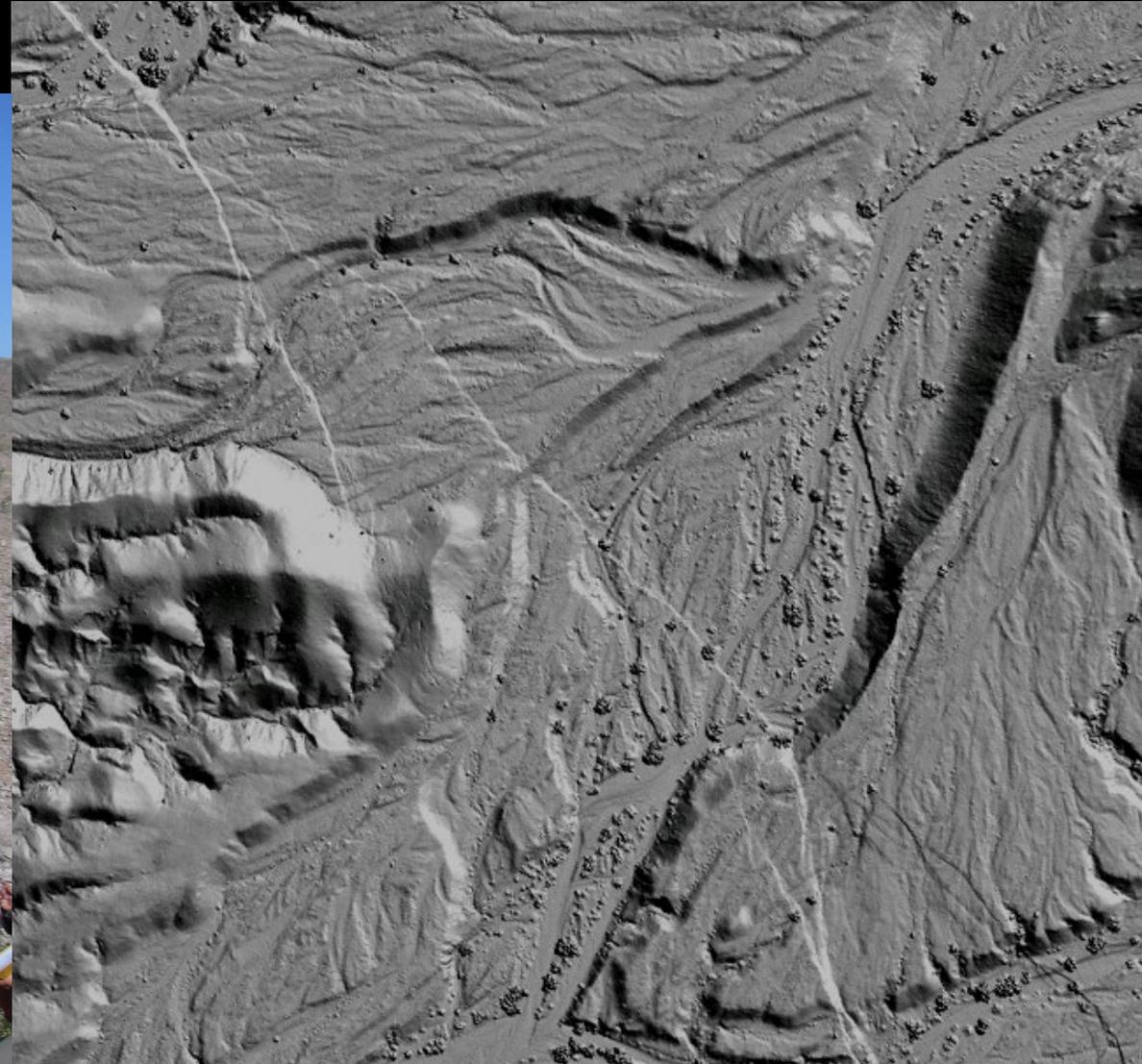


The role of earthquake geology in earthquake forecasting: Review and one San Andreas Fault example



J Ramón Arrowsmith
School of Earth and Space Exploration



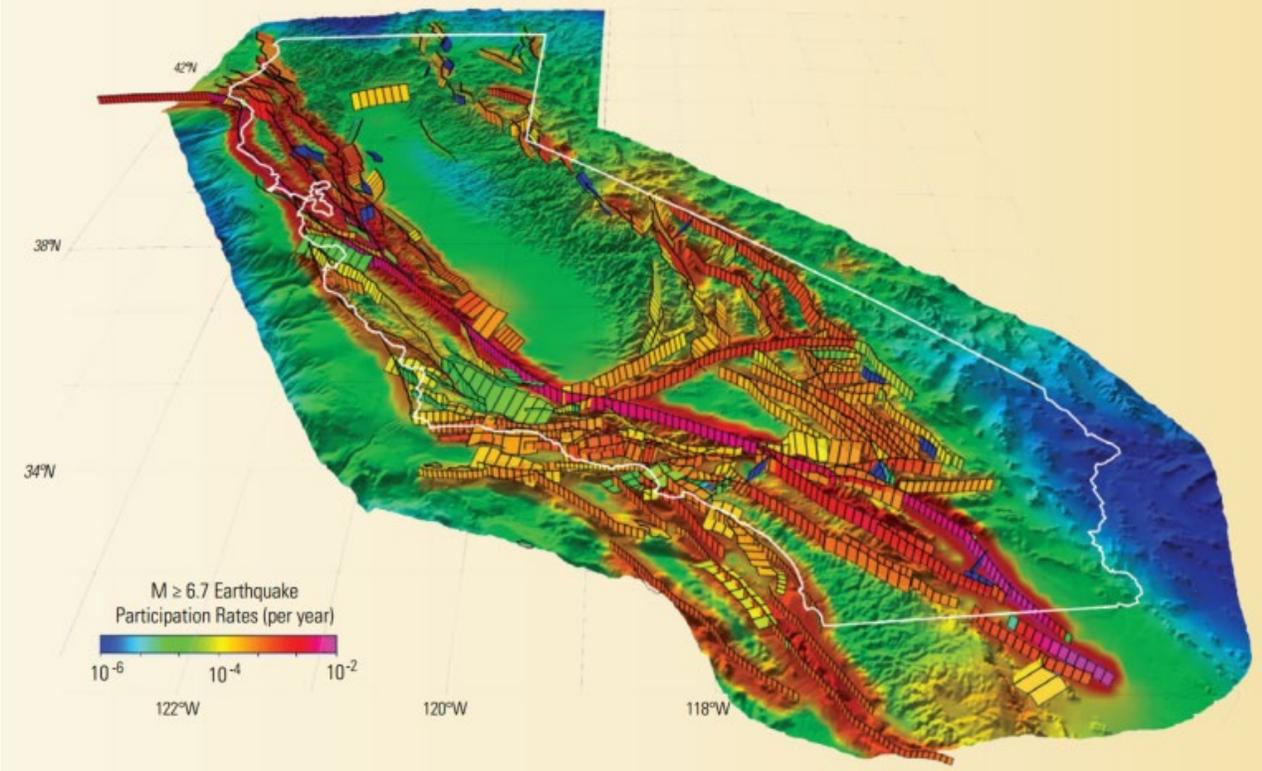
2010 El Mayor-Cucapah earthquake surface rupture (Tom Rockwell photo)

Oskin, M., Arrowsmith, J.R., Corona, A.H., Elliott, A.J., Fletcher, J.M., Fielding, E., Gold, P.O., Garcia, J.J.G., Hudnut, K.W., Liu-Zeng, J., Teran, O. J., Complex surface rupture of the El Mayor-Cucapah earthquake imaged with airborne lidar: *Science*, v. 335, p. 702-705, 2012.

- Earthquake geology provides information on fault geometry, earthquake history, offset, coseismic effects, and empirical constraints: “it happened”
- Largely derived from field observations

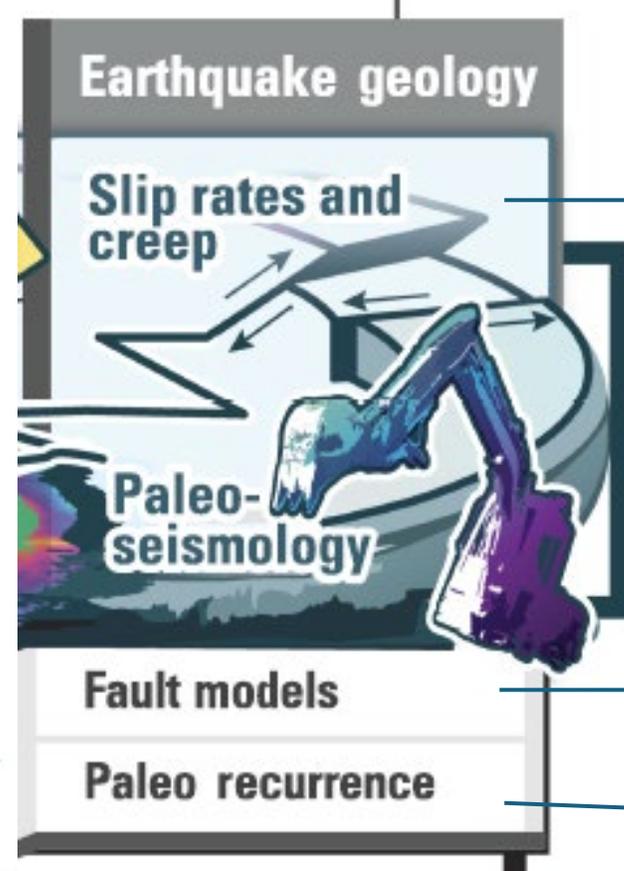
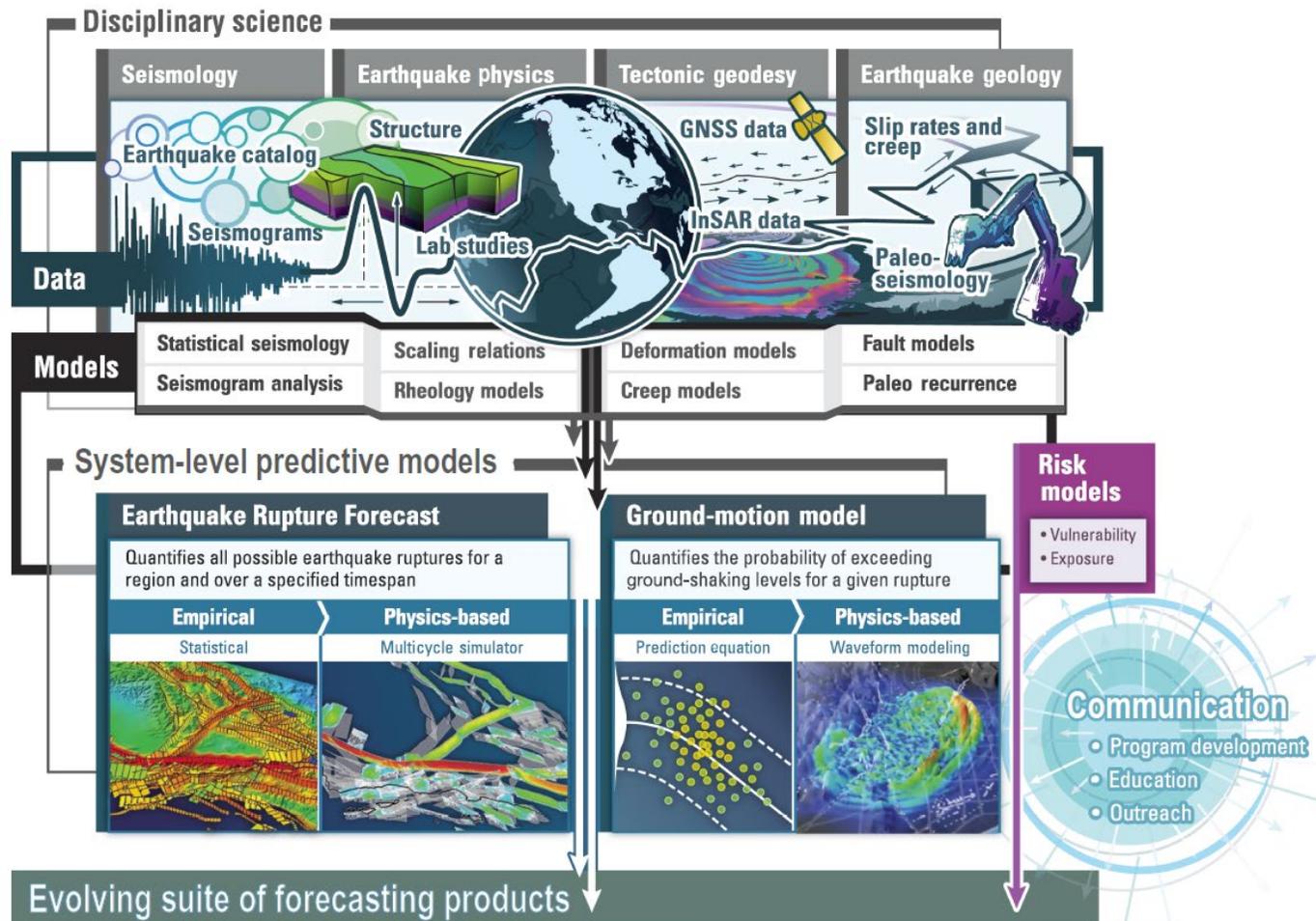


The Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3)—The Time-Independent Model



Field, E. H., Arrowsmith, J R., et al., *Bulletin of the Seismological Society of America*, doi: 10.1785/0120130164, 2014.
 And
 Field, E. H., Jordan, T. J., Page, M. T., Milner, K. R., Shaw, B. E., Dawson, T. E., Biasi, G. P., Parsons, T., Hardebeck, J. L., Michael, A. J., Weldon II, R. J., Powers, P. M., Johnson, K. M., Zeng, Y., Bird, P., Felzer, K. R., van der Else, N., Madden, C., Arrowsmith, J R., Werner, M. J., Thatcher, W.R., A Synoptic View of the Third Uniform California Earthquake Rupture Forecast (UCERF3), *Seismological Research Letters*, Volume 88, Number 5, doi: 10.1785/0220170045, 2017.

