Integration
geoConvention 2013
geoscience
engineering
partnership

Stress Re-Distribution During Long-Term Steam Injections and Its Potential Influence on Reservoir Development

Katherine Buckingham*, Engineering Seismology Group, Kingston, Ontario, Canada
Katherine.buckingham@esgsolutions.com
and
Adam Baig, Ted Urbancic, Anisa Kassam, Engineering Seismology Group, Kingston, Ontario, Canada

Summary

Numerous studies have been carried out to calculate source mechanisms associated with hydraulic fracture stimulations and identify the potential fracture orientations responsible for observed seismicity as well as the modes of failure consisting of fracture opening, closing, slipping, or some combination thereof (e.g. shear-tensile). However, relatively little work has been done to investigate the source processes occurring during EOR steam injection activities, primarily due to the lack of coverage provided by typical single array networks. The monitoring of microseismicity generated by reservoir activities include the identification of steam chamber development, cap-rock issues, casing failures, and fault activation. A number of logistical issues make moment tensor analysis of reservoir monitoring data more difficult than the same analysis for hydro-frac data. To assess the potential for assessing reservoir activities, we have carried out a moment tensor analysis for a dataset recorded over a period of approximately eight months at a steam injection site in an oil reservoir. A cluster of 583 moment tensors were analyzed to reveal the source mechanism behavior of the region near a steam injection well. The early events in the cluster occur during and just after steam injection, and appear to be related to thermal changes and/or stress redistribution. A large number of events occur more than a month after the end of injection, and show quite different source mechanisms and strain orientations from the earlier activity. The progression of source behavior indicates a rotation of the local stress field and an apparent change in the driving cause of the microseismic activity over time.

Introduction

Long-term steam injection for enhanced oil recovery is performed in many petroleum reservoirs, both new and aging. To observe steam chamber growth and for early warning of possible environmental problems, many such projects are monitored with microseismic systems.

In hydraulic fracture monitoring, a great deal of work has been done studying the source mechanisms of the recorded microseismic events, revealing a general pattern of fracture growth (e.g. Baig and Urbancic, 2010). Source mechanisms for events occurring in this sort of regime tend to fall along a continuum from tensile crack opening through double couple (shear, slip on a fracture plane) to crack closure. However, relatively little has been done to study the source mechanisms which are recorded during steam injection production processes, such as CSS or SAGD. Such projects are often monitored by microseismic systems, but the number which have multi-array monitoring configurations required to resolve moment tensors is relatively few. Also, because event rates are lower for these long-term projects, it can take months to years of monitoring before the microseismic dataset is large enough to provide statistically significant information about what is going on.

For the case study presented here, a multi-array microseismic monitoring system was installed to observe the activity associated with the steam injection process in an oil reservoir. Monitoring has been ongoing for a period of two and a half years since the start of steaming. For the purposes of this study, we have focused on an eight-month period that includes injection-related and post-injection microseismicity. Steam is injected in a few wells to mobilize the petroleum, which migrates down-dip to be produced from other wells. A large number of events were recorded by the microseismic system. These events are highly clustered spatially. Some clusters of events correlate with steam injection, while others do not appear to. The largest cluster of events is analyzed in detail here with the moment tensor results to determine the underlying processes that are occurring.

Site Setup and Dataset

Six arrays of three-component geophones were deployed downhole around the area of steam injection to monitor microseismicity. There are two steam injection wells in the immediate area, and a few others more distant from the arrays. During the period of interest, a total of 824 events were recorded on two or more sensor arrays and determined to be well-conditioned for Seismic Moment Tensor Inversion (SMTI^{TM}). Spatially, these events fall into six separate clusters around the pad. The largest cluster includes 583 events, while the smallest includes only 10. In this case study we focus on the largest cluster of events, as it provides the most statistically significant information about the underlying processes. Figure 1 shows the locations of the events in this cluster. The lines in this figure are wellbores; blue wells have sensor arrays deployed in them, and red wells are used for steam injection. There is an injection well at the left-hand side of the cluster in Figure 1, which the events do connect to.

