Induced fracture analysis from microseismic catalogues: Salton Sea EGS case study

Juan M. Reyes-Montes
Applied Seismology Consulting, Shrewsbury, United Kingdom

ABSTRACT: Enhanced Geothermal Systems (EGS) use hydraulic fracturing to create a fracture network that facilitate the circulation of water between injection and extraction boreholes. Microseismic monitoring provides a unique method for the evaluation of the effectiveness and impact of the stimulation and reducing potential risks such as uncontrolled growth or induction of high magnitude seismic events. This study presents tools to interpret the geometry of the induced fracture network and quantify the changes in fluid conductivity induced in the reservoir during stimulations applied to a catalogue of over 8,000 events recorded at the Salton Sea Geothermal field over a 4-year period. The method integrates the temporal, spatial and size characteristics of the induced events to quantify the degree of interaction and connectivity between the fractures within the network, identify enhanced paths for fluid flow and highlight potential zones of induction of larger seismic events.

Keywords: Microseismicity, Induced seismicity, Enhanced Geothermal Systems, Clustering, Discrete Fracture Network.

1 INTRODUCTION

The objective of Enhanced Geothermal Systems (EGS) is the creation of a fracture network geometry that facilitates the maximum circulation of fluid between injection and production wells to maximize heat exchange avoiding interaction with in-situ faults that may potentially trigger damaging seismicity at the surface and neighbouring infrastructures. Ensuring that the suitable fracture network is stimulated and permeability is enhanced requires careful planning that typically involves modelling of the fracture growth based on local stress magnitude and orientation, reservoir rheological and fluid conductivity properties and characteristic of the in-situ Discrete Fracture Network (DFN). However, the impact of heterogeneity, local stress shadows and rotation and the fracturing process itself can result in unpredicted fracture growth deviating from the target objectives.

Microseismic monitoring of the microseismic activity associated to the induced fractures provides an essential feedback in EGS operations by imaging the fracturing process as it develops allowing the adoption of remedial actions that reduce potential risks. A valuable information extracted from the microseismic catalogue is the interpretation of the geometry of the induced fracture network, the connectivity within the network and its relation with mapped in-situ structures.

2 DATA

The Salton Sea Geothermal Field locates to the southeast of the Salton Sea, in Imperial County in southeast California (Figure 1) and has been in operation since the 1980's with a total of 28 production wells and 41 injection wells for disposal of brine and maintaining the reservoir pressure. Tectonically, this region is the extensional step-over between the San Andreas and Imperial faults (Muffler & White 1969). The reservoir is at a depth between 1,500 and 2,000 m. In general, seismicity in the area is characterized by small, M<1.5 events at shallow depths between 0.5 and 3.5 km (Gulpin & Lee 1978), due to the high heat flow observed in the area, with focal mechanisms mostly consistent with a system of en-echelon, right-lateral , strike-slip transform faults. While most of the monitored seismic activity in the area is closely related to the stress changes during extraction and injection of fluids, there are observations of activity triggered by large regional events, e.g. the 2010 M_w 7.2 El Mayor-Cucapah earthquake (Meng et al. 2010) and teleseismic events (e.g. Castro et al. 2017).

The data set analysed in this study consists of a catalogue of 8,383 microseismic events recorded over a four-year period between 2008 and 2012, processed and published by the Lawrence Livermore National Laboratory (2013) located within the geothermal field.

