2011 CSPG CSEG CWLS Convention

Using Seismic Source Parameters to Characterize Reservoir Deformation

Marc Prince*, Adam Baig and Ted Urbancic
Engineering Seismology Group, Kingston, ON, Canada
marc.prince@esg.ca

Summary

Microseismic data sets have been acquired for numerous years in order to determine fracturing distribution and fluid placement in heavy oil reservoirs. Processes such as waterflood, cyclic steaming, steam assisted gravity drainage and hydraulic fracturing have been used to increase permeability and recovery from the reservoir. Primarily, the microseismic event locations and first level source parameters are calculated and analysis of the data is performed in order to gain insight into the fracturing processes that are occurring in the reservoir. As demonstrated by Urbancic et al. (2002), the fracturing processes that occur in the reservoir are complex and can lead to unplanned movement of the injection fluid and/or hydrocarbon. Understanding these processes lead to a better understanding on how to optimize the treatment of the reservoir and in addition can provide some measure of safety during stimulation.

In this study, advanced analysis of seismic source parameters are calculated preceding and during an episode where loss of containment of steam occurred during a CSS operation. This behaviour suggests that real-time microseismic monitoring has the potential to probe the dynamic strain conditions of the reservoir, allowing for a better understanding of the causes of seismicity during injection operations, and leading to the development of response criteria during field operations.

Seismic Deformation Parameters

During enhanced oil recovery operations, microseismic monitoring is performed in order to locate events and calculate first order characteristics of the fracturing processing (e.g., magnitude). Beyond this initial analysis of location and magnitudes, additional analysis of the waveforms provides insight into the conditions responsible for the failure. It is important to note that microseismic events do not occur in isolation but do occur in the context of dynamically evolving deformation and stress conditions in the reservoir. For instance the seismic moment, which is directly utilized to obtain moment magnitude, is a measure of the strain induced by the event, and is related to the seismic waveforms through the low frequency behaviour of the displacement (Brune, 1970). Seismic moment is one measure of the size of an event but it does not indicate how energetic the failure is (how quickly the slip happens). In order to assess the slip rate the events seismic energy, E_s, can be analyzed giving us more information about the fracturing process. It should be noted that energy during the fracturing process is partitioned in multiple forms and the seismic energy is only the energy that is expressed as seismic waves; other process such as the friction of the fault surface and the fracture initiation (Aki and Richards, 2002) together typically release an order of magnitude more energy than the generation *of P* and *S* waves.

In general, fracturing processes generating seismicity during injection will show correlation between the seismic energy, E_s, and the moment magnitude, M_w. Because the entire frequency range is used to calculate the seismic energy, and only the low frequency component is considered to determine the seismic moment, deviations from this correlation can be indicative of different faulting types. To quantify this effect, we define a balanced energy ratio (EI) as a function of seismic moment and consider if the volume (or system) considered is retaining energy as compared to expected values. As shown in Figure 1, expected energy release values $\overline{E_S}$ are based on a least squares fit of the scatterplot of moment magnitude versus seismic energy. As such, regions with high energy index are undergoing deformation more energetically than average given the moment of the events.

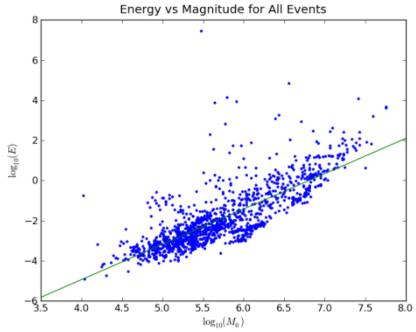

Figure 1. Log-log scatterplot of seismic moment versus seismic energy for the events over a several month period. Although there is correlation, significant distance from the best-fitting line (green) indicates a variety of deformation styles

In addition to the parameters discussed above, the apparent volume of events generated during the injection processes is also analyzed. Many zones of permanent deformation and complex geometry are accompanied by a local volume change. Apparent volume can be used to provide insight into the rate and the distribution of coseismic deformation and/or stress transfer in a rockmass.