Earthquake hazard and risk forecasting enterprise



Localization over different time scales, cumulative deformation

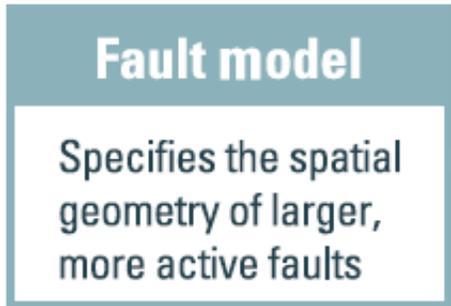
Geometry; primary and secondary; segmentation

History of ground rupture, slip/event

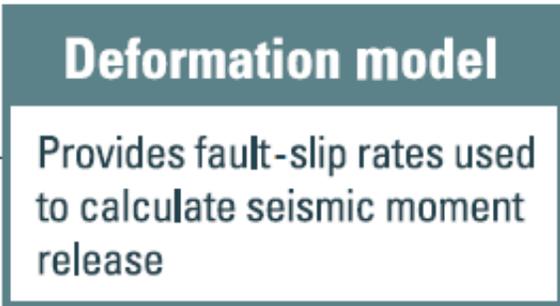
*Variable levels of ambiguity
Both Aleatory variability and
Epistemic uncertainty are important*

Field, E. H., A. E. Hatem, B. E. Shaw, M. T. Page, P. M. Mai, K. R. Milner, A. L. Llenos, A. J. Michael, F. F. Pollitz, J. Thompson Jobe, et al. (2025). **A Scientific Vision and Roadmap for Earthquake Rupture Forecast Developments, A USGS Perspective**, *Bulletin of Seismological Society of America* 115, 2523–2552, doi: 10.1785/0120240217

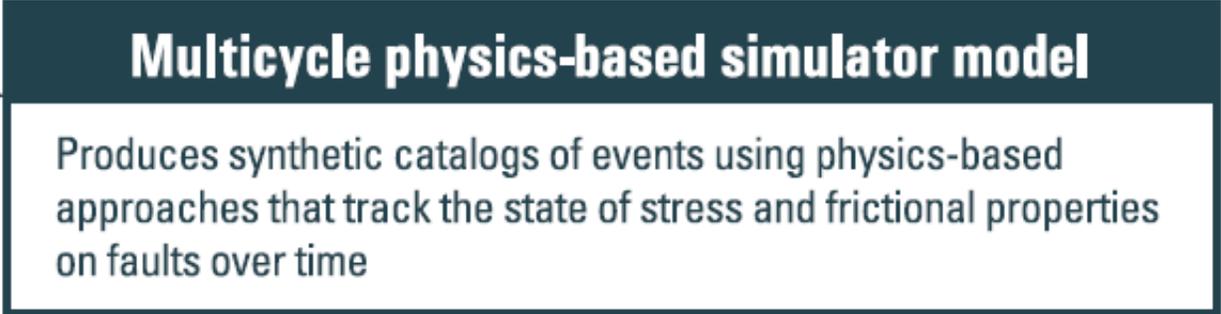
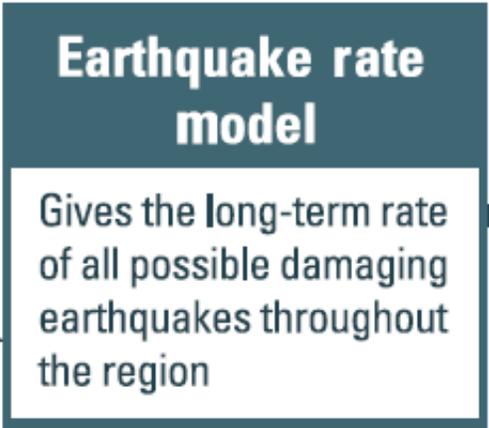
Earthquake geology can provide:



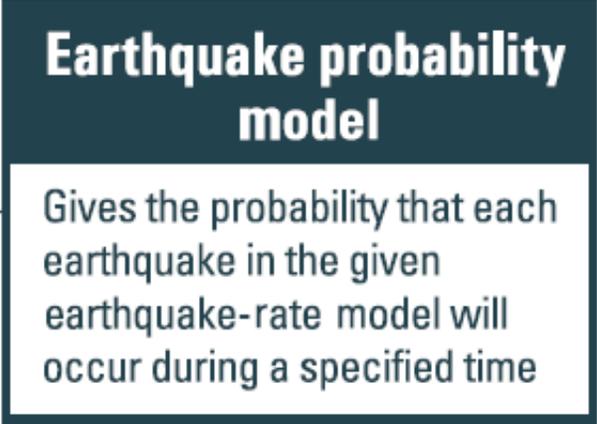
- Surface trace
- 3D geometry, incl. segmentation
- Sense of slip
- Geologic framework: crustal structure and tectonic regime
- Thermal and rheological constraints on seismogenic thickness



- **Slip rates and distributed deformation over 10^2 - 10^5 yr timescales**

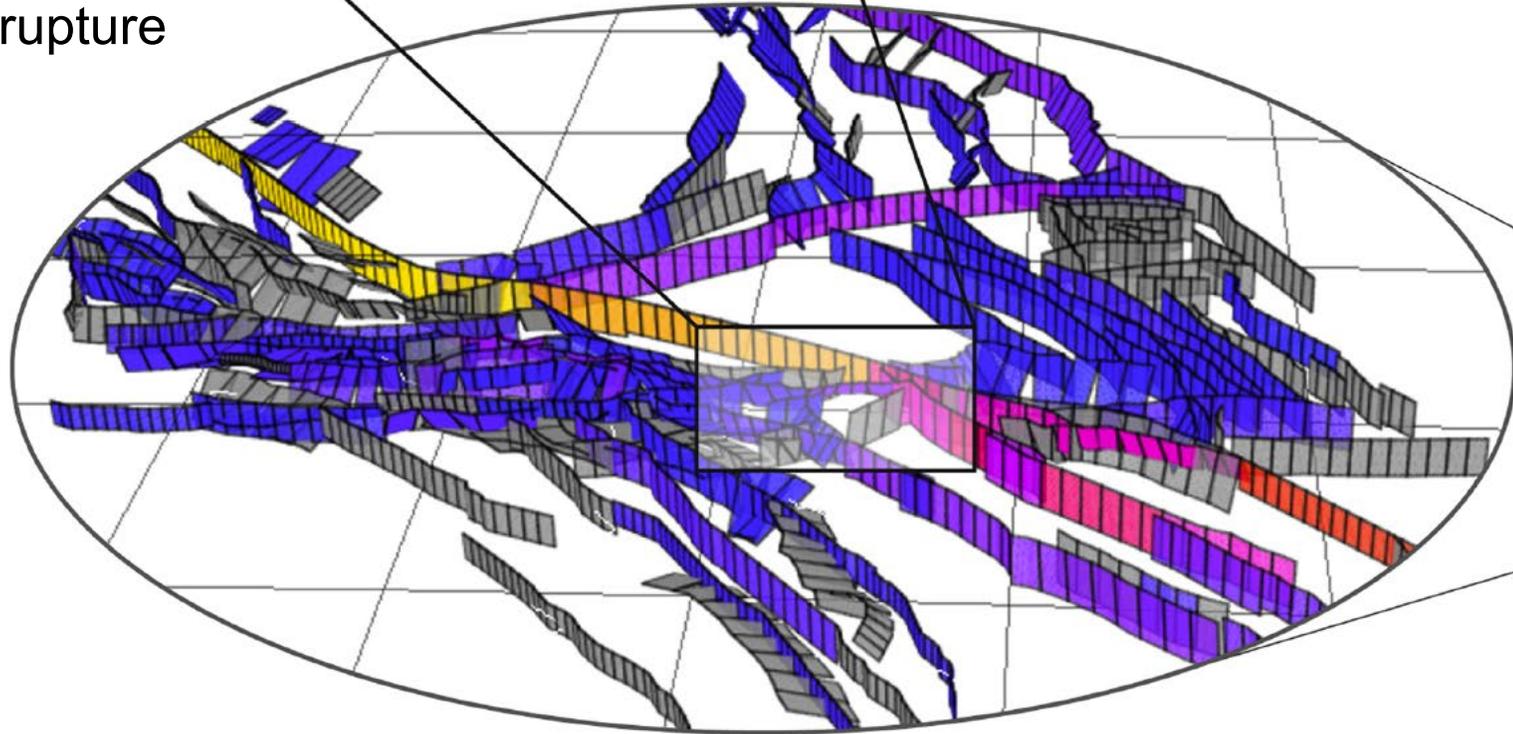
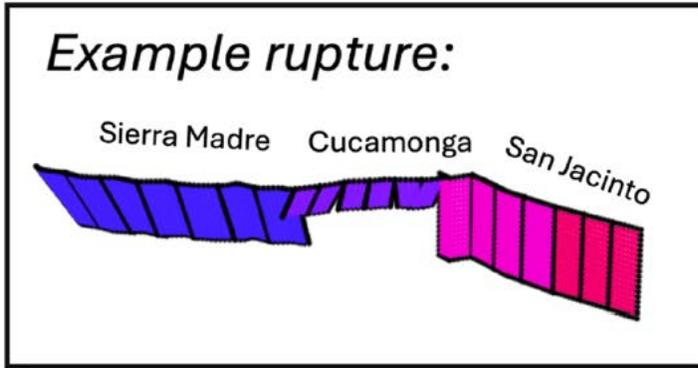


- **Paleo recurrence timing and slip/event**
- **Magnitude-frequency distribution**
- System scale plausibility
- Longer time scale unexceeded ground motions from fragile geologic features



Field, E. H., A. E. Hatem, B. E. Shaw, M. T. Page, P. M. Mai, K. R. Milner, A. L. Llenos, A. J. Michael, F. F. Pollitz, J. Thompson Jobe, et al. (2025). **A Scientific Vision and Roadmap for Earthquake Rupture Forecast Developments, A USGS Perspective**, *Bulletin of Seismological Society of America* 115, 2523–2552, doi: 10.1785/0120240217

Inversion based
rupture forecast
(colored by rupture
rate)



Mostly EQ geology inputs

Fault-slip rates: v_s is the subsection slip rate and D_{sr} is the average slip on the s th subsection in the r th event.

$$\sum_{r=1}^R D_{sr} f_r = v_s$$

Paleoseismic event rates: f_s^{paleo} is a paleoseismically inferred event rate estimate, G_{sr} specifies whether the r th rupture utilizes the s th subsection (0 or 1), and P_r^{paleo} is the probability that the r th rupture would be seen in a paleoseismic trench.

