

Open Intervals, Clusters and Supercycles: 1100 years of Moment Release in the Southern San Andreas Fault System: Are we Ready for the Century of Earthquakes?

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“The southern San Andreas fault is 10 months pregnant”

Kerry Sieh, 1986

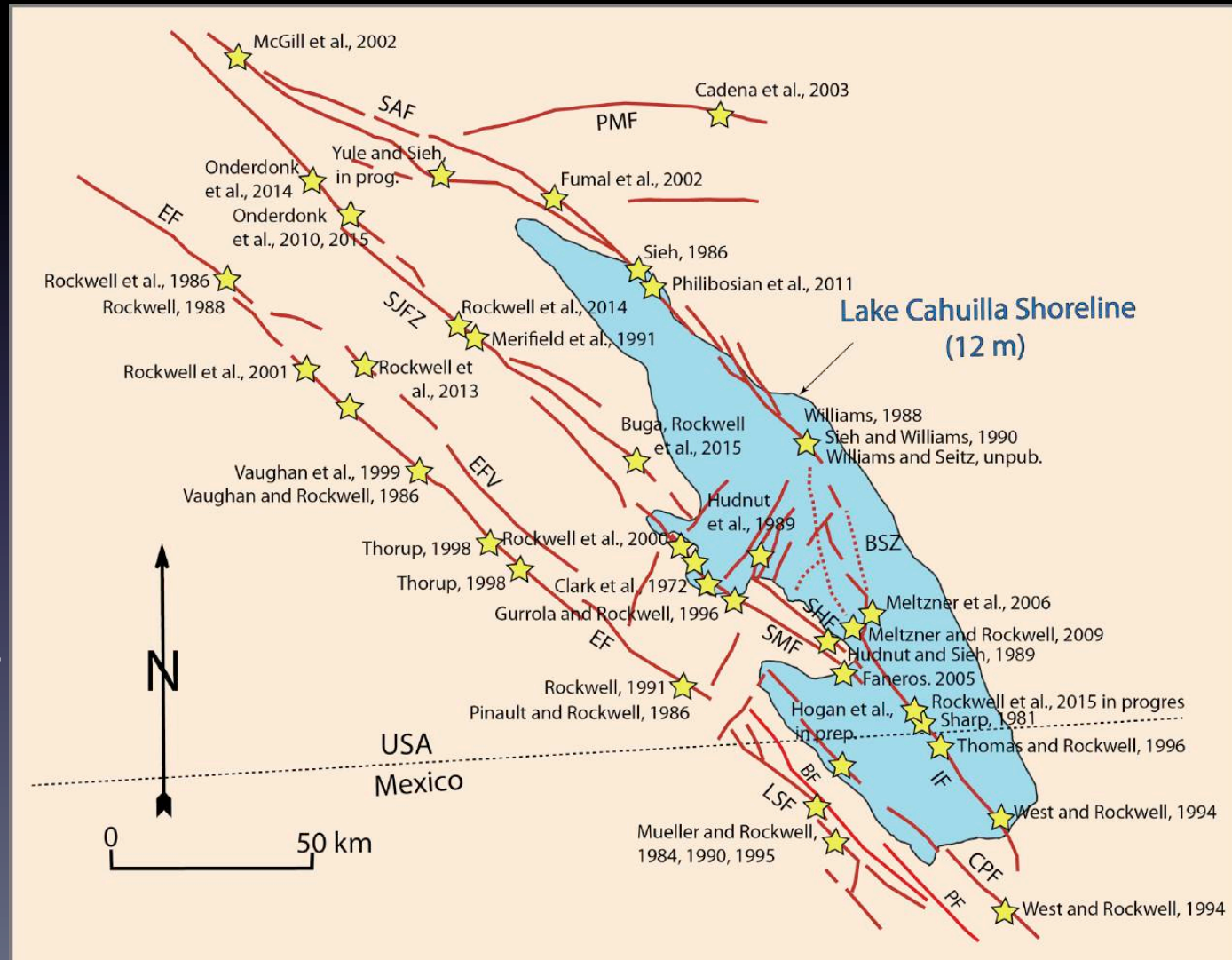
What does that mean?

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.

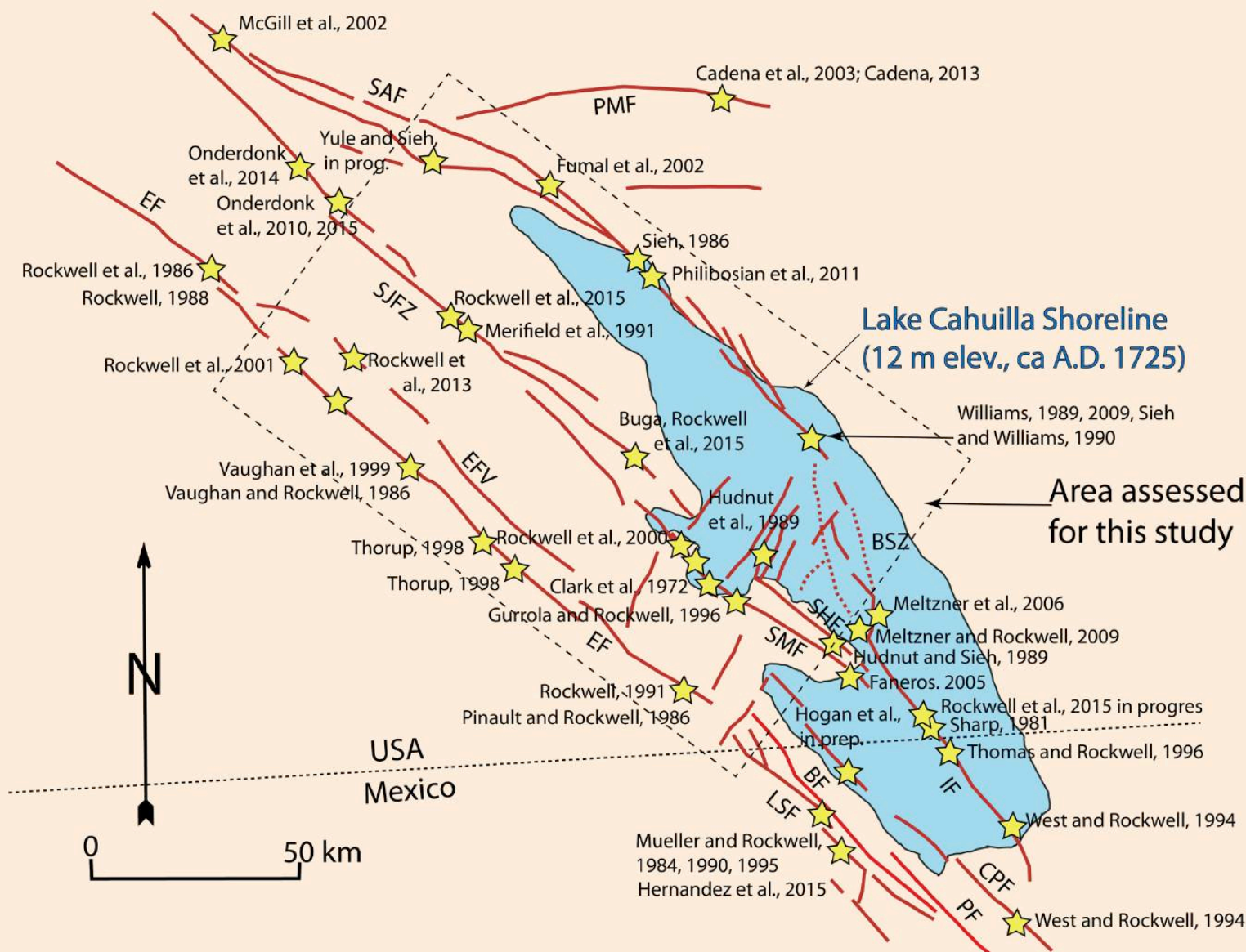
So, what's going on?

