# Natural or Induced: Identifying Natural and Induced Swarms from Pre-production and Co-production Microseismic Catalogs at the Coso Geothermal Field

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## Abstract

Discrimination between induced and natural seismicity is especially difficult in areas that have high levels of natural seismicity, such as the geothermal fields at the Salton Sea and Coso, both in California. Both areas show swarm-like sequences that could be related to natural, deep fluid migration as part of the natural hydrothermal system. Therefore, swarms often have spatio-temporal patterns that resemble fluid-induced seismicity, and might possibly share other characteristics.

The Coso Geothermal Field and its surroundings is one of the most seismically active areas in California with a large proportion of its activity occurring as seismic swarms. Here we analyze clustered seismicity in and surrounding the currently produced reservoir comparatively for pre-production and co-production periods. We perform a cluster analysis, based on the inter-event distance in a space-time-energy domain to identify notable earthquake sequences. For each event *j*, the closest previous event *i* is identified and their relationship categorized. If this nearest neighbor's distance is below a threshold based on the local minimum of the bimodal distribution of nearest neighbor distances, then the event *j* is included in the cluster as a child to this parent event *i*. If it is above the threshold, event *j* begins a new cluster. This process identifies subsets of events whose nearest neighbor distances and relative timing qualify as a cluster as well as a characterizing the parent-child relationships among events in the cluster.

The cluster identification method used yields a hierarchy of links between multiple generations of parent and offspring events. We analyze different topological parameters of this hierarchy to better characterize and thus differentiate natural swarms from induced clustered seismicity and also to identify aftershock sequences of notable mainshocks. We find that the branching characteristic given by the average number of child events per parent event is significantly different for clusters below than for clusters around the produced field.

## Coso Geothermal Field and seismicity

- Young volcanic system
- Situated in Eastern California Shear Zone (transition from SAF to Basin and Ranges)
- Exploration 1970s – 1980s
- Base-line microseismic surveys:
  - Summer 1974 (Combs & Rotstein, 1975)
  - Sept 1975 – Sept 1977 (Walter & Weaver, 1980)
- Production online since 1987
- Local catalog 1996 – 2012 with >140,000 events

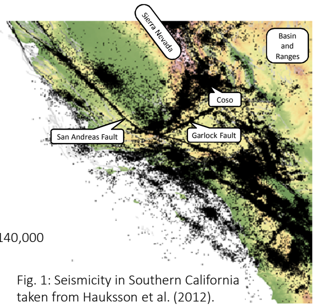


Fig. 1: Seismicity in Southern California taken from Hauksson et al. (2012).

- WW80 (Walter & Weaver, 1980)
  - Sept 1975 – Sept 1977
- SCSN (Hutton et al, 2010)
  - SCSN network all over CA
  - 1932 – present
- HYS (Hauksson et al., 2012)
  - SCSN relocations
  - 1981 – 2013

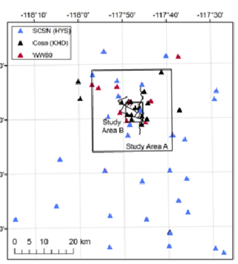


Fig. 2: Seismic monitoring networks used by the WW80 base-line survey, the local monitoring system and the Southern California Seismic Network

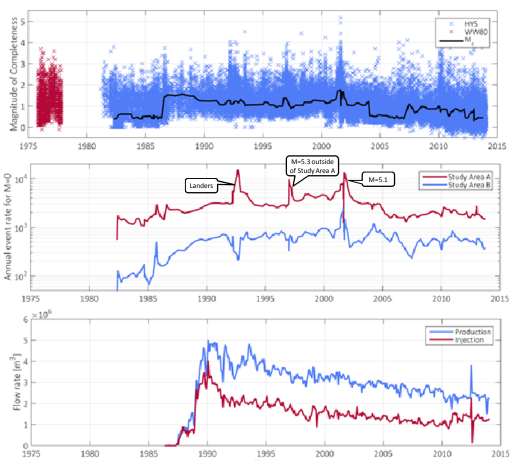


Fig. 3: Production and seismic history at the CGF in study area A (Figure 2). (Top) Earthquakes from the HYS and Walter & Weaver (1980) catalogs and time-varying magnitude of completeness of the HYS catalog. (Middle) Background seismicity rate for the HYS catalog normalized by $M_c$. (Bottom) Monthly production and injection rates of the CGF from 1981-2014 obtained from the California Department of Conservation.

## Identification of clusters

- Computation of space-time-energy distance (Zaliapin & Ben-Zion, 2013):

$$\eta_{ij} = \begin{cases} t_{ij}(r_{ij})^d 10^{-bm_i}, & t_{ij} > 0 \\ \infty, & t_{ij} < 0 \end{cases}$$

$t_{ij}$ Inter-event time
$r_{ij}$ Inter-event distance
$d$ Spatial dimension
$m_i$ Magnitude
$b$-value

- Every event is part of a cluster
- Add event to cluster if nearest previous event is within threshold, otherwise define new cluster

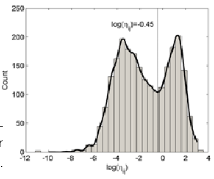


Fig. 6: Histogram of the nearest-neighbor-distance $\min_j(\eta_{ij})$ for each event of the WW80 catalog.