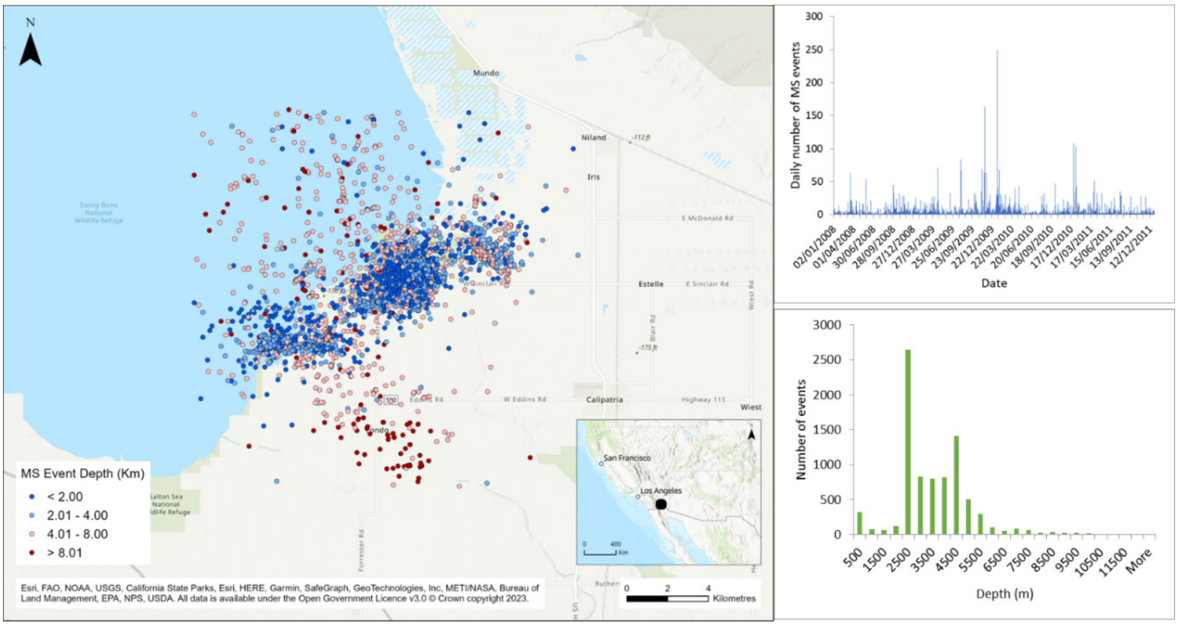

Figure 1. Map view of the microseismicity induced around the Salton Sea Geothermal Field between January 2008 and December 2011. Events are coloured by depth. Histograms show the temporal (top) and depth (bottom) distribution of the 8,383 MS events located during this period.

3 MICROSEISMIC CATALOGUE ANALYSIS

A series of statistical analysis can be applied to microseismic catalogues in order to characterize the underlying geometry of the induced or mobilized fracture network. The initial inspection of the MS events in the geothermal field clearly shows that events group in distinct spatial clusters as indicated by the pair analysis and quantified by the degree of spatial randomness (Figure 2). The deviation in the distribution of interevent separation from what would be obtained for a uniform random distribution observed at short interevent separations is typically observed in induced seismicity or aftershock series (e.g., Eneva et al. 1992). In the case of the events analysed in this study, a clear deviation from a uniform distribution is observed for distances below approximately 2,000 m, giving an indication of the dimension of interconnected fractures corresponding to a single stimulated macro-fracture. A simple k-means clustering is used to objectively separate the events into the optimum number of clusters using a proximity regrouping of the starting number, splitting the population into three principal clusters.

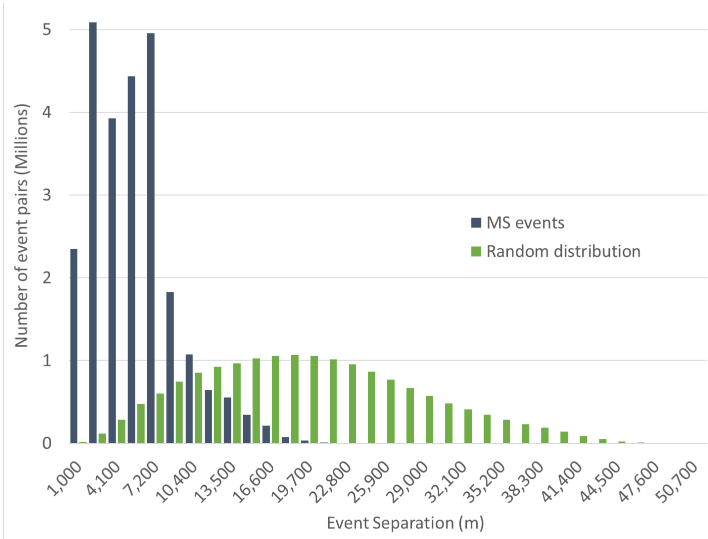

Figure 2. Distribution of intervent separation for the population of 8,383 events in the case study (blue) compared with the distribution obtained for a similar population of events uniformly distributed in the same volume. The deviation between both distributions is an indication of the non-randomness of the activity.