Is the apparently long extended interval a result of mis-interpretation of paleo-events? The historical record reads for itself !

Let's look at the
past 1100 years of
surface ruptures
for the entire
system



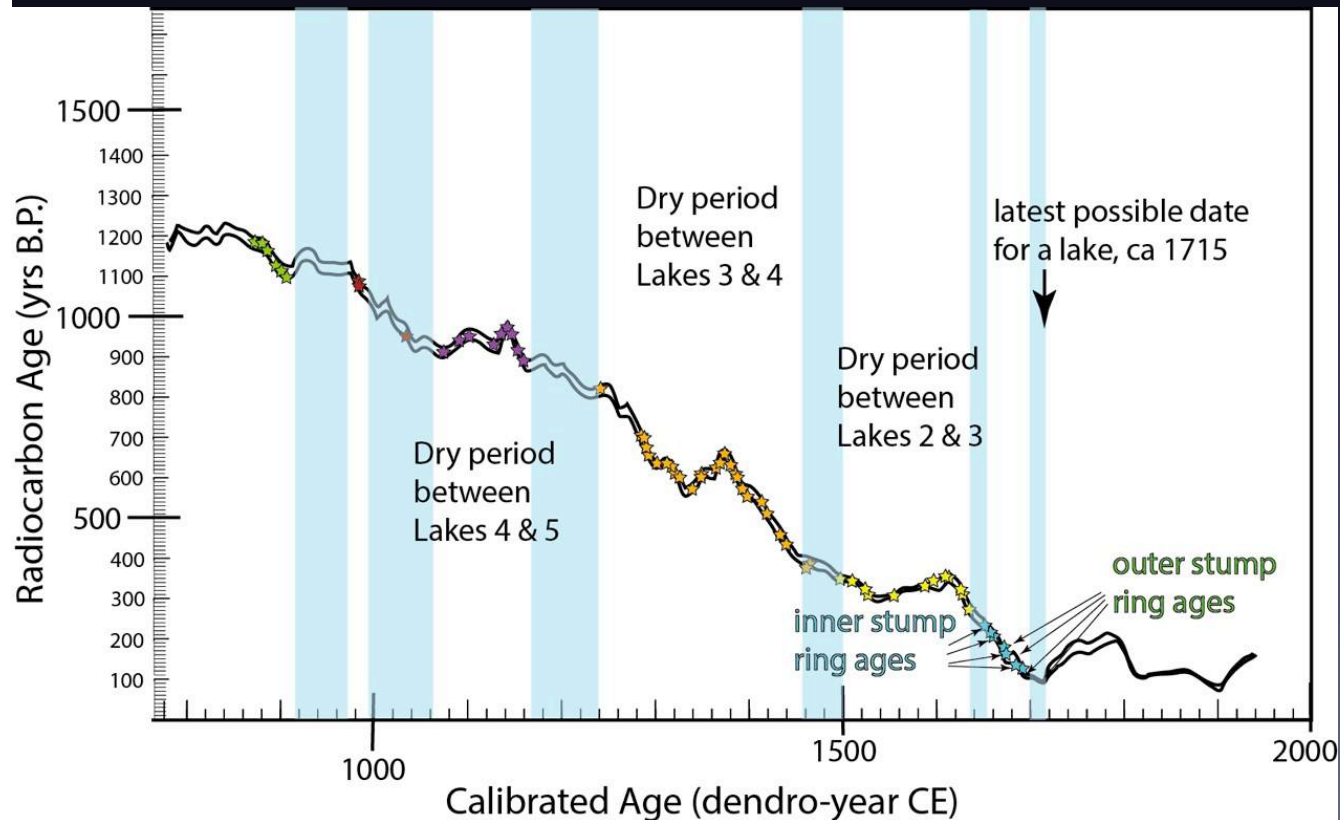
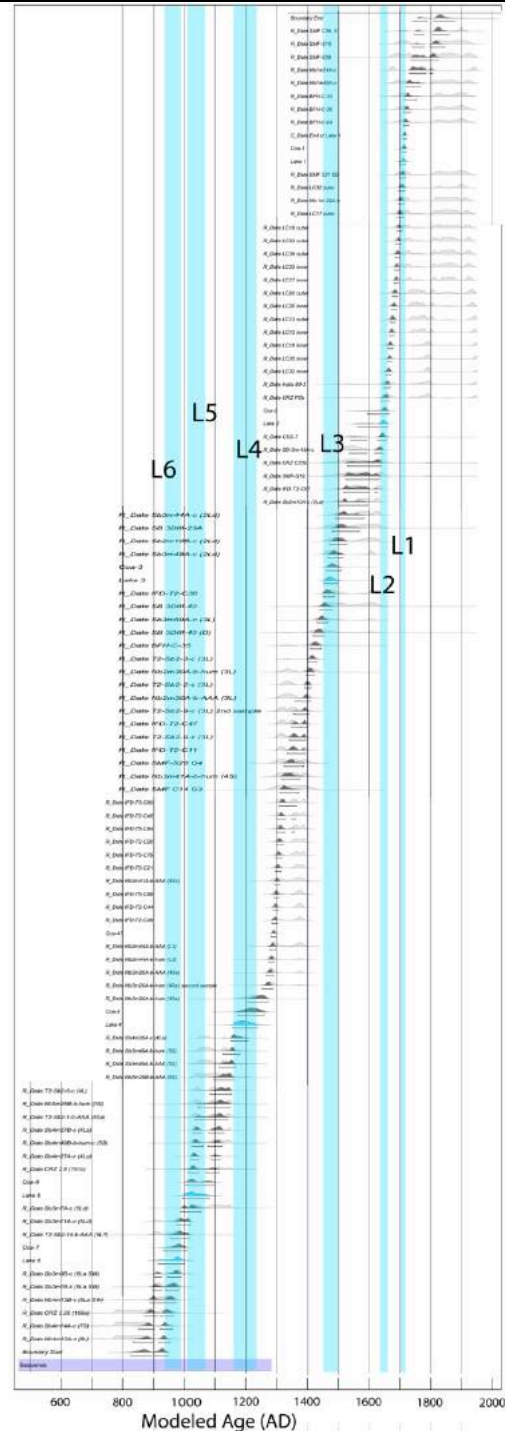
First, for the southern 160 km of the San Andreas fault system – we need to develop a common chronology