Data

Microseismic data was acquired utilizing a downhole multi-well, multi-level 3C network over multiple months in a CSS operation. During this period, events were observed to migrate into the formation overlying the reservoir, suggesting a potential over-pressuring of the reservoir has occurred. Changes in nearby pressure measurements during this period were also observed. A subset of the data covering a three week interval surrounding the volume of interest was analyzed to determine if there was any correlation between the observed seismic parameter responses, as discussed earlier, and the recorded pressure measurements. These events, coloured by moment magnitude, are shown in Figure 2.

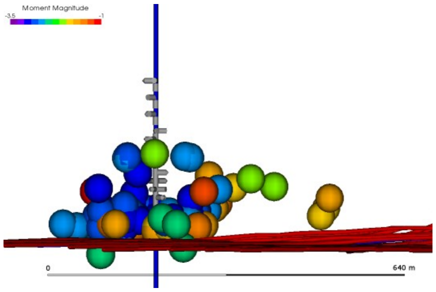

Figure 2. Events located during the three weeks of steaming, coloured by moment magnitude with purple corresponding to Mw=-3.5 and red Mw=-1.

Figure 3 shows the pressure that was recorded during the injection program. There is an initial increase in the pressure as the steam treatment begins, followed by an inflation one week later. During this inflation period, the pressure increases steadily until it begins to spike, corresponding to a possible over-pressuring of the volume.

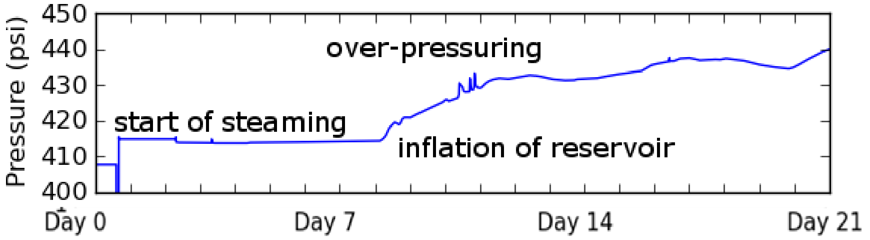

Figure 3. Pressure curve for a 21 day period.

The overall inflation is reflected well in the plot of cumulative moment with time, shown in Figure 4. The cumulative moment is calculated both for reservoir level events (green) and for above reservoir, mid-level events (red). The moment can be taken to be a measure of the strain in the reservoir, and it mirrors the trend of the pressure curve plotted in Figure 3. Highlighted in blue is the period of observed over-pressuring, which also corresponds to a vertical movement of seismicity into the mid-level region. In general, the cumulative seismic moment does not show any specific change to identify any anomalous changes have occurred during this period.

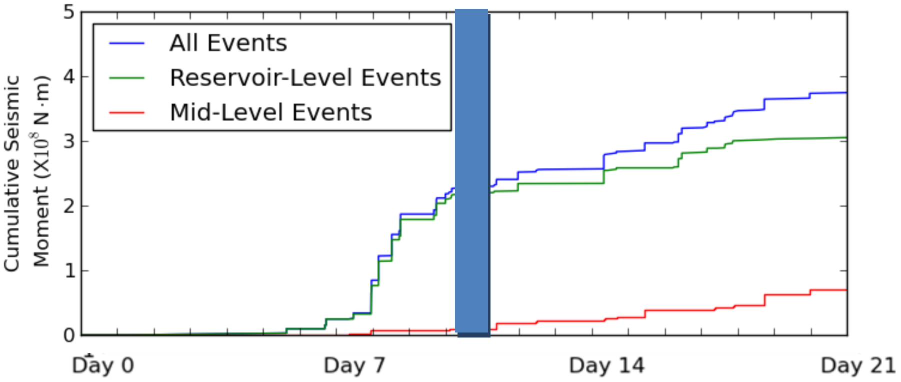

Figure 4. Cumulative seismic moment during the 21day monitoring period. The over-pressured interval is highlighted in blue.

