Large Events on the Southern San Andreas Fault Modulated by Lake Filling Events

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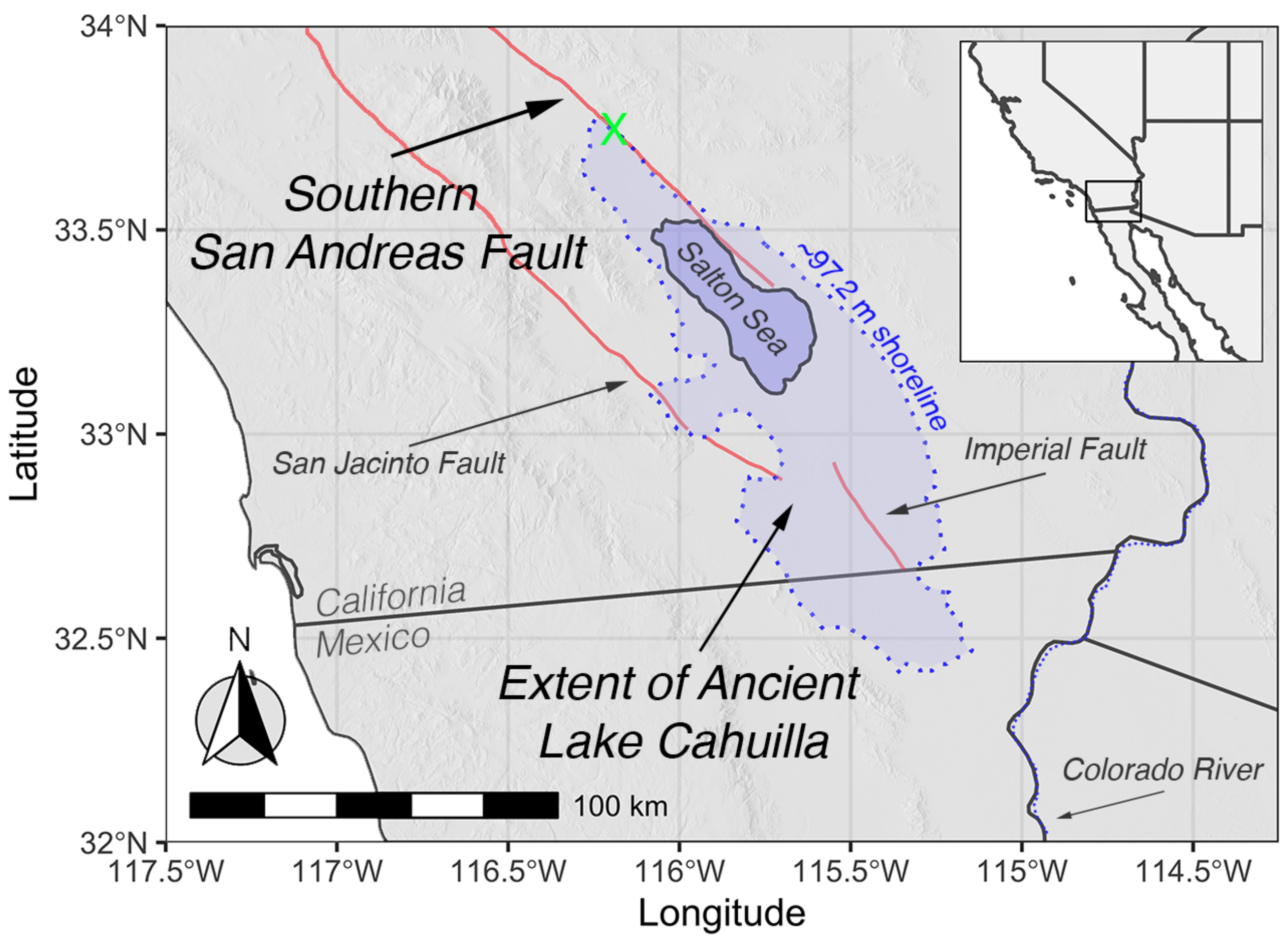
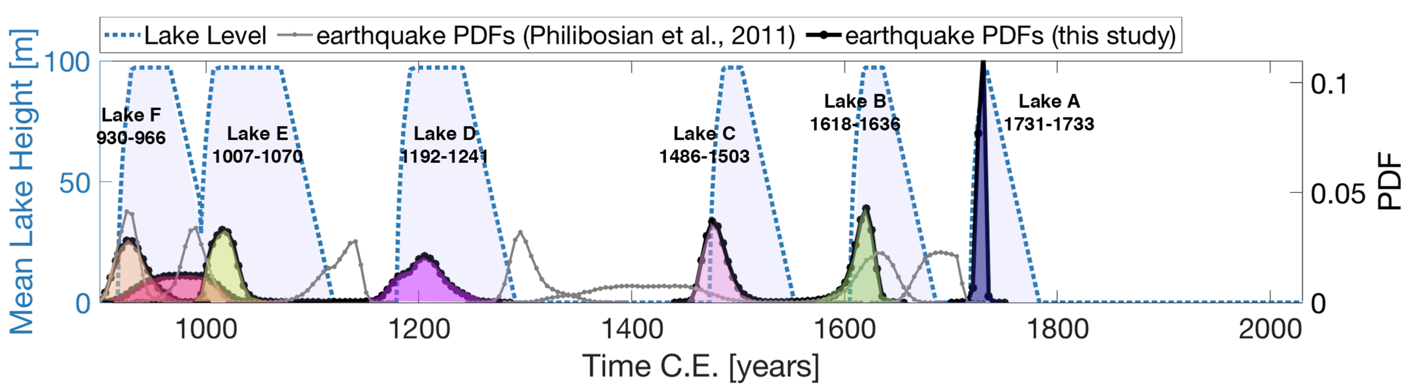
Abstract