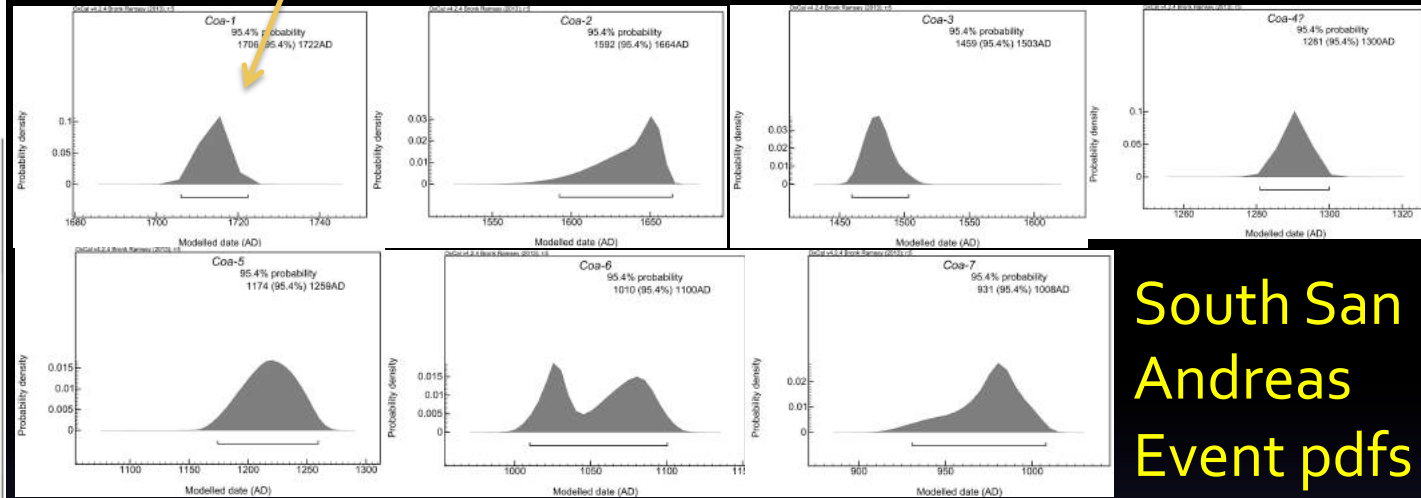
Lake Cahuilla covered portions of the so. San Andreas fault, San Jacinto fault, Imperial and Cerro Prieto faults

382 radiocarbon dates from paleoseismic sites at or below the shoreline of Lake Cahuilla

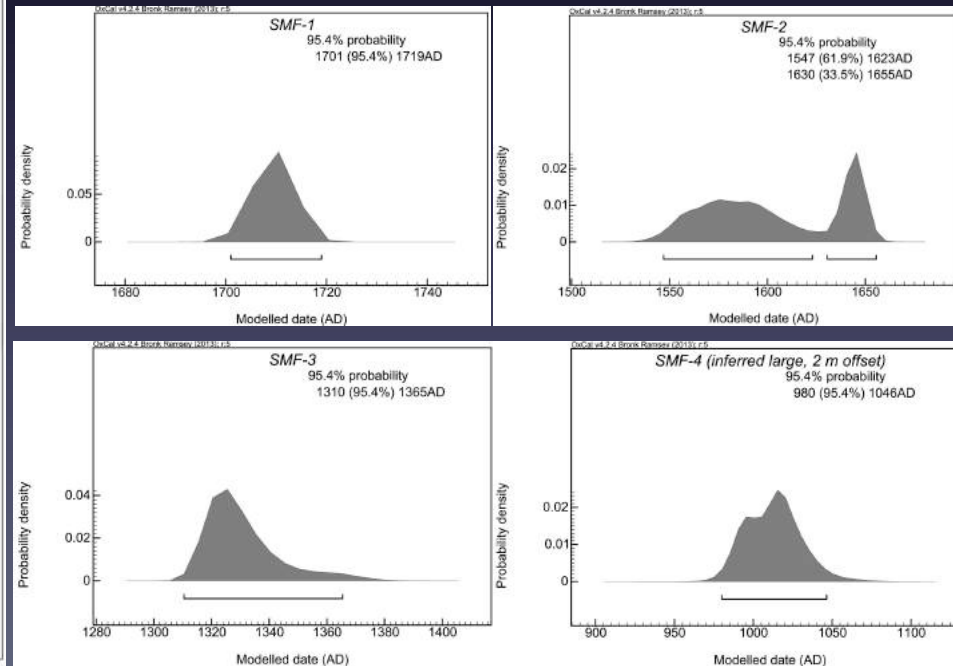
Used 88 dates in the Oxcal model to resolve the timing of lake high-stands



