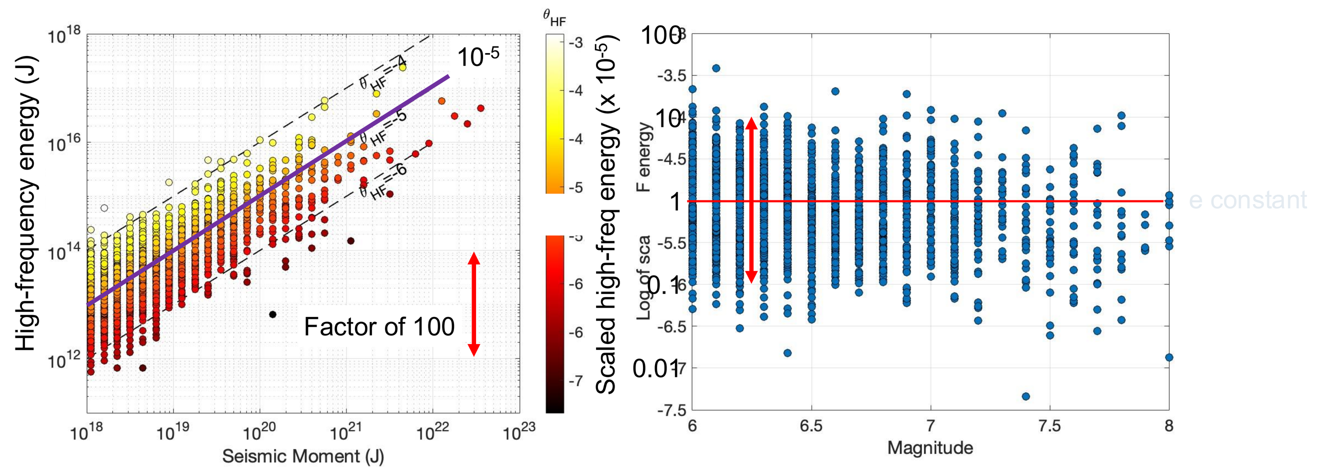
Earthquake shaking scales with rupture complexity

John Vidale and Hao Zhang, USC

Scaled high-frequency energy of earthquakes

High frequency (0.5-2 s) energy-to-moment ratio varies considerably



E_{HF}/M_0 ratio ~ 10^{-5}

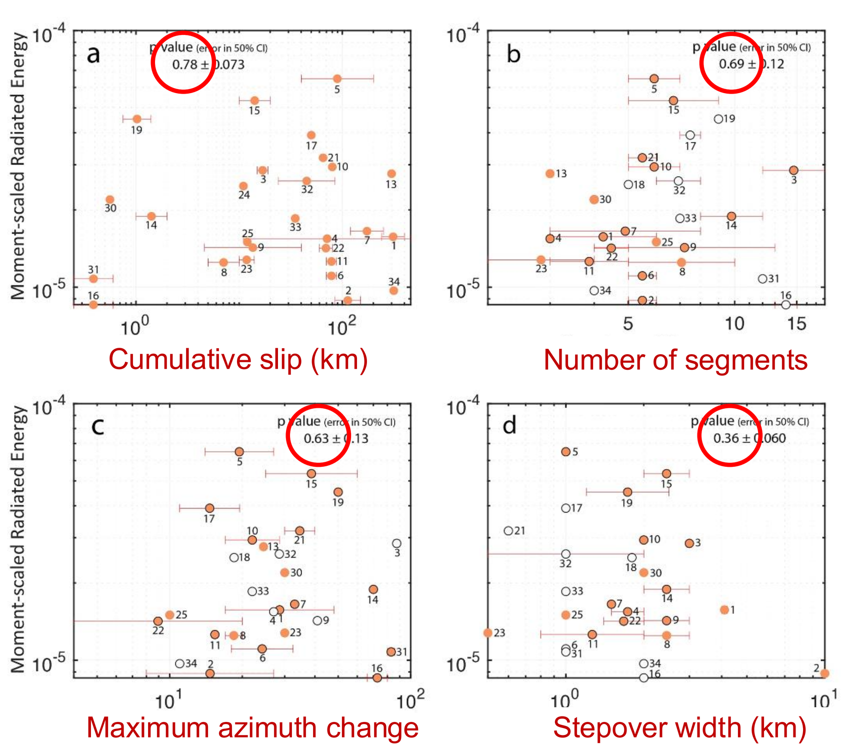
There is no clear magnitude dependence

Earthscope, with method of Convers and Newman, 2011

Has proven difficult to explain variation

Does complex geometry raise stress drop?

