Real-Time Induced Seismicity Monitoring During Wellbore Stimulation at Paralana-2 South Australia

Michael Hasting[1&4], Julie Albaric[2], Volker Oye[2], Peter Reid[3], Mathieu Messeiller[3], Ella Llanos[3], Peter Malin[4], Eylon Shalev[4], Mathew Hogg[4], Mark Alvarez[4], Alex Miller[4], Christina Walter[4], Carolin Boese[5], Nora Voss[6]

m.hasting@auckland.ac.nz or hasting.michael@gmail.com

[1]Hasting Micro-Seismic Consulting, 1233 Quail Way, Ridgecrest CA 93555 USA +1-760-608-7542

[2]NORSAR, Gunnar Randers vei 15, 2007 Kjeller, Norway

[3]Petratherm Ltd, Australia, Level 1, 129 Greenhill Road Unley SA 5061, Australia

[4]IESE and the University of Auckland, 58 Symonds Street, CBD Auckland, 1142, New Zealand

[5]Victoria University, School of Geography, Environment and Earth Sciences, Kellburn Parade, Victoria University of Wellington, Wellington 6012, New Zealand

[6]GZB, International Geothermal Center, Hochschule Bochum, Lennershofstraße 140, 44801 Bochum, Germany

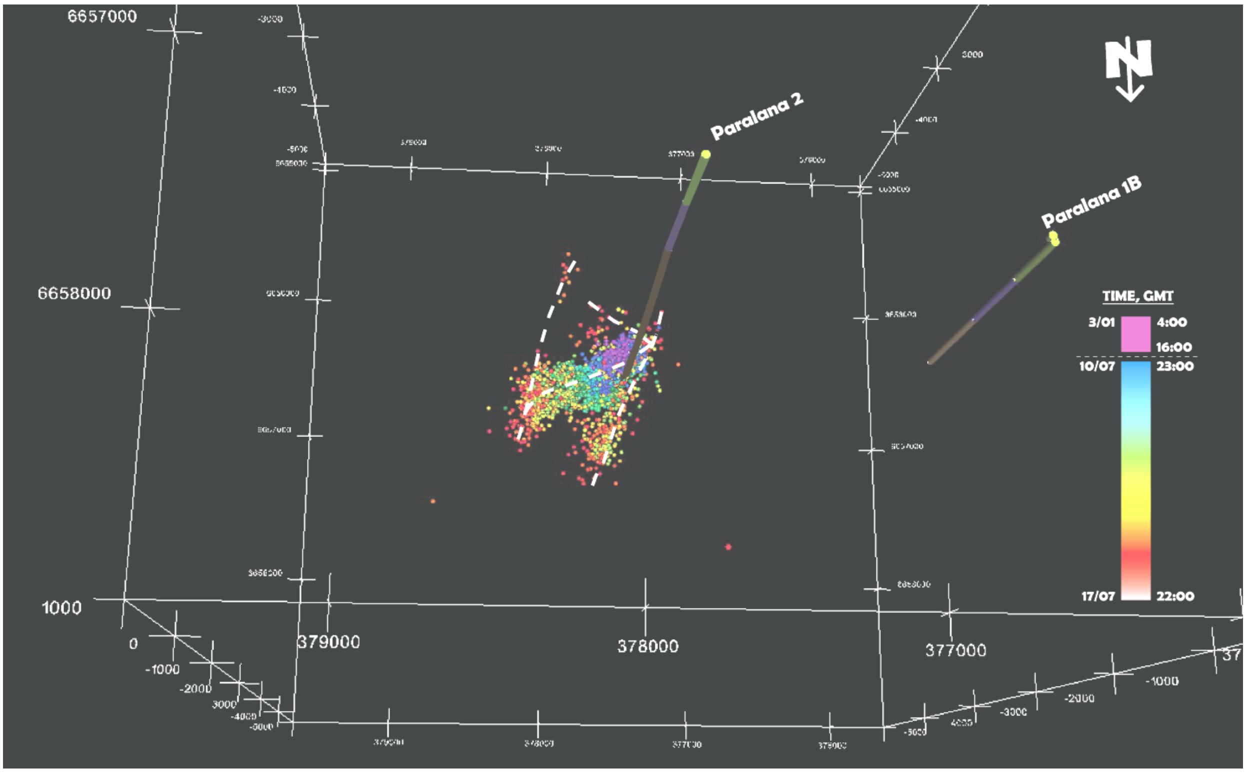
In 2009 the Paralana JV, drilled the Paralana-2 (P2) Enhanced Geothermal System (EGS) borehole east of the Flinders Range in South Australia. Drilling started on June 30th and reached a total depth of 4,003m (G.L AHD) on Nov 9th. A 7- inch casing was set and cemented to a depth of 3,725m and P2 was officially completed on the 9th Dec 2009. On Jan 2nd 2011 a six meter zone was perforated between 3,679 and 3,685 mRT. A stimulation of P2 was carried out on Jan 3rd by injecting approximately 14,668 litres of fluid at pressure of up to 8.7 kpsi and various rates up to 2 bpm. During the stimulation ~125 micro-earthquakes (MEQ) were triggered in the formation. Most of the MEQ events occurred in an area about 100 m wide and 220 m deep at an average depth of 3,850 m. The largest event, a M_W 1.4, occurred after the shut-in.

Between 11th and 15th of July 2011, the main fracture stimulation was carried out with ~3 M litres injected at pressures up to 9 kpsi and rates up to 10 bpm. Over 11,000 MEQ were detected by the seismic monitoring network. This network consisted of 12 surface and 8 borehole stations with sensor depths of 40 m, 200 m and 1,800 m. Four accelerometers were also installed to record ground motions near key facilities in the case of a larger seismic event. MEQ were automatically triggered and located in near-real-time with the software MIMO provided by NORSAR. A traffic light system was in operation and none of the detected events came close to the threshold value. More than ½ of the detected events could be processed and located reliably in the full automatic mode.

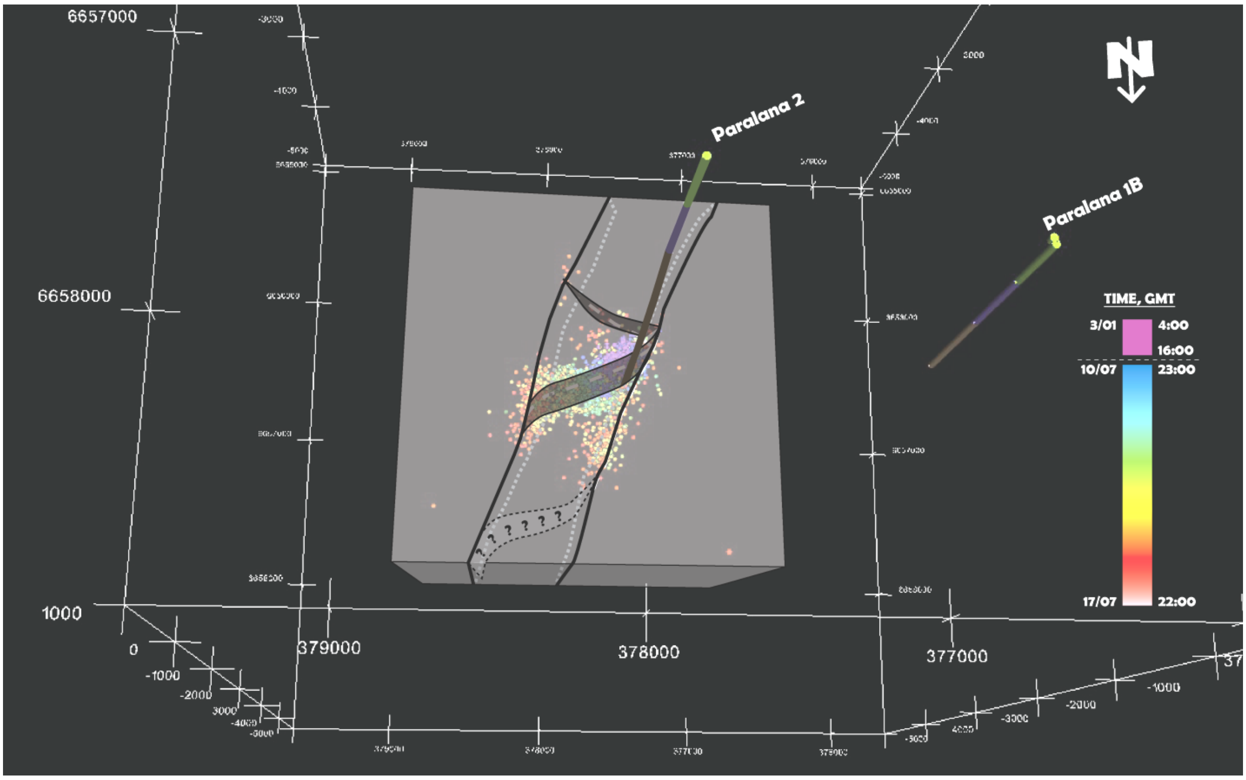
Selected MEQ events were also manually picked on site in order to improve the location accuracy. A total of 875 MEQ events were picked, located and plotted on site to give the operator, Petratherm, a sense of the fracture created while post processing yielded another 1,025 events. After a data download in mid August an additional 750 events were located from this data set. As such over 2,600 events were hand-picked and located to form the final picture of the stimulation fracture. Results show that fracturing occurred in three swarms. The 1st swarm occurs near the well and deepened with time from 3.7 km to over 4.1 km. The 2nd swarm occurred a few days in and shows as a circular patch extending a few hundred meters east of the 1st one. The 3rd swarm occurred after shut-in and extends downwards to the NNW and reaches 4.4 km depth. Petratherm believes that there is a primary NE/SW structure that takes most of the fluid. Then, two NNE/SSW structures are highlighted after day 5 to 6 and continue growing after shut-in. The first fracture appears to have a sygmoidal pattern. The two later structures appear to act as boundaries to the East and West and are subparallel to the major faults that define the graben in which P2 was drilled. They appear to deepen towards the north. A later shallower structure is highlighted to the SE of the well. Overall, it appears that at least 4 structures have been enhanced and stimulated. The well head pressure after the minifrac and after the main frac shows a value of about 3940 psi. This shows that the injection of fluids in P2 has connected into a naturally fractured network, with *in situ* fluid. While drilling P2, overpressured brines were intersected at depths between 3680 and 3860m. We believe that this zone of fracture permeability has been connected to and enhanced. The MEQ cloud shows a complex fracture network of at least 4 structures that can be interpreted as conjugated faults/fractures. Refer Figure 1a and 1b below:

The "Post" injection seismicity also shows that events occurred on the outer edges of the main injection swarm and that there are four distinct areas of continued seismicity. All events form primarily along a northeast trending structure that is steeply dipping to the northwest with a total length of over 1,350 m and depth of between 3,200 m and 4,200 m.