Figure 5 shows the curves of cumulative apparent volume with time. There is a clear response in the mid-level events to the observed over-pressuring as the cumulative apparent volumes for these events are very large. This suggests, that an induced change in deformation has occurred. In particular, the co-seismic deformation accompanying these events is very large and much of the strain induced by the reservoir level events is inducing a transfer of stress above.

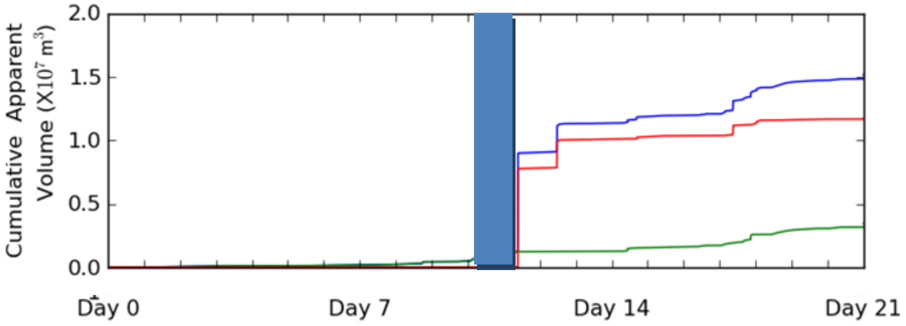

Figure 5. Cumulative apparent volume during the 21 day monitoring period.

The energy index plot, shown in Figure 6, completes the picture of the seismic deformation in the volume of interest. Here the reservoir-level events show a large decrease in energy index of energy corresponding to the initiation of the inflation of the reservoir. This drop would indicate that these events are putting more energy into the reservoir and less into seismic radiation than expected given their moments. The mid-level events show a moderate decrease in energy index after the over-pressuring interval, which suggests that energy is not being radiated away but potentially being stored as deformation in the volume.

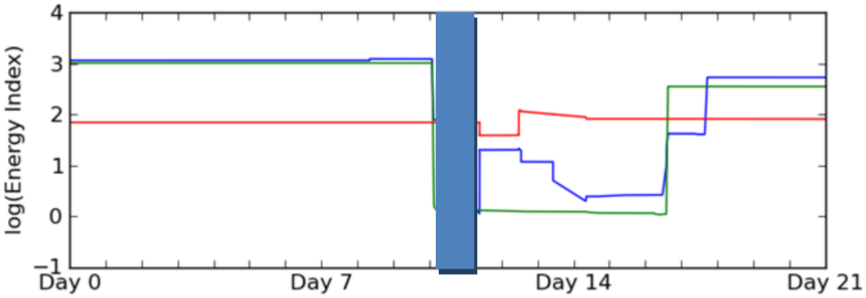

Figure 6. Energy index plot for the 21 day monitoring period.

Conclusions

Seismic waveforms contain significant information on the source characteristics generating seismicity and inherently the rock behaviour associated with the activity. Additionally, source parameters give higher-order insight into how the rockmass deforms and the states of stress and strain in the reservoir. In the example provided, the inflation of the reservoir is observed in the cumulative seismic moment and a subsequent over pressure situation is mirrored in the apparent volume. The initiation of these processes can be seen in the energy index plots. As such, it can be suggested, that additional analysis of source characteristics provides an opportunity to potentially identify spatial and temporal conditions associated with changes in reservoir conditions.

References

Aki, K. and Richards, P. G. (2002), *Quantitative Seismology*, Second Edition, University Science Books.

Brune, J. N. (1970), Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, **75**, 4997-5009, *Correction in J. Geophys. Res.,* **76**, 5002, 1971.

Urbancic, T. I., Maxwell, S. C., Steinsberger, N., and Zinno., R. (2002), Microseismic Imaging of Hydraulic Fracture Complexity in a Naturally Fractured Reservoir, 64th EAGE Conference and Exhibition, Florence, Italy.