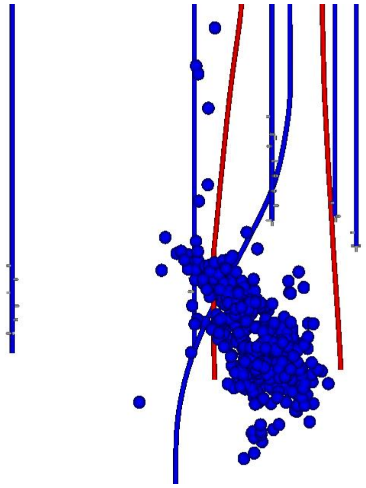

Figure 1: Locations for all events analyzed.

The moment tensor solutions for these events have been obtained in two different ways. General solution moment tensors were well-conditioned for 455 of the 583 events. General solution SMTI solves for the full moment tensor, with six free parameters. The remaining 128 events had poorly conditioned general solutions, and instead have moment tensors calculated by assuming the deformation is completely described by slip on a fracture plane. These double couple (DC) mechanisms require only four free parameters, making the inversion more stable than for general solutions. DC solution SMTI provides less information about the microseismicity, but it is still useful for determining the orientation of the strain occurring (and by extension the overall state of stress).

Temporal Analysis

For the majority of the events it is clear that the activity tends to occur in short bursts separated by longer quiet periods. For further analysis, the cluster is broken down into five temporal divisions as indicated in Figure 2, which have been labeled as Development and Bursts 1 through 4. The Development period includes all activity in this region from the start of monitoring until the beginning of Burst 1. Figure 2 also shows the steam injection data for the nearest injection well. There is no steam injection during Bursts 1 through 4, so the cause of the microseismic activity cannot be immediately attributed to steam injection. Figure 3 shows the locations of events in each of these sub-divisions.