The next step is analysing and quantifying the interaction between the individual fractures forming each of the identified clusters. For this analysis, an approach to quantify the degree of spatial clustering of seismic events, based on the Cluster Index (Lockner et al. 1992 and Falmagne, 2002) that combines event location and size is applied. The Cluster Index is based on the concepts of critical crack spacing and density, modelling the decay of the tension induced by dilating cracks, applying it to the source of MS events interpreted as fractures with radii given by their source radius measured from the corner frequency of the recorded spectrum. Hanks and Wyss (1972) consider the ratio $d_{ij}/L \approx 2$ as the maximum limit for crack interaction, where d_{ij} is the separation between fractures and L their length. Based on this criterion an index is defined to quantify the interaction between neighbouring fractures:

$$CIf_{ij} = \frac{1}{2}\left[1 + cos\left(\frac{\pi}{2}\frac{d_{ij}}{r_{0i}+r_{0j}}\right)\right] \text{ and}$$

$$\boldsymbol{CIf_{ij} = 0} \qquad \text{for } \frac{\boldsymbol{d_{ij}}}{(\boldsymbol{r_{0i}+r_{0j}})} > \boldsymbol{2} \qquad (1)$$

where r_{0i} and r_{0j} are the source radii, and d_{ij} their separation. The total degree of interaction for a particular fracture with all their neighbours (N) can therefore be quantified by the sum $\mathrm{cCI_i} = \sum_{j=1}^{N} \mathrm{CIf_{ij}}$. Based on this, cCI = 0 indicates an isolated event that is essentially out of the neighbouring events stress fields, and cCI > 0.5 indicates that the event has coalesced with a single neighbour or is interacting with several neighbouring events. A value 0 < cCI ≤ 0.5 indicates potential interaction with one or more neighbouring events but no coalescence.

The use of the Cluster Index allows the identification of events generated from isolated, potentially interacting and coalescing fractures. The latter set of events can be used to delineate the zones with enhanced conductivity and identify potential growth of major failure zones, which could correspond to unmapped faults with potential for the generation of larger magnitude events. Figure 3 shows the effect of using the Cluster index to filter out isolated events from the seismic cloud to highlight the 5,786 events related to fractures with potential for enhancing the fluid conductivity within the reservoir or most critically interact with critical structures outside of the target area. The Cluster Index is used to quantify the degree of interaction within the three clusters of induced microseismic events (Figure 4). The percentage of clustered events shows that the fracturing process is mostly controlled by growth along interacting fractures, particularly in the central cluster where ~70% of the located events are within the interaction volume of a neighbour event.

