“The southern San Andreas fault is 10 months pregnant”

Kerry Sieh, 1986

What does that mean?

It has been ~300 years since the last large southernmost San Andreas surface rupture, and the average recurrence interval for the past 1000 years is more like 200 years.

So, what’s going on?

Is the apparently long extended interval a result of mis-interpretation of paleo-events? The historical record reads for itself!
Paleoseismology is reproducible – multiple trench sites along a fault usually yield the same information on the timing of past earthquakes, and determination of displacement demonstrates that these “events” are real earthquakes.

35 years of paleoseismic work in the southern San Andreas fault system

Let’s look at the past 1100 years of surface ruptures for the entire system.
First, for the southern 160 km of the San Andreas fault system – we need to develop a common chronology.
382 radiocarbon dates from paleoseismic sites at or below the shoreline of Lake Cahuilla

Used 88 dates in the Oxcal model to resolve the timing of lake high-stands
MRE on the so. SAF is ca 1715 AD

South San Andreas Event pdfs

Superstition Mountain Fault Event pdfs
Southern San Andreas Fault - Coachella Paleoseismic Site (Philibosian et al., 2011)

Multiple lines of evidence for surface ruptures in multiple trenches
Two most recent southern San Andreas events occurred during Lakes 1 and 2. Beautiful seismites, slump features indicate presence of water in both events – occurred during high lake stands.
Coachella paleoseismic site, southern San Andreas fault (Philibosian et al., 2011)
Displacement estimates for the southern San Andreas fault from offset geomorphic features, such as small channels, rills, bars, etc. (UCERF3 offset database)

Inferred to average about 3-3.5 m for the past several earthquakes, with a range of ~2-4 m (most are 3-3.5 m)

For this analysis, I use 3 m for average displacement
Southern San Jacinto Fault Zone

Superstition Mountain Fault
Superstition Hills Fault
Coyote Creek Fault
Figure 2. Map showing the trench sites relative to the 1968 surface rupture, Superstition Mountain, the Cahuilla shoreline and area of lake inundation.
The north margin of the unit E channel is traced into and across the fault zone, yielding ~2.2 m of RL offset in the MRE.

Superstition Mountain Fault, Northern Shoreline Site

Three surface ruptures in past 1100 years

2.2 m in MRE
Superstition Mountain Fault, Carrizo Wash Site
Map of trenches, Carrizo Wash Site

- Clay filled channel pinch out (units 156d to 161)
- Channel pinch out, unit 168
- Evidence for 2 events in past 1 ka
- Evidence for 3 events in past 1 ka
- Edge of wash bottom
- Edge of upper paleo-channel (units 80 - 90)
- ~ 6 m

Legend:
- T1
- T2
- T3
- T4
- T5
- T6
- T7
- T8
- T1 ext
Superstition Mountain Fault - Carrizo Wash Site

Three large surface ruptures recognized in the same stratigraphic positions as at the Northern Shoreline Site, producing a total of 6 m of lateral displacement.

Small “cracking” event recognized near the top of the section.
en-echelon strike slip fault. 9 cm right lateral slip.

Paleosurface bench 1a (hard surface II)

Trench 2

paleosurface on bench level 1

ripple mark from horizontal separation=7cm

three branches of en-echelon fault C
Bottom line – we can resolve both timing and displacement, even for moderate-sized earthquakes, and distinguish moderate from large earthquakes – just takes work!

Micro-3D trenching to resolve slip on each individual strand
South Break Site on the southern Coyote Creek fault
Construct rupture history of the southern San Jacinto fault zone
New LiDAR and field mapping results on slip distribution from the Coyote Creek Fault
Northern Coyote Creek Fault: ~1-1.5m slip per event
Okay, what about the south central San Jacinto fault?
Hog Lake T4 - records ruptures and folding
Development of a long record requires an exceptional site with excellent preservation of strata and abundant dateable material, such as peat or seeds.
Primary fault breaks to a paleo-ground surface, and is capped by undeformed strata
Dating the events: There are lots of options at sites like Hog Lake.
Earthquake occurrence is quasi-periodic

Hog Lake Rupture Sequence, Model 1 - all radiocarbon dates, all earthquakes
4000 year recurrence interval = 184 ± 100 yrs

Hog Lake Rupture Sequence, Model 2 - best radiocarbon dates, all earthquakes
CV = 0.63  
4000 year recurrence interval = 186 ± 107 yrs