New geologic and paleoseismic data demonstrate that the past 6 major earthquakes on the Southern San Andreas Fault (SSAF) correlate with high-stands of the ancient Lake Cahuilla, a ~236 km^3 body of water adjacent to the SSAF. To investigate the possible causal connections, we computed relative time-dependent Coulomb stress changes produced by lake level fluctuations over the last ~1100 years. Simulations were numerically solved using a fully coupled 3-D finite element model incorporating a poroelastic crust overlying a viscoelastic mantle. We find that the Coulomb stress perturbations on the SSAF are positive (i.e., promoting failure) throughout the lake loading history. For an acceptable range of material properties of the Earth's crust and well constrained lake ages, the estimated stress perturbations are of the order of 0.5 MPa, likely sufficient for triggering. Stress perturbations are dominated by pore pressure changes, but are enhanced by the poroelastic 'memory' effect whereby increases in pore pressure due to previous lake high stands do not completely vanish by diffusion and constructively interfere with the undrained response in subsequent high stands. Our preferred model suggests that the lake loading modulated the interseismic stress accumulation on average by as much as 16-44%. The destabilizing effects of lake inundation are enhanced by a non-vertical fault dip, presence of a fault damage zone, and lateral pore pressure diffusion. Our results are applicable to other regions where hydrologic loading, either natural or anthropogenic, is associated with significant seismicity.

