Foreshocks and Mainshock Nucleation of the 1999 M_w 7.1 Hector Mine, California, Earthquake

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Foreshocks moved north with time, toward eventual mainshock location; seismicity rate did not accelerate leading up to mainshock

Foreshocks ruptured adjacent areas along fault with little overlap; mainshock initiated where foreshocks locally increased stress

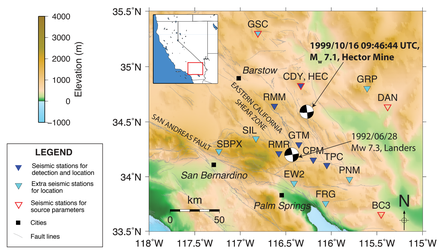
Hector Mine foreshocks and mainshock were triggered by a cascade of stress transfer

Introduction

1999/10/16 M_w 7.1 Hector Mine, California, earthquake: 18 catalog foreshocks, 20 hours before mainshock

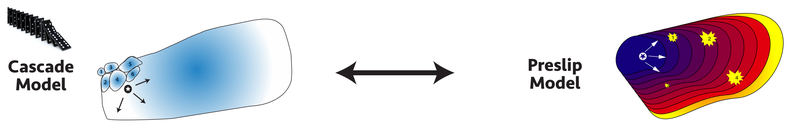
- What is the relationship between the Hector Mine earthquake and its foreshock sequence?
- How did the Hector Mine earthquake nucleate?

Common theme for methods: exploit similar waveforms from pairs of nearby foreshocks for precise seismological analysis



END-MEMBER MODELS: FORESHOCK GENERATION AND MAINSHOCK NUCLEATION

Dodge et al. (1996); Beroza and Ellsworth (1996); Mignan (2014)



- Foreshocks trigger other foreshocks, and mainshock, only through stress transfer
- Foreshocks should adjoin each other in a compact, localized area
- No advance information about earthquake size: small and large earthquakes start the same way

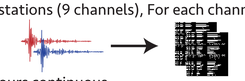
- Foreshocks are triggered by an underlying physical process, such as aseismic slip
- Foreshocks need not be adjacent; greater separation between foreshocks possible
- Foreshock area may predict eventual mainshock size: larger aseismic slip can trigger larger earthquakes

Foreshock Detection

Method: Fingerprint And Similarity Thresholding (FAST)

Goal: Systematic detection of smaller foreshocks with similar waveforms

7 stations (9 channels), For each channel:

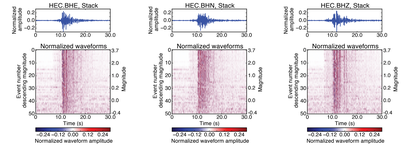


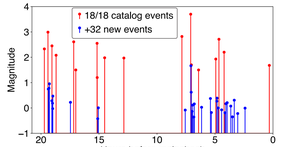
20 hours continuous seismic time series → 75,000 fingerprints

Yoon et al. (2015); Rong et al. (2018); Bergen and Beroza (2018); Yoon et al. (2019)

Source code + decimated/filtered data: https://github.com/stanford-futuredata/FAST

All 50 detected foreshocks: similar waveforms at nearest station HEC





FAST detected all 18 catalog foreshocks + 32 new foreshocks

Smaller foreshocks (M < 1) occurred close in time to larger foreshocks

Foreshock rate did not accelerate leading up to mainshock

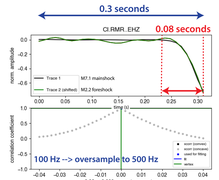
Foreshock Location

Method: Double-difference algorithm (hypoDD) *Waldhauser and Ellsworth (2000)*

Goal: Precise *relative* location of 42 largest foreshocks and mainshock

14 stations (20 channels)

Cross-correlation differential travel times between event pairs, including between the M 7.1 mainshock and M 2-3 foreshocks

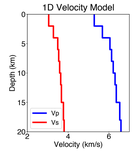


Cross-correlate only initial rise, not entire waveforms:

M7.1 mainshock with M2.2 foreshock

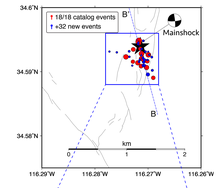
Nearest station 26 km away; cannot constrain absolute earthquake depths

Tested multiple trial starting depths (3, 5, 8, 10, 15 km), got consistent relative locations

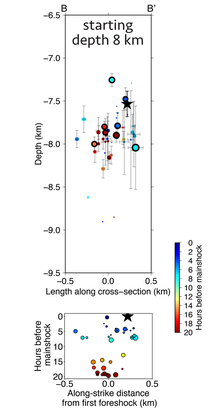


Kamer et al. (2017)

Map view



Along-strike view



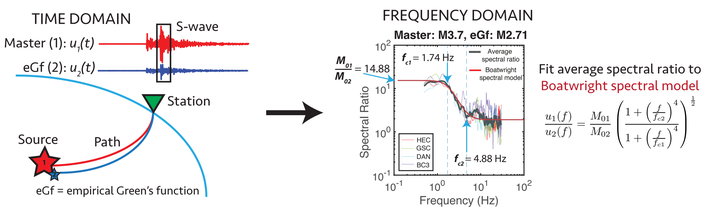
Foreshocks start tightly clustered and move north toward mainshock with time, but remain in compact zone (<2 km³)