RI = 194 ± 89
RI = 262 ± 114
RI = 123 ± 70

Note relatively high CoV – this is typical for all long Paleoseismic records in California

Rockwell et al., 2015
Near Anza

Salisbury et al., 2012
Clark strand of the San Jacinto fault (main strand)

590 ± 30 m offset since 45 ± 10 ka → 13.2 \( ^{+4.3/-2.9}\) mm/yr

Blisniuk et al., 2012.
Slip Rate can be built by repeated ruptures similar to the November, 1800 earthquake

So the paleoseismic record combined with the slip per event record should predict the long-term slip rate
MRE is same as at Hog Lake, with 2.1 m slip. Similar recurrence interval as Hog Lake large events.
Rupture history of the San Jacinto fault

Rockwell et al., 2015
Catalogue and Model Construction

Use slip rates determined from geology, GPS and InSAR (cf. Fialko, 2006)

Combine with estimates of locking depth (cf. Smith-Konter et al., 2011)

Estimate expected moment release for past 1100 years

Compile all paleoseismic data, including timing and displacement

Build a catalogue that includes estimated magnitudes based on displacement data. Estimate seismic moment based on displacement and the same locking depth used to estimated expected long-term moment accumulation.

Compare inferred moment release to expected moment release for the past 1100 years
Table 1. Catalog of Paleoseismic Events in the southern 150 km of the San Andreas fault system