Assuming that injected fluids went into opening of new fractures a volume change must occur. Using a variation of the Brune formula (JGR, VOL. 73,



Figures 1a: 3D Plots Showing Induced Seismic Events



Figures 1b: Geological interpretation of main fractures based on the seismicity and a 2D seismic survey of the area

NO. 2, PP. 777-784, 1968) for estimating seismic moment and converting to a "Moment Magnitude", M_W, we estimated that a total M_W=3.12 is needed to accommodate the fluids. Summing the M_W of the 2,600 hand-picked events yields a total measured M_W=3.05. As such most of the fluids must have gone into the opening of fractures and have created a new geothermal reservoir.

Keywords: Induced Micro Earthquakes, MEQ, EGS, Stimulation, Injection, Paralana, Petratherm, IESE, MIMO, NORSAR, Reftek

Introduction

Between April 2008 and January 2011 the Institute of Earth Science and Engineering (IESE) conducted a background micro-seismic study of the area around the Paralana geothermal project area. Results of this study showed very little seismic activity within the footprint of the seismic array. However during the drilling of the Paralana-2 (P2) borehole we did see several micro-seismic events associated with the cementing of the casing. On 3 January 2011 a stimulation experiment of P2 was carried out. During this experiment, a mini-frac, the Paralana MEQ network detected over 300 seismic events in a four hour timeframe around the stimulation. Of the 300 seismic events approximately 125 were large enough to be located. During this phase of operations the network consisted of twelve stations, four at the surface and eight in boreholes (Figure 2). It should be noted that six of the borehole stations were installed at a depth of 200 m below surface, one at a depth of 40 m and one at a depth of 1,797 m.

All sensors measured three components and were configured in a traditional X, Y, and Z configuration. The surface station used 2Hz sensors while most of the borehole station used a 4.5Hz borehole SONDE. For station B05, deployed into the bottom of the Paralana-1B borehole, due to the size of the casing a custom built 15Hz sensor was deployed measuring 1.75 in (44.45 mm) OD and including the coupling weights over 9 ft (2.75 m) long. Figure 3 shows this sensor being deployed. Sampling rate on the data loggers were set to 1000 Hz to record the maximum frequency content of the earthquake during the fracture. Post processing of the data showed that for most all stations a sampling rate of 250 Hz would have been acceptable due to the strong attenuation of the signals in the softer sediments in the area.

During the July 2011 main stimulation, the MEQ network was upgraded using 900 MHz spread-spectrum radios to a real-time network and nine more stations were added to the array. Of the nine new stations, four of these were strong motion accelerometers while the rest were standard 2 Hz velocity sensors. Figure 4 shows the configuration of the Paralana MEQ network during the main stimulation. Due to the limitation on the real-time communications, and the results of the mini-frac, a sampling rate of 250 Hz was used on all station in the network. During the main stimulation of P2 over 11,000 events were detected by the MEQ network with over 6,000 events being automatically located by the MIMO software. Approximately 875 events were also manually phase picked and located by IESE staff while on site and an additional 1,725 events were hand-picked during post processing. Figure 5 shows a plot of all events manually picked and located by IESE.

Results of the main stimulation event locations show that primary fracturing occurred along a generally northeast to southwest structure steeply dipping to the northwest. Later development of the fracture network involves two NNE/SSW

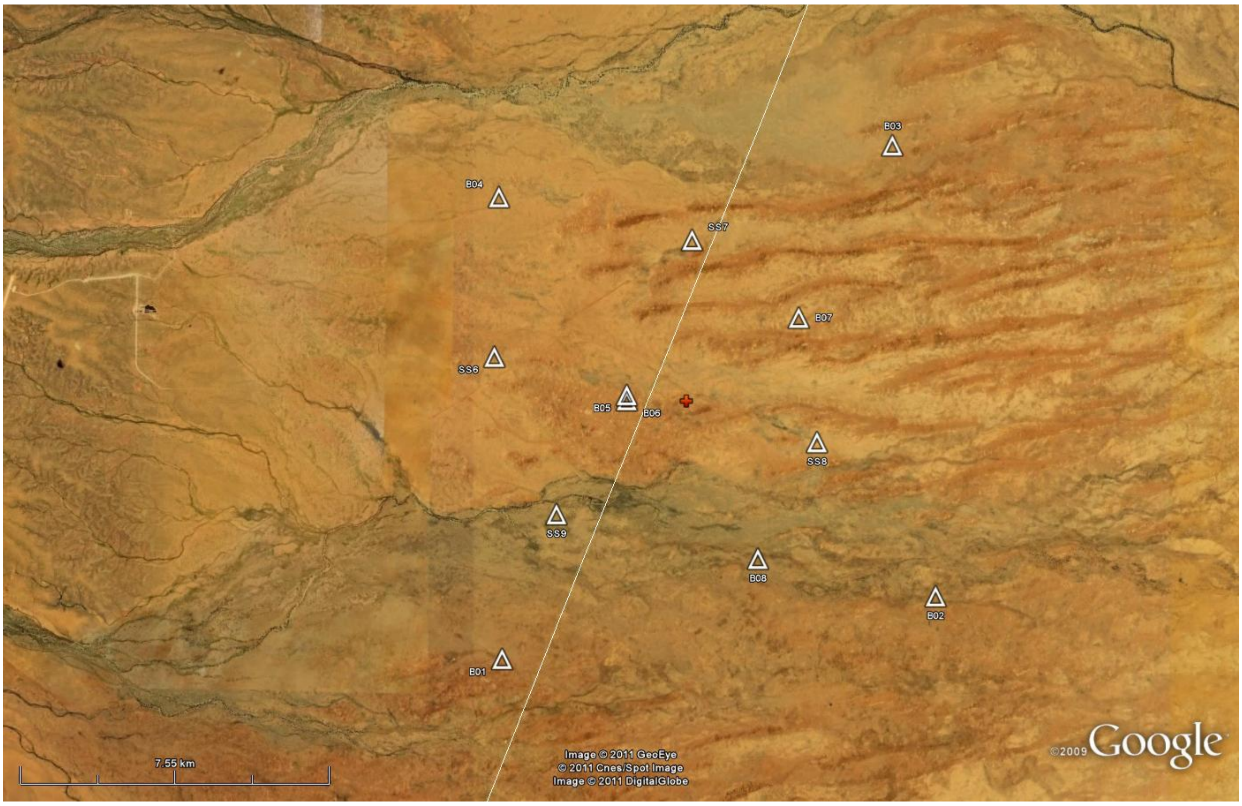


Figure 2: Paralana MEQ network station layout for mini frac. Top of Paralana-2 borehole is represented by a red cross.

Figure 3: 15Hz Sensor being deployed into the Paralana-1b borehole. Station name = B05

structures. In figure 5 the events plotting north of the main injection event swarm are deeper events along the main fracture and will be shown in cross-sections in later plots. Additionally the fracturing during pumping operations was significantly different than fracturing while the wellhead was shut-in under pressure. Most of the events occurring after the shut-in of the wellhead occurred on the outer edges of the main swarm. This will be shown in later figures. It should be noted that fracturing of the rock was still occurring more than 30 days after P2 was shut-in and as such the figures in this paper will be updated as data is downloaded and events are located.

Mini Stimulation

The primary purpose of the mini-frac experiment was to determine the pressures and flow rates needed for achieve the main stimulation. It gave IESE the ability to evaluate the network performance and determine the recording parameters needed for the main-frac monitoring program. From the results of the mini-frac monitoring we were able to determine the best location for new stations and the level of effort it would take to provide Petratherm with the necessary onsite support for recording and locating events in near-real-time.

As noted above, during the mini-frac of the P2 borehole ~125 seismic events were located (Figure 6). As shown in the figure, the events occurred vertically over a range of about 300m and align roughly along the path of the borehole. The largest event, a M_W1.45, occurred in the middle of the swarm. From figure 7 it can be seen that the main event occurred at, or just after, the time of shut-in and just as the pressure started to decrease. It should be pointed out that while

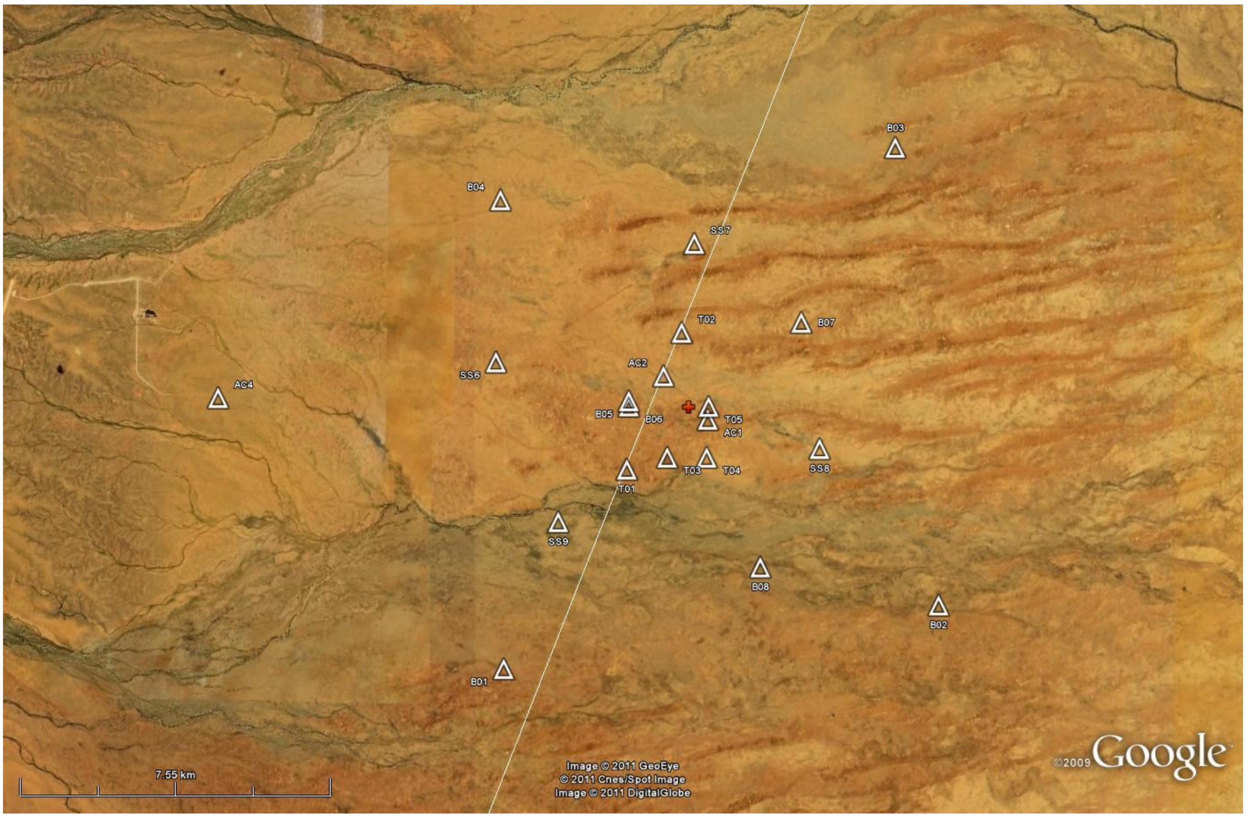


Figure 4: Paralana MEQ network station layout for main frac. Top of Paralana-2 borehole is represented by a red cross.