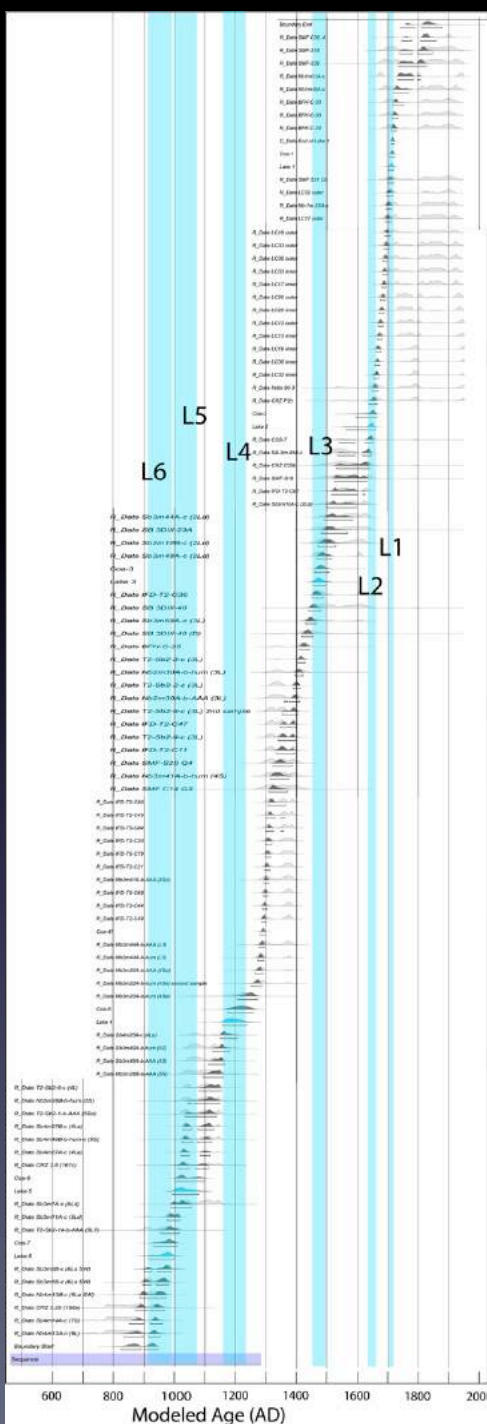
MRE on the so. SAF is ca 1715 AD



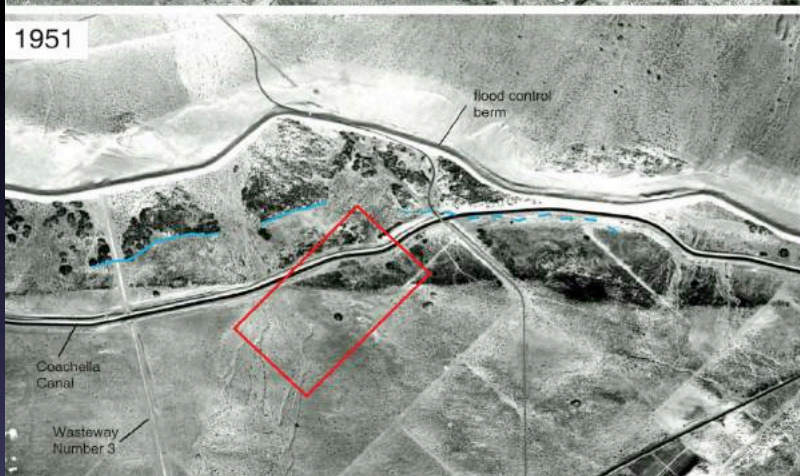
South San
Andreas
Event pdfs



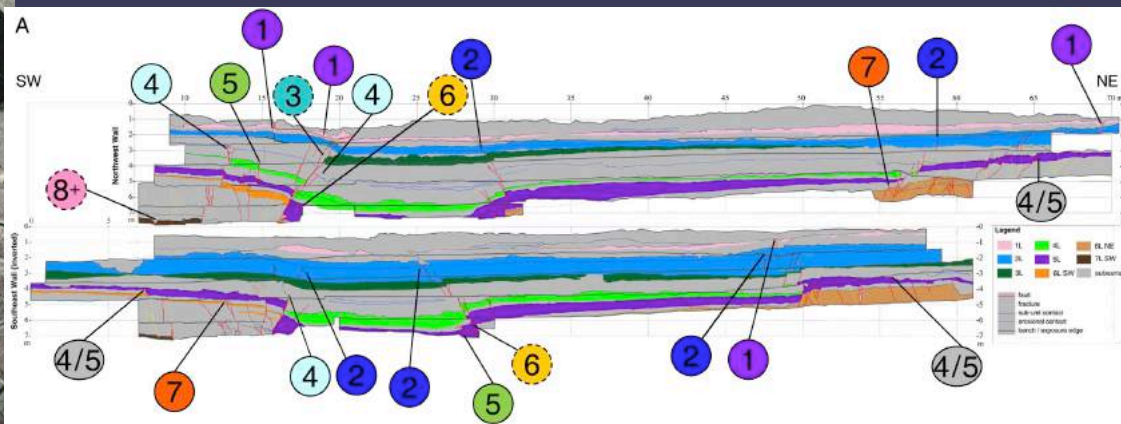
Superstition
Mountain Fault
Event pdfs



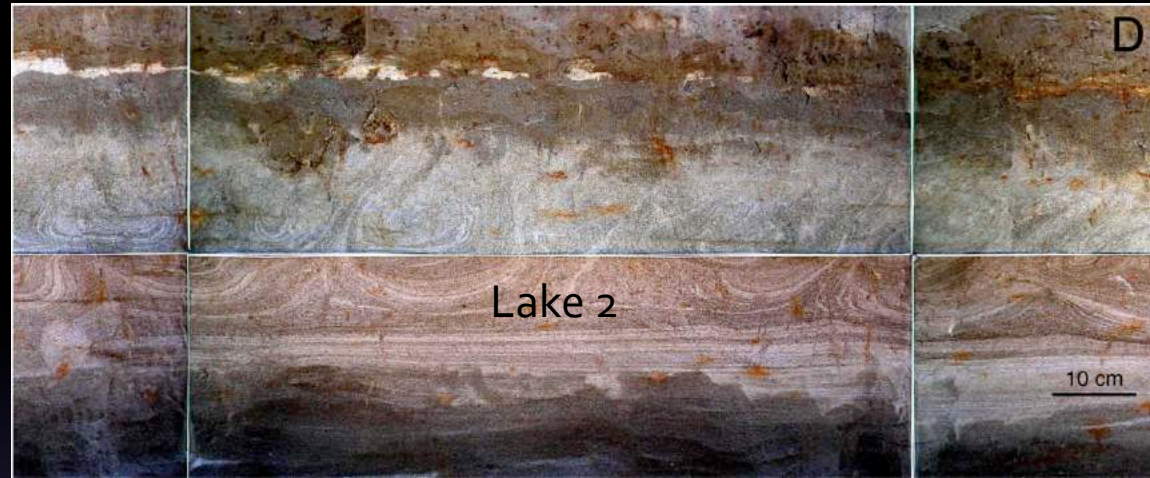
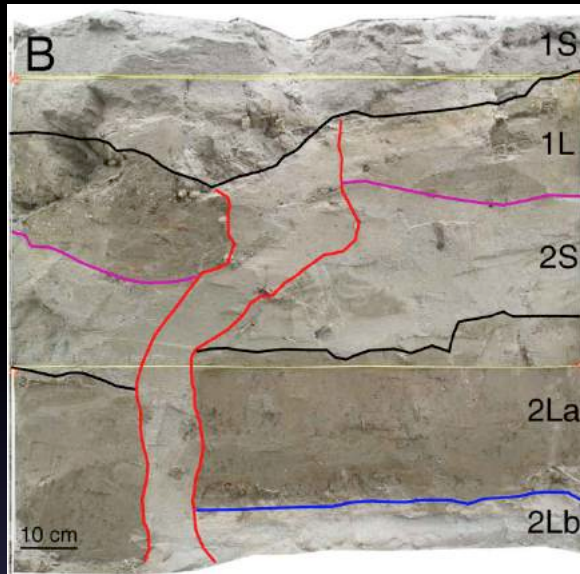
Southern San Andreas Fault - Coachella Paleoseismic Site (Philibosian et al., 2011)