<table>
<thead>
<tr>
<th>Fault</th>
<th>EQ Date (AD)</th>
<th>Uncertainty range (95%)</th>
<th>EQ Date (2)</th>
<th>Uncertainty range (95%)</th>
<th>Magnitude Estimate</th>
<th>Rupture Average Slip (m)</th>
<th>Rupture length (km)</th>
<th>Rupture depth (km)</th>
<th>Inferred Seismic Moment (Mw)</th>
<th>References and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Andreas F</td>
<td>1715</td>
<td>1700-1722</td>
<td>1696</td>
<td>&gt;1520-1680</td>
<td>7.4</td>
<td>3</td>
<td>150</td>
<td>12</td>
<td>1.53×10^27</td>
<td>Phillippusen et al. (2013); Coachella site on SAF south of the juncture between the Banning and Mission Creek faults; event 3 questionable; ages recalculated based on new Lake Calahorra model of Rockwell et al. (2016 in progress).</td>
</tr>
<tr>
<td>Clark strand, SIF</td>
<td>Event 1</td>
<td>1918</td>
<td>5.7</td>
<td>1.25</td>
<td>26</td>
<td>13</td>
<td>1.30×10^26</td>
<td>Rockwell et al. (2015)</td>
<td></td>
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<tr>
<td></td>
<td>Event 2</td>
<td>1800</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>9.76×10^26</td>
<td>Boga et al. (2015); Inferred to be same event as at Hog Lake based on geochronology and radiocarbon dating of event stratigraphy.</td>
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<tr>
<td></td>
<td>Event 3</td>
<td>1577</td>
<td>6.7</td>
<td>1.25</td>
<td>26</td>
<td>14</td>
<td>9.76×10^26</td>
<td>Salzer et al. (2012); slip distribution and average slip in past 3 large Clark F earthquakes, plus slip in 1918.</td>
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<tr>
<td></td>
<td>Event 4</td>
<td>1357</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
<td>Moment estimates from Rockwell et al. (2015)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Event 5</td>
<td>1311</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
<td>Needed to decrease average slip estimate by 10% to match slip rate.</td>
<td></td>
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<tr>
<td></td>
<td>Event 6</td>
<td>1289</td>
<td>6.7</td>
<td>1.25</td>
<td>26</td>
<td>14</td>
<td>9.76×10^26</td>
<td></td>
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<tr>
<td></td>
<td>Event 7</td>
<td>1193</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Event 8</td>
<td>1080</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Event 9</td>
<td>947</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>9.76×10^26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casa Loma strand, SIF (assumes it ruptures with most or all Clark or Claremont fault events)</td>
<td>1899</td>
<td>5.5</td>
<td>0.5</td>
<td>20</td>
<td>18</td>
<td>6.70×10^25</td>
<td>Topozzici et al. (1990)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Event 2</td>
<td>1800 or 1812</td>
<td>6.5</td>
<td>0.5</td>
<td>20</td>
<td>18</td>
<td>6.70×10^25</td>
<td>Most events are inferred to have possibly ruptured with either the Clark fault or the Claremont fault when they move (Ono et al., 2015; Rockwell et al., 2015). The Casa Loma fault should rupture about every 10 years with a fault slip rate of 11 mm/yr. If it breaks on its own, it behaves like the or the Claremont or the Sierra Nevada.</td>
<td></td>
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<tr>
<td></td>
<td>Event 3</td>
<td>1688</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
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<tr>
<td></td>
<td>Event 4</td>
<td>1577</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
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<tr>
<td></td>
<td>Event 5</td>
<td>1528</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
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<tr>
<td></td>
<td>Event 6</td>
<td>1357</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
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<td></td>
<td>Event 7</td>
<td>1311</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
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<tr>
<td></td>
<td>Event 8</td>
<td>1289</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
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<tr>
<td></td>
<td>Event 9</td>
<td>1193</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
<td></td>
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<tr>
<td></td>
<td>Event 10</td>
<td>1080</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
<td></td>
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<tr>
<td></td>
<td>Event 11</td>
<td>947</td>
<td>7.3</td>
<td>2.5</td>
<td>30</td>
<td>14</td>
<td>1.00×10^26</td>
<td></td>
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<tr>
<td>Supersition Mtn - Coyote Creek F</td>
<td>CCF-1</td>
<td>1968</td>
<td>6.3</td>
<td>0.3</td>
<td>30</td>
<td>12</td>
<td>3.35×10^25</td>
<td>Rockwell et al. (2000); Ragona et al. (2003); Verde et al. (2007)</td>
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<tr>
<td></td>
<td>CCF-2</td>
<td>1719</td>
<td>6.7</td>
<td>1.1</td>
<td>35</td>
<td>12</td>
<td>1.43×10^26</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>CCF-3</td>
<td>1710</td>
<td>6.8</td>
<td>0.3</td>
<td>30</td>
<td>12</td>
<td>3.35×10^25</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>SMF-2 (SMF-CF)</td>
<td>1620</td>
<td>7.1</td>
<td>1.7</td>
<td>50</td>
<td>12</td>
<td>5.70×10^26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF-3 (SMF-CF)</td>
<td>1323</td>
<td>7.1</td>
<td>1.7</td>
<td>50</td>
<td>12</td>
<td>5.70×10^26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF-4 (SMF-CF)</td>
<td>1017</td>
<td>7.1</td>
<td>1.7</td>
<td>50</td>
<td>12</td>
<td>5.70×10^26</td>
<td>Yields 6.8 mm/yr for the Coyote Creek - Supersition Mountain fault, 1100 yrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrizo Mtn cross fault</td>
<td>1942</td>
<td>6.5</td>
<td>6.5</td>
<td>26</td>
<td>12</td>
<td>6.70×10^25</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Supersition Hills F</td>
<td>Event 1</td>
<td>1967</td>
<td>6.5</td>
<td>0.7</td>
<td>26</td>
<td>12</td>
<td>6.77×10^25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Event 2</td>
<td>ca. 1790</td>
<td>1680-1892</td>
<td>6.5</td>
<td>0.7</td>
<td>26</td>
<td>12</td>
<td>3.38×10^26</td>
<td>Site rate is poorly constrained. At 4 mm/yr, should generate a Mw of 6.5 about every 17 years.</td>
<td></td>
</tr>
<tr>
<td>Southern Elsinore F</td>
<td>Event 1</td>
<td>ca. 1750</td>
<td>1680-1800</td>
<td>7.1</td>
<td>1.8</td>
<td>34</td>
<td>12</td>
<td>2.28×10^26</td>
<td>Moment sum assuming a Mw of 6.5 every 175 years, 5 events in 1100 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Event 2</td>
<td>ca. 1400</td>
<td>800-1200</td>
<td>7.1</td>
<td>1.8</td>
<td>34</td>
<td>12</td>
<td>2.28×10^26</td>
<td>Assumes rupture of entire EF within the box.</td>
<td></td>
</tr>
<tr>
<td>Central Elsinore F</td>
<td>No ruptures past 1200 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Elsinore F</td>
<td>Event 1</td>
<td>ca. 1750</td>
<td>1680-1810</td>
<td>7.1</td>
<td>2.1</td>
<td>80</td>
<td>12</td>
<td>6.25×10^26</td>
<td>Vaughan et al. (1999); Rockwell et al. (1986b); Rockwell et al. (2001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Event 2</td>
<td>1375</td>
<td>1274-1474</td>
<td>7.1</td>
<td>2.1</td>
<td>80</td>
<td>12</td>
<td>6.25×10^26</td>
<td>(from Whittle/Chine bifurcation to Palomar Mtn)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Event 3</td>
<td>1050</td>
<td>1015-1104</td>
<td>7.1</td>
<td>2.1</td>
<td>80</td>
<td>12</td>
<td>6.25×10^26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum of moments on major faults</td>
<td>2.33×10^28</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Yields to 33 mm/yr, includes most faults with incomplete records.
≥M7 earthquakes