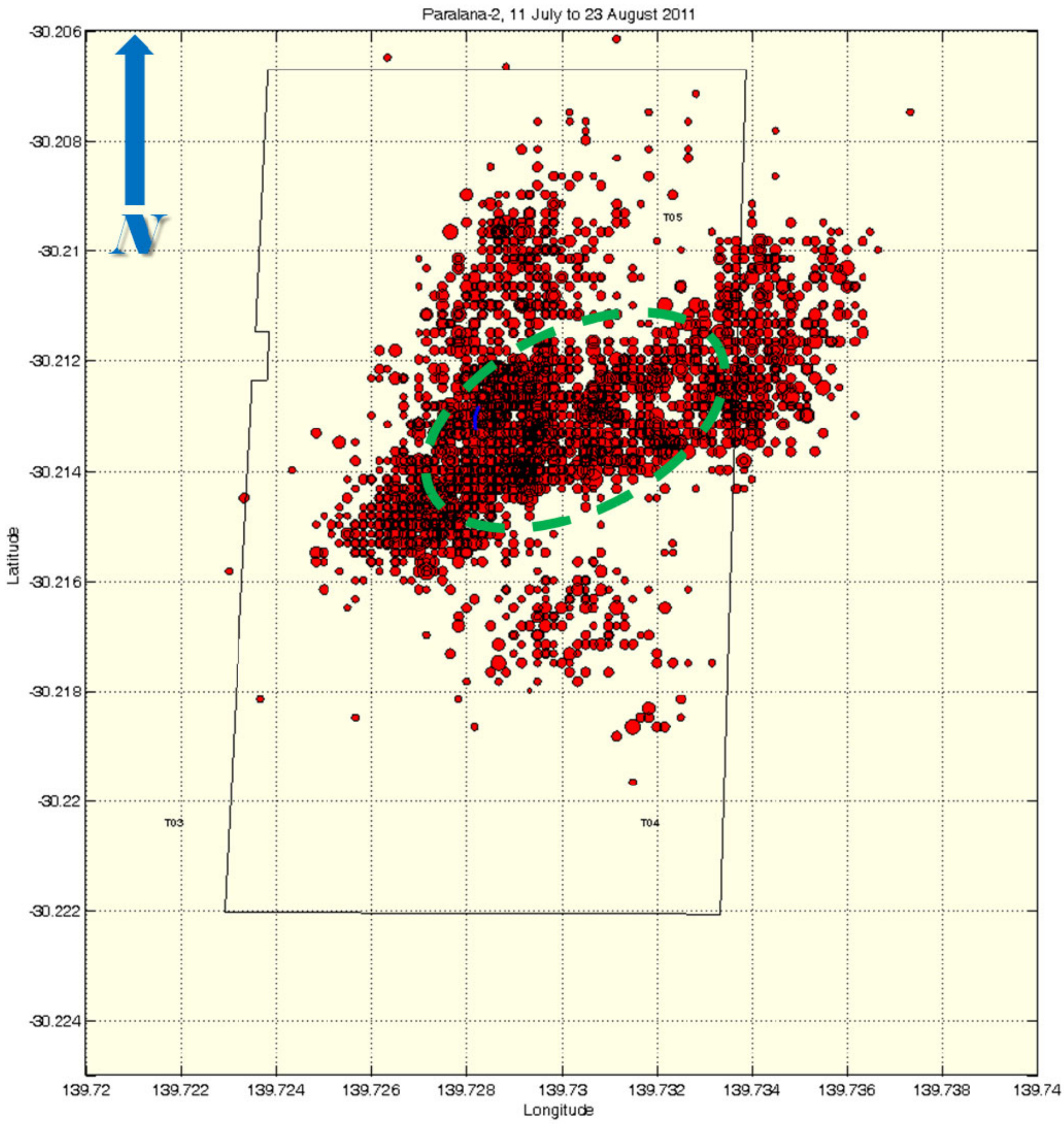


Figure 5: Plot showing map view of all +2,600 seismic events recorded during and after the main stimulation/injection of the Paralana-2 borehole. Black line is the Paralana-2 fence boundary. Events to the north are deeper than the main northeast-southwest trend. Green dashed line = main injection swarm area

seismic recordings were timed by GPS, it is not known if there was a timing offset on the computer used to record the pressure data. This may indicate the collapse of a larger section of fracture rock that was being held open by the increased pressure and when the pressure decreased it could no longer support the opening of the fracture. Note that the equilibrated wellhead pressure after the minifrac was 3940 psi, suggesting that P2 was connected to a natural fracture with overpressured brine.

Main Stimulation

The primary objective of the main stimulation was to generate a fracture with a minimum length of about 500 meters and width/depth of between 200 to 300 meters in size. This would provide a minimum surface area of 100,000 to 150,000 sq-meters. This objective was exceeded and an area of approximately 850,000 sq-meters was generated.

Event Locations

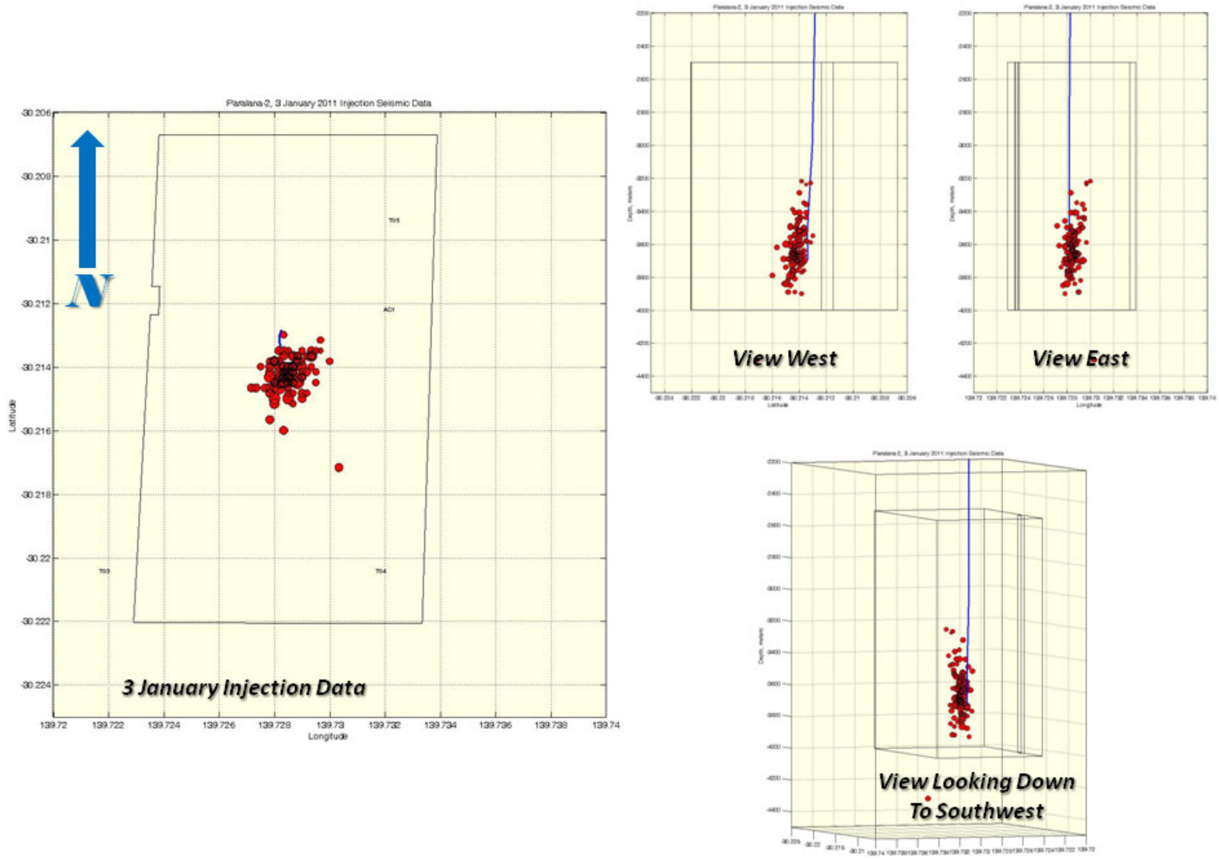


Figure 6: Mini-frac seismic events; blue trace on cross section plots is the Paralana-2 wellbore location. Inner box is for reference only and is a subsurface projection of the Paralana-2 fenced boundary.

During the main stimulation of the P2 borehole, the Paralana MEQ network was run in a continuous recording mode with all data from each station being sent to the central site for real-time processing. For the real-time data processing we used both the Refraction Technologies (RefTek) software RTPD for recording the data, RTCC for controlling the station, and RTMonitor for viewing the data in real-time. IESE staff also provided the fracing operators with a real-time feed of the seismic waveforms so that they could view the events as they happened. As such they were able to follow the seismicity and make adjustments as

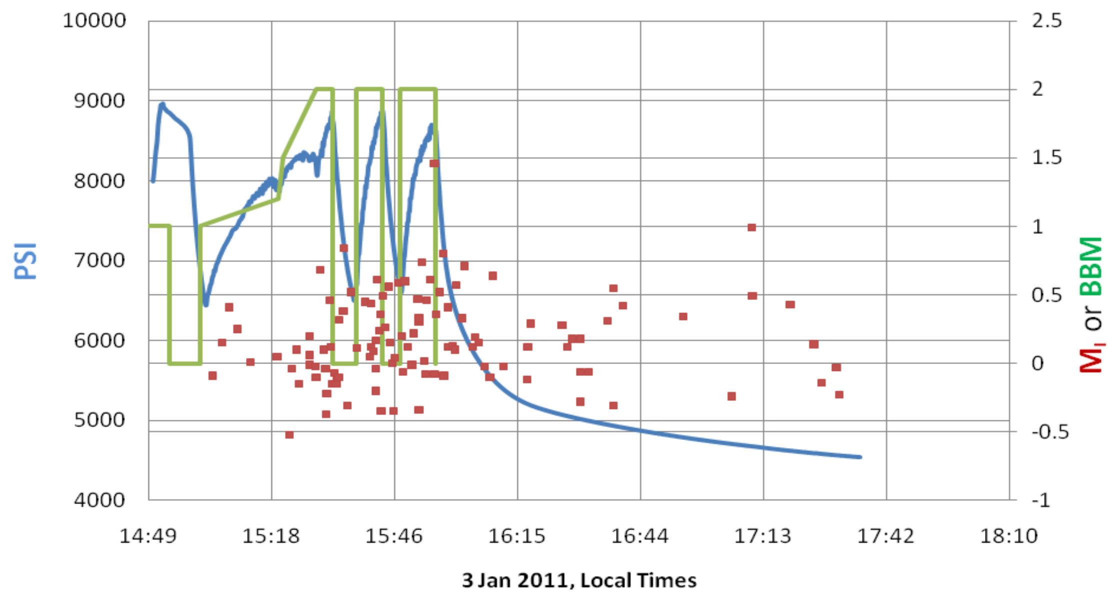


Figure 7: Plot of injection pressure (blue line) vs. seismic data (red dots) and pumping rates (green line)