Multiple lines of evidence for surface ruptures in multiple trenches

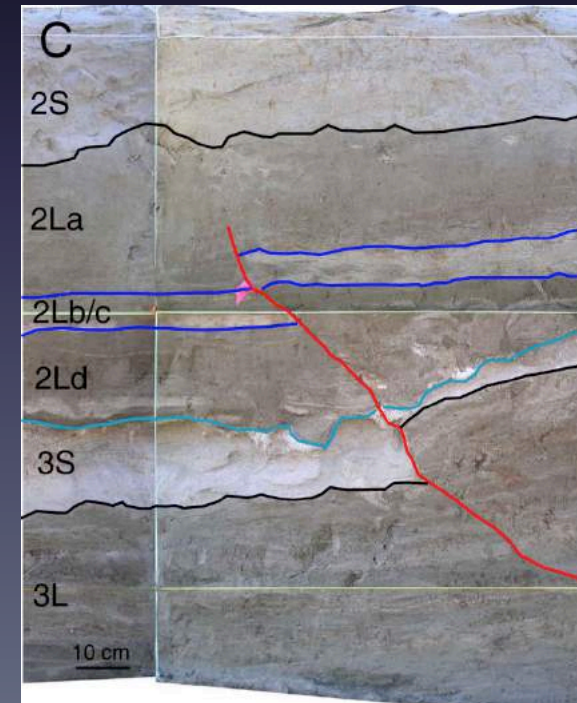
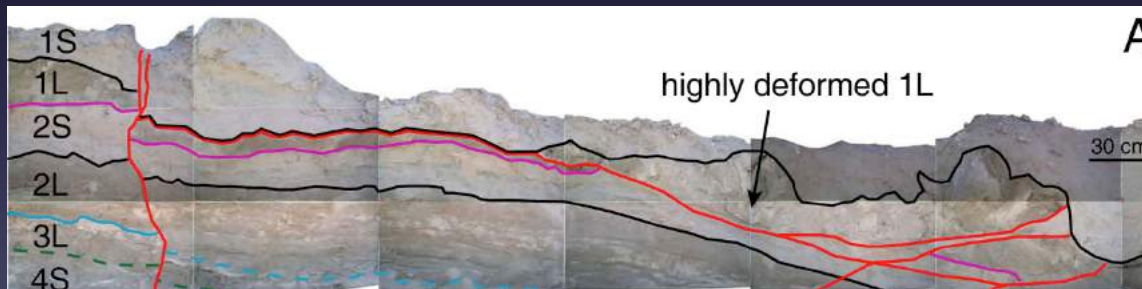


Coachella Site – southern San Andreas Fault (Philibosian et al., 2011)

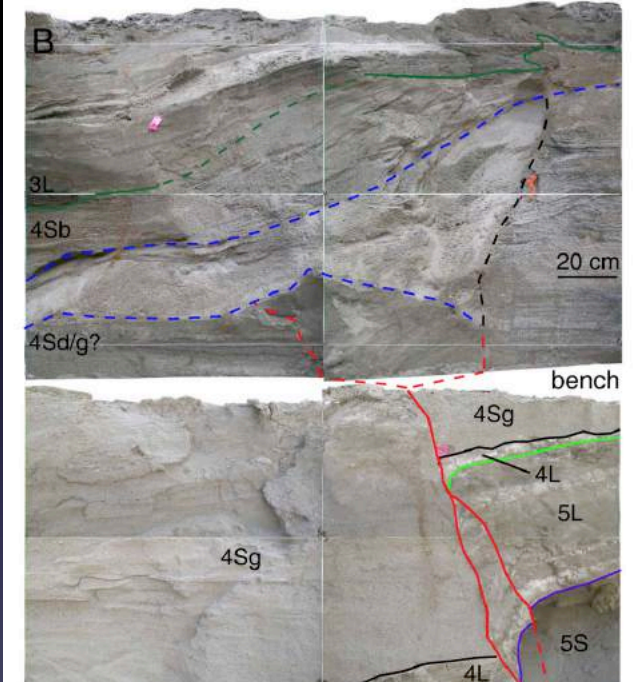
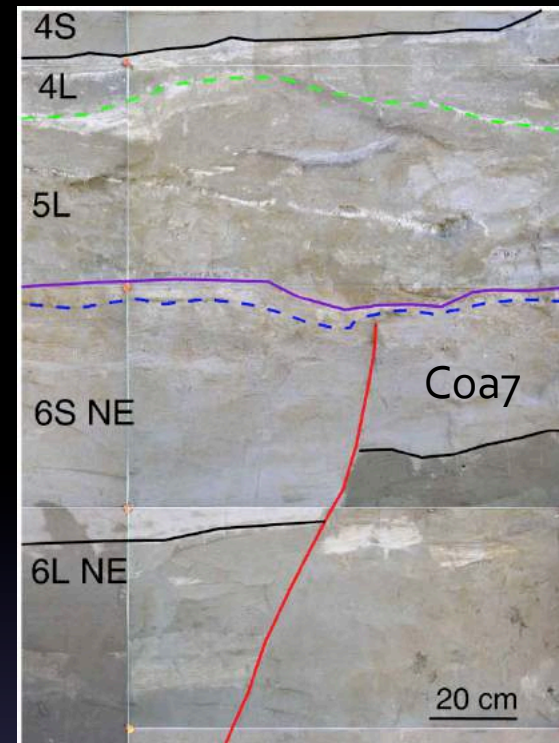
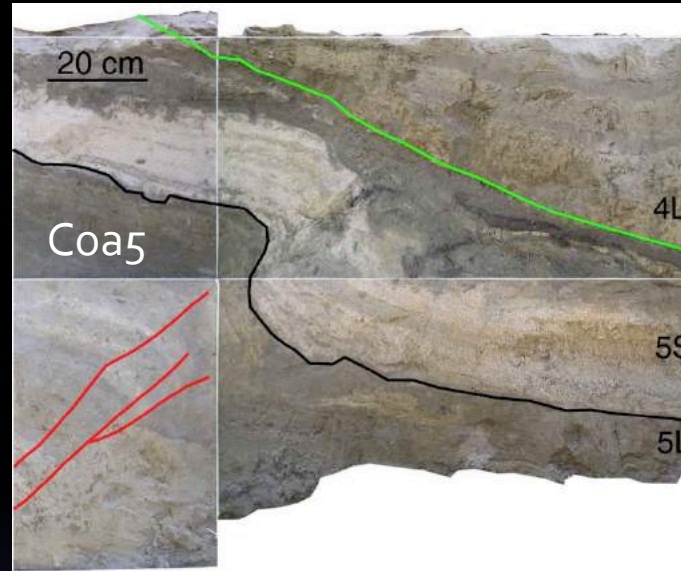
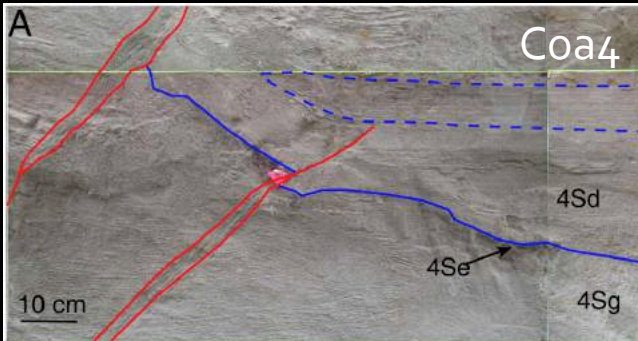