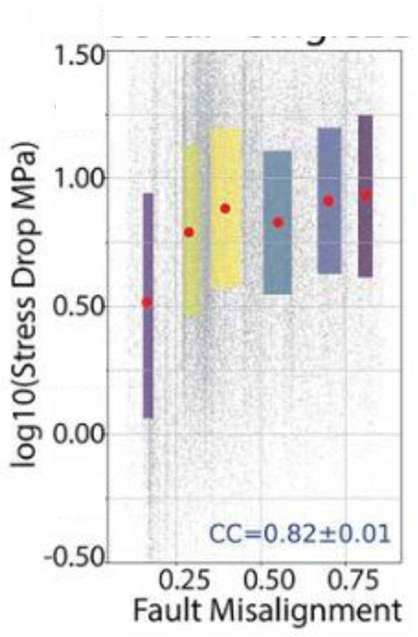
Scaled energy compared to many surface trace parameters

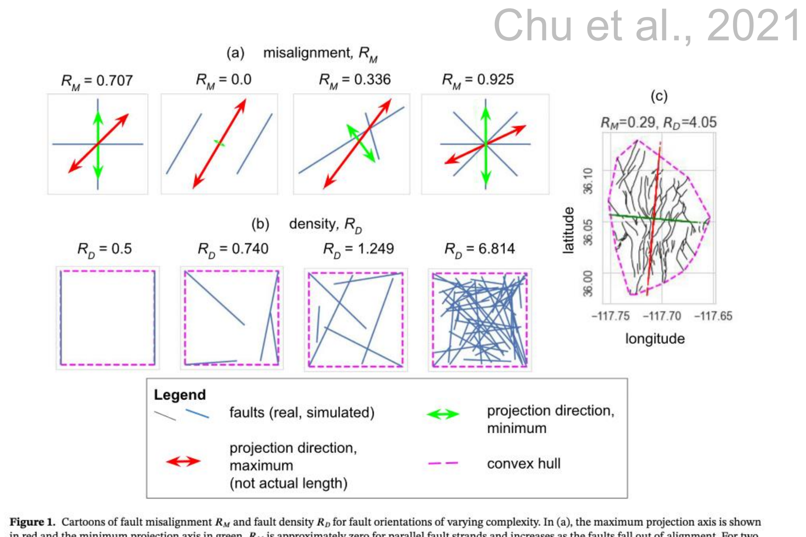


Guo et al., 2023

Surface fault misalignment vs stress drop, only weak correlation

Chu et al., 2021

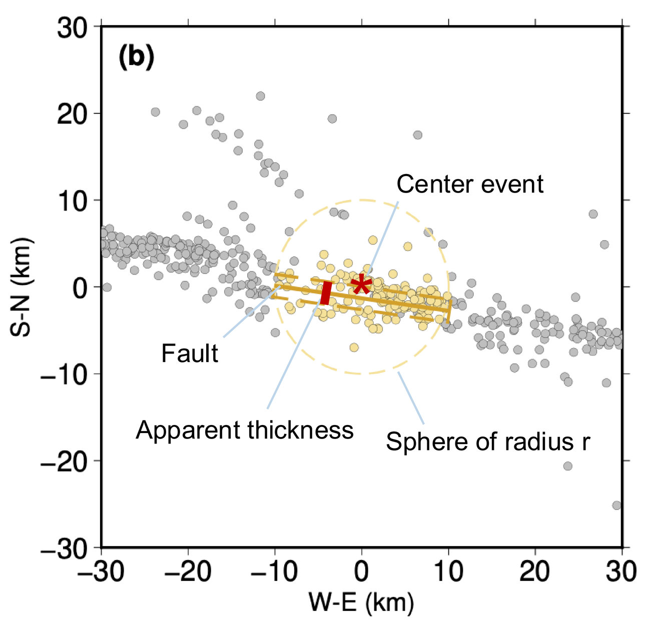




Lee, Tsai, Trugman, Hirth, Chatterjee, 2025

Our new measure – aftershock complexity

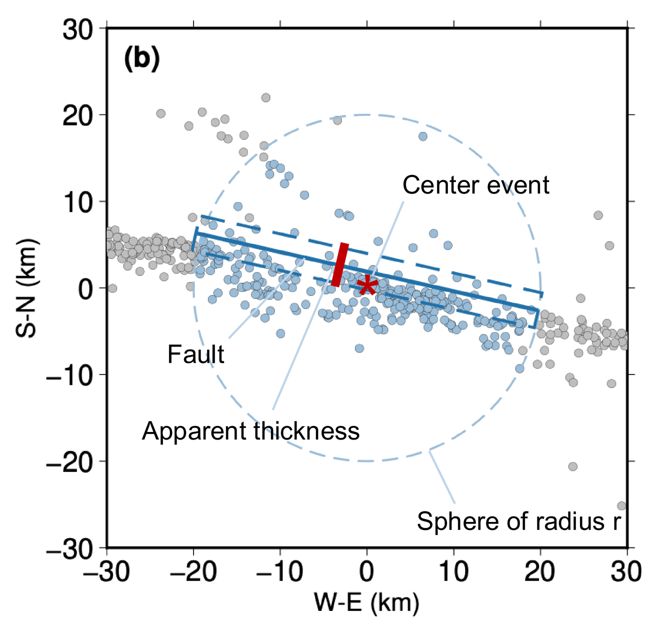
Apparent fault zone thickness at scale r



Given a catalog, we pick one event as the center event and calculate the apparent thickness of the fault around it within a characteristic distance r.