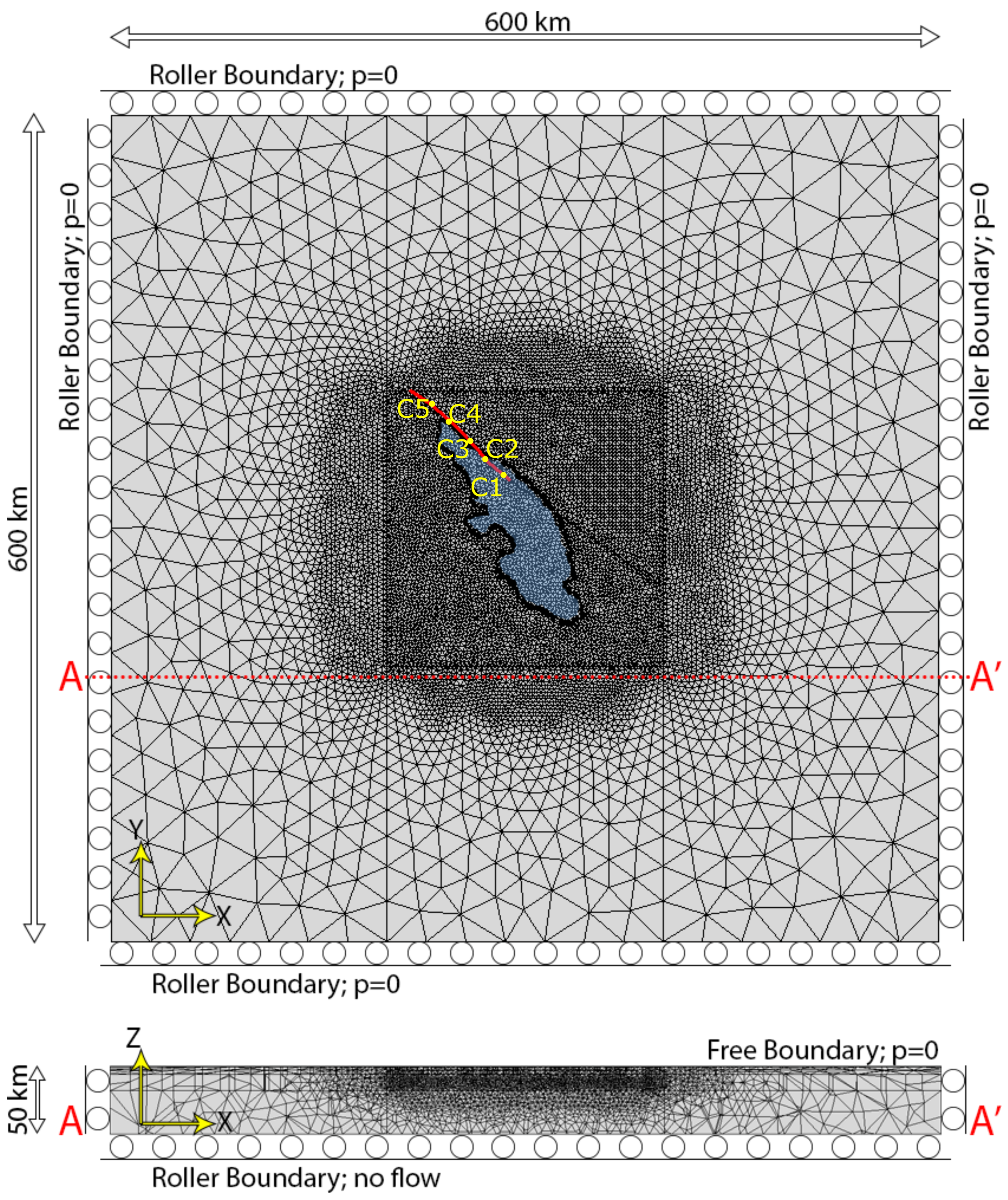


Regional Context. Map of the Salton Trough and present-day Salton Sea (9.5 m mean head) with the historical extent of ancient Lake Cahuilla (97.2 m mean head). The 13 m above sea level shoreline are the same coordinates used by Luttrell et al., 2007. Fault traces are from Quaternary fault and fold database (USGS). Green 'X' symbol marks the location of a previous paleoseismic study at the Coachella Paleoseismic site (Philibosian et al., 2011).