Coa-1 – ca 1715 AD

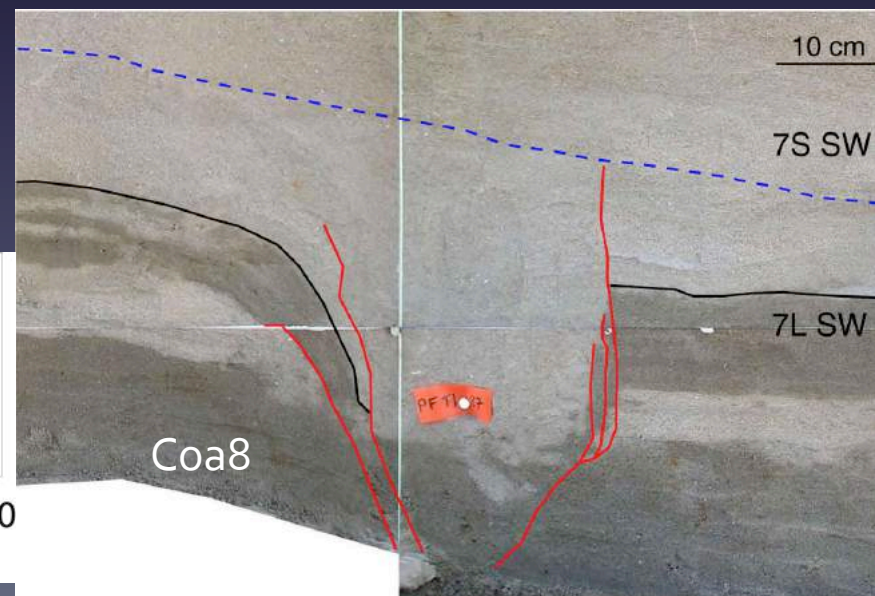
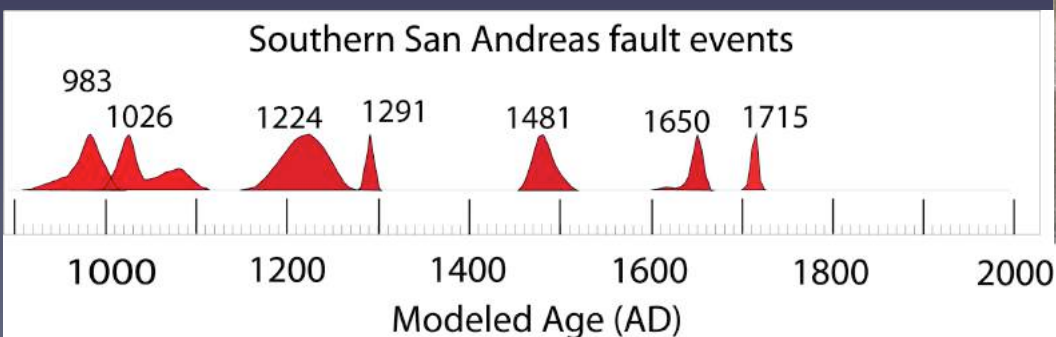
Coa-2, ca 1640 AD



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)

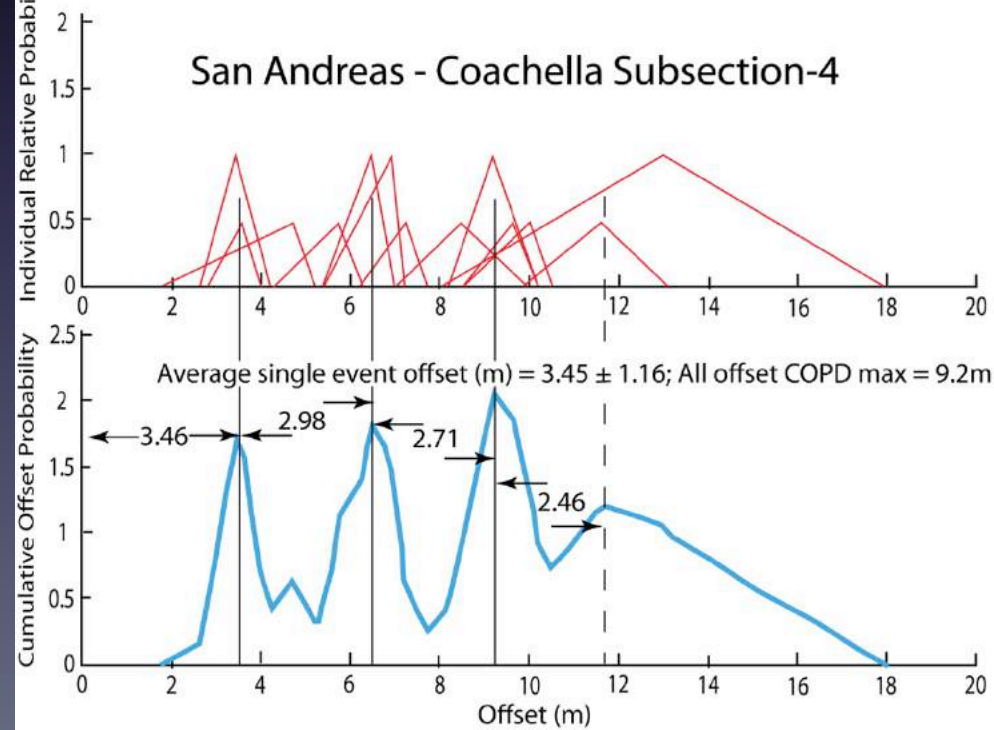
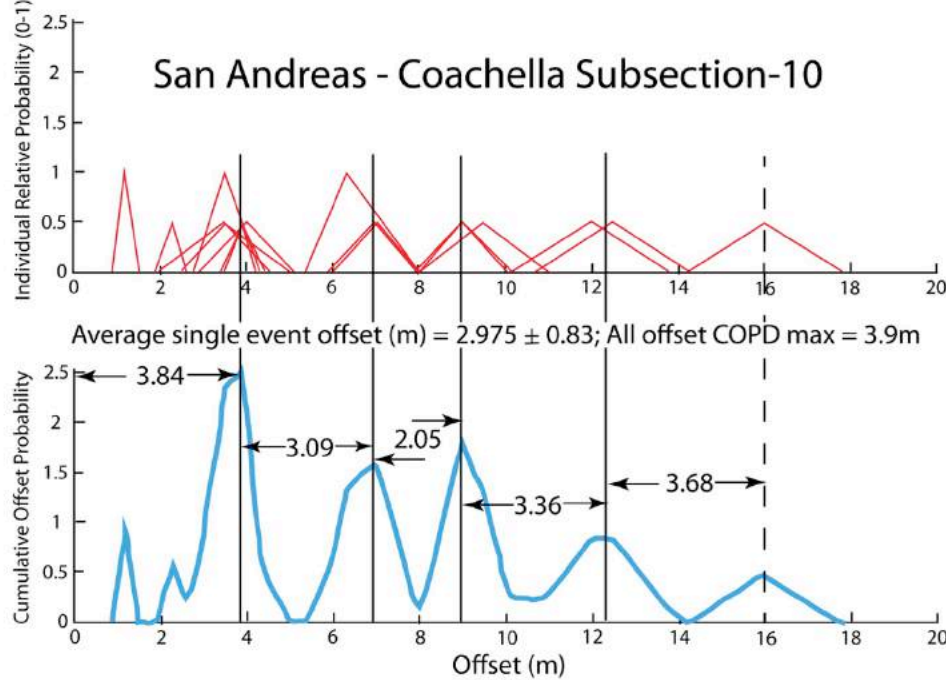


