WEEKLY REPORT #3 TO ALTAROCK ENERGY INC.

PROCESSING OF INDUCED EARTHQUAKES ASSOCIATED WITH THE NEWBERRY EGS INJECTION STARTING SEPTEMBER 2014

GILLIAN R. FOULGER & BRUCE R. JULIAN
Brief summary

**Difficulties with transferring the complete data from the ISTI system to our computers still have not been fully resolved. Approximately 10% of the data are lacking from the files provided to us.**

We made some progress with relative relocations and have identified a high-quality subset of 177 earthquakes which we are exploring further.

We derived an additional nine moment tensors, bringing the currently available set to 24. As part of the moment-tensor derivation process, we pick arrival times of P- and S-waves extremely carefully, rotating the seismograms to the epicenter and re-examining post-location residuals in a number of passes. The locations cluster very tightly in two clusters separated in depth by a ~ 200 m zone within which no earthquakes occurred. It will be interesting to see if this pattern is maintained when more earthquakes are processed.

Moment tensors fall in the range +Dipole to -Dipole with approximately equal numbers of earthquakes showing crack-opening and crack-closure. The T-axes, which gives an indication of the direction of \( \sigma_3 \), cluster sub-horizontally \( S \pm 20^\circ \) or so. The P- and I-axes are more scattered.

1 **Task 1 – Planning, conference calls, discussion of work, correspondence, followup**

We continued to exchange frequent emails with other team members, primarily ISTI (Paul Friberg and Stefan Lisawski) as we worked to improve the completeness of the data. We participated in an AltaRock conference call 10/22.

2 **Task 2 – System Setup**

We are still experiencing difficulties with incomplete data, including missing earthquakes and missing channels. Our seismic processing methods use digital seismograms stored in AH format, which is machine-independent and easily generated from any other commonly used seismic format (miniseed, SAC, SEGY, etc.). In attempts to deal with problems of incompleteness and timing errors, we used to date several methods for obtaining data. None of these have proven to be entirely satisfactory:

- SAC-format files from AltaRock via VPN. These data often are truncated (traces beginning too late or ending too early) and/or have gross timing errors.
- “AH-format” files from AltaRock via VPN. These files are not in proper AH format and cannot be read.
- SEISAN-format files transferred via web browsers using the Dropbox facility. These data have damaged channel codes, which require time-consuming manual correction.
- AH files generated automatically by ISTI and stored on the server icedragon. This is the source of most of the data we have processed, but the files still contain many errors.

Appendix 1 shows the number of traces currently available for each station and for all triggered earthquakes between Sept. 26 and Oct. 19, 2014. Out of a total of 13,872 expected traces (292 triggers
× 48 traces/trigger), 1506 are missing altogether. Many others (which are difficult to count automatically) are truncated or have gross timing errors.

Dealing with these problems has occupied quite a lot of time, and the most troublesome problems have been ironed out. Nevertheless, as can be seen from the figures quoted above, about 10% of the data continue to be elusive.

We have pressed on with the data processing despite this data leakage. The high quality of the recordings has meant that many good and excellent moment tensors have been obtainable despite the problems. 24 moment tensors have been calculated to date, with earthquakes as small as magnitude M 0.68 yielding excellent solutions. It is likely that the ~ 100 moment tensors originally requested by AltaRock will be calculable.

3 Task 3 – Quality control of prepicked MEQs and preparation for relocation and moment tensor calculation

We continued to derive moment tensors, prioritorising the largest earthquakes. We continue to use the same procedure as described in our Weekly Report #1. We report here an additional nine moment tensors. The entire list of earthquakes processed to date is given in Table 1. We have provided the locations and moment tensor decomposition data to Trenton Cladouhos of AltaRock electronically, by email attachment.

Table 1: The 24 earthquakes for which moment tensors have been obtained. Locations given below are from the webpage http://fracture.lbl.gov/Newberry/locations.txt.
4 Task 4 – Improved locations and relative locations

4.1 Absolute locations

We updated our relocation of the earthquakes using qloc, our in-house location program. The epicentral locations up to Oct. 20 are shown in Figure 1, and a depth vs. time plot for the same locations is shown in Figure 2.

Figure 3 shows the week-by-week development of the seismic sequence.

Figure 4 shows ISTI epicentral locations for comparison with Figure 1.

The general picture has not changed with the addition of ~15 earthquakes. The cluster is still centered centered 100 to 200 m north of the bottom of well NWD 55-29 and is quasi-circular with a diameter of ~500 m.