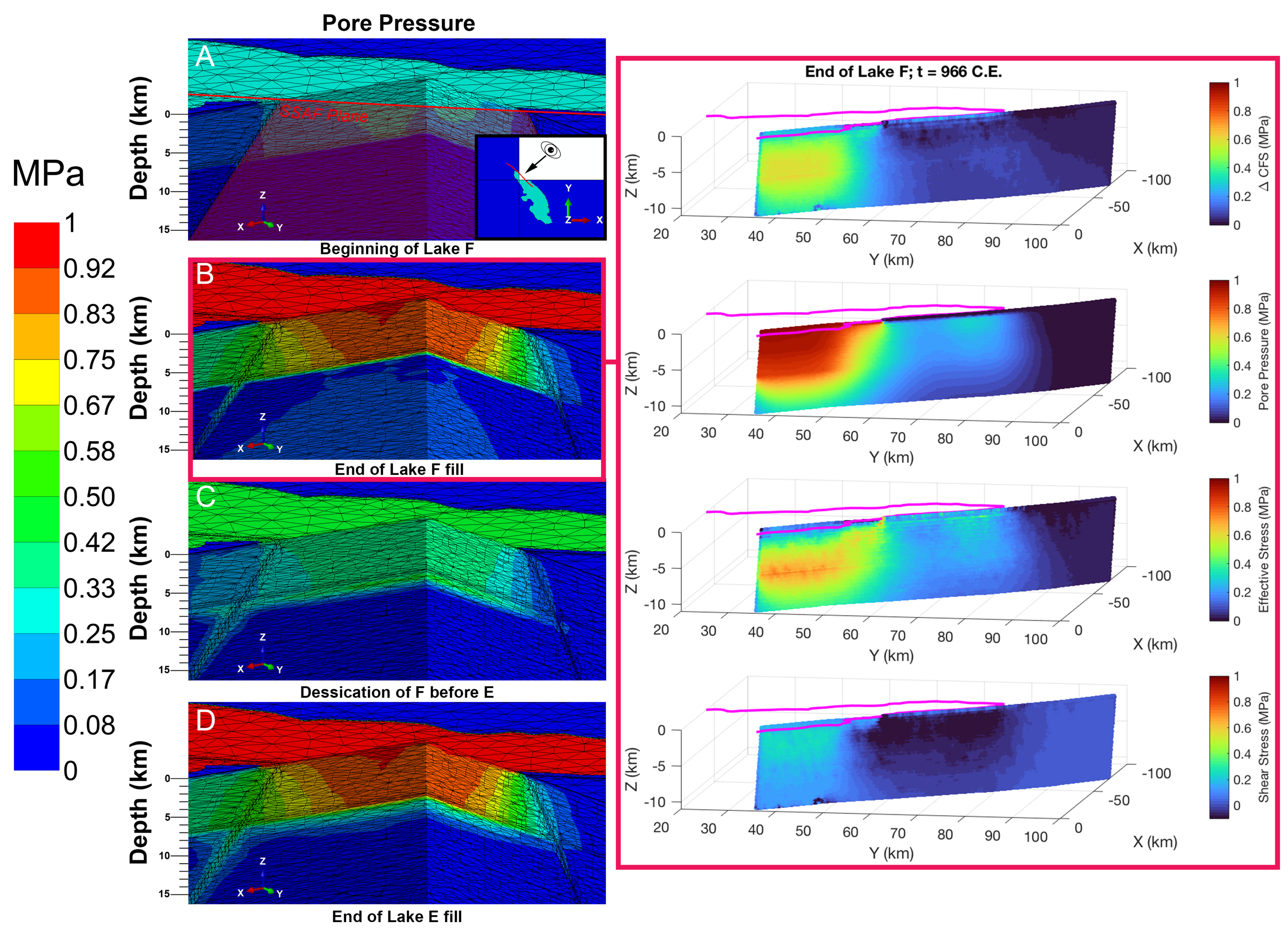


Lake and Earthquake History. Earthquake PDFs superimposed on the relative lake loading history used in this study. Colored PDFs are the reinterpreted and refined earthquake distributions used in this study (Rockwell et al., 2022). Coa-1 is blue, Coa-2 is green, Coa-3&4 is pink, Coa-5 is magenta, Coa-6 is yellow, Coa-7 is red, and Coa-8+ is orange. Gray distributions are the previous earthquake distributions reproduced from Philibosian et al., 2011 including the lower confident Coa-6 and Coa-3.