$$\sum_{r=1}^R G_{sr} P_r^{\text{paleo}} f_r = f_s^{\text{paleo}}$$

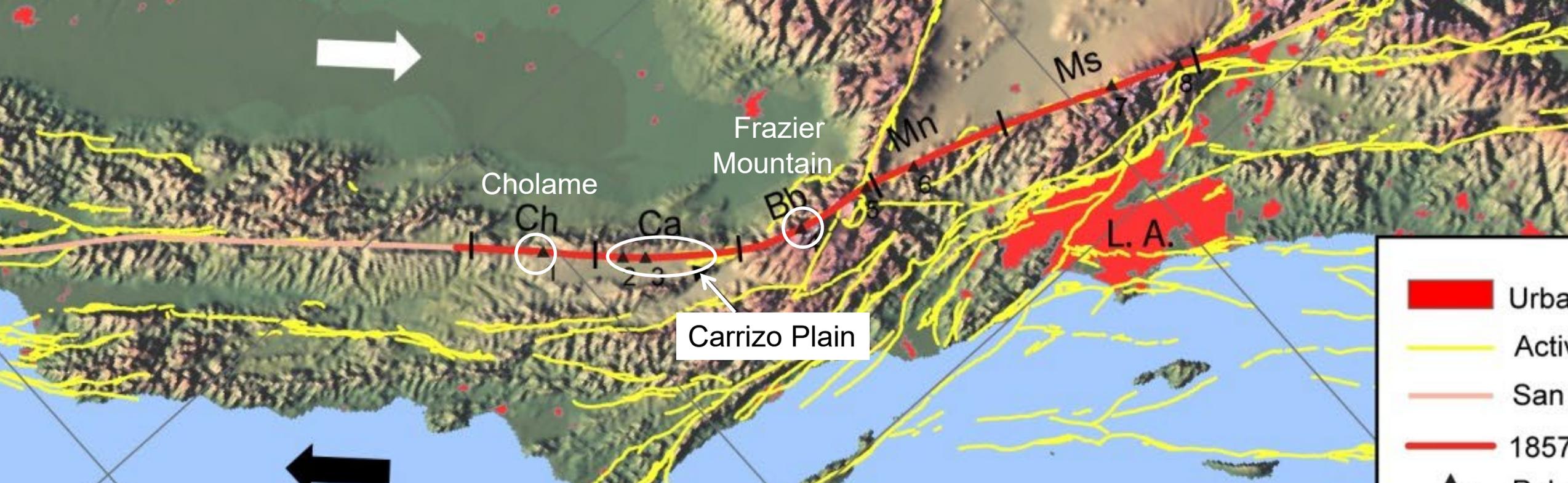
Magnitude–frequency distribution: This forces a group (g) of ruptures (e.g., those in a geographic region or those at a point on a fault) to have a specified total MFD. R_g^m represents the nucleation rate for the m th magnitude bin for the g th rupture group. Matrix M_{gr}^m indicates whether the r th rupture is both part of the g th group and falls in the m th magnitude bin (0 or 1).

$$\sum_{r=1}^R M_{gr}^m f_r = R_g^m$$

Fault segmentation: This limits the extent to which neighboring fault sections (s and \hat{s}) can rupture together. Specifically, this limits the corupture rate ($R_{s\hat{s}}$) to be less than a specified fraction ($F_{s\hat{s}}$) of the lowest rupture rate on either subsection (R_s and $R_{\hat{s}}$). A fault-jump distance version of this is applied by replacing $F_{s\hat{s}}$ with $\text{Min}(1, e^{-(d_{s\hat{s}}-\delta)/d_0})$, in which $d_{s\hat{s}}$ is jump distance, d_0 is a decay parameter, and δ is an offset parameter (no penalty is applied up to this distance).

$$R_{s\hat{s}} \leq F_{s\hat{s}} \text{Min}(R_s, R_{\hat{s}})$$

* f_r represents the frequency or rate of the r th rupture (what we are solving for).



The recurrence interval for earthquakes of different magnitude at a given point on the fault is believed to follow the relation:

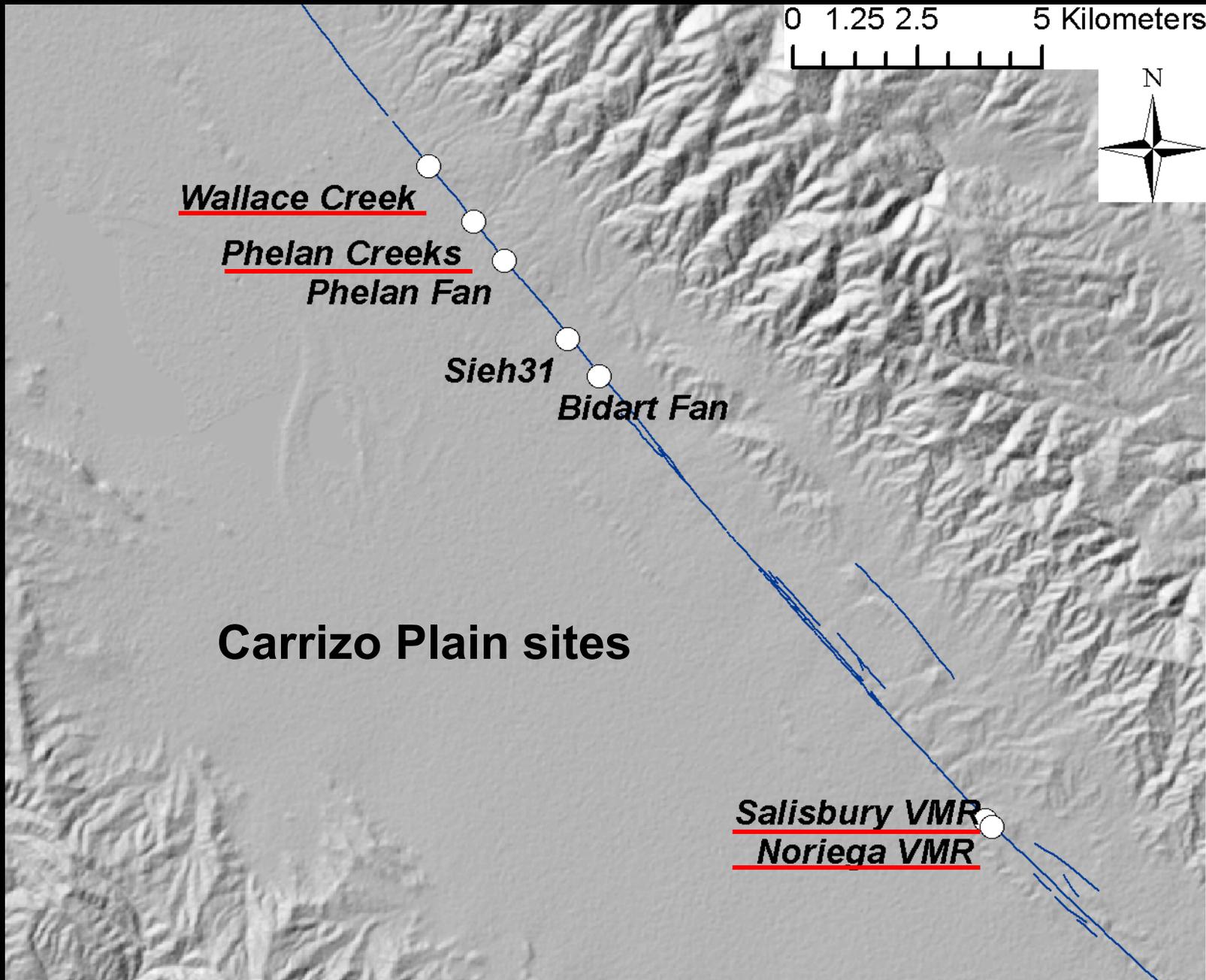
$$R_x = \frac{D}{S - C} \quad (1)$$

where: R_x = recurrence interval at a point on the fault,
 D = displacement accompanying an earthquake of given magnitude (related empirically to Richter magnitude),
 S = long-term strain rate (from offset of geologic units),
 C = tectonic creep rate. Wallace, GSAB, 1970

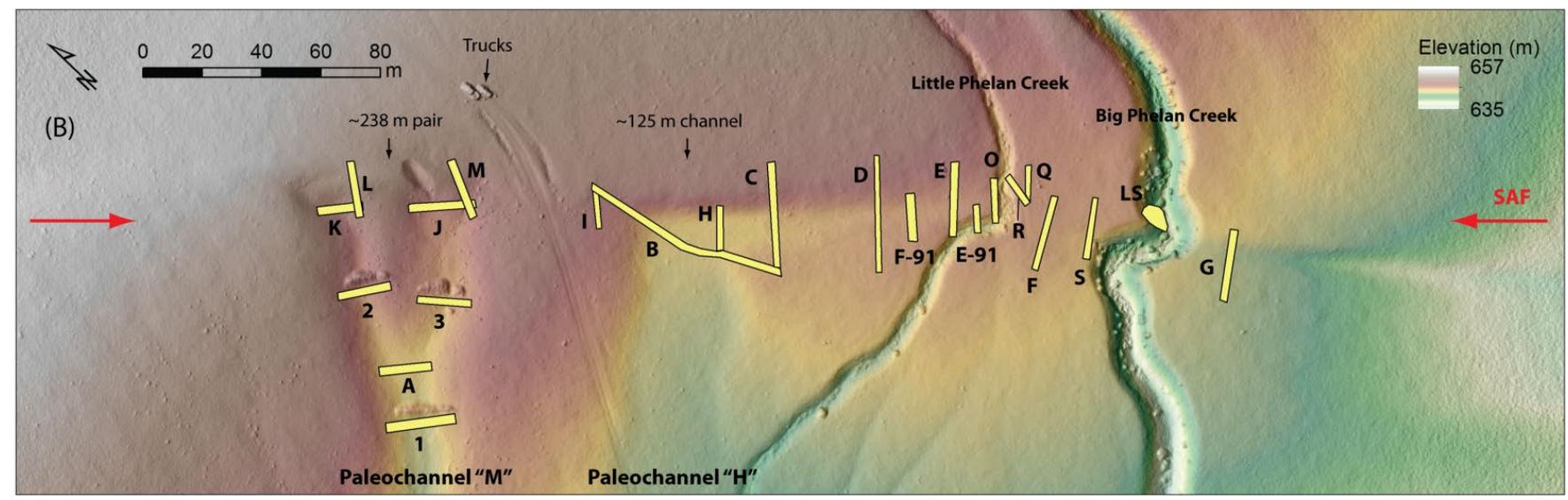
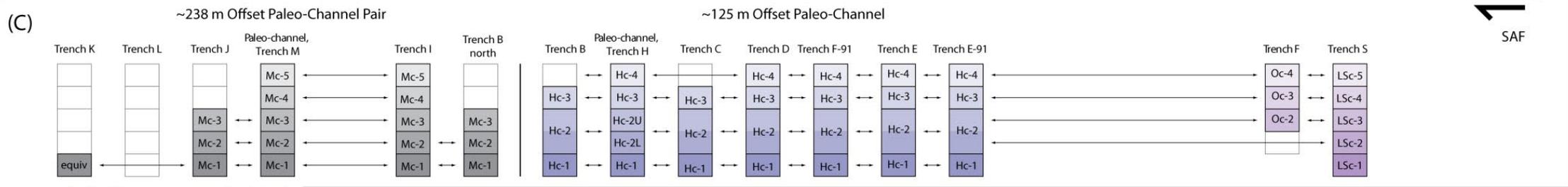
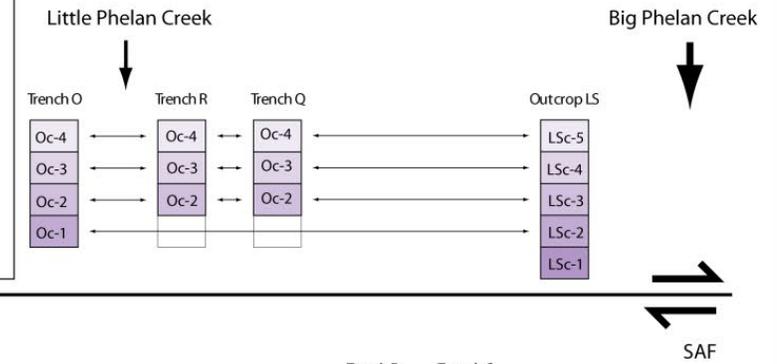
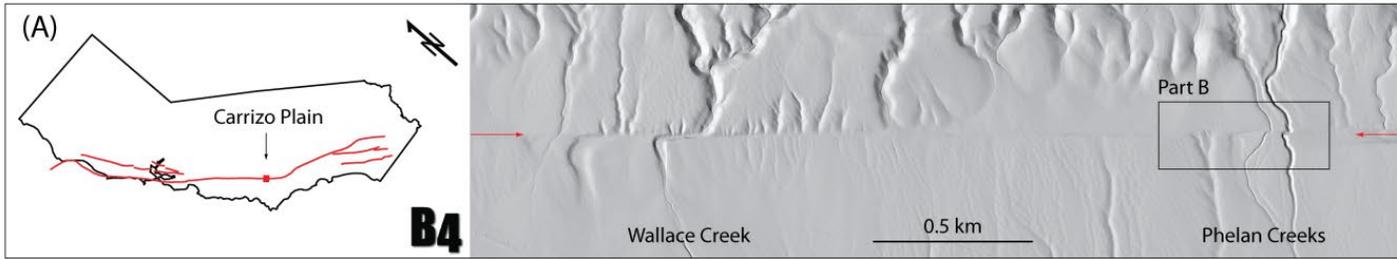
Review of last decade of research along SCSAF:

- 1) Holocene-recent slip rate (S)
- 2) Earthquake recurrence over the last millennium (R_x)
- 3) Slip per event(s) (D)
- 4) Integration:
 S is ~ steady
 R_x is quasi periodic and ~100yrs
 D and Length and M are variable (bimodal?)