We do this by finding the best-fit plane of events, then defining the average fault thickness for scale r as the average distance from the plane of all the events in the sphere.

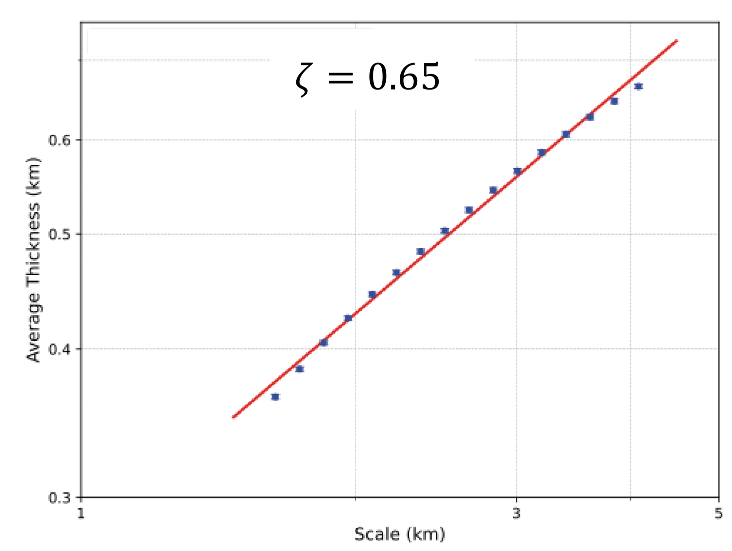
Find thicknesses at a range of scales



Now measure a range of scales r, we use 20-50% of median event distance from aftershock centroid, with a cap of 25 km.

(Magnitude and time doesn't matter, which means catalog completeness is not required, an advantage.)

How does thickness scale with r ?