Model & Results

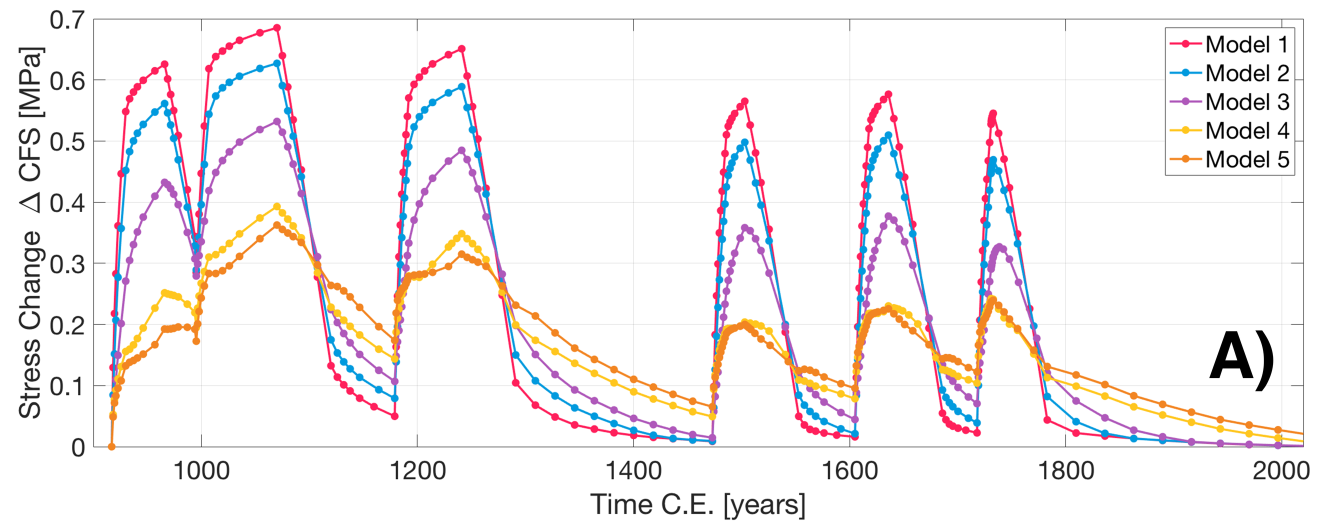


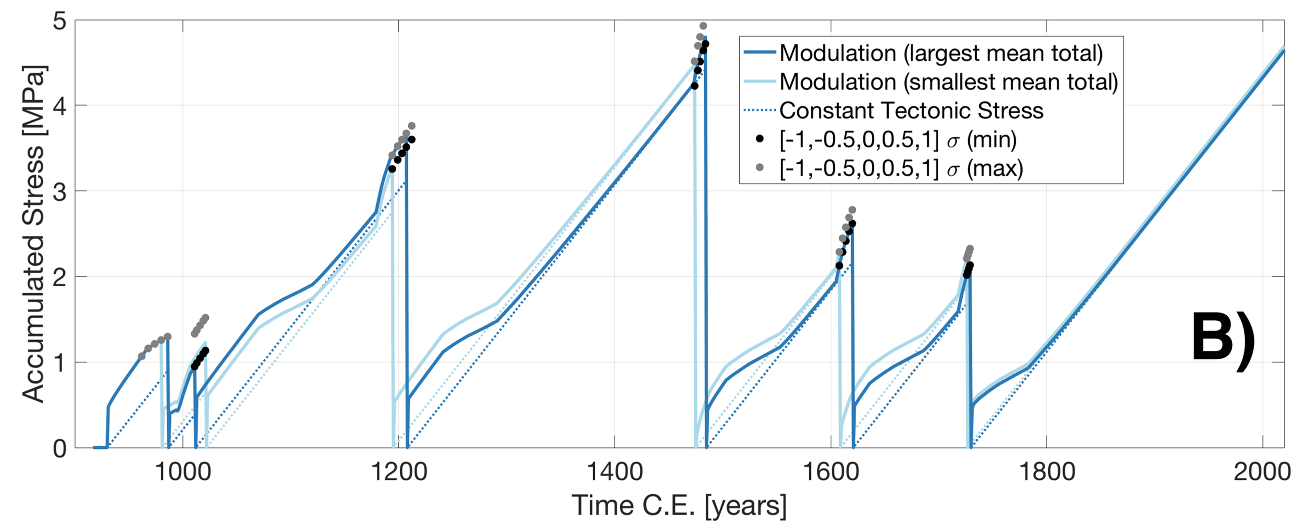
Hydrostratigraphy Unit	Depth Range [km]	Poisson's Ratio	Young's Modulus [GPa]	Hydraulic Conductivity [m/s]	Porosity %	Drained Bulk Modulus of Rock [GPa]	Reference
Post Brawley / Brawley	0-0.5	0.25	50	2e-6	35	33	Thompson et al. (2008)
Palm Springs / Borrego	0.5-3	0.25	50	1.2e-5	12	33	Thompson et al.(2008)
Imperial	3-7	0.25	50	9e-7	3	33	Thompson et al. (2008)
Crystalline Basement	7-18	0.25	58.5	1e-11	1	39	Shmonov et al. (2003)
Mantle*	18-50	0.36	140	/	/	/	Turcotte and Shubert (2002)
Variable Fault	0-18	0.25	$\frac{1}{2}$ host rock	1e-7,1e-8,1e-9,1e-10	host rock	host rock	(Fialko et al., 2003) (Lindsey et al., 2013)