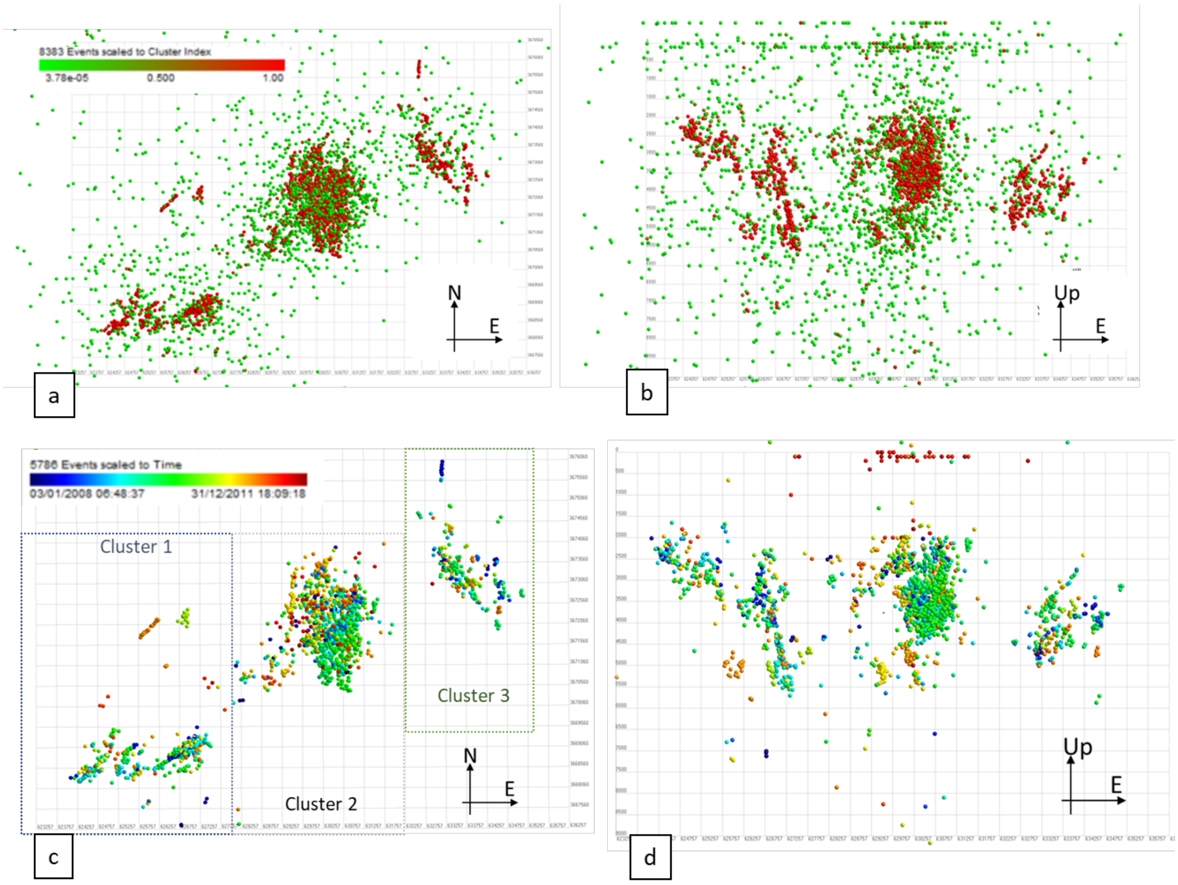

Figure 3. Distribution of microseismic events detected and located between January 2008 and December 2011 in the Salton Sea Geothermal Field. Top row shows all events colour scaled to the value of the Cluster index with red colour indicating potentially coalesced fractures. a, map view, b, side view looking North. Bottom row, the 5,786 events with Cluster index>0.5 colour scaled to time to highlight the induced or mobilised fractures potentially coalesced, corresponding to zones of enhanced fluid conductivity. c, map view, d, side view looking North. Grid spacing: 500 m.

The geometry of the induced or mobilised fracture network, particularly the orientation of the fracture plane, is crucial for the evaluation of the change in fluid conductivity within the reservoir and also for estimating potential risks of interaction with known geological structures. To investigate the structure within the seismic cloud and characterize the geometry of the mobilised fracture network a statistical analysis of the event distribution is used, applying the three-point method (e.g. Reyes-Montes & Young 2006 and Fehler et al. 1987), to automatically calculate the orientation of planes that fit every unique combination of three events. By plotting the poles of the calculated planes on a stereogram, preferential orientations are highlighted by areas of high density and allow the automatic identification of any preferential orientation within each cluster (Figure 5), which can be correlated with the orientation of the induced or mobilised macrofracture. The preferential orientation observed in the pole plot can be interpreted as the orientation of the macro-fractures formed by multiple microcracks that describe a macroscopic active Discrete Fracture Network (DFN). Further analysis of the distribution of the separation and extent of the fitted planes following the observed dominant orientation can be used to obtain information about the spacing and persistence of the dominant fracturing, providing the essential information for the definition of the active DFN.

The results show well-defined maxima for the three identified clusters, with dominant structures defining in general sub-vertical planes, with azimuth along the observed maximum horizontal regional stress, ~NE-SW (Heidbach et al. 2016) in the case of the central cluster which includes most of the microseismic activity. Clusters 1 and 3 show dominant orientations rotated with respect to the central cluster by 45°-60°, likely responding to local geological structures or stress rotations. Further investigation is required to confirm the correlation of the observed trends with local geological data, e.g. in-situ fabric, heterogeneity or known structures.