The apparent thickness increases with scale, following a power-law relationship:

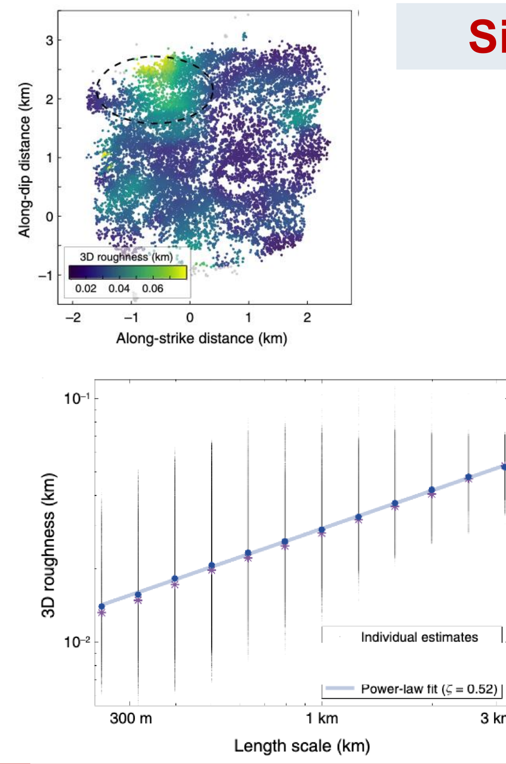
$$\bar{h}(r) \propto r^{\zeta}, 0 < \zeta < 1$$

- For a simple plane of seismicity $\zeta = 0$
- For uniformly distributed events $\zeta = 1$

The uncertainty of the mean is shown, variance is much larger.

We call this value the **complexity** ζ

Similar to Hurst Exponent

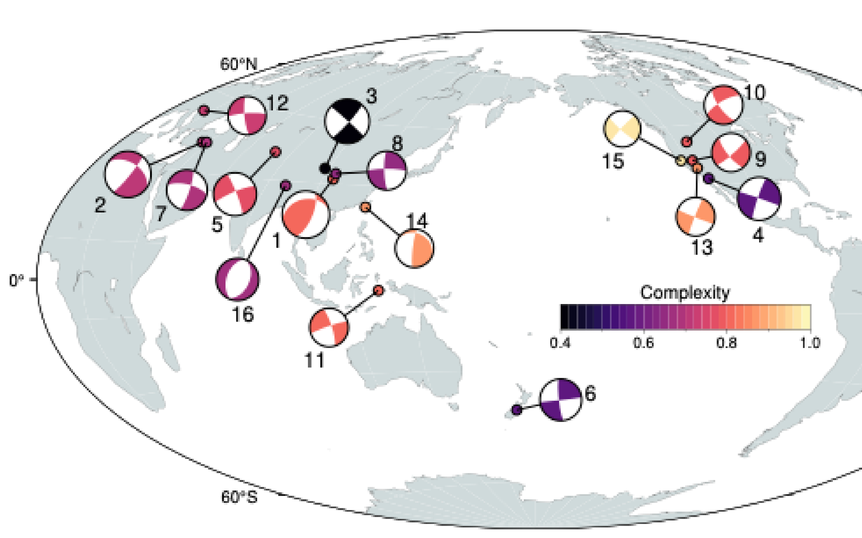


Hurst exponent has the same fractal math, same catalog input, except:

- Our complexity is a volume ~1 km thick that has multiple fault surfaces. Caused by static and dynamic stresses.
- Hurst exponent shows topography of the primary fault surface, measured in this example to be 20-60 m, with true width of faulting inferred to be even much smaller. Static stresses, shows anisotropy.