- Southern San Andreas events
- South-Central San Jacinto events
- Superstition Mountain events
- Southern Elsinore events

Probability Density

Calendar Year (AD)

- ~1000
- 978 1026 983 1062 1015
- 1224 1212
- 1291 1286
- 1325
- 1375
- 1481
- 1645 1650 1715
- ~1750 1710 1800
- 2000
All paleoseismic events

Moment Release (10^{27} dyne-cm)

- SAF
- SJF
- EF
- SMF-CCF

Moment Release Scale:
- Mw6.3
- Mw6.5
- Mw6.7
- Mw6.9
- Mw7.1
- Mw7.3

~2.2 \times 10^{28} dyne-cm for 160 km of plate margin in 1100 yrs = 34-36 mm/yr

Geodetic rate is ~39-40 mm/yr
1.76 x 10^{26} \text{ dyne-cm} of moment release in past 125 years in M5-M6.3 sized earthquakes equates to 2.3 mm/yr (5.8\%) of southern San Andreas slip rate.

- 1900 Brawley Seismic Zone, M6.1
- 1890, 1892 Earthquake Valley F., M6.3 and M6.3
- 1906 Brawley Seismic Zone, M6.1
- 1948 Desert Hot Springs, M6
- 1937 Terwilleger V., Clark F. or cross-fault, M5.9
- 1954 Arroyo Salada, So. Clark F., M6.3
- 1955 Brawley Seismic Zone, M5.4
- 1969 Coyote Ridge, CCF, M5.9
- 1980 Clark F., M5.5
- 1981 Westmorland, M5.8
- 1986 No. Palm Springs, Banning F.
- 1987 Elmore Ranch F., M6.2
- 2005 Brawley Seismic Zone, M5.1
- 2012 Brawley Seismic Zone, M5.4, M5.3, M5
Evidence for Coa-3 on the SAF was weak – what if this was not an Earthquake? (Philibosian actually describes it as only a possible event!)

>\textbf{M7} earthquakes 
No Coa3 SAF event

- Southern San Andreas events
- South-Central San Jacinto events
- Superstition Mountain events
- Southern Elsinore events

- Probability Density

- Calendar Year (AD)
Results in a more “clustered” behavior

No Coa3 on San Andreas F.

- SAF
- SJF
- EF
- SMF-CCF

Moment Release (10^{27} dyne-cm)

- Mw6.3
- Mw6.5
- Mw6.7
- Mw6.9
- Mw7.1
- Mw7.3

Year (AD / CE)

- 1899
- 1918
- 1942
- 1968
- 1987
today

200 year open interval

cluster or super cycle?

150 year open interval

cluster or super cycle?
Is there a relationship between Lake Cahuilla highstands (water loading) and earthquakes? Maybe so…

All paleoseismic events

Moment Release Scale
- Mw6.3
- Mw6.5
- Mw6.7
- Mw6.9
- Mw7.1
- Mw7.3

Lake loading may influence southern San Andreas earthquakes, as suggested by Lutrell et al. (2007) and Brothers et al. (2011). Can the lack of a refilling of Lake Cahuilla partially explain the current long open interval in the southern San Andreas system??
Mode-switching (Ben-Zion et al. EPSL, 1999): Long-term fluctuations between overshoot and undershoot seismic activity on heterogeneous faults (for which steady state response does not exist)

A large individual fault system: Frictional weakening and some dissipation of stress transfer --> Mode Switching

Coupled evolution of earthquakes and faults: Loading timescale ~ healing timescale --> Mode Switching
Take home message

The best paleoseismic data includes information on both timing and displacement, and there is a lot of it for the Southern San Andreas fault system.

Need to look at the entire fault system, not just one element

Appear to have been periods of higher and lower strain release resulting in apparent clustering of earthquakes

Past extended open intervals were followed by rupture of several faults, so a single large event may simply be the beginning. Will this result in the century of earthquakes?