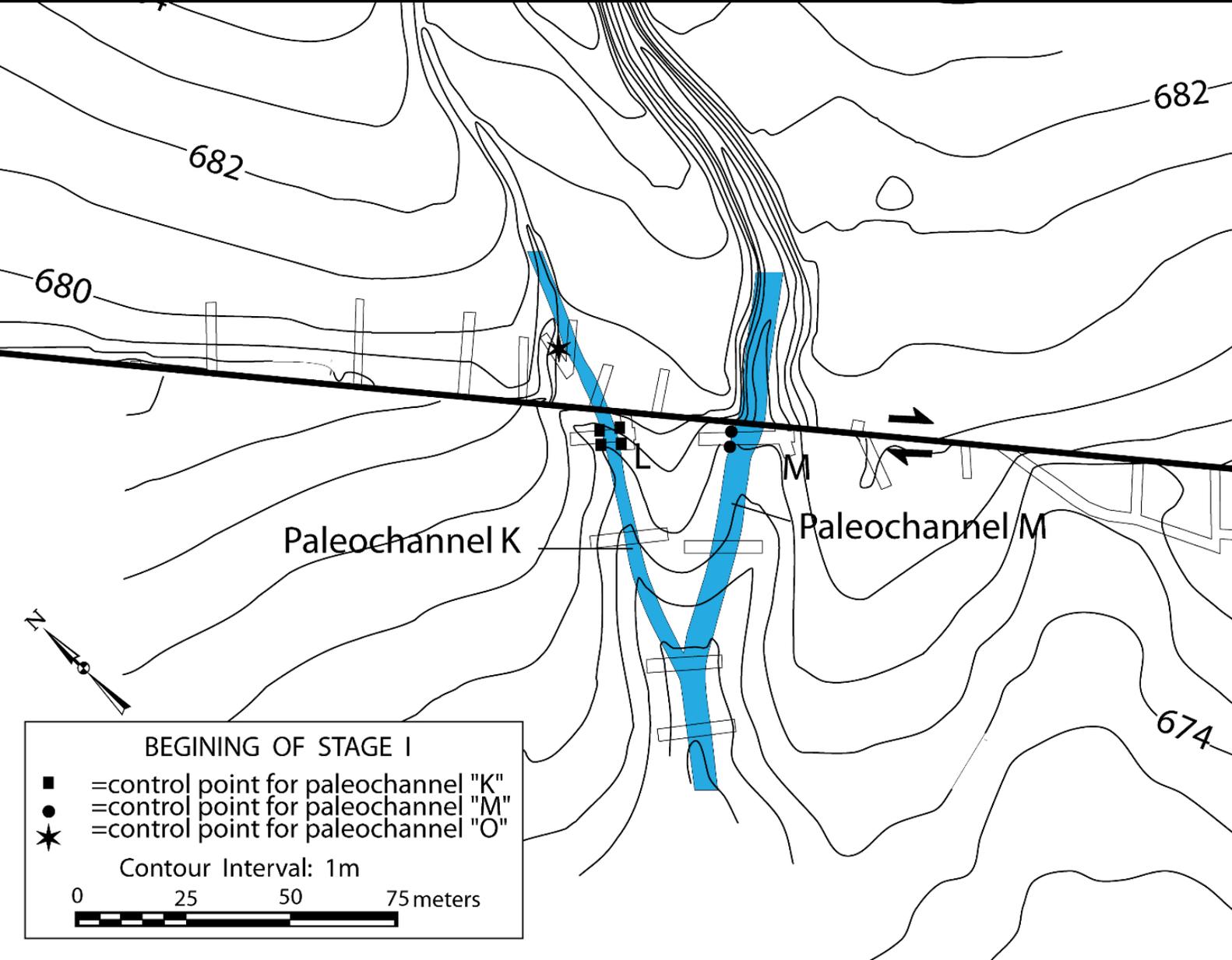
Holocene-recent slip rate



Phelan Creeks slip rate



$<35.1 \pm 0.6 \text{ mm/yr}$



Stage I

Age:

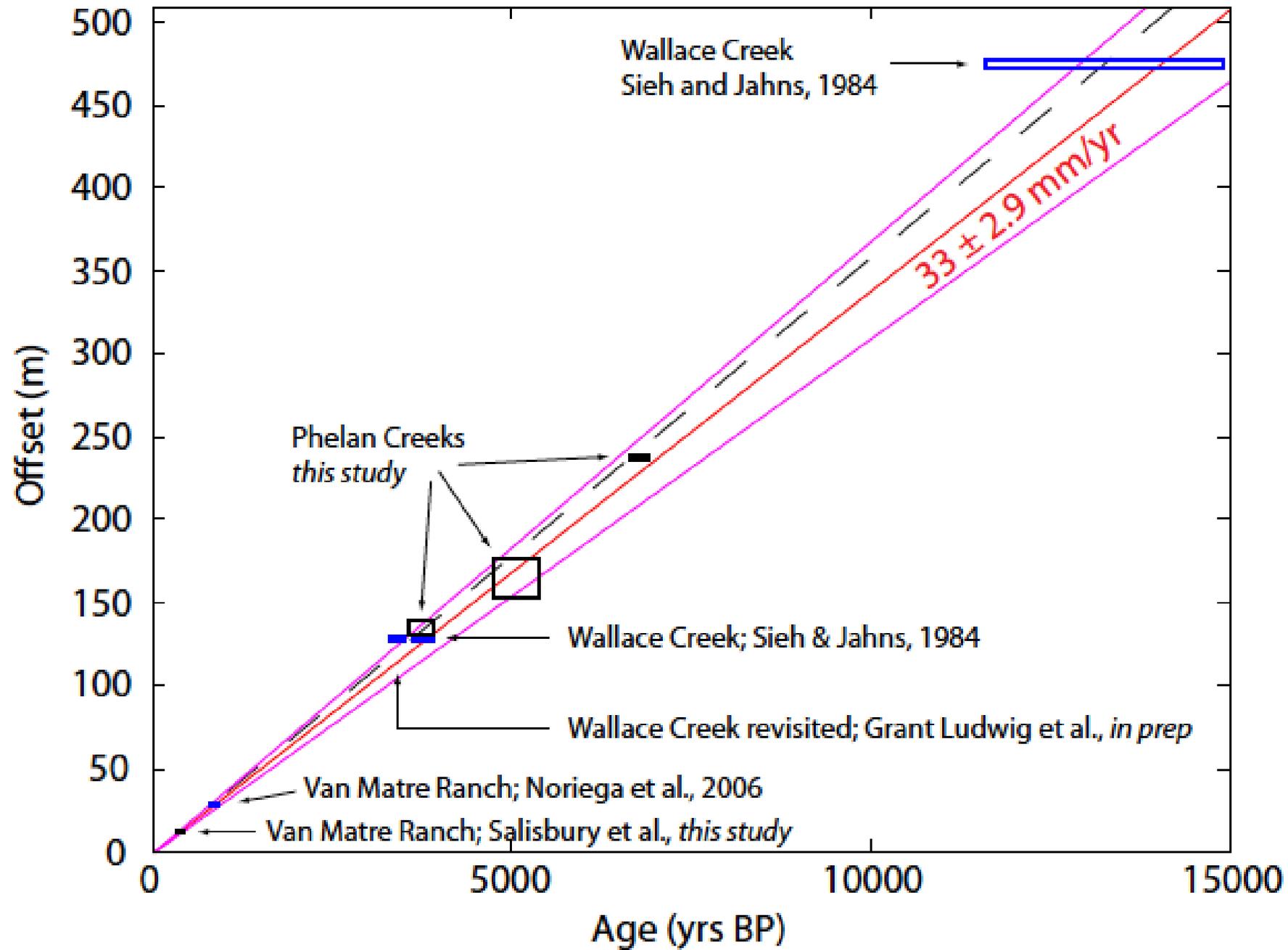
$12,373 \pm 357 \text{ Cal BP}$ -
 $<6,780 \pm 110 \text{ Cal BP}$

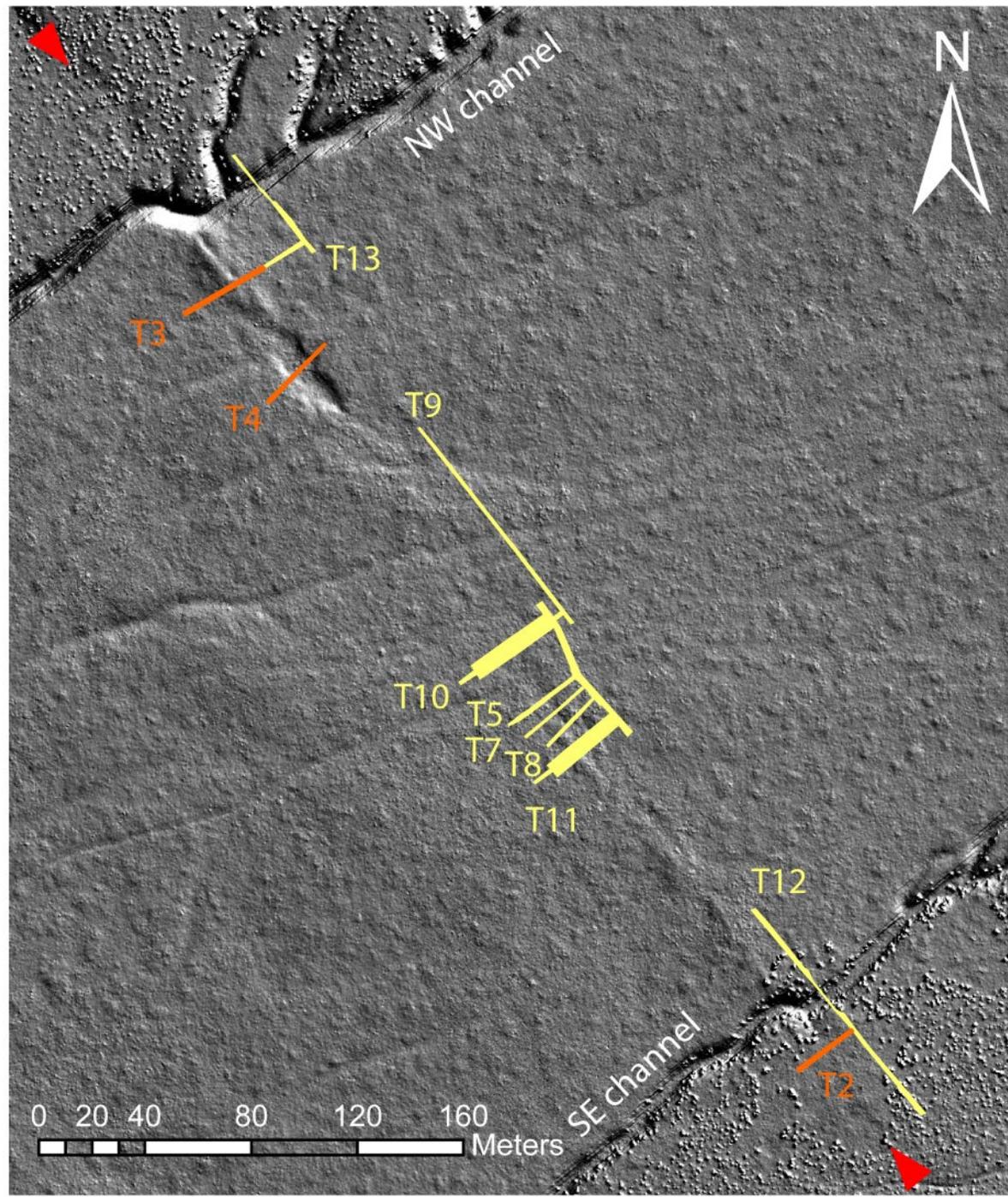
Event:

Initial cutting of
channels K and M

Cumulative Offset:
 $238 \pm 1.5 \text{ m}$

Slip rate summary: ~steady strain accumulation and release

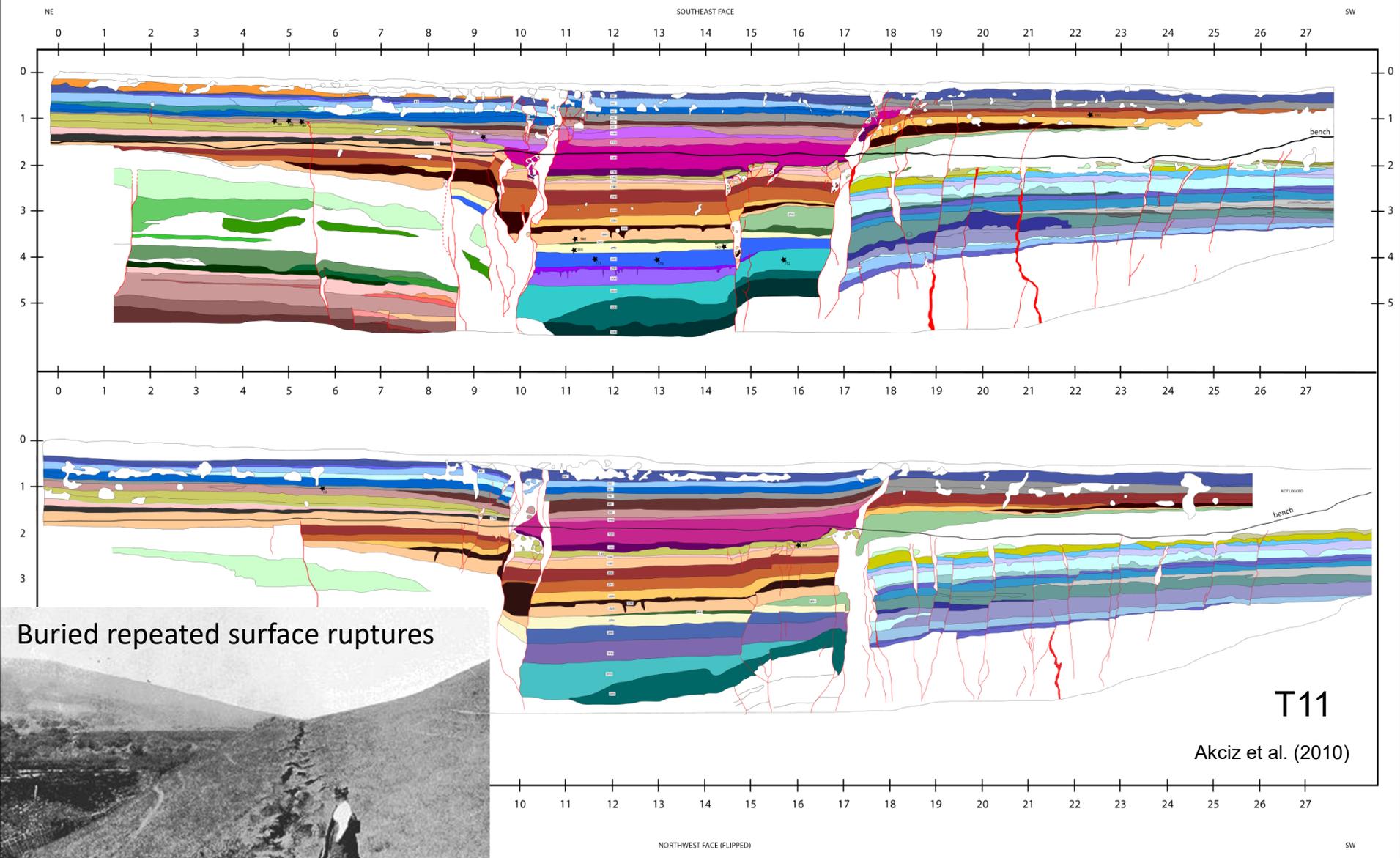




Paleo
occurrence:
Extensive
paleoseismic
investigation at
Bidart Fan





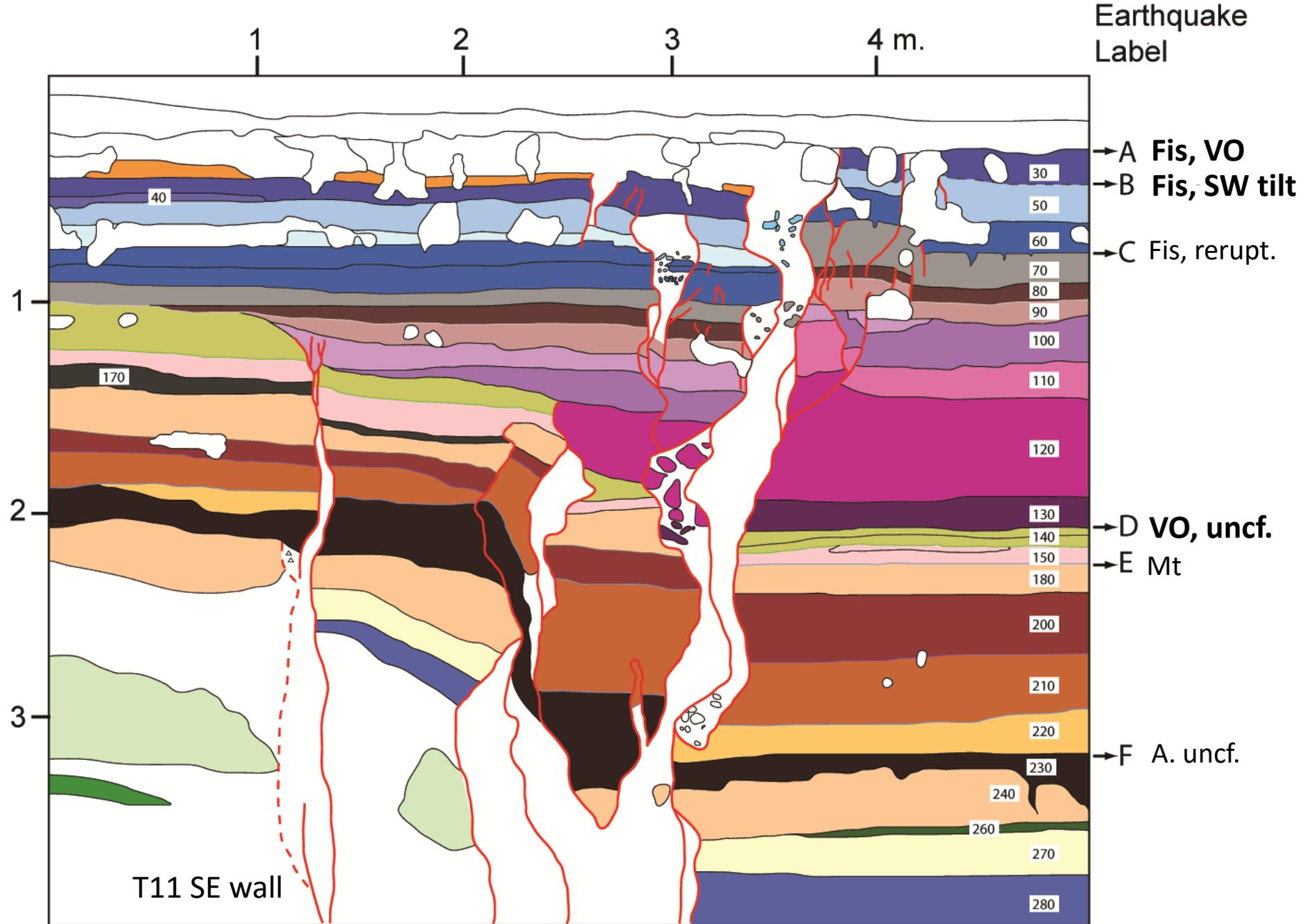


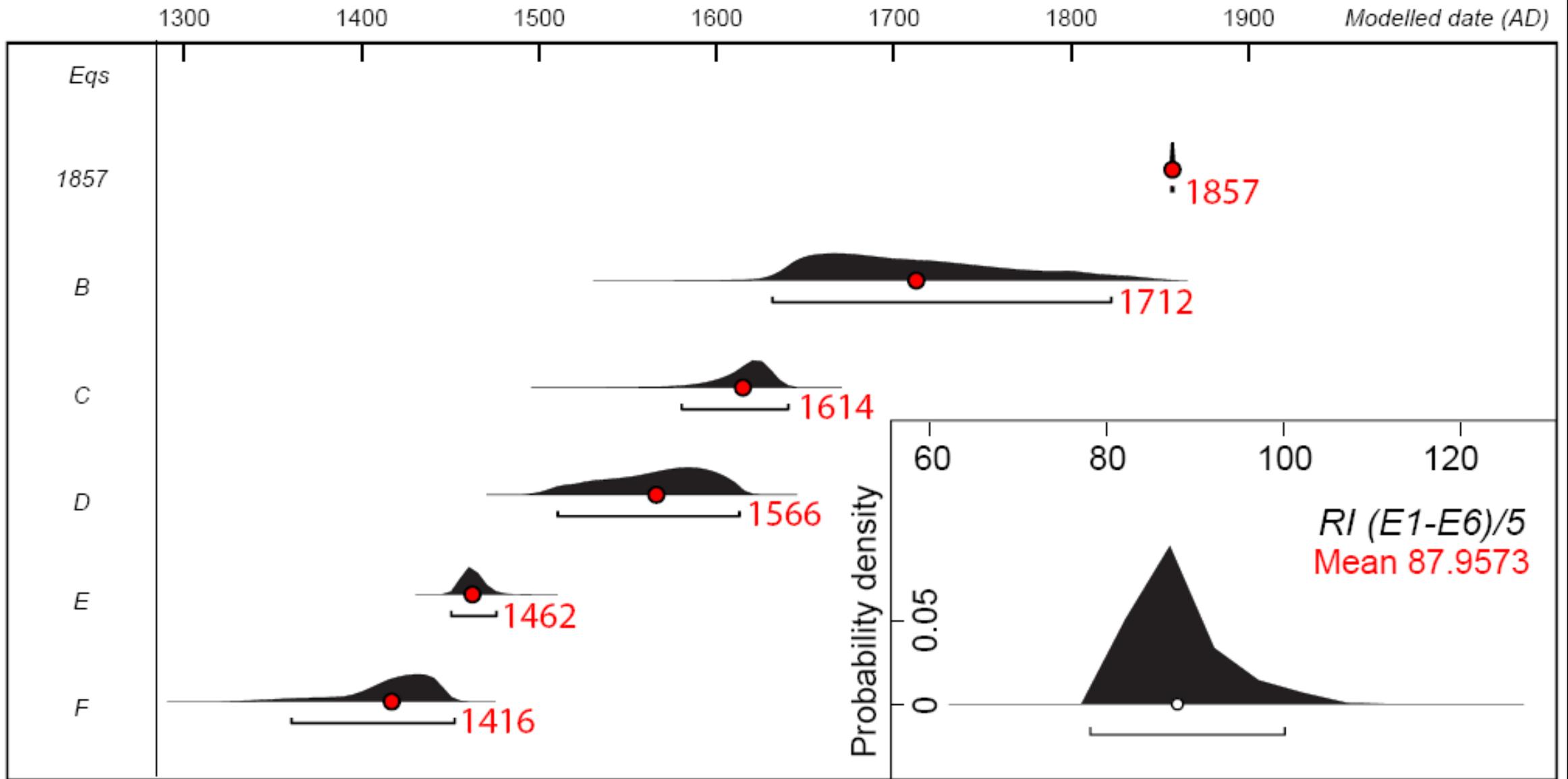
Buried repeated surface ruptures



T11

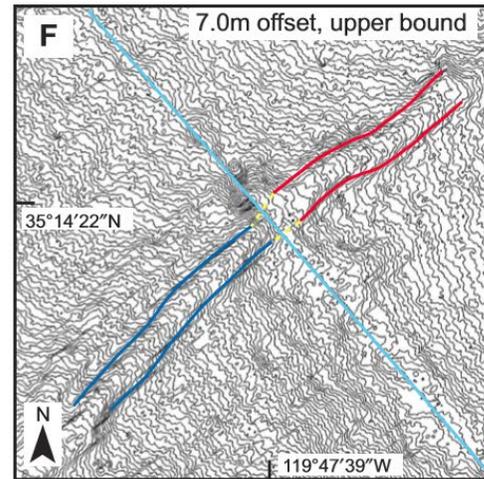
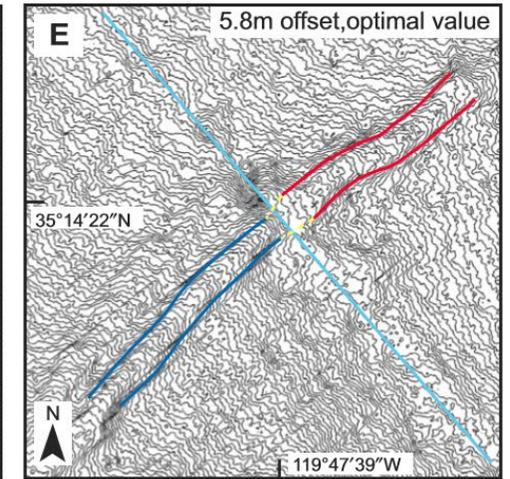
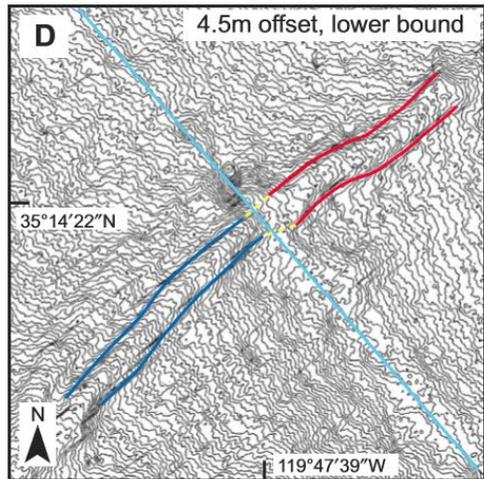