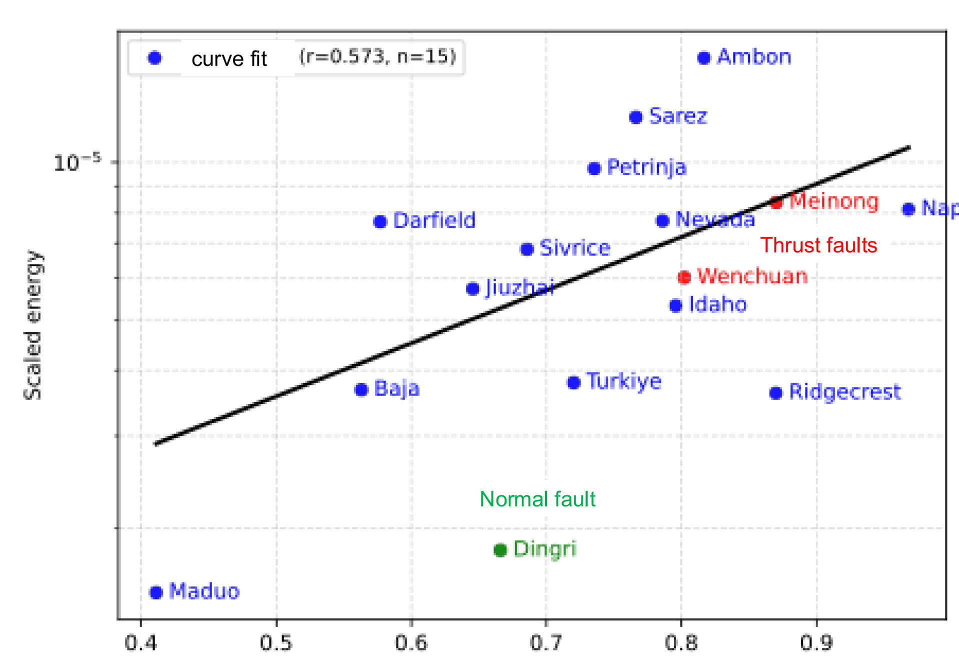
Cochran et al., 2023

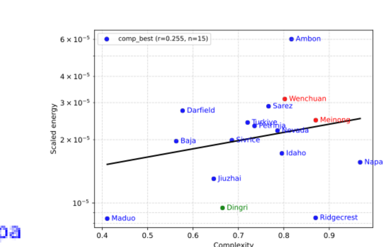
A global survey on rupture complexity



1	Wenchuan	9	Nevada
2	Turkey	10	Idaho
3	Maduo	11	Ambon
4	Baja California	12	Petrinja
5	Sarez	13	Ridgecrest
6	Darfield	14	Meinong
7	Sivrice	15	Napa
8	Jiuzhai	16	Dingri

16 large earthquakes with precisely relocated aftershock catalogs
(fit is just 15 events, omitting Dingri)





Broadband energy correlates (0.255) more poorly with complexity.

Complexity is measured over the distance range from 20 to 50% of the mean distance from aftershocks to the centroid, which is 1 to 15 km.