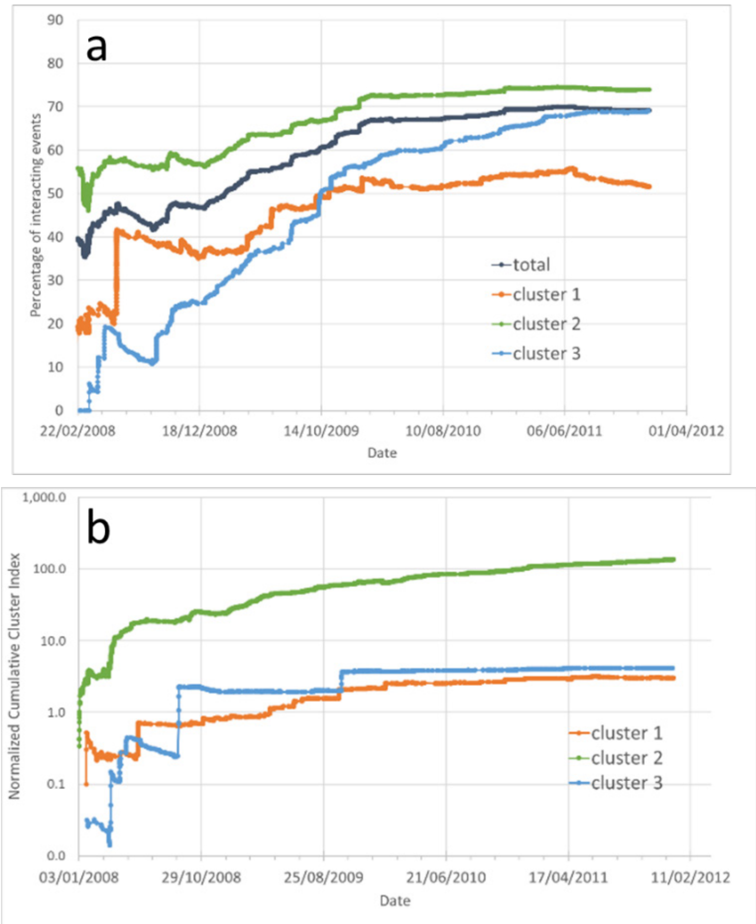

Figure 4. a. Percentage of induced events with cluster index>0.5, indicating that locate within the interaction volume of neighbour events and indicate potential coalescence and creation of paths for fluid circulation. The analysis is shown for the total catalogue and split between the three observed clusters. b, Evolution of the cumulated cluster index in the three clusters of microseismic events.

The analysis of the catalogue of microseismic events induced in the area of the Salton Sea Geothermal Field has shown the potential of microseismic monitoring for imaging the fracturing process and extracting information on the changes in the permeability of the stimulated reservoir and the geometry of the mobilised fractured network. This process can be implemented in real time to provide immediate feedback on the impact of reservoir stimulation operations and allowing remedial actions when seismicity locates out of formation or in the proximity of large faults with potential for triggering of damaging seismic event.