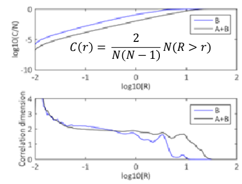


Fig. 4: Correlation dimension for Study Areas A-B and B.

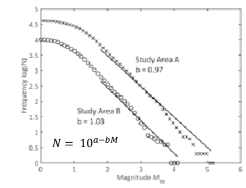


Fig. 5: Maximum likelihood estimate of the Magnitude-Frequency relation for seismicity in Study Areas A and B.

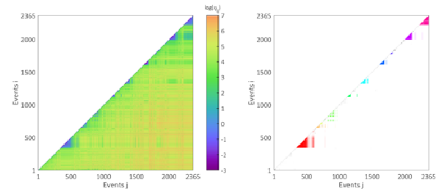


Fig. 7: (left) Inter-event space-time-energy distance matrix for the WW80 catalog. (right) Matrix of identified clusters with > 20 events.

## Seismicity 1981-2013

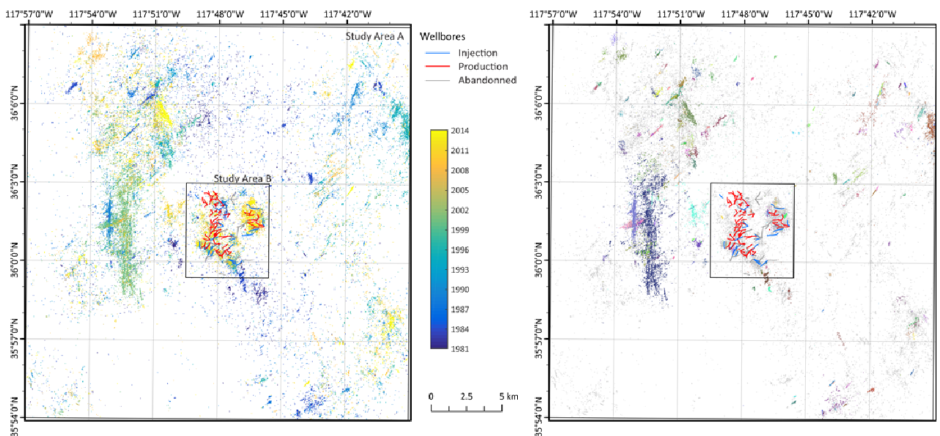


Fig. 8: HYS catalog color-coded by time (left) and colored by cluster-membership as identified by space-time-energy distance (right).

## Cluster hierarchy

Cluster 433 – Main shock-aftershocks

Cluster 353 – Swarm

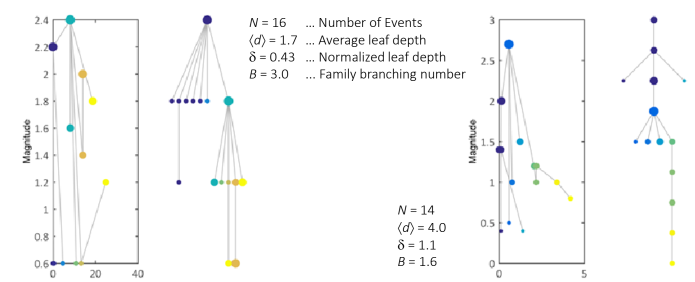


Fig. 9: Magnitude-time and hierarchy plots for two smaller clusters with lines connecting each cluster event with its nearest neighbor. Dot size represents event magnitude, dot color the timing within the cluster as defined by the magnitude-time plots. Cluster 433 (Left) is two connected mainshock-aftershock sequences with many direct offspring of the two mainshocks, whereas cluster 353 (Right) is a typical swarm with long chains of events.

## Cluster properties in pre- and co-production phases

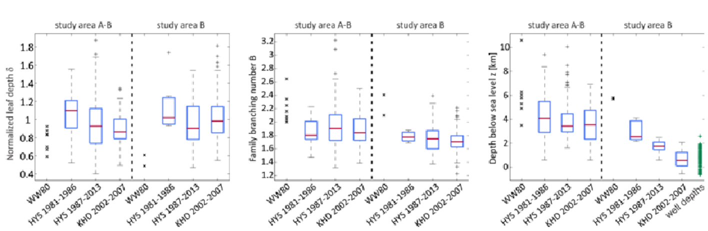


Fig. 10: Boxplots of depth, normalized leaf depth δ and family branching number B of the clusters identified from the catalogs for study areas A-B and B. Aftershock sequences were removed for this analysis. Due to small number of clusters in the WW80 catalogs, only the individual quantities are plotted. In subfigure (a) the depths of the wells in study area B are plotted for comparison.

## Conclusions

- The Coso area provides great opportunities to study natural and induced seismicity in a comparative manner
- Topological features of natural and induced swarm seismicity appear similar
- Both types of swarms are different to main shock-aftershock sequences
- Average swarm depth bsl changed in produced area after production started

## Acknowledgements

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