Figure 5 shows the locations of the MEQs for which moment tensors were derived. These earthquakes are the largest and best-located, have been subject to the most careful processing and outlier-rejection. They are the most accurately located earthquakes available to date. They cluster in two very tight clusters near the bottom of well NWD 55-29, a shallower cluster slightly to the north of the well and a deeper cluster slightly to the south. An expanded view of these epicenters is shown in Figure 6. The depth distribution is shown in Figure 7. The earthquakes clearly fall into two depth intervals - one shallower than 1 km b.s.l. and the other deeper. There is a depth interval of ~200 m within which no earthquakes occurred.
Figure 1: Estimated hypocenters of 287 microearthquakes between Sept. 26 and Oct. 20, 2014 within the NMSA network. Most events lie within a circle about 500 m in diameter and centered 100 to 200 m north of the bottom of well NWD 55-29, which is shown in blue. These locations were obtained by using the qloc program to invert P- and S-phase arrival times measured by personnel of the ISTI Corporation on digital seismograms from the NMSA network.
Figure 2: Estimated depths, with respect to sea level, of 287 microearthquakes within the NMSA network as a function of time. The average depth decreases slightly with time because of a decrease in the number of deeper events. These depths were obtained by using the qloc program to invert $P$- and $S$-phase arrival times measured by personnel of the ISTI Corporation on digital seismograms from the NMSA network.
Figure 3: Estimated hypocenters of microearthquakes within the NMSA network as a function of time. (a) 2014 Sept. 26 – Oct. 02; (b) Oct. 03 – Oct. 09; (c) Oct. 10 – Oct. 16; (d) Oct. 17 – Oct. 19 (shorter interval). There is no clear tendency of events to migrate with time.

Figure 4: Estimated hypocenters of 298 microearthquakes between Sept. 26 and Oct. 20, 2014 within the NMSA network, as given in the earthquake catalog of the ISTI Corporation. These locations are slightly but significantly west of those shown in Figure 1, which were derived from substantially the same seismic data but using a different computer program. Well NWD 55-29 is shown in blue.
Figure 5: High quality estimated hypocenters of 24 microearthquakes that occurred between Sept. 30 and Oct. 05, 2014, and for which moment tensors were derived. These locations are computed using arrival times measured carefully in connection with the moment-tensor analysis. Well NWD 55-29 is shown in blue.
Figure 6: Expanded view of the area of the locations of the earthquakes for which moment tensors were derived.

Figure 7: Depth distribution for moment-tensor earthquakes.
4.2 Relative locations

Our relative location work is still at a preliminary stage because a great deal of time has been spent dealing with data difficulties. We show our very first results here.

Figure 8 shows a subset of the highest quality earthquakes extracted by the relative location program from the entire 287 set. This subset contains 177 earthquakes. These are the earthquakes that are “linked” to neighboring events by the largest number of “links”, i.e., they are recorded on the largest number of common stations. We are currently exploring the behavior of this high-quality subset.

Figure 8: Subset of 177 earthquakes that are well linked to one another and which will be used to calculate relative locations.
5 Task 5 Moment tensor calculations

Moment tensors were derived for an additional nine earthquakes using the same procedure as described in Weekly Report #1. There is no shortage of events that yield good or excellent results. The numerical results of the catalog to date are given in Table 2. Graphical results are shown in Appendix 2.

The source types for the entire 24-event set are shown in source-type space in Figure 9. The events form a distribution from the +Dipole to the -Dipole points, indicating a mixture of crack-opening and crack-closing events in approximately equal numbers.

Figure 10 shows a plot of the P-, T- and I-axes, approximately corresponding to the directions of $\sigma_1$, $\sigma_3$ and $\sigma_2$. Most notable is that the T axes cluster quite systematically subhorizontally and to the S $\pm 20^\circ$ or so. The orientations of the P- and I-axes are more scattered.

Table 2: Numerical moment tensor results for the 24 MEQs studied to date. N=North, E=East, D=Down.

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Foulger Consulting
Figure 9: Source-type plot showing all the 24 earthquakes for which moment tensors have been derived to date.
Figure 10: Plot of pressure ($P \sim \sigma_1$) and tension ($T \sim \sigma_3$) and intermediate ($I \sim \sigma_2$) axes for the 24 earthquakes for which moment tensors have been derived to date.

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Appendix 1: Chart showing number of traces provided, by station, for each earthquake. The expected number is three. Zero traces are available for many earthquake/station.

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Note: The expected number of traces per station is three. Zero traces are indicated by a zero value.
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- P: SH
- P: SV
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**Total Penalty** = 0.362

### Polarities

#### P

- North: 1.04e-01, 1.46e-01, 1.27e-01
- East: 1.46e-01, 2.54e-01, 1.36e-02
- Down: 1.25e-03, 1.33e-02, 7.33e-02

Scalar N0 = 2.783e-01

T = 0.164 k = 0.065
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2014 Oct 1 9:57:99 UTC
Lat: 43.7335 Lon: -121.108 Depth: 1.208
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Scalar NMO = 2.825e-01
T = 0.038 k = 0.026
Total Penalty = 0.198

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North East Down
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East -6.13e-02 -2.19e-02 3.52e-02
Down -3.52e-02 3.52e-02 2.09e-01

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2014 Oct 2 14:56:13.242 UTC
Lat: 43.7267 Lom: 121.106 Depth: 0.718
43.43.5996 N 121 18.4938 W

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Lat: 43.73517 Lon: -121.808 Depth: 1.235

Scalar N0 = 2.994e-01
T = 0.49s k = 0.060
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