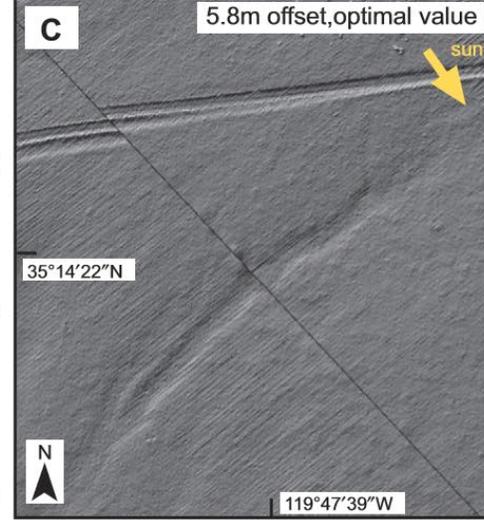
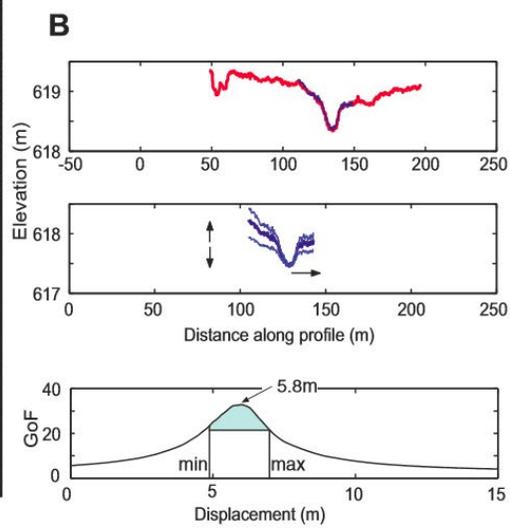
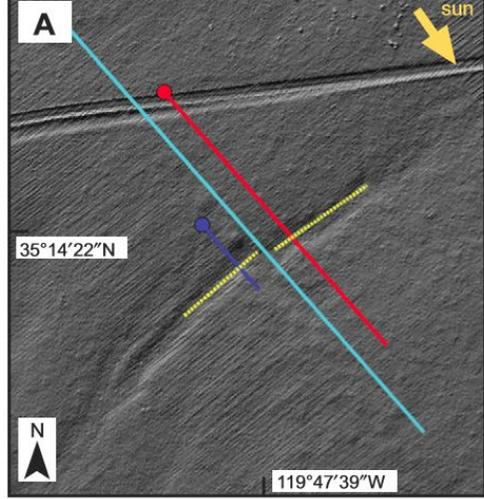
Akciz et al. (2010)



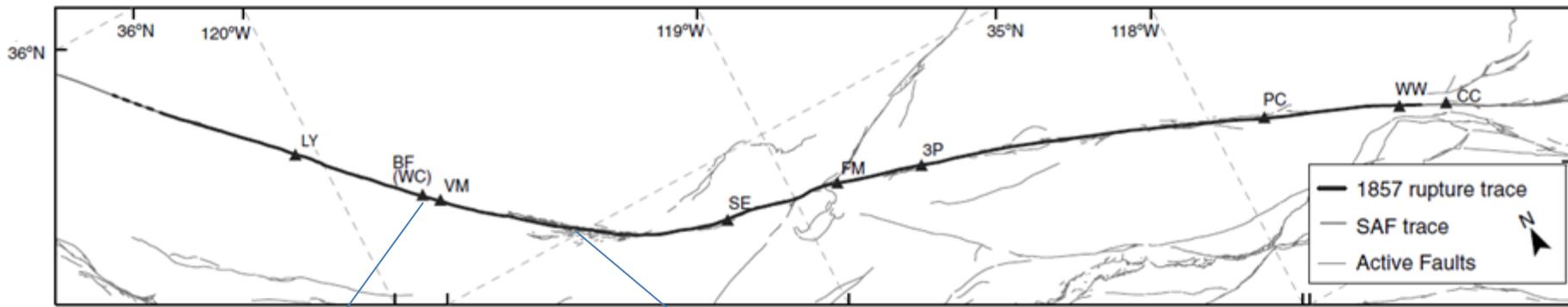


Summary probability distributions for ages of last 6 south-central San Andreas Fault Earthquakes: 88 ± 41 yr, or 99 ± 46 yr including open interval

Slip per event from geomorphic markers: assume marker formation rate is more rapid than earthquake recurrence rate

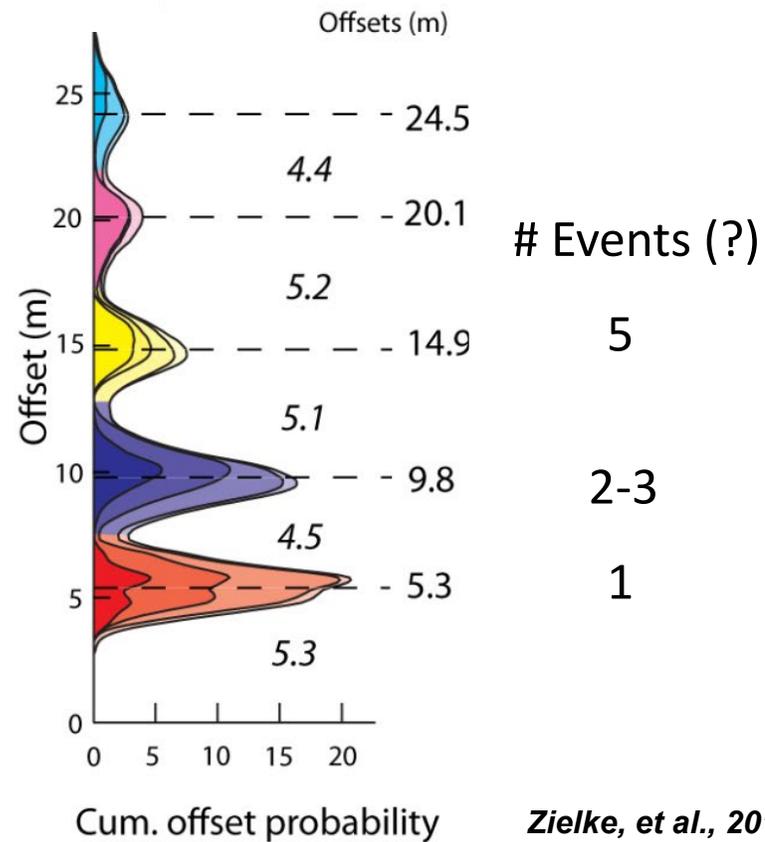
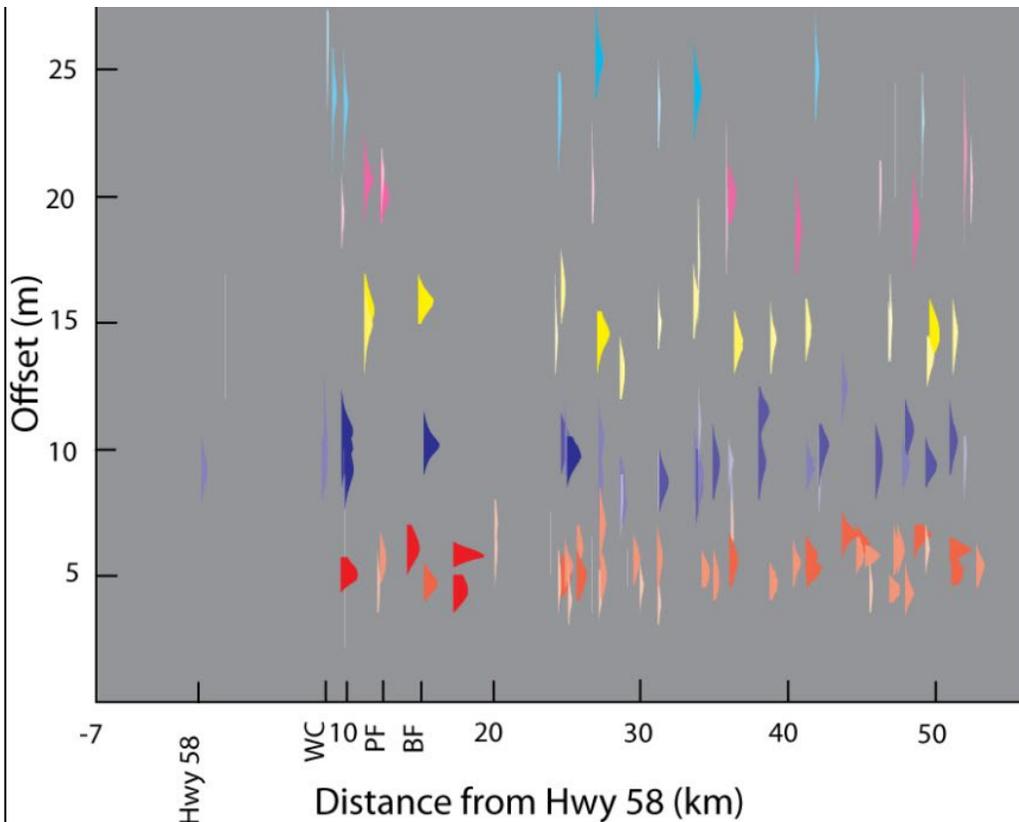