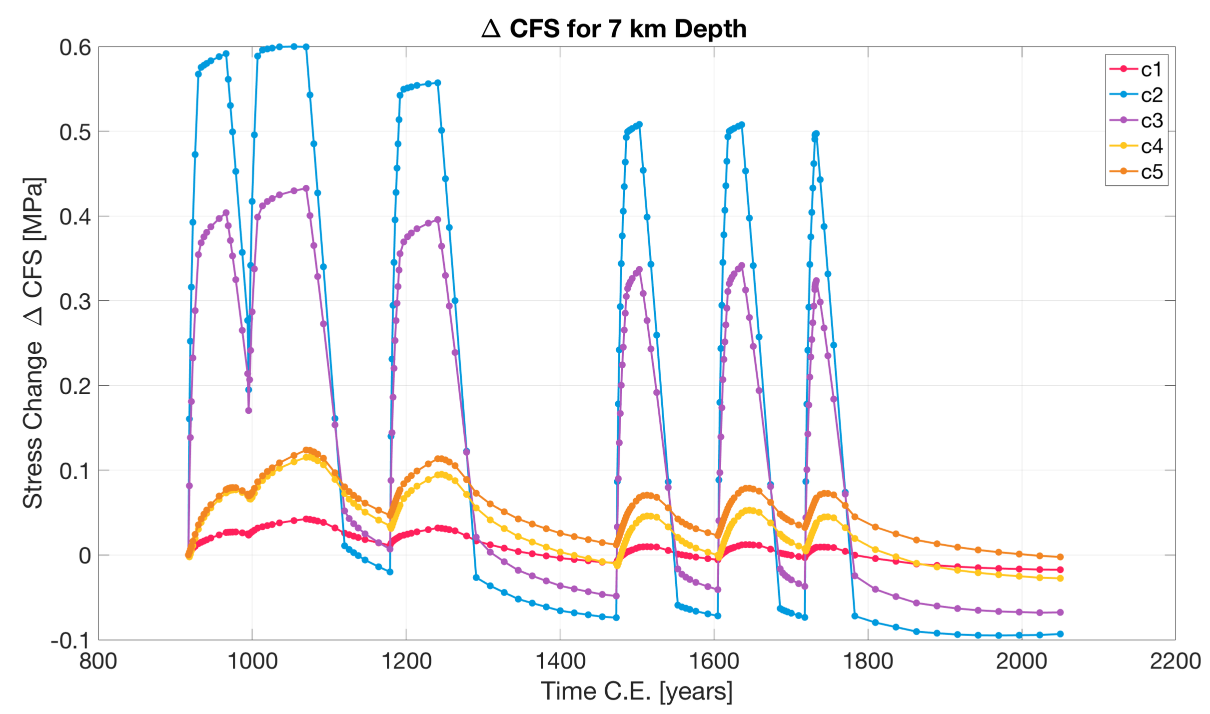
Finite Element Model & Results. The model mesh contains ~2 million tetrahedron elements. The light blue color represents the extent of Ancient Lake Cahuilla. The prescribed vertical load is hydrostatic, to the lake average water head (97.2 m). The solid red line is the SSAF fault trace. The fault zone is modeled as a slab dipping to the north-east at 60◦, with the assumed thickness of 200 km. The table describes the hydrostratigraphic parameters. The load changes based on the lake history and the spatiotemporal evolution of pore pressure & stress for a single lake cycle of ancient Lake Cahuilla is shown. The cross section cuts through the northwestern end of the lake and through the embedded dipping fault.

Results (cont.)





Stress Effects of Lake Loading. *A)* Maximum relative change in CFS(MPa) on the SSAF as a function of time C.E. (years) for 7 km depth. Color lines correspond to models assuming different permeability of the fault zone (see Table), from highest (Model 1) to lowest (Model 5, no permeability contrast with the host rocks). *B)* Variations suggested by our preferred model (model 2), assuming an average tectonic stressing rate of 16 kPa/yr (dashed line). Dark and light blue solid lines denote the maximum and minimum stress perturbations, respectively, based on a grid search across all possible earthquake timings (+/- 1 sigma). Circles represent the minimum and maximum modulation in the grid search results for a range of sigma. Stress perturbations are with respect to the (unknown) background stress at the beginning of simulation. The averaged stress load contribution plotted here is 32.33% for the lowest mean total and 43.70% for the largest mean total.



Stress Effects of Individual Points. While the maximum ΔCF S resolved on the fault remains positive through time, at certain fault locations our model predicts negative ΔCFS for sufficiently long dry periods, including the present 300 yr-long open interval.

Conclusion

- New paleoseismic and paleolake records combined with an advanced fully coupled poroelastic model provide new isnights on water level variations of ancient Lake Cahuilla and the past 6 major earthquakes on the SSAF

- We find that increases in lake level result in positive Coulomb stress changes on most of the SSAF (due to lateral pore pressure diffusion along a permeable fault zone), bringing it closer to failure.

- Our results also suggest an intriguing possibility: that the current 300 yr-long quiescent period on the SSAF is modulated by a gradual decrease in water level since the last high stand of ancient Lake Cahuilla, and its current remnant, the Salton Sea.

References:

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