Spatial and temporal analysis of earthquakes in Southern California based on K-means clustering and b-value analysis

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Motivation

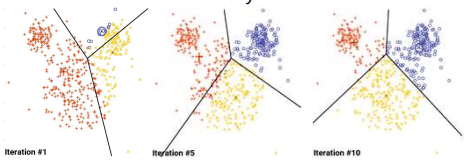
- Analyzing earthquake clusters offers insight into seismic hazards of different geological and tectonic settings.
- Unsupervised **clustering algorithms** provide more objective clustering more efficiently than clustering done by human experts.

Objectives

- **Improve** spatial clustering of earthquakes by adding earthquake-fault distance constraints to a classical K-means algorithm.
- **Analyze and evaluate** spatial and temporal variations of the b-value of the earthquake clusters derived from the modified algorithm.

Methods

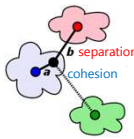
- **K-means:** widely used in earthquake clustering and seismic hazard analysis[5]



- **Silhouette score (S):** measures how well data is clustered (averaged over all points i)[6]

$$s_i = \frac{b_i - a_i}{\max(a_i, b_i)}$$

$$S = \bar{s_i}$$



- **Gutenberg-Richter Law:**

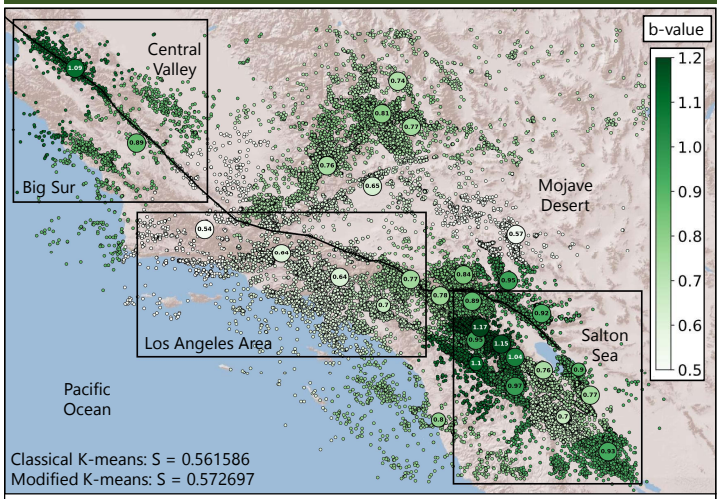
$$\log N = a - bM$$

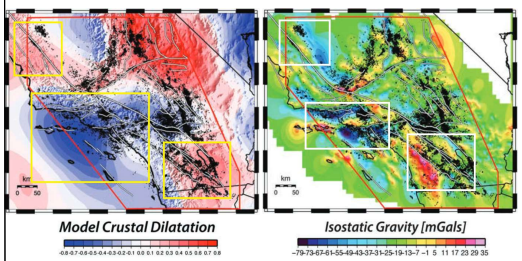
  - N: earthquakes above magnitude M
  - a, b: constants
- **b-value:** the value of b in the G-R Law, roughly the ratio of small to large earthquakes
- **Magnitude of completeness (M_c):** minimum magnitude where all earthquakes are detected by the local seismic network, estimated using the entire magnitude range (EMR) method[2]

References

1. Fiedler, B. et al (2018). Detection of Gutenberg-Richter *b*-value changes in earthquake time series. *Bulletin of the Seismological Society of America 108*, 2778-2787.
2. Woessner J., Wiemer S. (2005). Assessing the quality of earthquake catalogs: estimating the magnitude of completeness and its uncertainty. *Bulletin of the Seismological Society of America 95*, 684-698.
3. Ross, Z. et al (2019). Searching for hidden earthquakes in Southern California. *Nature 364*, 767-771.
4. Hauksson, E. (2011). Crustal geophysics and seismicity in Southern California. *Geophysical Journal International 186*, 82-98.
5. https://en.wikipedia.org/wiki/K-means_clustering
6. http://sujitpal.blogspot.com/2018/03/an-implementation-of-silhouette-score.html