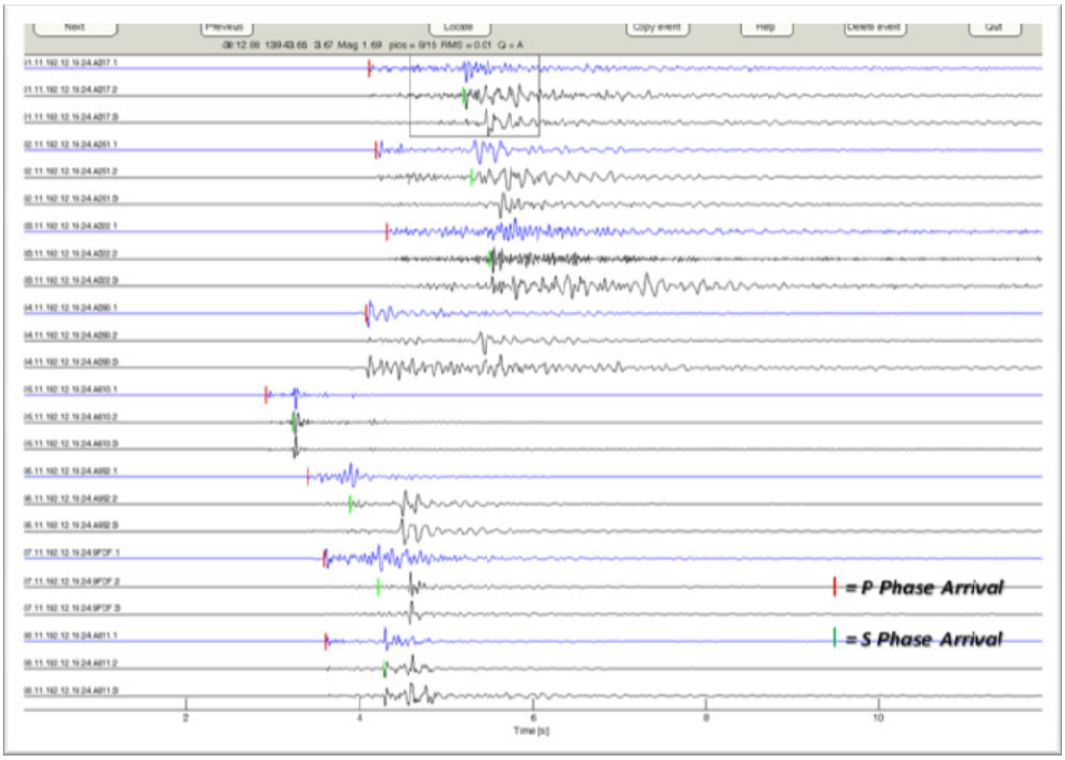


Figure 8: M_W 1.69 event located near the beginning of the main stimulation.

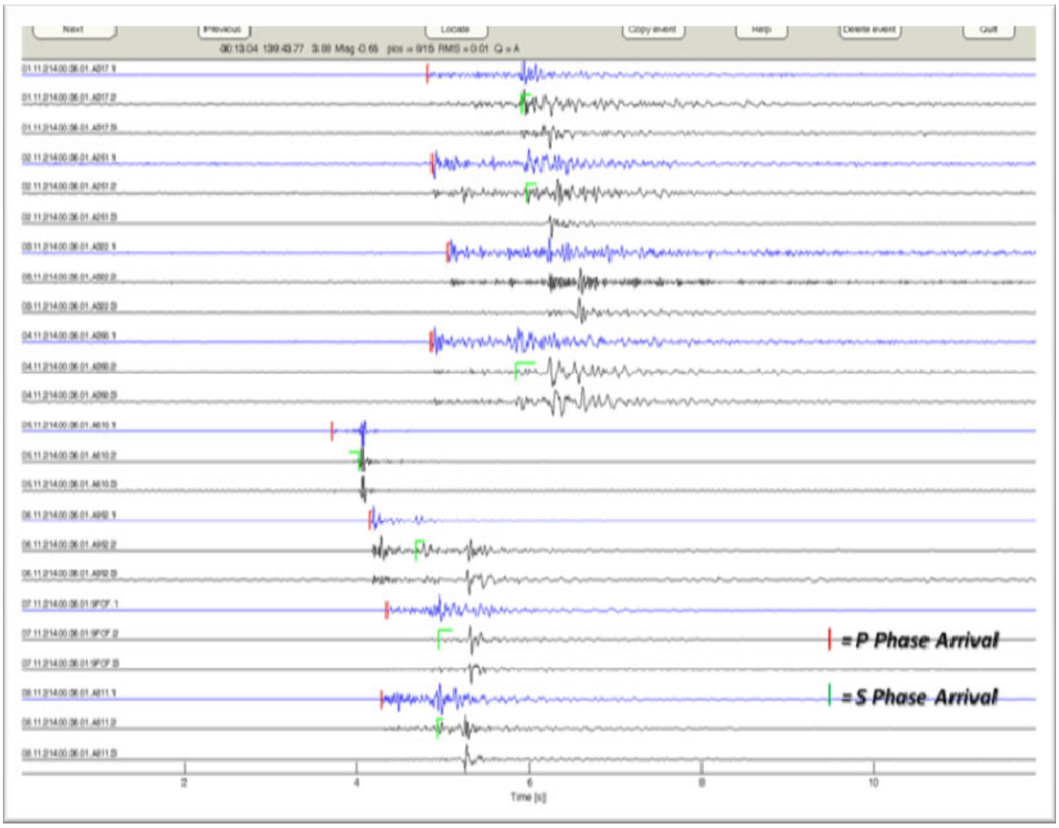


Figure 9: M_W -0.65 event that occurred several days after the stimulation had been completed.

necessary during the fracing operations.

During the real-time monitoring efforts onsite we ran a program (RTP2SEGY) which converted the raw RefTek data packages and converted them to a SEGY data stream and segmented them into 2 min data files. These SEGY files were then processed by MIMO to provide near-real-time event triggering, detection and preliminary locations and magnitudes. Since we had to wait for each 2 min file to be completed, there was a small delay in the event processing. MIMO was provided by NORSAR and helped give the operators a feel as to the size of the fracture being created in near-real-time. However, because it was set to trigger on very small events and tried to locate them, over 11,000 events were triggered on and located. Of these automatically triggered events, about 5,000 were so small that they were hard to locate and as such made the image harder to read. Post processing of the automated data locations helped to clear up the image of the fracture.

While MIMO was processing data in near-real-time every few hours, IESE onsite staff would download the raw RefTek data and run the raw data through a set of triggering MATLAB algorithms developed by IESE staff. Since we were dealing with a large number of events, the triggering ratios were set to detect the larger events ($M_W > -0.5$). Triggers were associated into events and then "event files" were generated. These event files were typically only 12 second in length. Figures 8 and 9 show examples of some of the event file waveforms for a M_W 1.67 and M_W -0.65 events respectively. As you can see, even the smallest events recorded by the Paralana MEQ network show a good signal to noise ratio, making it easy to pick the phase arrivals. While on site over 875 events were hand-picked using the IESE software and an additional 1,725 events were hand-picked in post processing.

While on site the Paralana Picking Crew (Figure 10) hand-picked over 875 of the larger events using the IESE software, along with help from the onsite Petratherm staff (Figure 11). An additional 1,725 events were hand-picked in post processing by Michael Hasting to help form the final picture of the fracture pattern generated by the main stimulation.

Figure 12 shows the final event locations after post processing for all hand-picked events. The events in Red are seismic events recorded and located during the actual injection of fluid into the P2 borehole at pressures up to 9,000 psi. The Stimulation, or Injection, of fluids started at about 23:00GMT on the 10th of July and ended at about 09:00GMT on the 15th. The events in Green are seismic events recorded and located after the shut-in of the injection stimulation of P2 with pressures ranging from 9,000 psi to just over 4,000 psi. As shown in Figure 12, many of the events during injection occurred in the center of the seismic swarm, while events after shut-in occurred on the outer edges of this central swarm. The extent of the seismic swarm is approximately 1,350 m in the northeast to southwest and has a vertical extent ranging in depth from 3,400 m to over 4,200 m.

We compared the events from the mini-frac experiment to the start of the main stimulation. Figure 13 shows the locations of the mini-frac events (Red) and events from the first few hours

Figure 10: Paralana picking crew, from left to right, Dr Julie Albaric NORSAR, Alex Miller, Christina Walter, Michael Hasting IESE, Carolin Boese VUC and Nora Voss Hochschule Bochum.

Figure 11: Petratherm onsite crew, from left to right, Peter Reid, Ella Llanos, Mathieu Messeiller

during the main stimulation (Green). As you can see in Figure 13, during the main stimulation seismicity first occurred in the same area as the mini-frac experiment. After a few hours of pumping during the main stimulation, the fracture pattern started extending to the northeast and downward, forming an ellipsoid. Over time, this ellipsoid had a breakout on the fourth day of pumping shooting outwards further to the northeast by about 300-400 m and downward to the northwest by about 250 m. This can be seen clearer in later figures.

