Fault System Behavior of the Eastern California Shear Zone
Unsteady Loading Rates and Clustered Earthquake Activity

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Fault System Behavior of the Eastern California Shear Zone

- Geologic, Rock-Mechanics, and Geodetic views of faulting
- Paleoseismic evidence for slow ECSZ slip rates and regional earthquake clusters
- Compilation of new long-term slip rate data to test for elevated ECSZ loading rate
- Implications for fault-zone mechanics and hazards
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Observations

Fractured Rock
Pulverized Rock

Decoupling, Flow?

Fault Core
Mylonite

Anisotropic Fabric

Scholz (1992)

Depth, Pressure, Temperature

Byerlee Friction
Elastic Core
Power-Law Creep
Shear Heating,
Fabric Development,
Grain-Size Sensitive Creep

Weak Faults

Regenauer-Lieb et al. (2006)

Brace & Koliastedt (1980)

Long-Term Strength
Elastic Loading ‘Slip Rates’

- Far field loading rate ⇒ slip rate if loading constant (assumed constant?)

- Near-field strain rate gradient ⇒ locking depth & slip rate (may vary over the EQ cycle)

- If far-field rate is unknown, there is a trade off between locking depth and loading rate.

Note: Viscous models give similar results (Meade and Hager, 2005)
Elastic Block Model

Simultaneous Fit (*assuming constancy of....*):
Geodetic strain rates, strain gradients, & path-constraints

MEADE AND HAGER: SOUTHERN CALIFORNIA BLOCK MODELS
Could transiently elevated strain accumulation rate lead to earthquake clustering?

1.2 mm/yr LOS step centered on the Blackwater Fault

Peltzer et al., (2001)

Dextral Slip: $7 \pm 3$ mm/yr

Geologic slip rate: $0.49 \pm 0.04$ mm/yr

No evidence of Late Holocene activity

Oskin and Iriondo (2004)
Paleoseismic clusters from the ECSZ south of Barstow

From T. Rockwell, S. Lindvall, and C. Rubin

Earthquake Timing
Well-constrained
Poorly-constrained

Average Earthquake Recurrence of 3 to 9 kyr

Recent cluster began ~1000 ka

Paleoseismic clusters from the ECSZ south of Barstow
Geodesy
$12 \pm 2 \text{ mm/yr}$

Paleoseismology
$5$ to $7 \text{ mm/yr (Estimate)}$
High shear strain in eastern California prior to 1992
How much of present-day loading rate across the ECSZ is transient?
Landscapes as recorders of fault slip

Abandoned Alluvial Fans
Active Alluvial Fan
Distinctive Clast Source

Displacement of alluvial fans from distinct sources

Deflection of inset channels
Alluvial Fan Markers of Fault Slip

Abandoned Wash Surface

Alluvial Fill

Active Wash Surface
Development of Alluvial Fan Stratigraphy

Desert Pavement

Soil Development
Cosmogenic Exposure Dating

$^{10}\text{Be}$: $t_{1/2} = 1.36 \text{ Myr}$

$^{3}\text{He}$: stable, rare
Pipkin Cinder Cone 740±40 ka

Calico Fault

Sheep Spring Wash

3 km

Slip Rate Measurements

Pipkin Cinder Cone 740±40 ka
Oskin et al. (2007)
Q2b Fan Surface

Quartz Monzonite & Basalt Boulders

Quartz and Basalt Pebble Desert Pavement
Cosmogenic Dates from Q2b Terrace and Modern Wash

Quartz Monzonite $^{10}$Be

Basalt $^{3}$He

$^{10}$Be Age - Inheritance: $56.4 \pm 7.7$ ka
Restoration of Q2b Terrace Displacement

100 ± 10 meters  1.8 ± 0.3 mm/yr
LENWOOD FAULT

Slip Rate: 0.8 $^{+0.2}_{-0.3}$ mm/yr

Canyon Incision & Abandonment of Q2b Alluvial Fans
Ludlow Fault

Q2a fan
Smooth, slowly eroding fan surface
Minimum Age: $50 \pm 20$ ka (update: $80 \pm 30$ ka)
What about distributed deformation?

Central Mojave Transect

- Lenwood Fault
- Camp Rock Fault
- Calico Fault
- Pisgah-Bullion Fault
- Ludlow Fault

0.8 ± 0.2 mm/yr
1.8 ± 0.3 mm/yr
1.0 ± 0.2 mm/yr

≤0.8 ± 0.2 mm/yr
≤1.4 ± 0.6 mm/yr
≤0.4 ± 0.2 mm/yr

Total: ≤6.2 ± 1.9 mm/yr

(95% confidence, errors summed as root mean square, $^{10}$Be production rate uncertainty added after summation)

Oskin et al., 2008
InSAR Deformation Gradient Map

MAP: Low-pass filtered line-of-sight deformation post 1999 H.M. Earthquake

RESULT: Deformation of 1-2 km-wide fault zones due to static stress change

Fialko et al. 2002
23% of total slip occurred via distributed shear.