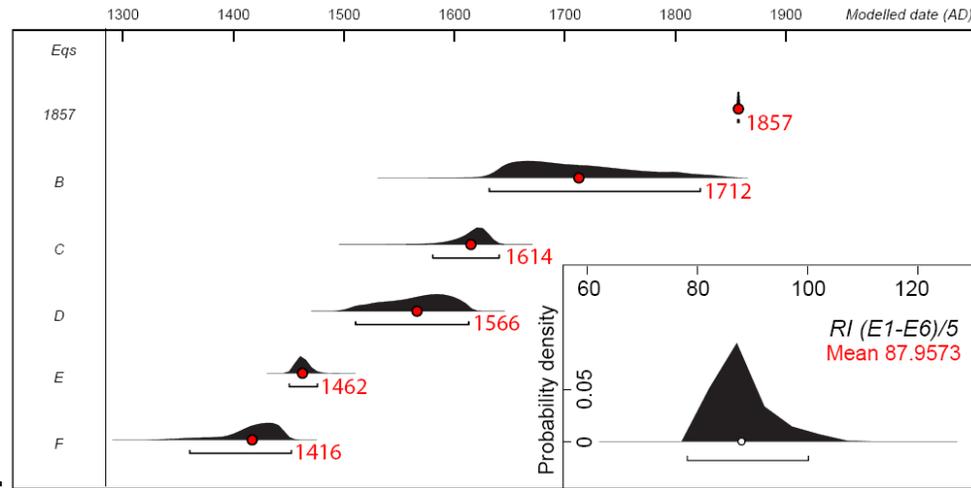
- Zielke, O., and J R. Arrowsmith, LaDiCaoz and LiDARimager -MATLAB GUIs for LiDAR data handling and lateral displacement measurement, *GeoSphere: Special issue on high resolution topography*, v. 8, no. 1, p. 206-221, doi:10.1130/GES00686.1, 2012.
- Zielke, O., Klinger, Y., Arrowsmith, J R., Fault slip and earthquake recurrence along strike-slip faults-- contributions of high-resolution geomorphic data [Invited Review], *Tectonophysics*, Volume 638, Pages 43-62, <http://dx.doi.org/10.1016/j.tecto.2014.11.004>, 2015.
- Salisbury, J. B., Haddad, D. E., Rockwell, T., Arrowsmith, J. R., Madugo, C., Zielke, O., & Scharer, K. (2015). Validation of meter-scale surface faulting offset measurements from high-resolution topographic data. *Geosphere*, 11(6). <https://doi.org/10.1130/GES01197.1>



Paleoseismic information from nearby suggests ~ 100 yr recurrence intervals

Slip rate is well defined at ~ 35 mm/yr

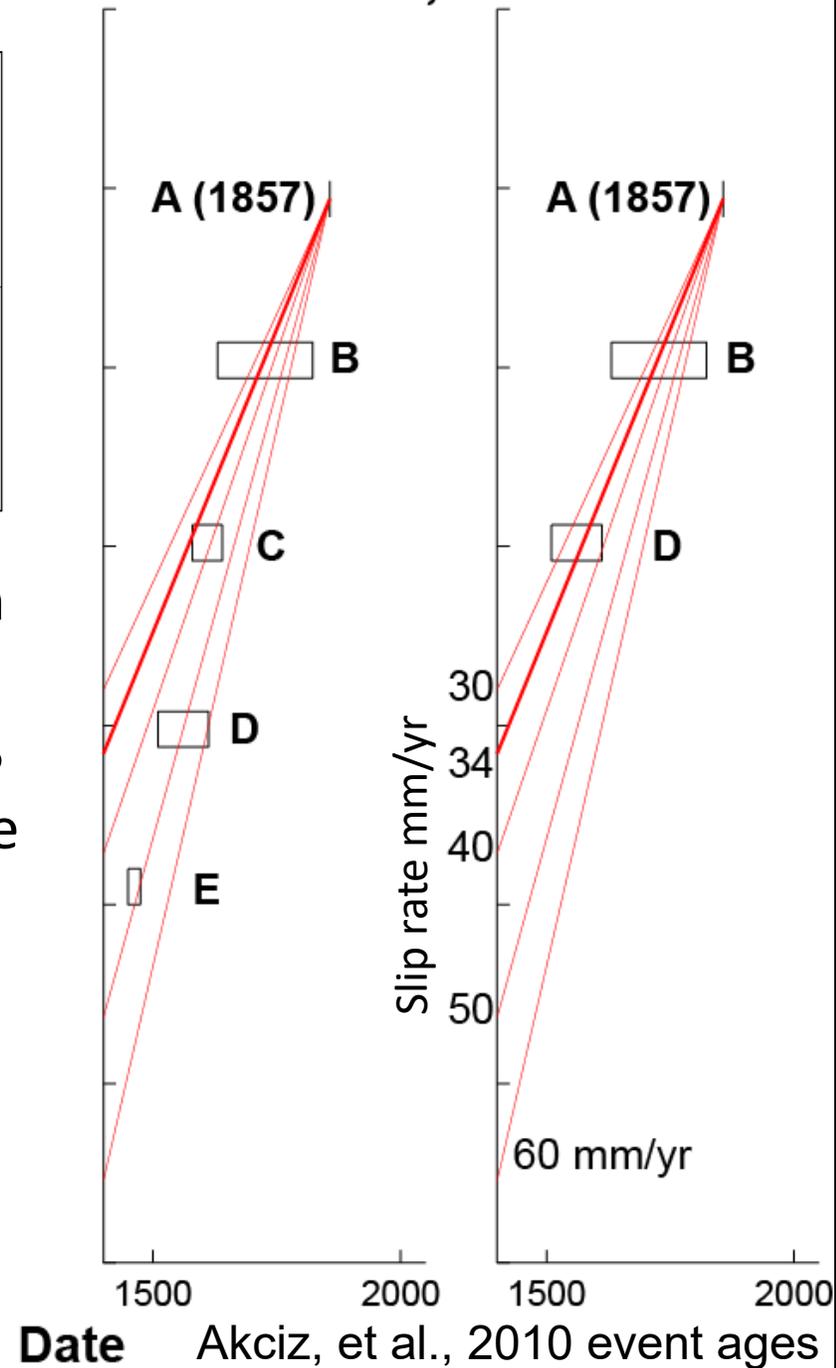




One to one correlation between offset landforms and events provides too high slip rate (right)

If there is variable slip/event and only B and D are significant geomorphically, the event rate and slip/event can reconcile

Zielke, et al. offsets



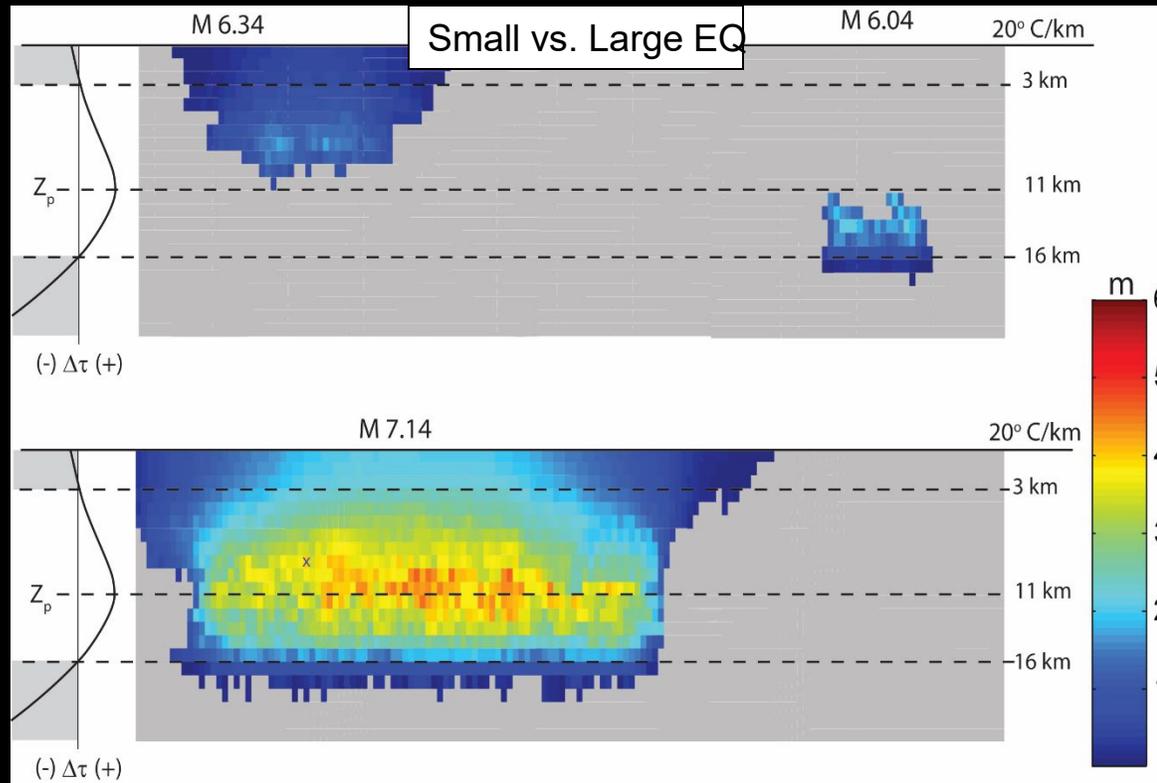
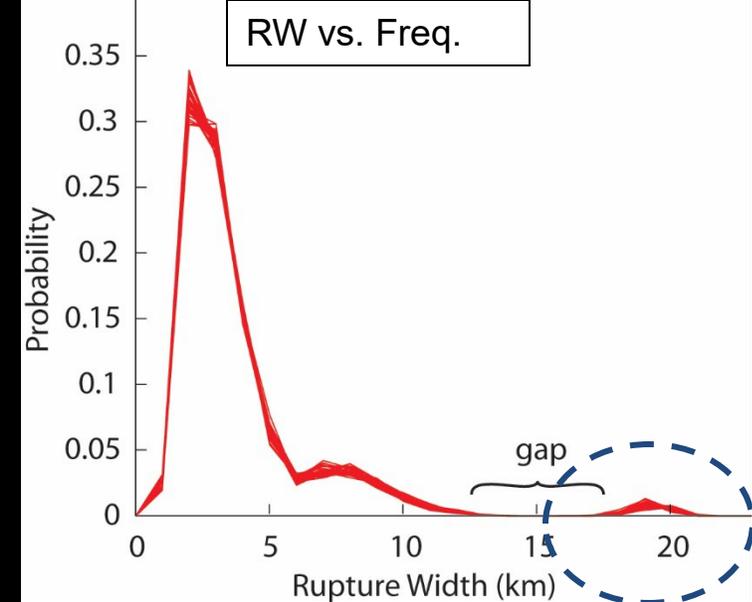
Bimodal Seismicity Distribution from earthquake simulator

Down-dip rupture width RW of small EQs is limited by peak of coseismic stress drop at z_p

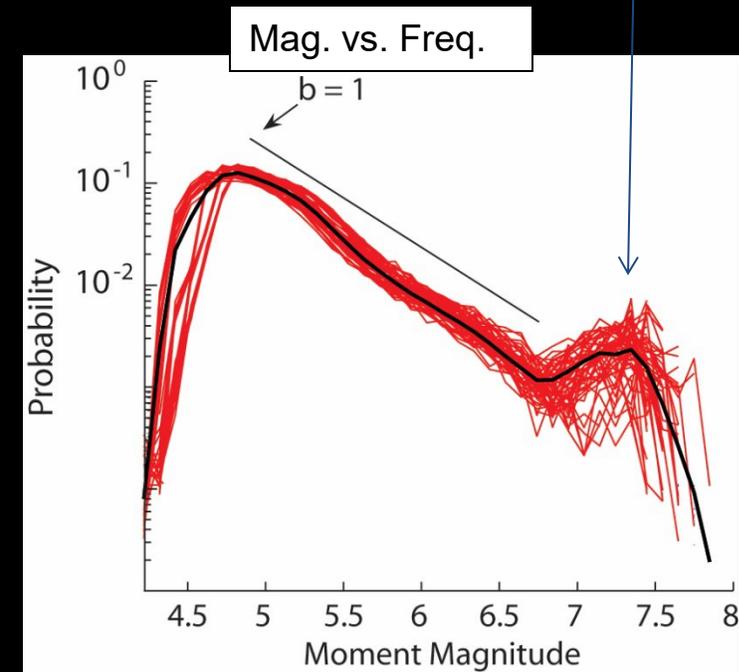
Rupture of strength barrier z_p causes activation of full seismic zone