Mainshock on same fault plane as foreshocks
Inconsistent with *Zanzerkia et al. (2003)*
Consistent with *Chen and Shearer (2013)*

Source Parameters and Slip Models of 8 Largest Foreshocks

Method: Spectral Ratio *Imanishi and Ellsworth (2006)*

Goal: Reliable source parameter estimation for 8 largest foreshocks -> model slip and stress changes



Fit average spectral ratio to Boatwright spectral model

$$\frac{u_1(f)}{u_2(f)} = \frac{M_{01}}{M_{02}} \left(\frac{1 + \left(\frac{f}{f_{c2}}\right)^4}{1 + \left(\frac{f}{f_{c1}}\right)^4} \right)^{\frac{1}{2}}$$

Source Model: assume circular fault rupture

Source radius

$$R = \frac{k v_s}{f_c}$$

k = 0.21 (*Madariaga, 1976*) dynamic rupture propagation

v_s = 3.54 km/s (*Kamer et al., 2017*) velocity model at 8 km depth

Average slip

$$D = \frac{M_0}{\mu \pi R^2}$$

μ = 30 GPa

(Static) Stress drop

$$\Delta\sigma = \frac{7}{16} \frac{M_0}{R^3}$$

(Eshelby, 1957)

Uncertainty analysis (independent of spectral ratio estimates): assume constant Δσ = 3 MPa, compute *R* and *D*

Slip model: *Andrews (1980)*

$$d(r) = D \left[1 - \left(\frac{r}{R} \right)^2 \right]^{\frac{3}{2}}, r < R$$

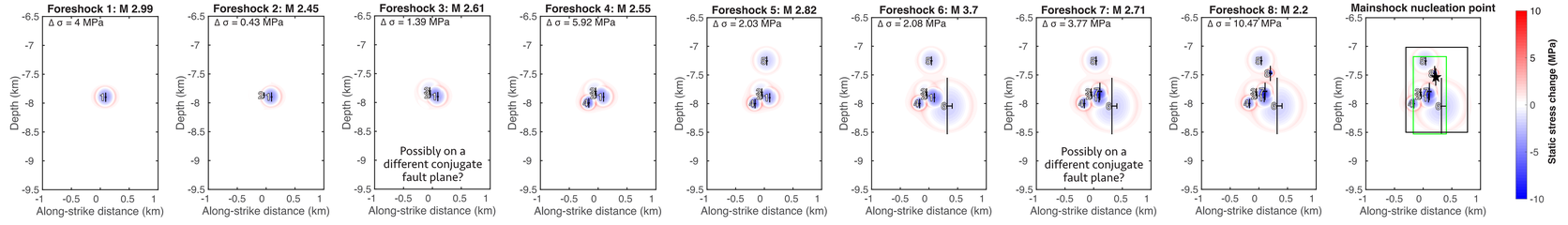
$$d(r) = 0, r > R$$

Stress change model: *Andrews (1980)*

Stress ↓ inside rupture;
Stress ↑ immediately outside rupture edge

Foreshock Space-Time Evolution and Mainshock Nucleation

CUMULATIVE STRESS CHANGE ON FAULT PLANE: 8 LARGEST FORESHOCKS



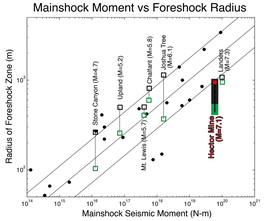


Figure modified from *Dodge et al. (1996)*

Area enclosing ruptures; Area enclosing hypocenters

Radius of nucleation region from *Ellsworth & Beroza*, 1995

Radius of Hector Mine foreshocks from *Chen & Shearer*, 2016

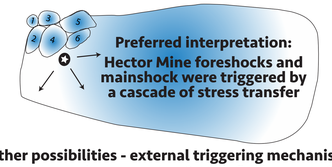
Does foreshock rupture area scale with eventual mainshock size?

NO. Hector Mine foreshock area smaller than expected for a M=7.1 mainshock

Inconsistent with Preslip Model; favors Cascade Model

Foreshocks ruptured adjacent non-overlapping areas along fault

Mainshock nucleated where previous foreshocks had locally increased stress



Limitations

Sparse seismic network, no nearby stations: uncertain absolute depth estimates

Uncertain source dimensions for foreshocks; not a finite fault model

Other possibilities - external triggering mechanisms?

Aseismic slip or transient? High fluid pressure?

Not necessary to invoke, but cannot rule out through independent observations either

Toward future advances in understanding of foreshocks and mainshock nucleation

- Imaging foreshock sequences, with precise locations, mechanisms, nonplanar finite fault models (dense near-field seismic networks)
- Quantitative, near-field geodetic constraints on aseismic slip (strainmeters)
- 2019 M_w 7.1 Ridgecrest, California earthquake sequence

Read the paper: Yoon, C. E., Yoshimitsu, N., Ellsworth, W. L., and Beroza, G. C. (2019). Foreshocks and mainshock nucleation of the 1999 M_w 7.1 Hector Mine, California, earthquake. *Journal of Geophysical Research: Solid Earth*, 124, 1569-1582. https://doi.org/10.1029/2018JB016383