Deformed Miocene Normal Fault bent and displaced by Calico fault.

7.56 km of fault slip restored

Oskin et al., 2007
Deflection of Linear Markers Approaching the Harper Lake Fault

Distributed strain = 19 ± 3% of fault slip

Shelef and Oskin, *in review*

Lines are normal to mylonitic lineation
Secondary Active Faulting Adjacent to the Lenwood Fault
CONCLUSION: Deformation zones active, absorb 10-30% of fault-zone slip

Secondary faults cutting Q2a alluvial fans

Secondary faults cutting Holocene alluvium
Fault System Behavior of the Eastern California Shear Zone

• System-wide clustered earthquake behavior, currently active

• Paleoseismic and longer-term geologic slip rates both sum to $6 \pm 2$ mm/yr, which is $\sim 1/2$ the geodetic rate

• 10-30% of deformation may be distributed in compliant zones surrounding faults
Garlock Fault: Opposite Geologic-Geodetic Discrepancy

Figure from McGill et al., (2009)
Geodetic Rates of Loading from Meade & Hager (2005)
Geodetic Simple Shear Eastern California

Savage et al.: Shear Zone in Eastern California

Ovens Valley 1974–1988
\[ \varepsilon_1 = 0.07 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \dot{\varepsilon}_2 = -0.05 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \phi = N \, 76^\circ \, W \pm 3^\circ \]

Garlock 1973–1984
\[ \varepsilon_1 = 0.07 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \dot{\varepsilon}_2 = -0.11 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \phi = N \, 78^\circ \, W \pm 3^\circ \]

Barstow 1979–1989
\[ \varepsilon_1 = 0.07 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \dot{\varepsilon}_2 = -0.06 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \phi = N \, 78^\circ \, W \pm 3^\circ \]

E. Mojave 1934–1982
\[ \varepsilon_1 = 0.02 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \dot{\varepsilon}_2 = -0.02 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \phi = N \, 32^\circ \, W \pm 25^\circ \]

W. Mojave 1934–1982
\[ \varepsilon_1 = 0.08 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \dot{\varepsilon}_2 = -0.08 \pm 0.02 \, \mu \text{strain/yr} \]
\[ \phi = N \, 86^\circ \, W \pm 5^\circ \]
Fold Axis (Bartley et al. 1990)

Uplifted Geomorphic Surfaces

Gravel Hills

Blackwater

Tiefort

Manix

Bicycle

Lake

Pisgah

Lenwood

Calico

Barstow

25 km
Garlock Fault Discrepancy
Geodetic: 0 to 3 mm/yr
Geologic: 5.6 $^{+1.2}_{-0.6}$ mm/yr

ECSZ Discrepancy
Geodetic: 10 to 14 mm/yr
Geologic: $\leq 6.2 \pm 1.9$ mm/yr

Shear & Extension
Shear & Compression
Coordinated fault activity on conjugate fault systems?

Figure from Dawson et al. 2003

Garlock Earthquakes & Clusters
Variable geologic slip rate

ECSZ Earthquake Clusters
Constant geologic slip rates, coordinated system behavior

Inactive
GPS
Active
What drives oscillatory loading behavior?

**KEY OBSERVATION:** GPS rates do not match long-term slip rates

**Candidate Processes:**
- Grain-size sensitive creep
  - Diffusion creep (?)
  - Grain-boundary sliding
- Variable fluid-pressure
Grain-Size Sensitive Creep Effect
Adapted from: Montesí and Hirth (2003)

Stress Evolution

\[ \dot{\sigma} = K[v_0 - \frac{(w_1 + w_2)A_D\sigma_{nD} - (w_1d_1^{r-} + w_2d_2^{r-})A_G\sigma_{nG}]}{w_1A_D}] \]

Grain-Size Sensitive Creep

\[ \dot{d} = A_D\sigma_{nD}(d_0\sigma_{r-} - d) \]

Earthquakes (imposed as abrupt grain size reduction)

Elevated loading as grain size recovers
Conclusions

- Present-day ~2x elevated strain rate coincides with a cluster of major earthquakes in the ECSZ
- Fault loading appears to oscillate between conjugate systems - an emergent system-level behavior?
  - DEXTRAL MODE: Dextral simple-shear regime of loading active with at least 3 mm/yr excess rate
  - Shear along Garlock fault suppressed, with comparable but opposite rate discrepancy
  - Past clusters of activity on the Garlock fault (Dawson et al. 2003) could indicate past periods of activity of conjugate SINISTRAL MODE with greater dilatation in ECSZ
- Time scale of variation likely within 1 to 5 kyr range
  - ~1 kyr time scale earthquake clusters in ECSZ, Garlock fault
  - Elevated loading of faults with consistent paleoseismic and geologic rates implies variable ductile fault-zone strength
  - Next step → Slip rate variability of faster strike-slip faults