Event Locations over Time

As noted above, over 2,600 seismic events were hand-picked and located during and after the main stimulation of P2. Figure 14 shows map view plots by day of these event locations. The events start near the wellbore of P2 and work out in a general northeast trend. On 14 July we start to see the development of events north of the main swarm of events. These events are located deeper and are still basically on strike with the main swarm. There was also a breakout of events to the northeast during a standby where pumping was not taking place but pressure was held on the wellhead. This northeast breakout occurred over a six to eight hour period and almost doubled the fracture area and extending it out by about 300 to 400 meters during that period. Both these breakout are circled on the 14 July figure below. On 16 July, after shut-in, we start to see the development of a small cluster southeast of the main swarm. This cluster becomes more

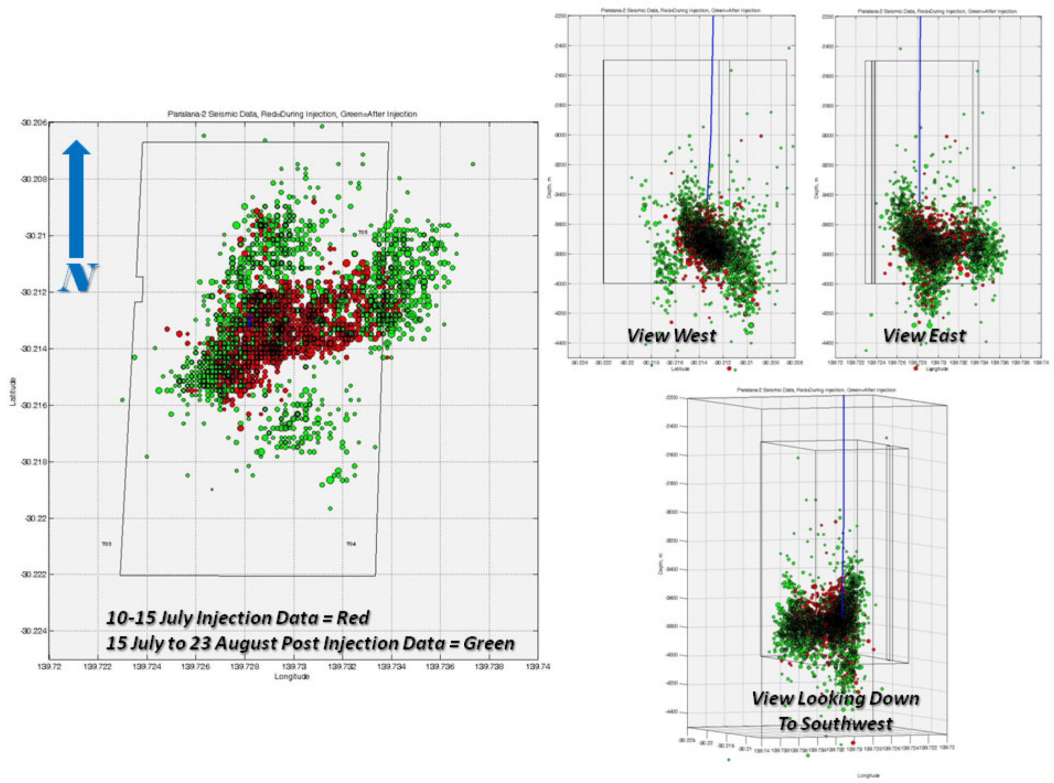


Figure 12: Paralan-2 micro-seismic events during and after stimulation, red = during stimulation, green = post stimulation

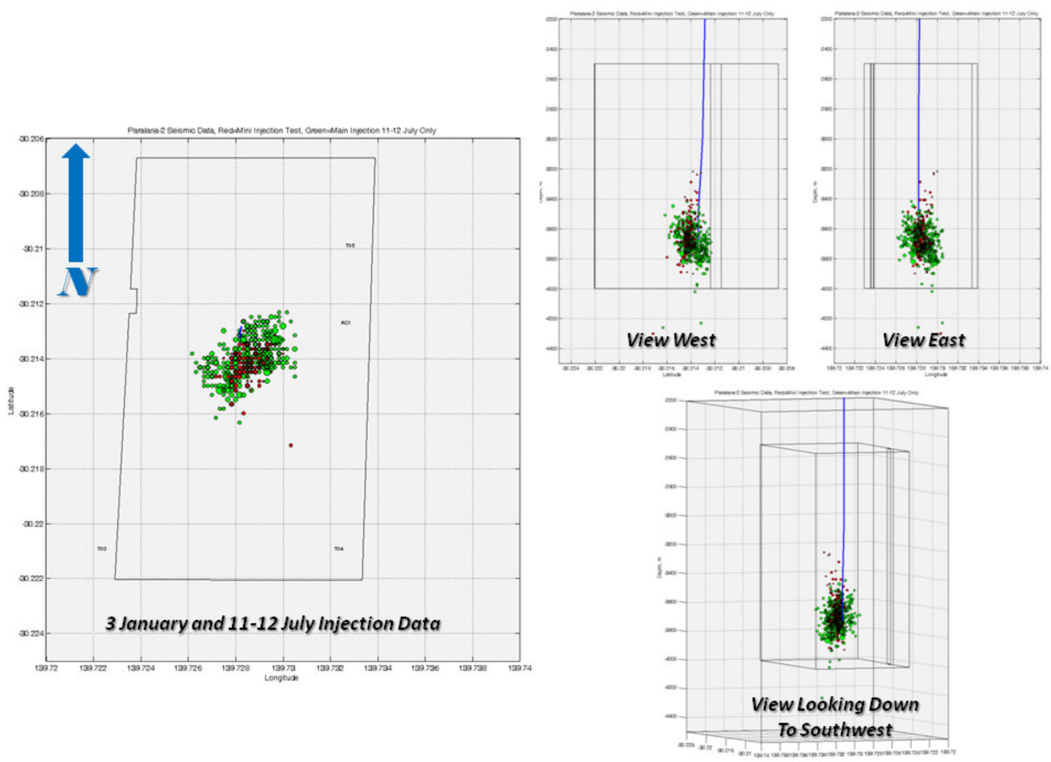


Figure 13: Mini-frac event in red and first few hours of the main-frac in green

pronounced over time and is off the main fracture swarm.

Over time, we see the continued growth of the main swarm to the northeast and southwest, as well as the deeper events located north of the main swarm. We believe the events to the west and east from the 14th of July are part of a second set of fractures. The preliminary frac is orientated on a NE/SW trend. Later events follow a different set of fractures, orientated NNE/SSW. There is a later frac to the SE. This growth, as well as the smaller cluster to the southeast, shows up as four cluster areas in the last plot of Figure 14. From figure 14 you can see that the lateral extent of the

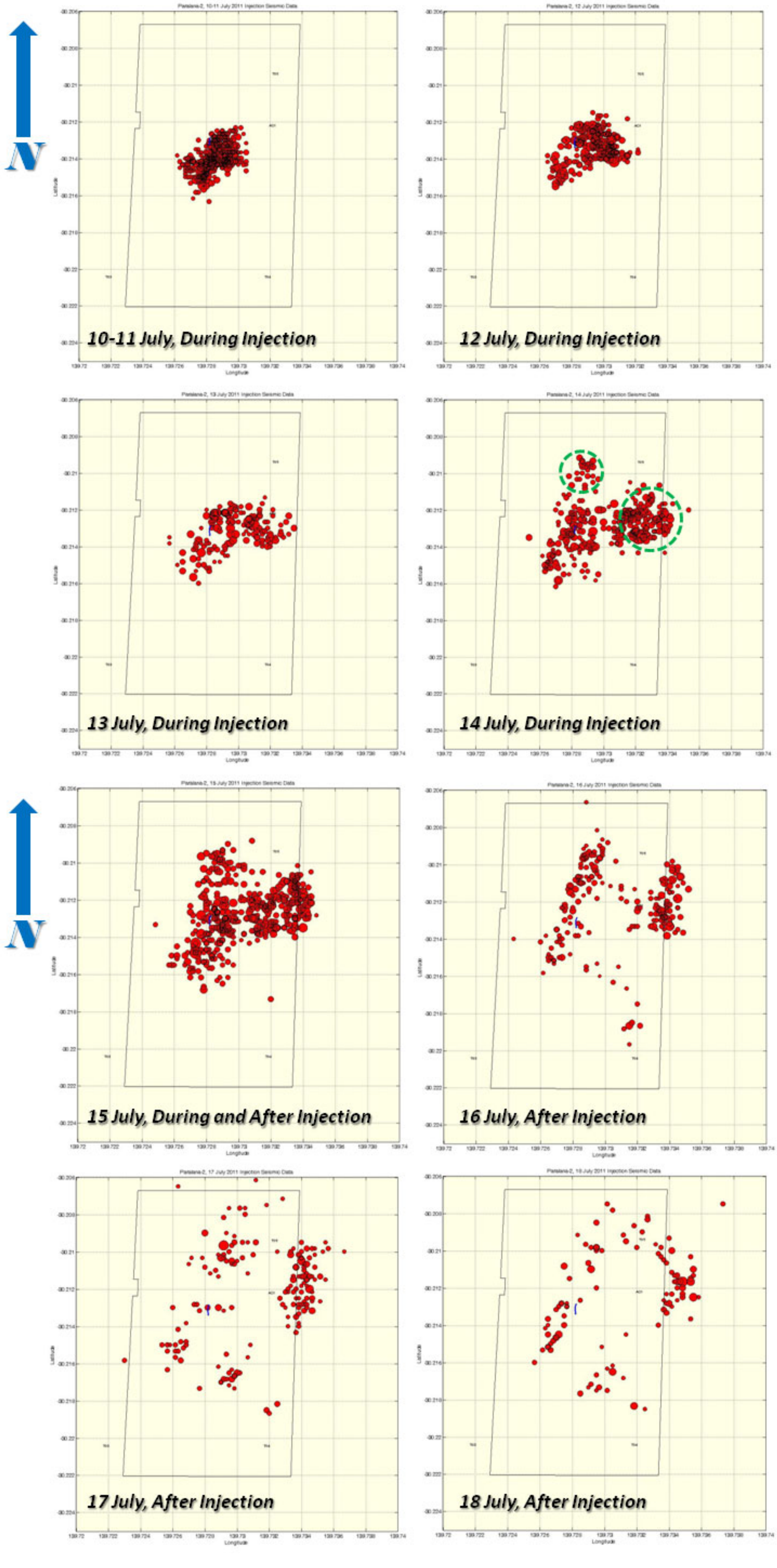


Figure 14: Map plot of hand-picked event location recorded by the Paralana MEQ network during and after stimulation. Note breakout on the 14th, green circles