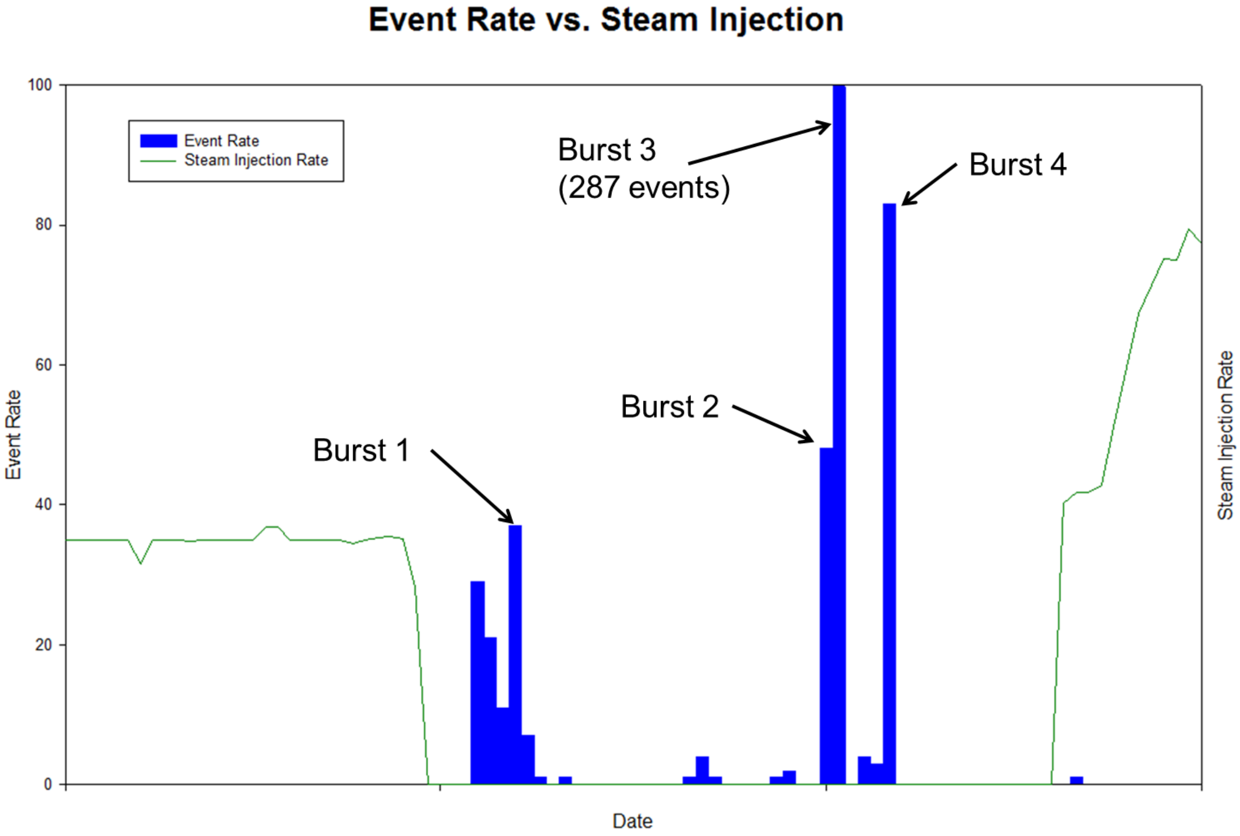

Figure 2: Daily event rate plotted with the steam injection data for the nearest injection well. This graph starts approximately 6 months after the start of steaming. Divisions of the Date axis are at 1-month intervals. Previous activity in the Development phase occurred during an earlier steam cycle.

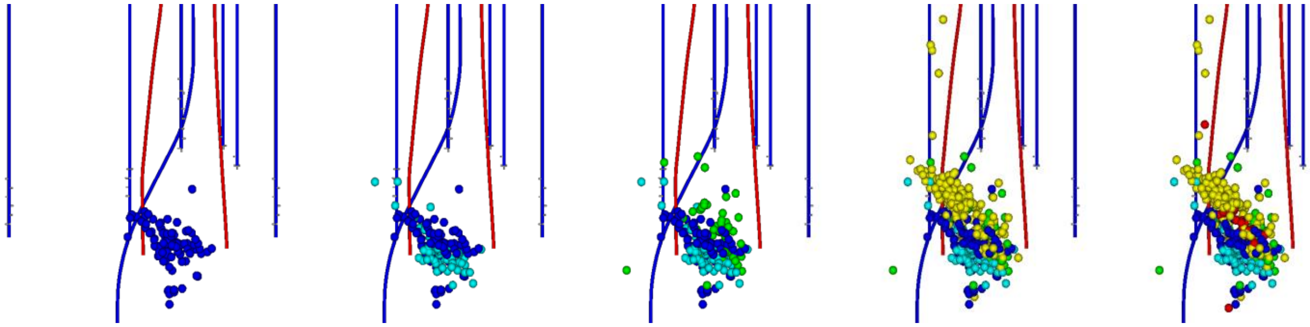

Figure 3: From left to right, cumulative locations for the five event sub-divisions (i.e. farthest left is Development only, next is Development and Burst 1, etc.).

Moment Tensor Results

Figures 4 and 5 show some of the results from the moment tensor analysis. Figure 4 shows source-type plots (after Hudson et al., 1989) for all general solution moment tensors for the five sub-divisions. Figure 5 shows the orientations of the primary strain axes (P and T) for each moment tensor, contoured on an equal-angle stereonet. The regional maximum horizontal compressive stress is oriented approximately NE-SW as shown. Based on these plots, the Development and Burst 1 phases show approximately the same behavior with nearly identical strain axis orientations and source mechanisms which are associated with single fractures (although Burst 1 is dominated by fracture opening while the Development period is more evenly split between opening and closure). Burst 2 appears to be some sort of transitional period, with both the source-type plot and strain axes showing characteristics of both the earlier and later phases of activity. Bursts 3 and 4 are dominated by source mechanisms between double couple and explosive, and have maximum compressive strain orientations (P axes) rotated approximately 90° from the Development and Burst 1 phases. The orientations of the P axes in Bursts 3 and 4 are consistent with the regional maximum horizontal stress direction, while the P axes observed in the Development and Burst 1 phases are generally not.

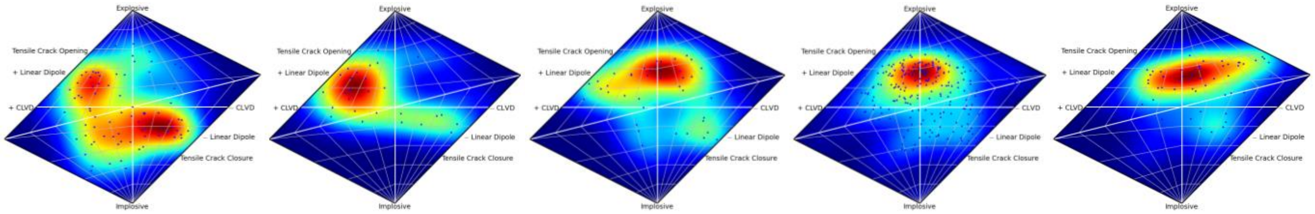

Figure 4: Source type plots for all five sub-divisions (general solutions only). From left to right: Development, Burst 1, Burst 2, Burst 3, Burst 4.