Offset per Event

Displacement estimates for the southern San Andreas fault from offset geomorphic features, such as small channels, rills, bars, etc. (UCERF₃ offset database)

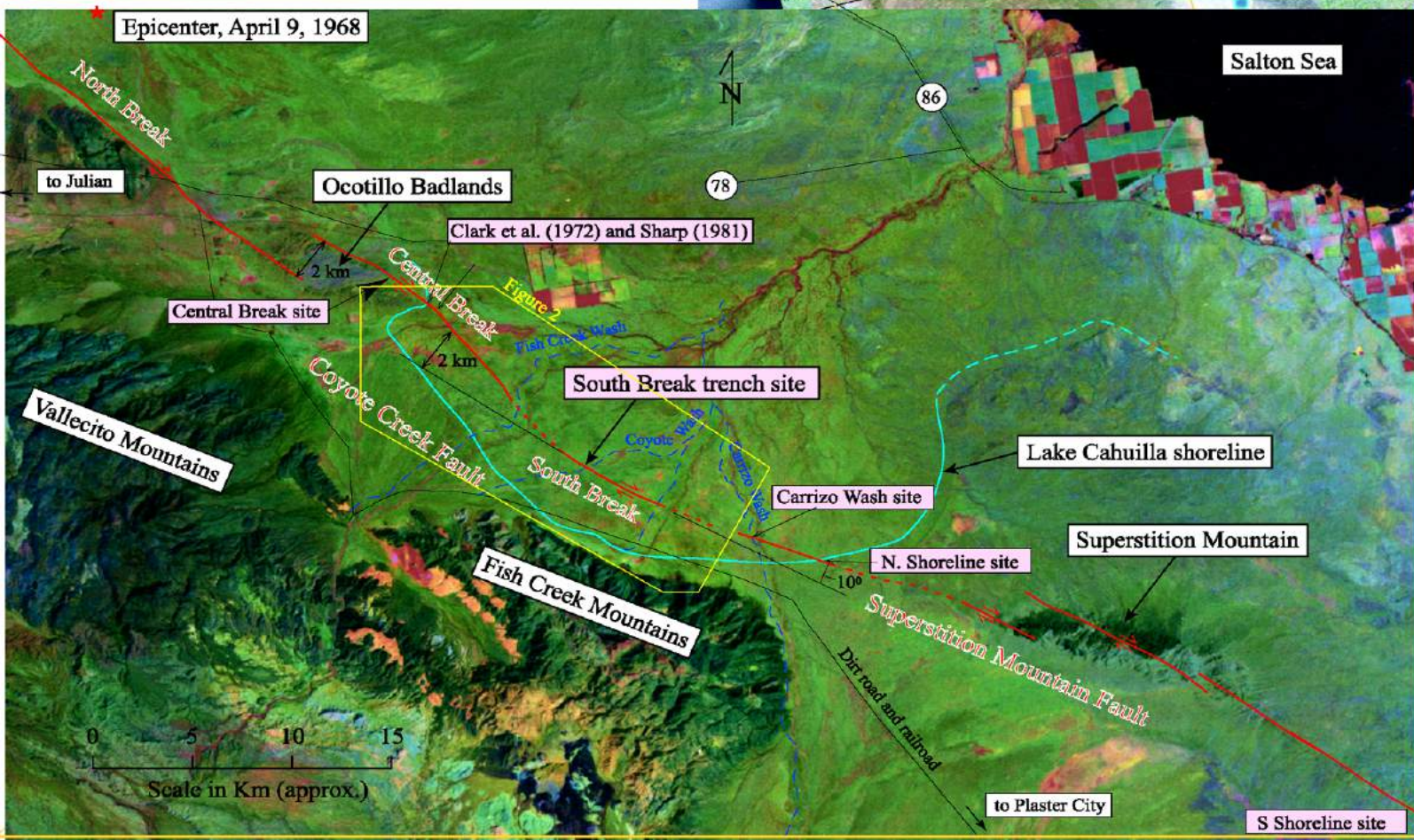
Inferred to average about 3-3.5 m for the past several earthquakes, with a range of ~2-4 m (most are 3-3.5 m)