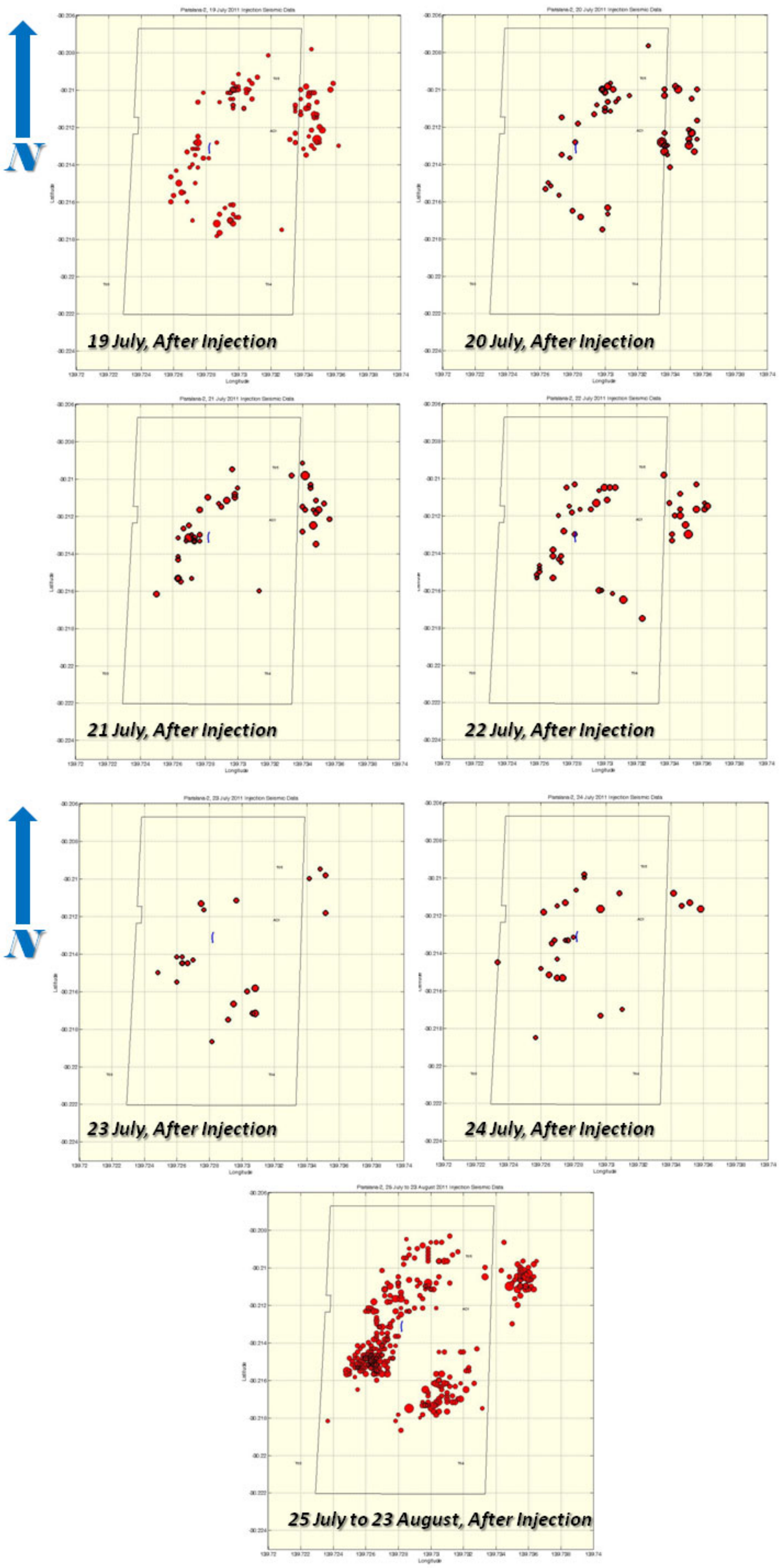


Figure 14 *(continued)*: Map plot of hand-picked event location recorded by the Paralana MEQ network during and after stimulation. Note breakout on the 14th, green circles

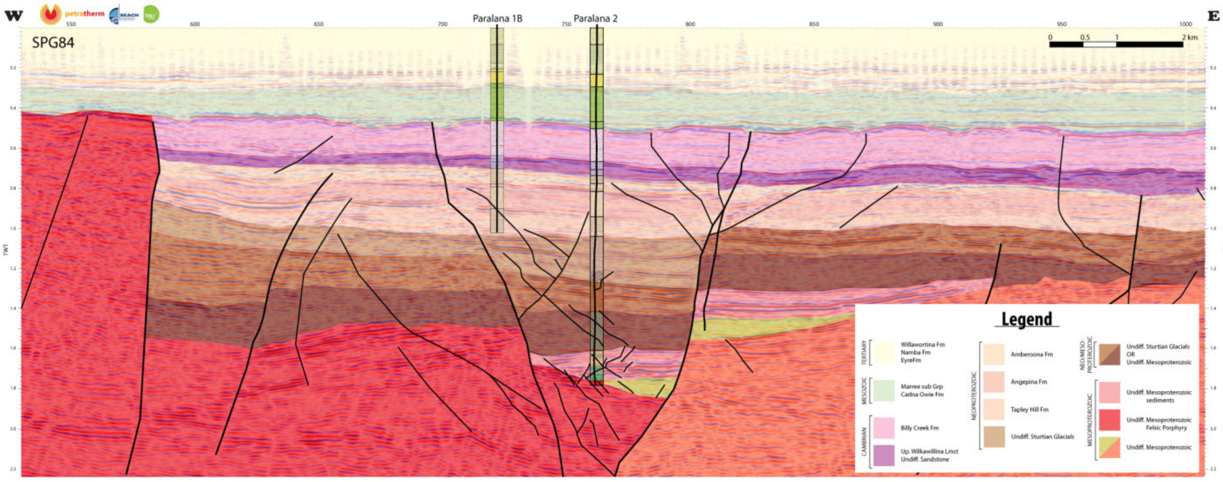


Figure 15: 2D seismic cross section showing mapped faults. Stimulation may have intercepted the main fault to the east of Paralana-2, as well as to the west.

faulting is about 1,350 m long and from figure 12 above you can see that the depth range of fracturing is between 3,400 m and 4,200 m in depth. Based on the SPG84 2D seismic crosssection (Figure 15) it appears that the fracturing to the northeast may have stopped near the mapped fault located about 1km to the east of the P2 trace outlined in the figure. On the 3D model, Figure 16, the frac stops before the main faults mapped on the seismic cross section. The structure acting as a boundary to the East is not the main fault, but is sub parallel to it. As you can see from the figures below, it seems there is still a few hundred meters before hitting the fault.

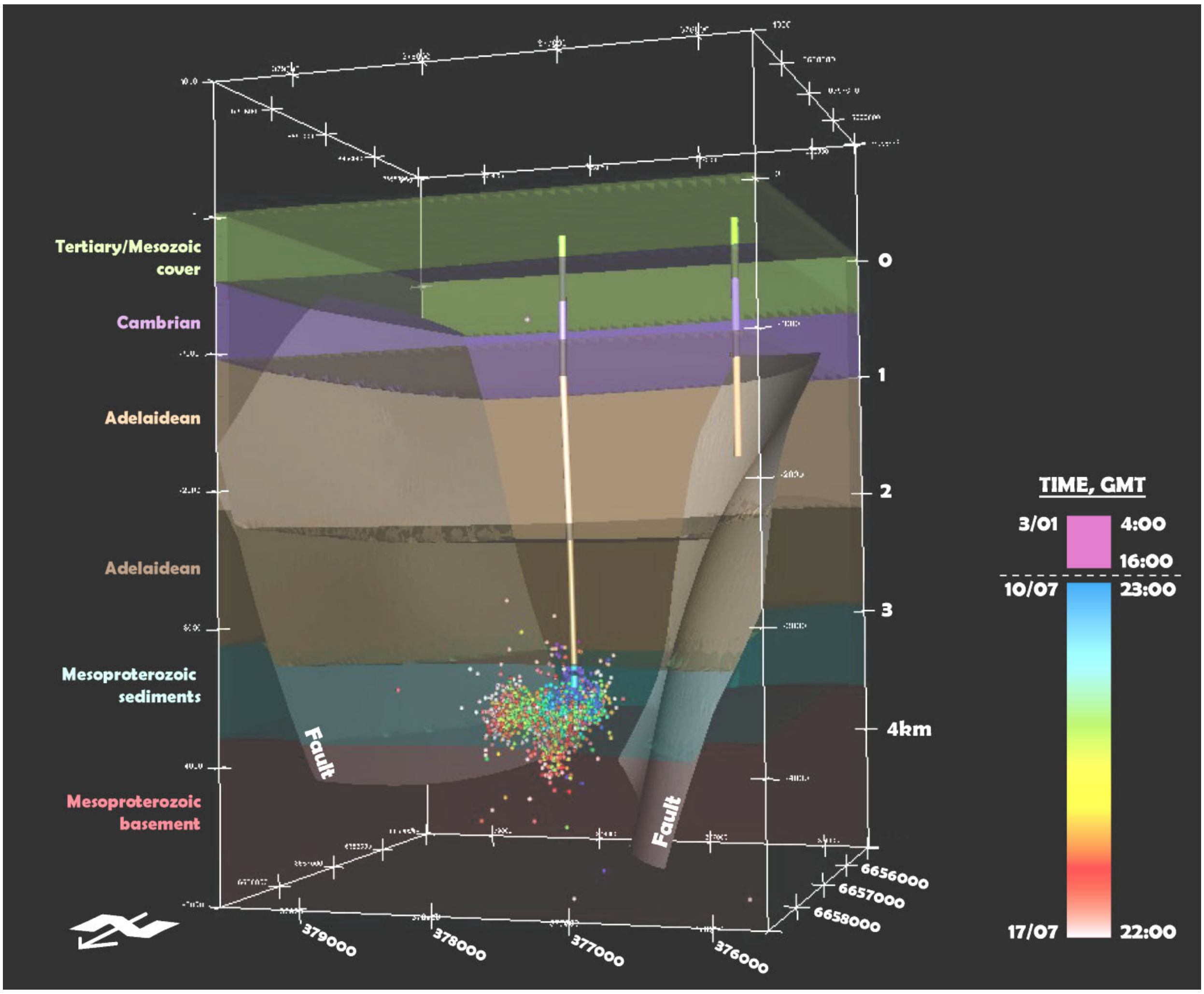


Figure 16: 3D model of the Paralana site

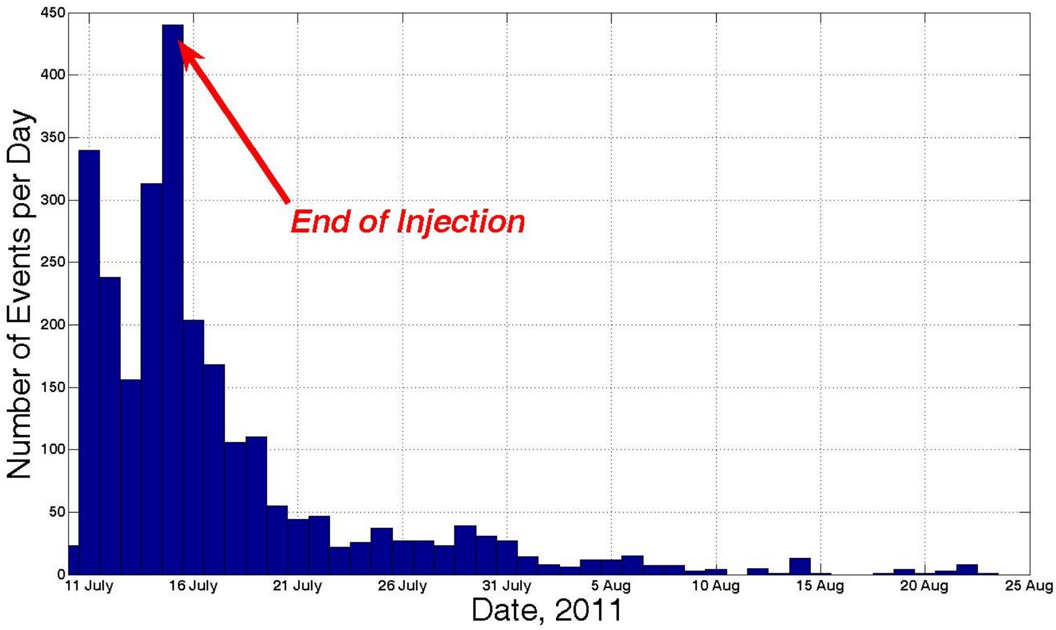


Figure 17: Decay plot of Paralana-2 seismic events over time between 10 July and 23 August