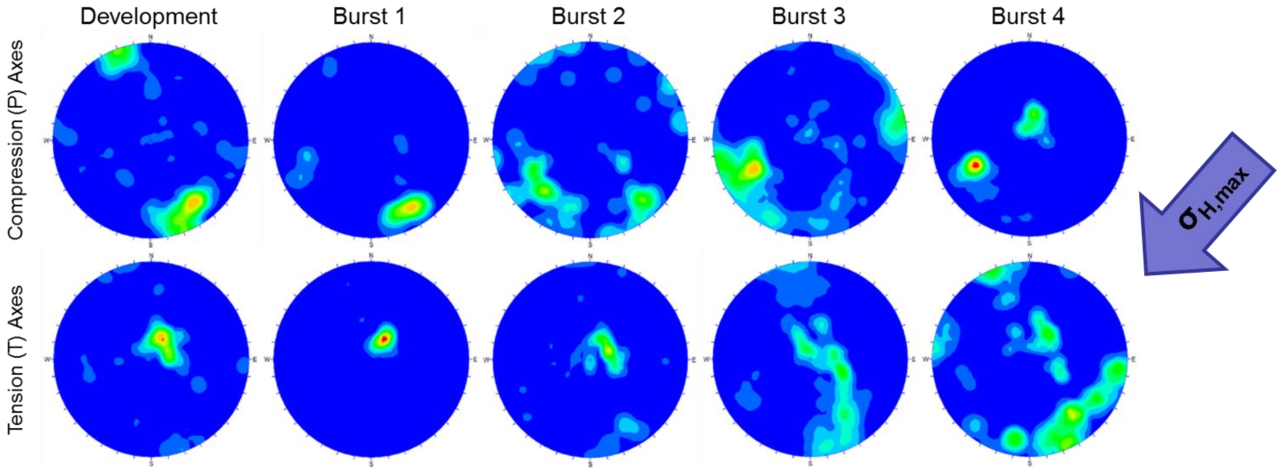

Figure 5: Stereonets showing the density of strain axis orientations for all five divisions (all moment tensors). These show a progression over time, likely indicating a rotation in the primary local stress directions. The arrow at right indicates the regional maximum horizontal stress direction.

Interpretation

With relatively little information about what was occurring on site, interpretations of the underlying physical processes are mostly speculation. The Development phase activity shows fracture growth behavior, and can be attributed to steaming (migration of either steam or petroleum through fractures in the reservoir). After steaming stops, there is some relaxation of the reservoir (end of Development and Burst 1 events) with continuation of the same fracture behavior observed during steaming. The strain axes orientations observed for this injection-related activity are inconsistent with the regional stress regime, indicating that steam injection has changed the local stress regime. After a few weeks of quiescence, a large amount of activity suddenly occurs (Bursts 2 through 4) showing upward migration of the events accompanied by a rotation of the local stress regime and a change to more inflationary source mechanisms. One possible interpretation of this later activity is that a pocket of steam was trapped in the reservoir and suddenly migrated upwards. The rotation of the observed strain directions show a return to a state of stress which is consistent with the regional stress regime after steaming stops.

Conclusions

Overall, the results show a temporal progression from the Development and Burst 1 phases to the activity observed in Bursts 3 and 4. Development and Burst 1 activity can be attributed to steam injection itself and residual thermal changes and stress redistribution after steaming stops. Bursts 2 through 4 occur just over a month after the end of steaming. The moment tensor data for these later phases shows a very different behavior from the early activity, requiring some other explanation for the cause of the microseismicity. Differences observed in the primary strain axes orientations indicate that the local stress conditions are changing over time after steam injection stops.

References

Baig, A. and Urbancic T.I., 2010, Microseismic moment tensors: A path to understanding frac growth: The Leading Edge, **29**, 320-324.

Hudson, J.A., Pearce, R.G., and Rogers, R.M., 1989, Source Type Plot for Inversion of the Moment Tensor: Journal of Geophysical Research, **94**, 765-774.