A model of a fractal fault system consistent with our data

The relative abundance of small to large faults is a power law with α

$$N(L) \propto L^{-\alpha}$$

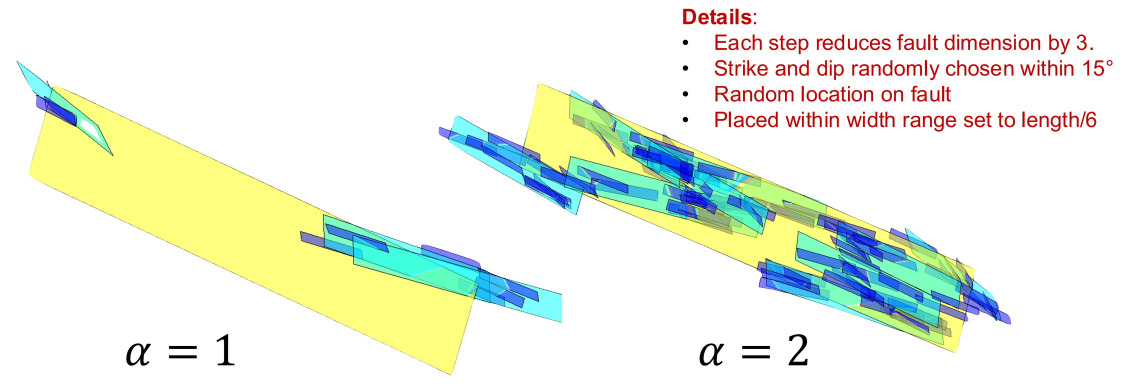
Start with two levels of subsets

1st level: 3^{α} subfaults added in addition to the main fault

2nd level: 3^{α} sub-subfaults added to each subfault

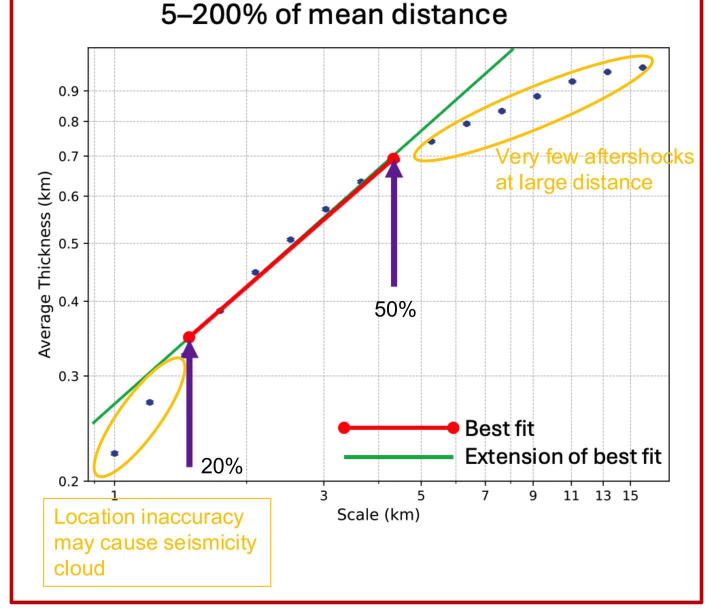
Details:

- Each step reduces fault dimension by 3.
- Strike and dip randomly chosen within 15°
- Random location on fault
- Placed within width range set to length/6



Example of Jiuzhai event

5–200% of mean distance



Why would larger ζ mean more shaking?

- **Larger** ζ => More seismicity in the outer zone as r increases => less sharp plane of seismicity and/or lower planarity of seismicity.
- More secondary faults involved in the rupture.
- Therefore, some combination of more edges, more zones of incompatibility, more rupture hesitation, more stress required to break.
- Or maybe stronger shaking causes the higher complexity.

Discussion

The high-frequency energy radiation efficiency of large earthquakes plays a critical role in determining their destructiveness. The efficiency varies by more than an order of magnitude, yet the underlying controlling factors remain poorly understood. Here, we demonstrate that high-frequency (0.5 to 2 Hz) energy radiation in large earthquakes correlates with the spatial complexity of their rupture processes.

We work on three fronts: First, we define a fractal measure of rupture complexity that is based on the effective width of the aftershock zone as a function of scale, applied without free parameters. Second, a model of fault complexity built from a power law density of secondary faults is constructed and calibrated against the complexity measure. Third, the measure is applied to 15 globally distributed magnitude 6 to 8, shallow, continental earthquakes with accurately located aftershocks. Scales considered range from about 2 to 15 km, and aftershock zone widths are about 300m to 1 km. For two well-studied events, we can observe that high frequency radiation is strongest at the spots along the rupture showing the highest complexity.

We find that greater rupture complexity produces higher energy radiation efficiency. The high-frequency energy to moment ratios vary by about a factor of 10 with a correlation coefficient of 0.57 and a significant p value of 0.019. In our model, the measured rupture complexity corresponds to a fractal subfault size-frequency distribution. Our findings highlight new ways of surveying an earthquake rupture, specifically the improvement from incorporating rupture complexity beyond simple planar fault models when modeling energy radiation. With a better understanding of energy radiation efficiency, seismic hazard estimation may be improved.

Summary

- **New measurement of rupture complexity based on aftershock distribution:**
  - The complexity measure is a fractal property
  - Captures prior ideas – fault maturity, fault zone width, mechanism misalignment
- **Issues not yet understood**:
  - Is complexity a property of a fault system or only individual earthquakes?
  - Which matters most: Variations in faulting geometry, stress, rupture velocity, friction?
- **Problems**:
  - E/M_0 scaling past corner??
  - Small number of events and several free parameters
- **High-frequency energy-moment ratio scales with the rupture complexity**
  - Studying more large earthquakes will better crystallize the pattern:
- **Model is a new framework for systematic analysis of data**
  - Motivates more testing with precise aftershock catalog locations
  - lower magnitude thresholds

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