties in more detail, by decomposing the signal using the maximum likelihood approach of Christoffersson et al (1988), to estimate the azimuth and apparent velocity for an assumed P-wave, permitting some interference from Rayleigh and Love-waves in the time interval under consideration. Figure 4 shows the estimated apparent velocity and coherence plotted for a 5-second section of noise at a single station. The figure shows that the recorded noise appears to temporally have high coherence from one particular quadrant, between 90-180 degrees, with apparent velocities in the 2.5-4 km/s range.

#### 4. PRE-LOCATION ANALYSIS

The focus in pre-processing before location analysis is on enhancing the quality of initial arrival picks and initial locations before subsequent double-difference location analysis is carried out. Initial arrival detection involves searching the continuous data files, with tuning to detect signal with energy in the 12-20 Hz frequency range, typical of small, local, microearthquakes, while rejecting noise in the 0-8 Hz frequency range (Bannister et al, 2008). Arrival detection is followed by manual arrival time picking and initial earthquake location, which is carried out using the program SEISAN (Havskov and Ottemoller, 2005). Subsequent double-difference relocation (e.g. Waldhauser and Ellsworth, 2000) is carried out once these initial hypocenters have been determined.



**Figure 3:** Spectra for 2 microearthquakes detected by the array, showing energy at between 5 and 30 Hz. These two events dominate over the background noise, while smaller magnitude events are much more difficult to resolve.



**Figure 4:** (a) Apparent velocity and (b) coherence plotted as a function of azimuth from the station, for a 3-second section of noise, illustrating that the background noise clearly arrives from one particular quadrant and is occasionally quite polarized (high coherency values).

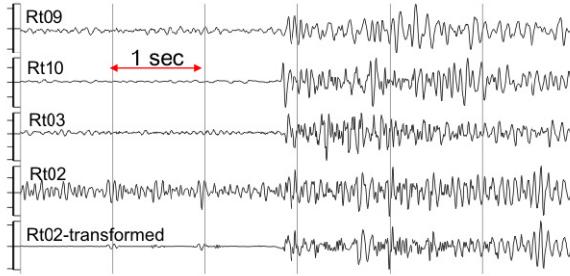
Success in detection, and subsequent arrival-time picking is however quite variable for the Rotokawa data set, primarily because of the high levels of background noise associated with the geothermal production taking place within the seismometer network. Accuracy in arrival time picking is essential with a small (3-4 km) diameter network, as the theoretical differences in arrival time between sites (for 2-3 km deep earthquakes) are quite small.

#### 4.1 S-transform for Denoising

We can obtain improvement in the signal to noise ratio for some of our stations by using time-frequency filtering of the seismogram, using the approach of Parolai (2009) which involves applying a frequency-dependent threshold to the S-transform (Stockwell, et al, 1996) coefficients to obtain optimally de-noised seismograms, allowing for non-stationarity of the signal. An example of the improvement that can be achieved is shown in Figures 5 and 6. Please note that the filter does not act as a very simple band-pass filter.

Although we have not yet applied this transform to the full 2008-09 data set we expect to obtain improved accuracy for subsequent arrival-time picking, especially for noisier data. More critically we also expect that, compared to the raw

data, the S-transformed data will be more suitable for waveform cross-correlation, necessary for subsequent double-difference relocation analysis.



**Figure 5: Improvement in signal/noise ratio achieved at station RT02, using the S-transform approach of Parolai (2009). Top 4 traces are the raw data, showing clean data on 3 stations, and moderate noise on station RT02. The bottom trace shows the RT02 data after a S-transform, cleanly highlighting the 1st arrival.**

#### 4.2 Slowness Estimation.

One aim of data filtering is to improve error quantification for slowness estimates; it is often noted that slowness estimates are often affected by the presence of coherent, polarized, noise (e.g. Greenhalgh et al, 2008). Reduction of the effect of such polarized noise, e.g. by using the S-transform approach described above, can lead to improved slowness estimation. Incorporation of slowness estimates, with quantified errors in the estimates, can strengthen the utility of fully non-linear global-search location algorithms for earthquake location (e.g. Oye & Roth, 2003); such an approach is especially important for microearthquake location in areas with highly heterogeneous velocity structure, as found in geothermal reservoirs. One advantage of this approach is that it offers the ability to thoroughly quantify errors in the event locations.

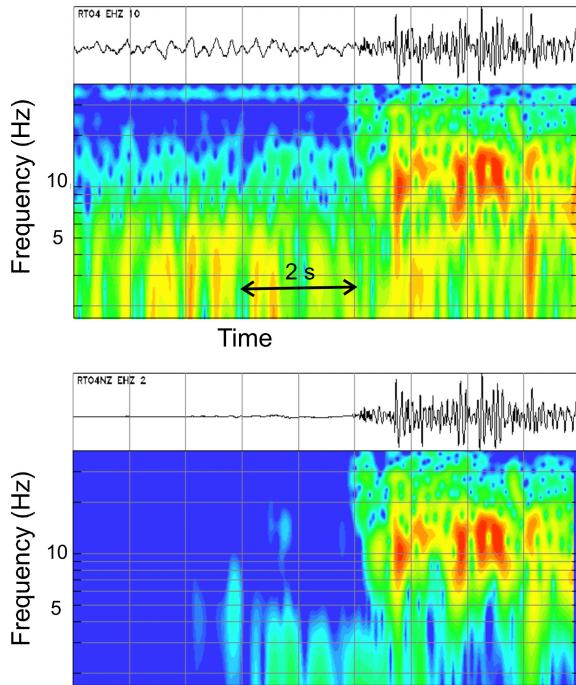
#### 4.3 Rotation to L-, Q-, T- Components

If slowness is able to be measured, within some reasonable error bounds, for a particular station-event record, then a very useful processing step involves rotation of the 3-component data into ray coordinates (L-,T-, and Q-components) (e.g. Oye and Roth, 2003). Such a rotation can help improve the signal-to-noise of the S-wave arrival and so reduce the error involved in picking the S-wave arrival time. We still find that manual picking is necessary for quality arrival times, although automatic approaches can still provide reasonable initial estimates.

#### 4.4 Waveform Cross-Correlation

Following initial location, double-difference relocation algorithms (e.g. that of Waldhauser and Ellsworth, 2000) can be applied to improve the relative locations of clusters of microearthquakes (e.g. Bannister et al, 2008). Double-difference approaches utilise differential times of catalogue P and S phase times, as well as waveform-based differential times (WBDT). Data processing described above can help to reduce the effect of coherent noise on WBDT estimates. As a check however we calculate the waveform-based differential times for all event-station pairs using both cross-correlation (CC) and bispectrum (BS) methods, following the approach of Du et al (2004). The combined examination of CC and BS estimates can be very useful for

data with a high level of coherent background noise, such as found at Rotokawa, and in other production reservoirs.



**Figure 6: Time-Frequency content of data (top) before S-transform application, and (b) after S-transform application, at station RT04, for a different event. The event arrival and signal is highlighted after the transform.**

#### 5. CONCLUSION

Accurate high-resolution location of reservoir seismicity requires precision arrival-time picking, which can be affected by high noise levels often found in geothermal production reservoirs such as Rotokawa. We expect that approaches for data denoising using S-transforms will improve subsequent arrival-time picking and cross-correlation estimation, necessary for subsequent location of the microearthquakes.

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