→ Abrupt increase in RW and RA at transition from small to large EQs

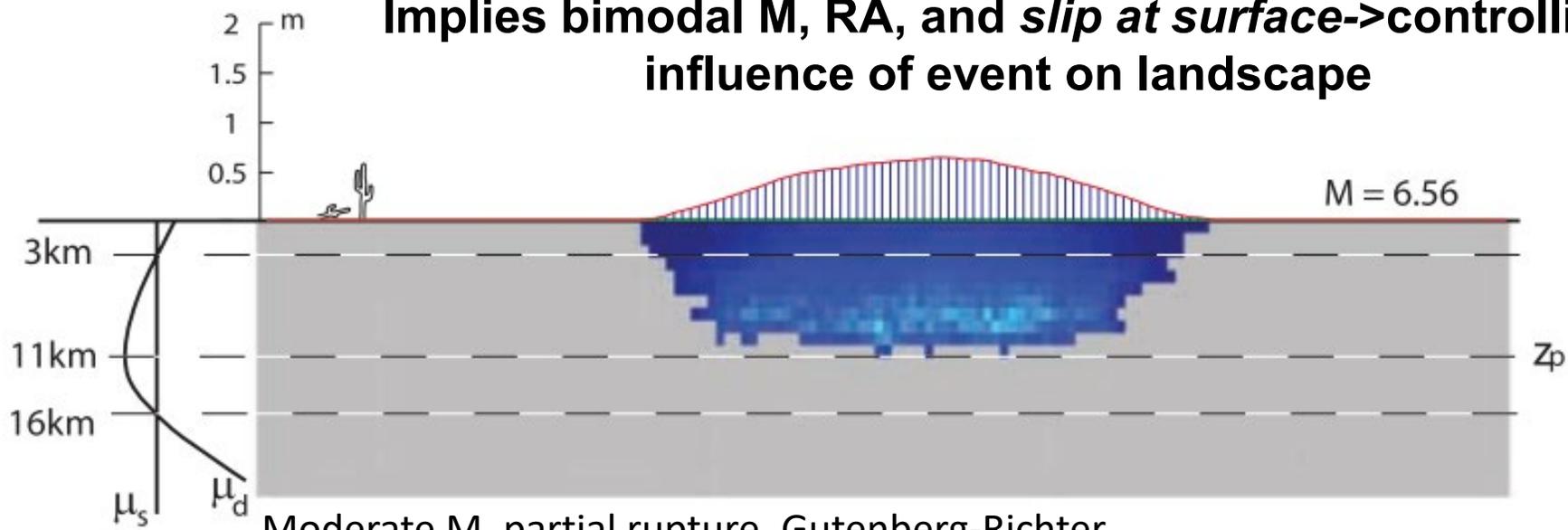
→ Abrupt increase in Magnitude



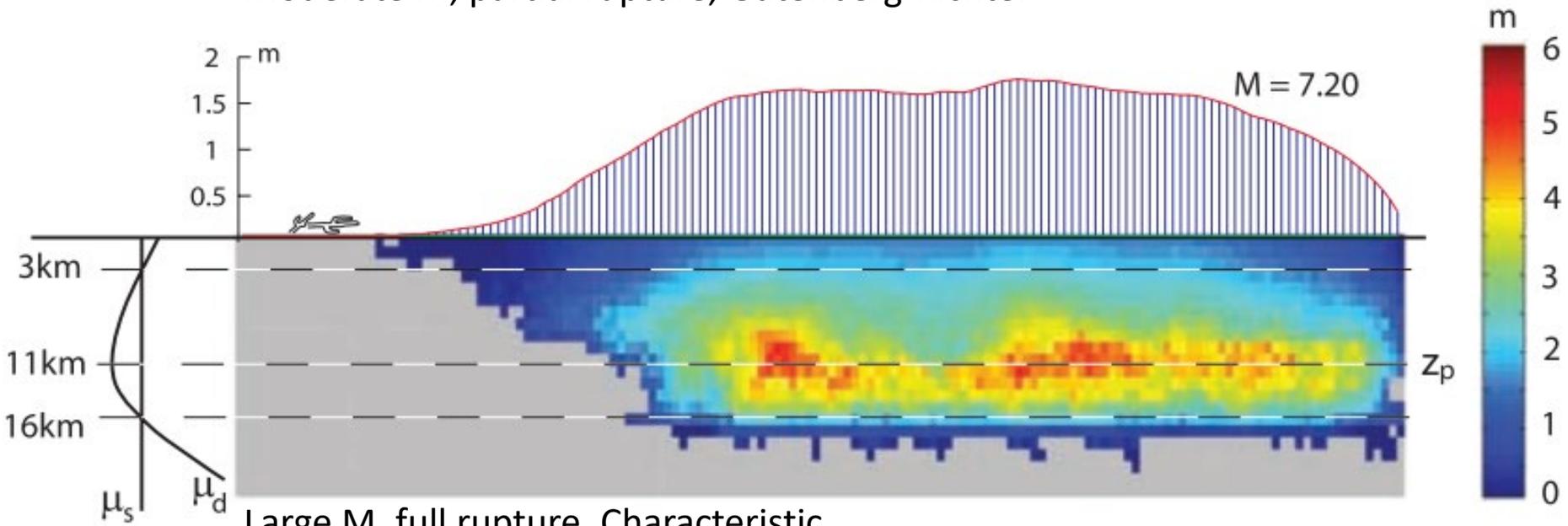
Zielke and Arrowsmith, 2008



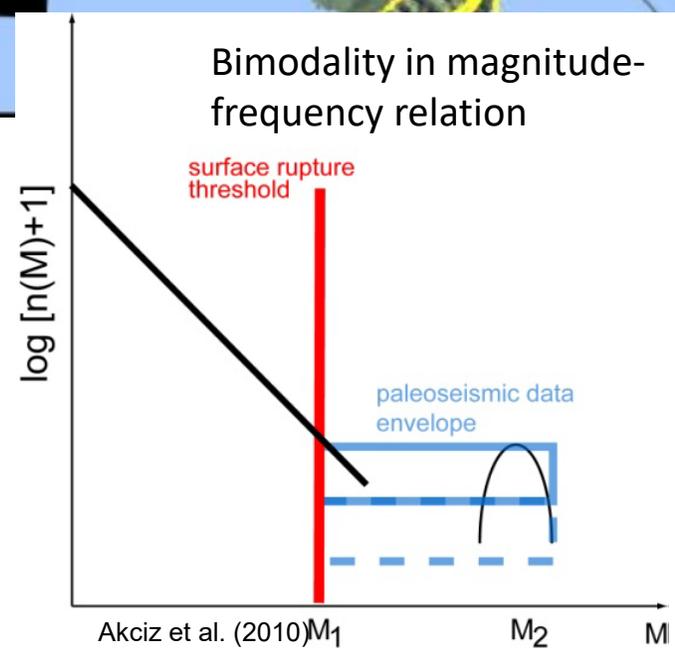
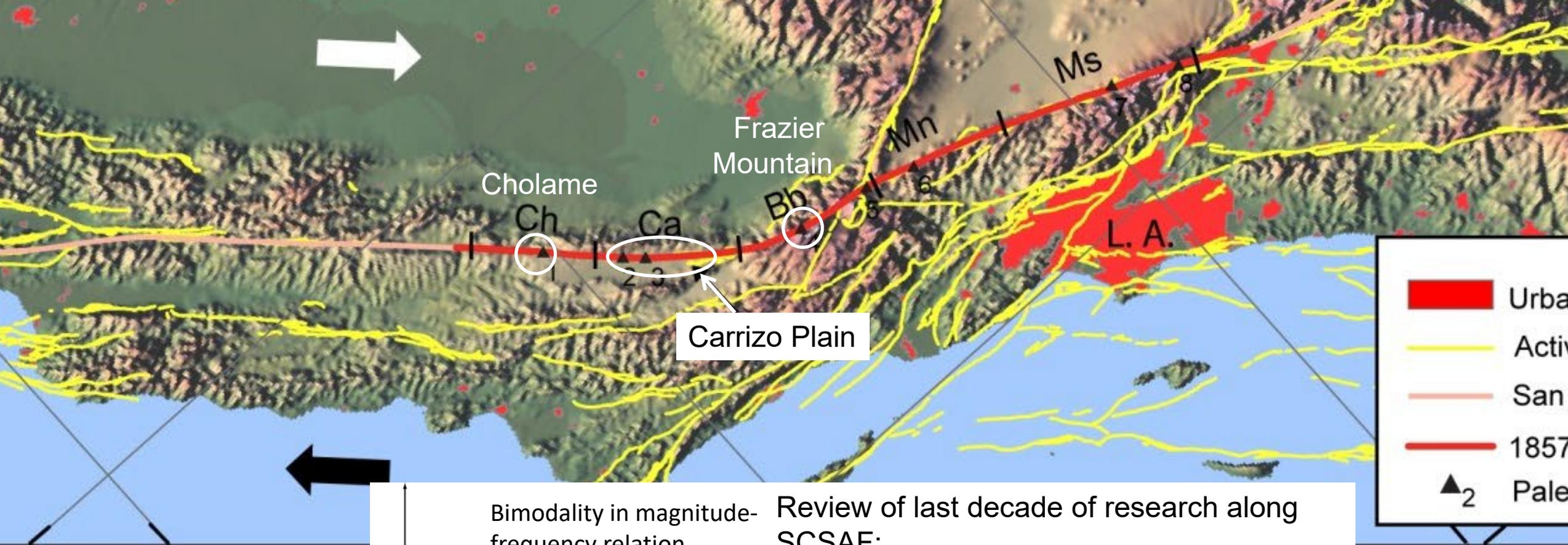
Implies bimodal M, RA, and slip at surface->controlling influence of event on landscape



Moderate M, partial rupture, Gutenberg-Richter



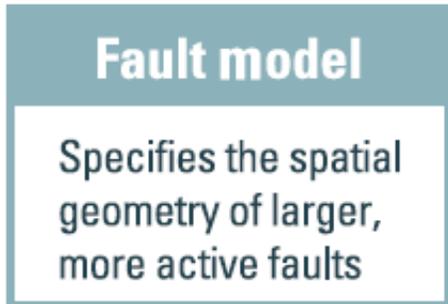
Large M, full rupture, Characteristic



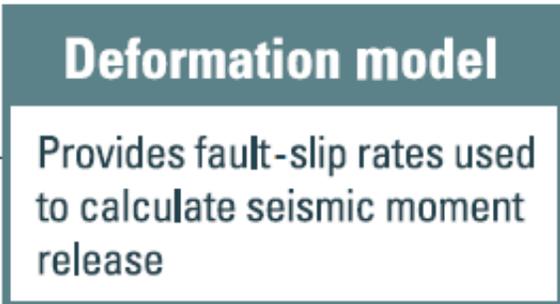
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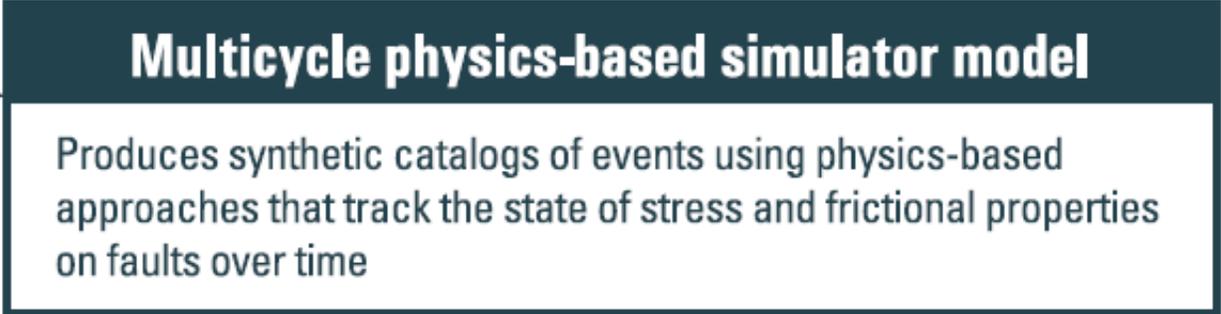
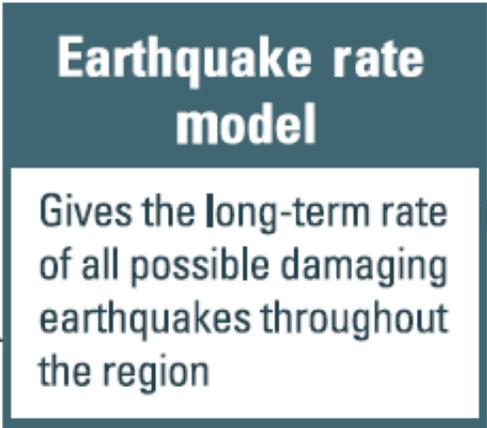
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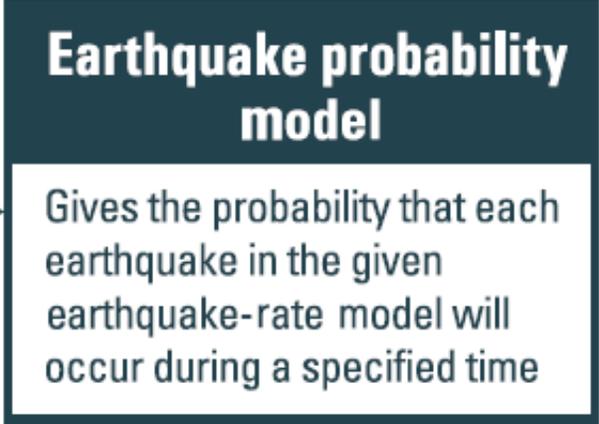
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