Results: Spatial variations of b-value





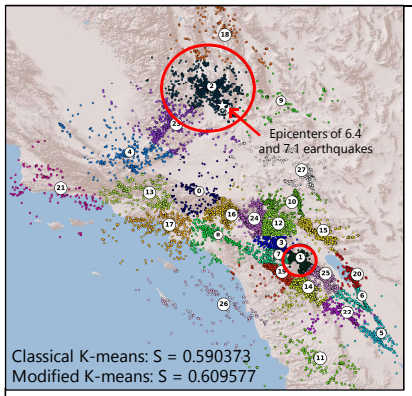
Data Set
- 2008–2017
- **900,000** earthquake locations

Locations obtained from earthquake template matching[3]

Maps of various physical properties: Hauksson (2011)[4]

- Notable spatial correlation with model crustal dilatation (extension or compression) and isostatic gravity (crustal density influence on gravity)
- Higher b-values in regions of crustal extension and in basin edges

Results: Temporal variations of b-value

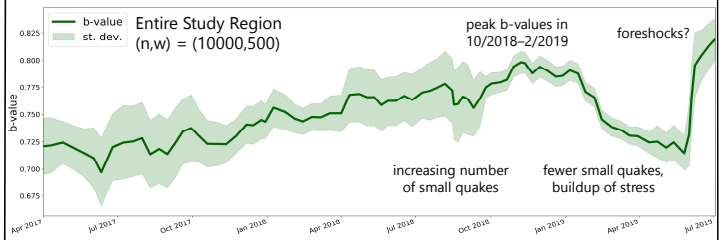


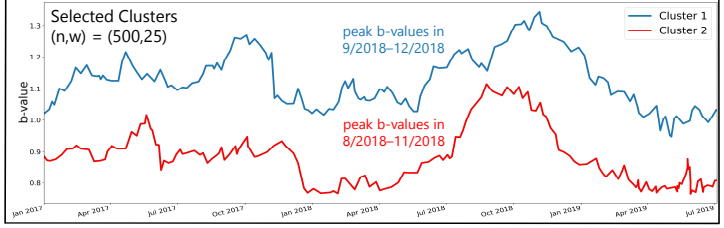
Data Set
- July 4, 2016 – July 3, 2019
- 53,000 earthquake locations
- Retrieved from Southern California Seismic Network

Ridgecrest Earthquakes
- July 4, 2019: M_w 6.4
- July 5, 2019: M_w 7.1

Largest earthquakes in the region over the last 10 years

Some distant clusters have similar time series: suggests interactions and distant stress transfer between faults



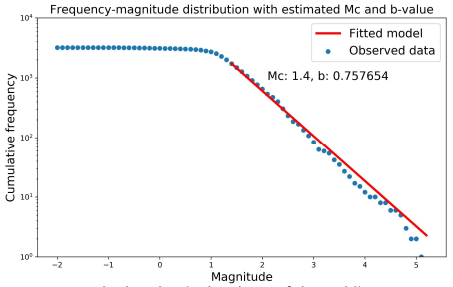


Methods, cont.

- Added **earthquake-fault distance constraints** for major faults in Southern California (e.g. San Andreas, San Jacinto, Elsinore) to K-means.
- Computed silhouette scores for combinations of faults and weights to find the best one.
- Derived a maximum likelihood estimate of the
- b-value from the G-R Law:

$$\hat{b} = \frac{\log e}{\bar{M} - M_c}$$

  - M_c: magnitude of completeness
  - $\bar{M}$: mean magnitude of events above M_c



The b-value is the slope of the red line.

Conclusions

- The modified K-means algorithm produced **better spatial clustering** of earthquakes.
- The spatial and temporal b-value analysis of earthquake clusters suggests that the **physical properties of the crust** control the earthquake spatial distribution and that the **interactions between different fault systems** can affect the occurrence of large crustal earthquakes.

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