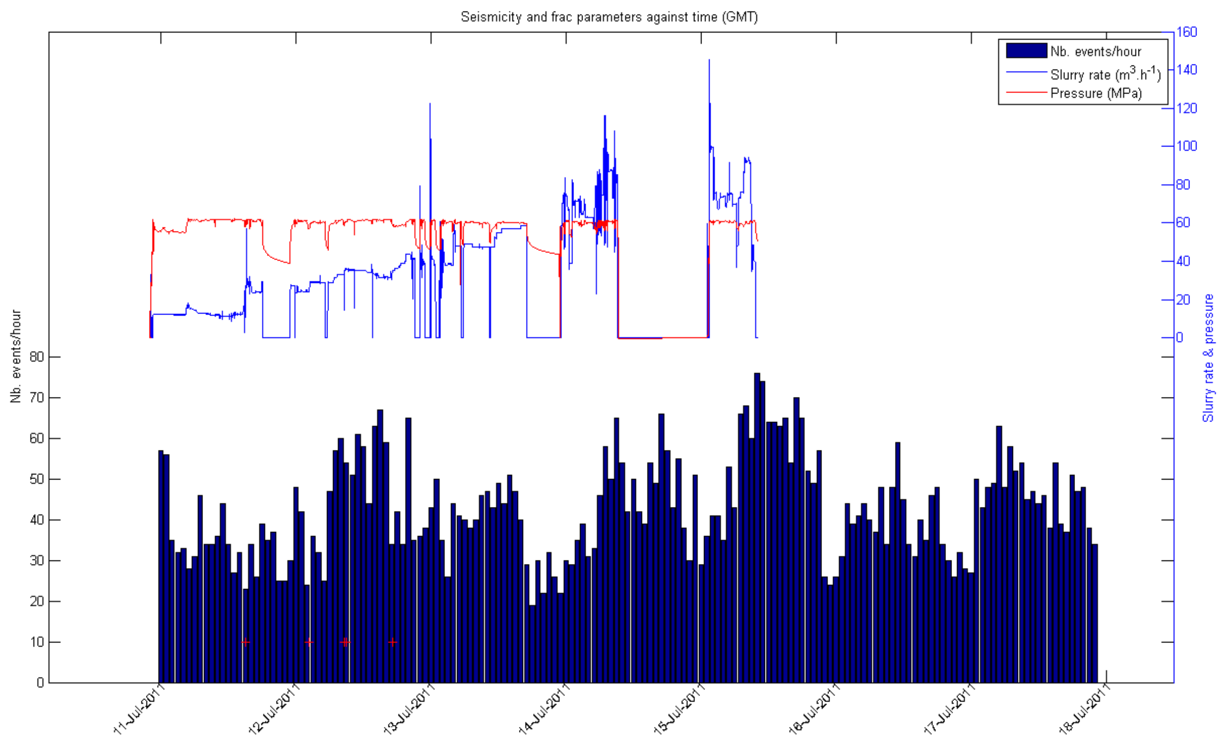


Figure 18: events per hour during and just after the main stimulation as recorded by MIMO

Additionally, the smaller fault to the west of P2 may have stopped the progression of fracturing to the southwest. Additional work is being on the integration of this 2D seismic cross section and the event locations.

In Figure 17 we show the rate of the seismicity during the main stimulation and the decay rate after injection was stopped. As you can see, as of the last data download on 23 August 2011 there were still small events occurring at an average rate of one to two per day. It should be pointed out that figure 17 shows only the events that we were able to locate and that there were about five times as many events that we were not able to locate due to their small size. Figure 18 shows a plot during and just after the main stimulation by hour as recorded by MIMO, along with the pumping pressures and rates provided by Halliburton.

Form the maximum length and depths measured for the fracturing, we get a minimum fracture area of around 875,000 m^2 generated during the main

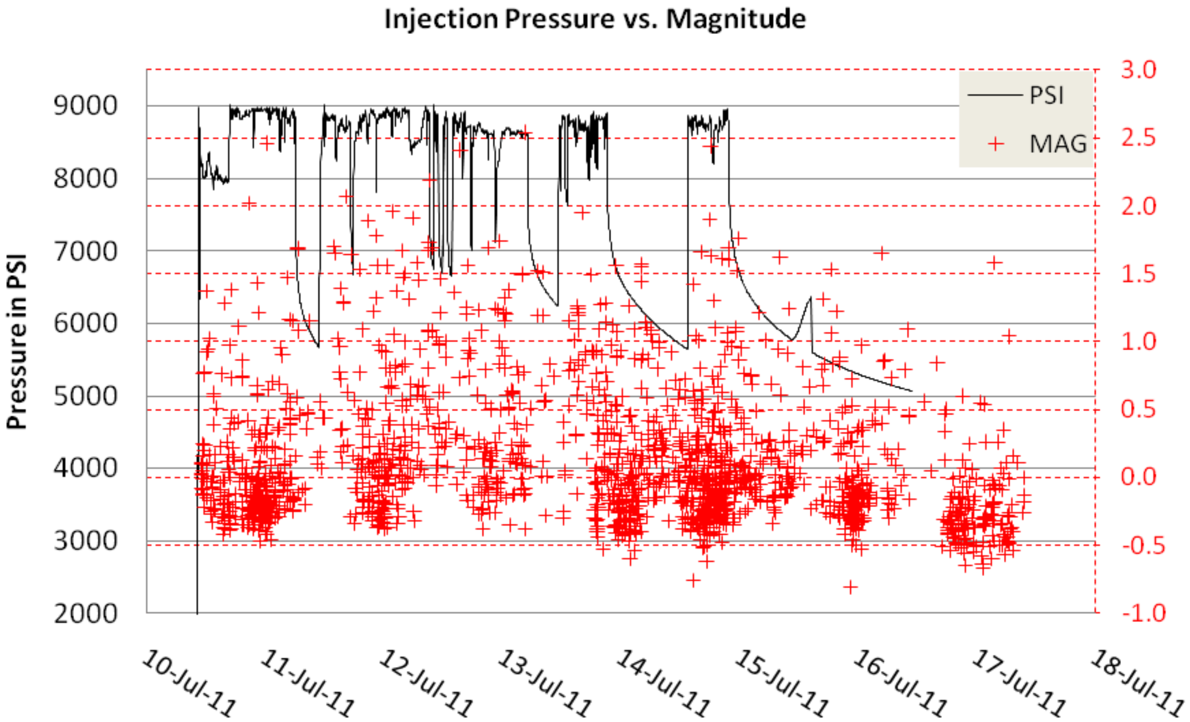


Figure 19: Injection pressure vs. magnitude during and just after pumping. Note lower limit due to triggering threshold used at the time the plot was made; smaller events were still occurring and located in post processing. Actual minimum limit of located events in post processing were ~M_l-1.4.

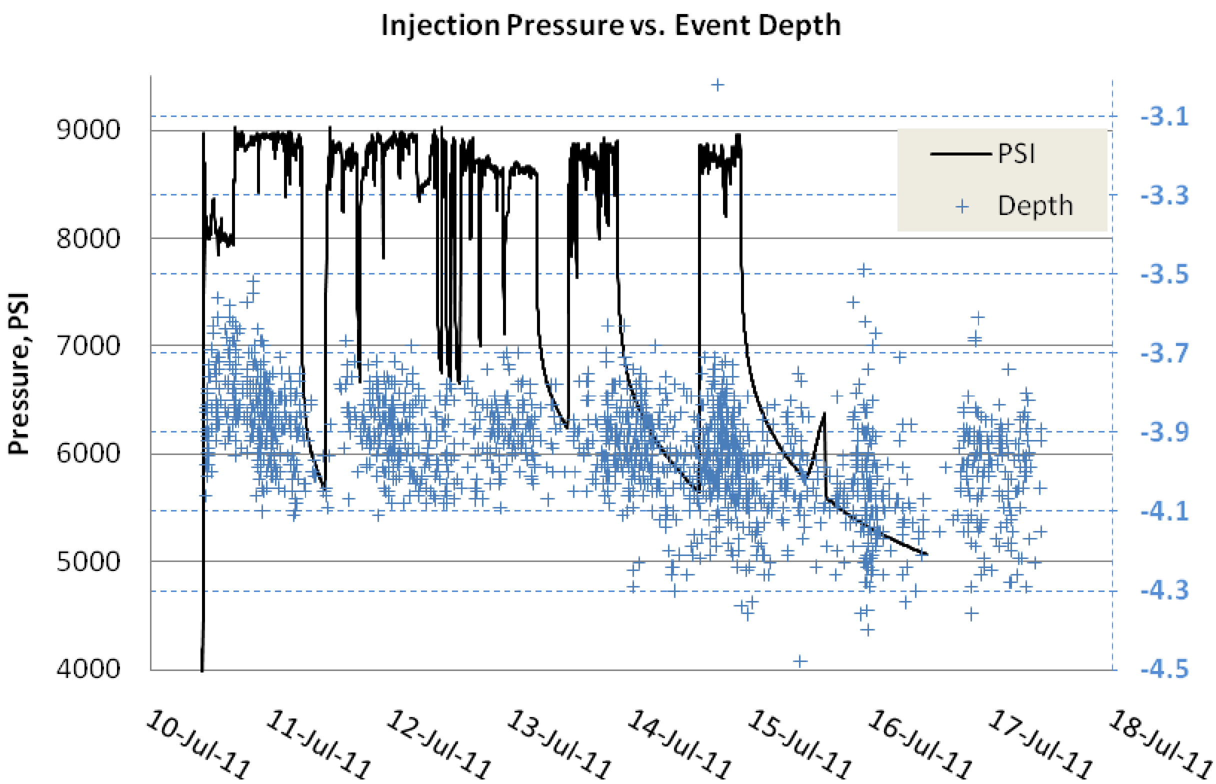


Figure 20: Injection pressure vs. depth during and just after pumping. Same dataset used in Figure 19.

stimulation. Dividing this into the total volume of injection (~3 M litres) we estimated that an average fracture displacement of between 3.5 and 4.5 millimeters would be required to accommodate the entire volume of injection over this area. While fractures may be larger or smaller throughout the volume, this gives us a good first approximation of the fracture density needed to accommodate the fluids. However it should be pointed out that due to the uncertainty of the event locations we cannot at this point tell if there were multiple parallel fractures occurring during the stimulation. As such, the estimation of 3.5 to 4.5 millimeters should be considered a maximum displacement value and the actual may be, and most likely is, less than this.