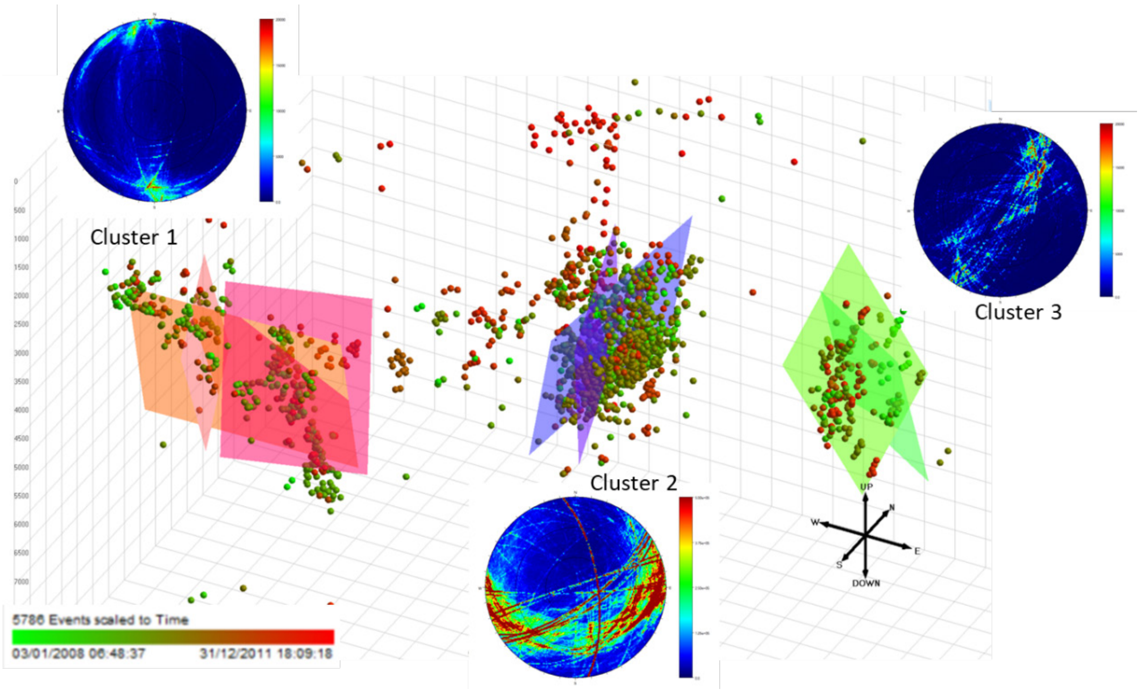

Figure 5. Analysis of the underlying structure within each of the three identified clusters of interacting events (Cluster Index>0.5). The stereographs show the poles to the planes fitted to every combination of three events within each cluster. The maxima in each stereograph indicates the dominant orientation and is interpreted as the trend of the fracture network. Planes corresponding to the maxima in each cluster are displayed in the 3-D view for illustration.

REFERENCES

Castro, R.R., Clayton, R. Hauksson, E. & Stock, J. 2017.Observations of remotely triggered seismicity in Salton Sea and Coso geothermal regions, Southern California, USA, after big (Mw>7.8) teleseismic earthquakes. Geofisica Internacional 56-3: 269-286.

Eneva, M., Hamburger, M.W., & Popandopulo, G.A. 1992. Spatial distribution of earthquakes in aftershock zones of the Garm region, Soviet Central Asia. Geophysical Journal International, Volume 109, Issue 1 (1992), 38–53,

Falmagne, V. 2002. Quantification of rock mass degradation using micro-seismic monitoring and applications for mine design, Ph.D thesis, Queen's University, Kingston, Canada.

Fehler, M., House, L., & Kaieda, H. 1987. Determining planes along which earthquakes occur – Method and application to earthquakes accompanying hydraulic fracturing. Journal of geophysical Research – Solid Earth and Planets, 92 (B9), (1987), 9407-9414.

Heidbach, O., Rajabi, M., Reiter, K., & Ziegler, M. 2016. World Stress Map 2016. GFZ Data Services. https://doi.org/10.5880/WSM.2016.002

Lawrence Livermore National Laboratory. 2013. Microearthquake Studies at the Salton Sea Geothermal Field [data set]. Retrieved from https://dx.doi.org/10.15121/1148809.

Lockner, D.A., Moore, D.E., & Reches, Z. 1992. Microcrack interaction leading to shear fracture, in Proceedings of the 33rd U.S. Symposium on Rock Mechanics, edited by J.R. Tillerson, and W.R. Wawersik, pp. 807-816, A.A. Balkema, Rotterdam.

Meng, X., Yu, X., Peng, Z. & Hong, B. 2012. Detecting earthquakes around Salton Sea following the 2010 M_w7.2 El Mayor-Cucapah earthquake using GPU parallel computing

Muffler, L.J., & White, D.E. 1969. Active metamorphism of upper Cenozoic sediments in the Salton Sea Geothermal Field and the Salton Trough, Southeastern California, Geol.Soc. Am. Bull., 80, 157-182.

Reyes-Montes, J.M., & Young, R.P. 2006. Interpretation of fracture geometry from excavation induced microseismic events. In Eurock 2006 – Multiphysics coupling and long term behaviour in rock mechanics. Van Cotthem, Charlier, Thimus and Tshibangu (eds). Taylor & Francis group.