Injection Pressure vs. Magnitude and Depth

During the main injection test, of the hand-picked events, only seven events had a magnitude greater than $M_W = 2.0$, with the largest being a M_W 2.6 which occurred near the end of pumping, on the 13th of July (figure 19). Over 95% of the hand-picked events which occurring during the injection test were smaller than M_W 1.5 and over 50% were smaller than $M_W = 0.0$. However, if we take into account the results from MIMO, over 90% of the "total" seismic events detected were smaller than M_W 0.0. As can be seen in figure 19, most all seismicity occurred during injection of fluids. It should be pointed out that figure 19 only shows the larger events that IESE triggered on, so the detection threshold limit was set to about $M_W = -0.5$ in size. Figure 20 shows injection pressure vs. event depth during and just after injection for the same events in figure 19. As can be seen in figure 18, events deepened over time by 250 to 350 meters, with the mean depth of events occurring at about 3.95 km depth.

Seismic Moment vs. Injection Volume

During the main stimulation injection over 19,000 barrels, or just over 3 M litres, of fluid were injected during the five day period between the 11th and 15th of July 2011. Assuming that all the fluids must be accommodated in the opening of fractures, a net volume change must occur. As such, we feel that the only way to accommodate this volume change is through the "opening" of fractures and not through slip along a fault. Using Brune's (1968) formula we can estimate the total seismic moment needed for the opening of the fractures:

$$M_O = \mu * L * W * D$$

Where M_O = the seismic moment, μ = the rigidity of the rock, and L, W and D are the length width and displacement respectively along the fault. If we assume L*W*D = the Volume of Injection then we can rewrite this as:

$$M_O = \mu * \text{Volume of Injection}$$

Using an average value of $\mu = 2.0 \times 10^{11}$ dyne-cm^2 (typical for a depth of 4 to 5 kilometers below surface but can vary from 1.0 to 3.0 x 10^{11} dyne-cm^2) we get a total seismic moment for the opening of the fractures during the injection of ~6.08 x 10^{20} dyne-cm. We can further convert this seismic moment estimation to a moment magnitude, M_W, using the Kanamori's (1983) formula where:

$$M_W = (\log(M_O) - 16.1)/1.5$$

Kanamori formula shows that a $M_W = 3.12$ is required to accommodate the total volume injected based on the assumed rigidity of 2 x 10^{11} dyne-cm^2. Summing up the total seismic moment from each event in the seismic catalogue of hand-picked events, we get a total seismic moment of $M_O = 4.23 \times 10^{20}$ dyne-cm released during the injection, 10 July to 09:00 on the 15th of July. We get a further seismic moment release of M_O = 5.24 x 10^{19} dyne-cm after the injection stopped, 09:00 on the 15th of July to 23 August, for a total seismic moment released between 10 July and 23 August of $M_O = 4.76 \times 10^{20}$ dyne-cm. Using the Kanamori equations yields a total magnitude of M_W 3.02 for the injection, M_W 2.41 for post injection and M_W 3.05 from 10 July to 23 August 2011. These magnitudes match nicely with the estimation of $M_W = 3.12$ for the total seismic moment needed to accommodate the injected volume of fluid as we have not included all the smaller events, which will make up much of the difference of $M_W = 0.07$ difference.

Future Work

Future work on the Paralana-2 seismic data will involve calculation on the first motion for the larger events where we have good phase arrivals. Fault plane solution will be generated and plotted to see how, or if, there are any changes in polarity between injection events, post injection events and for events occurring outside the main fracture area (i.e. cluster to the southeast of the main swarm). We will additionally undertake a study of stress drop for events occurring during and after the injection to see if there are any differences, and if we can connect these differences to different zones, as well as a tomographic inversion of the data to generate a better 3D velocity model around the wellbore.

We will also be looking at any event associated with the first flow testing of the Paralana-2 borehole, which has yet to be completed as of the writing of this paper. Additionally, while not reported in this paper, we will be investigating various late phase arrivals seen in the waveform data. These late phase arrivals most likely have to do with reflections in the subsurface structures and could be used to help map the area around the Paralana-2 borehole. Additionally during the main stimulation a 4D Magnetotelluric (MT) study was being carried out by the University of Adelaide. We plan to integrate our finds with the results of the 4D MT survey.

Conclusions

Based on the seismicity recorded during and after the main injection testing at the Paralana-2 borehole, we can conclude that most of the fluids injected opened fractures. While at this point in time we cannot say if these are new fractures, or older fractures that have been reopened, the well head pressure post stimulation suggests that there is a connection to a natural fracture network. But at this time we cannot quantify the volume of new fracture vs volume of enhanced existing fractures. However we can conclude that most all the injected fluids did produce a net volume change and went into the opening of fractures. As of this writing, we have yet to find any correlation between pumping rates, pressures and the size of the seismic events, except to say that the largest events occurred during or just after pumping and at pressures near 9,000PSI. However, we can conclude that in the Paralana region it is highly unlikely that a larger seismic event can be generated.

From the seismicity plots, we can see that a fracture system was created that is approximately 1.35km long and ruptured predominantly to the northeast of the borehole, with some extension to the southwest after pumping ceased. We can also see that at least 4 structures have been enhanced by the fracture stimulation. The fracture network extended mostly downward and to the northwest along a steeply dipping plane with a vertical extent of approximately from a depth of 3,400 m to over 4,200 m. Additionally, we estimated that a maximum fracturing displacement of 3.5 to 4.5 millimeters is required to accommodate the injected volume of fluid.

Based on 2D seismic cross section, we think that the northeastern extent of the fracturing stopped at a structure subparallel to the mapped fault defining the eastern boundary of the graben. This structure appears to have acted as a hydrological barrier. Why the events went deeper over time and did not extend to the southwest is still not clear and may have been constrained by another barrier to the southwest of P2 (i.e. the smaller faults mapped in the 2D seismic cross section).

Overall, the authors feel that the injection of +3M litres of fluid into the Paralana-2 borehole was a success as the fracture volume generated was greater than planned by almost 800 %. Additionally, the Paralana-2 borehole took all the fluids injected. Therefore a new geothermal reservoir has been created and/or existing fractured permeability has been enhanced at the Paralana site. Future testing will show whether a true EGS system can be maintained. Testing of the injected fluids through a flow tests will help planning the next steps of the Paralana Geothermal Project by collecting data on pressure, flow rates, temperature and fluid chemistry.

Additionally the Paralana-2 stimulation showed the necessity for having a suitable micro-seismic monitoring network in place before, during and after any wellbore stimulation. Additionally having a real-time network running during the main stimulation should be required for any stimulation project carried out whether for EGS applications or other such operations, i.e. carbon sequestration, coal seam gasification and even oil/gas well fracing. The application of a real-time network during stimulation projects provides the operator, as well as the state/government, real-time feedback on what is happening several kilometers below them.

References

Brune, J., 1968, Seismic Moment, Seismicity, and Rate of Slip along Major Fault Zones, Journal of Geophysical Research, VOL. 73, NO. 2, 777-784pp

Kanamori, H., 1983, Magnitude Scale and Quantification of Earthquakes, Tectonophysics, 93, 185-199pp

Acknowledgements

On behalf of all the authors on this paper I, Michael Hasting, would like thank Petratherm LTD, Beach Energy Limited and TRUEnergy (the JV Partners) for selecting IESE to be part of the Paralana project and the monitoring of the induced seismicity. In particular, I would like to single out Terry Kallis, Managing Director of Petratherm, and Derek Carter, Chairman of Petratherm, as well as the other board members (Simon O'Loughlin, Richard Hillis, Lewis Owens and Richard Bonython) for all their support over the years. I would like to give a special thank you to Louise McAllister, Betina Bendall, and Brett Meredith, former staff members of Petraherm, who were instrumental in the development and deployment of the MEQ array. Additionally, I would like to single out the efforts of Trevor Wadham, Alex Silz and Mark Pitkin of Beach Energy for arranging the actual onsite support for the fracing program at the Paralana-2 site. This was a hard job well done.

I want to thank the entire IESE staff back in Auckland, as well as the staff of Auckland UniServices and the University of Auckland, for all their support in getting this project completed. I would like to acknowledge the efforts of Lianne Skinner for getting all the people where they needed to be and when they needed to be there; this was not an easy job and I thank you for doing it. Additionally, I would like to thank Drs. Peter Malin and Eylon Shalev for their continued support; I/we could not have done it without your input and insight. To Matt, Zhan, Annie, Alex, Christina, Reid, Marcos, Lake, Liam: Alan and others, thanks for getting me the equipment and helping with the deployments when I needed it the most. To Gary Putt, Analeise Murahindy and Kelvin Keh of UniServices: thanks for the contract support and making sure the bills were paid.

I would also like to take the opportunity to personally thank Craig Bartels, President of Heathgate Resources PTY LTD, for letting us stay at the Beverly Mining camp during the perforation and main fracing operations, as well as the Wooltana and Wertaloona stations, and for supporting the Paralana Geothermal Project. I would also like to thank his staff at Beverly for the great meals, accommodations and conversations. And to Peter and Debbie Moroney, station managers for Wertaloona and Wooltana, and Lindsay and Sian Mengerson of Wooltana; a special thanks for all the, support, chin wags and X^4, may we have many for in the future, next one is on me.

I would like to give a big thank you to the Doug and Marg Spriggs and the entire staff at the Arkaroola Wilderness Sanctuary. Doug and Marg have been a big supporter of the Paralana project over the years and provided sanctuary when Matt Hogg and I were stranded by a flashflood…..many thanks for helping us out, for the loan of the truck and for the great meals. Doug, you still owe me a flight over the Flinders….or maybe it is I who owes you.

I want to thank all the authors on this paper. This was a large and important project and I could not have done any of it without your support. This was truly a global effort with help from Norway, Germany, France, USA, New Zealand, Kenya and Australia. And finally, to my wife, Judith, thanks for putting up with all my long absence while working in the outback of OZ and your support at home. Again thank you to all and to those that I have not mentioned.