For this analysis, I use 3 m for average displacement



Southern San Jacinto Fault Zone

Superstition Mountain Fault
Superstition Hills Fault
Coyote Creek Fault



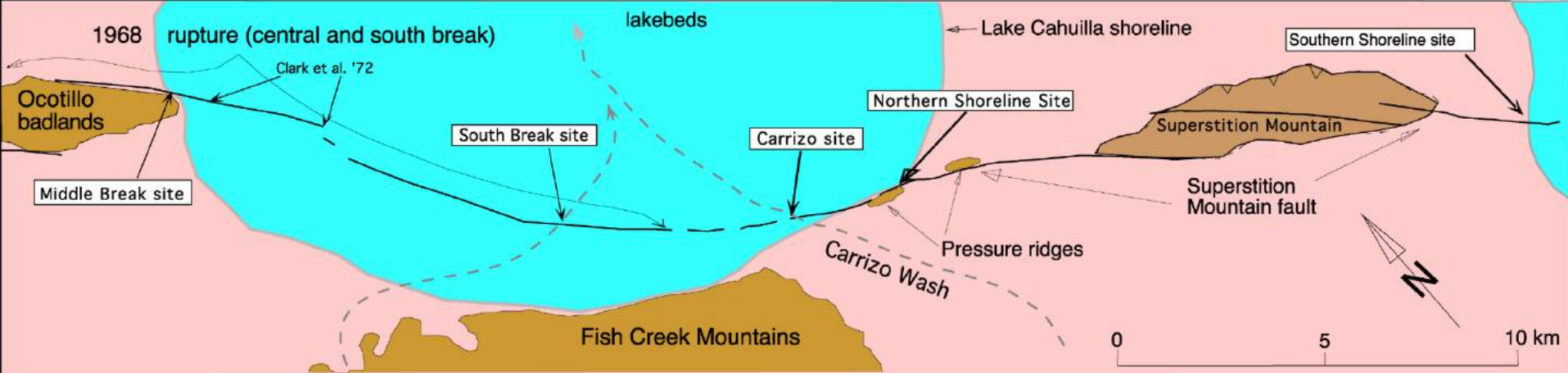
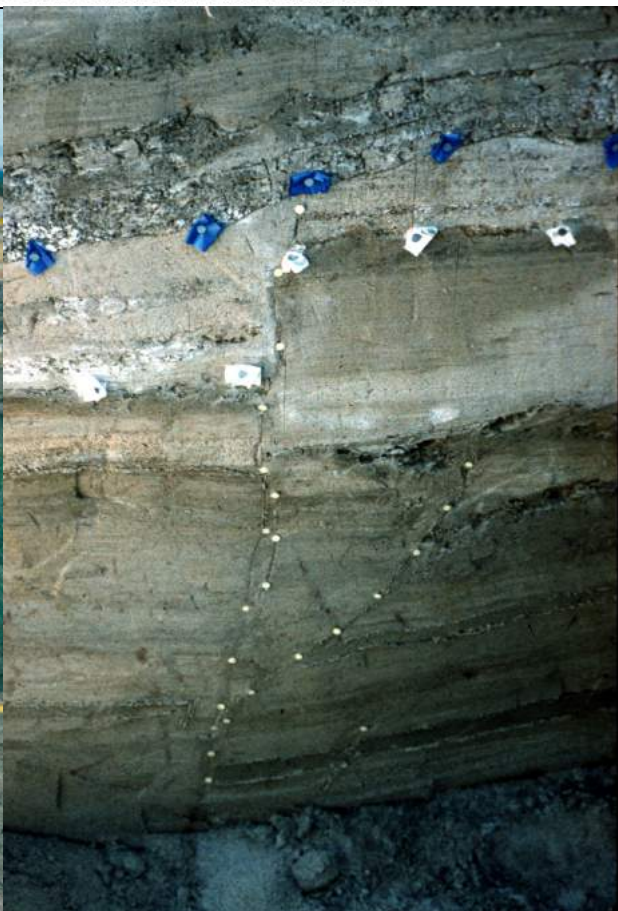
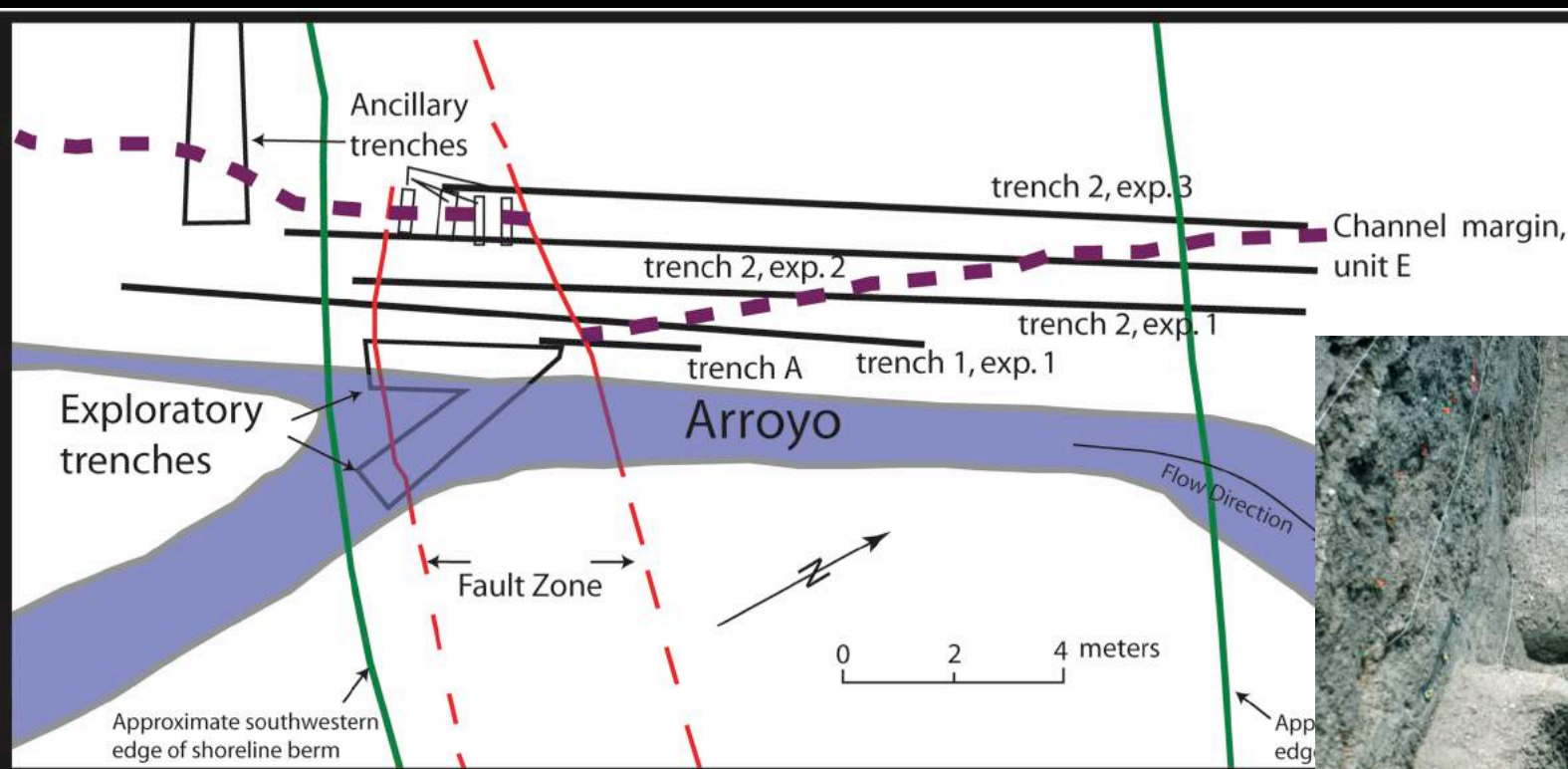


Figure 2. Map showing the trench sites relative to the 1968 surface rupture, Superstition Mountain, the Cahuilla shoreline and area of lake inundation.



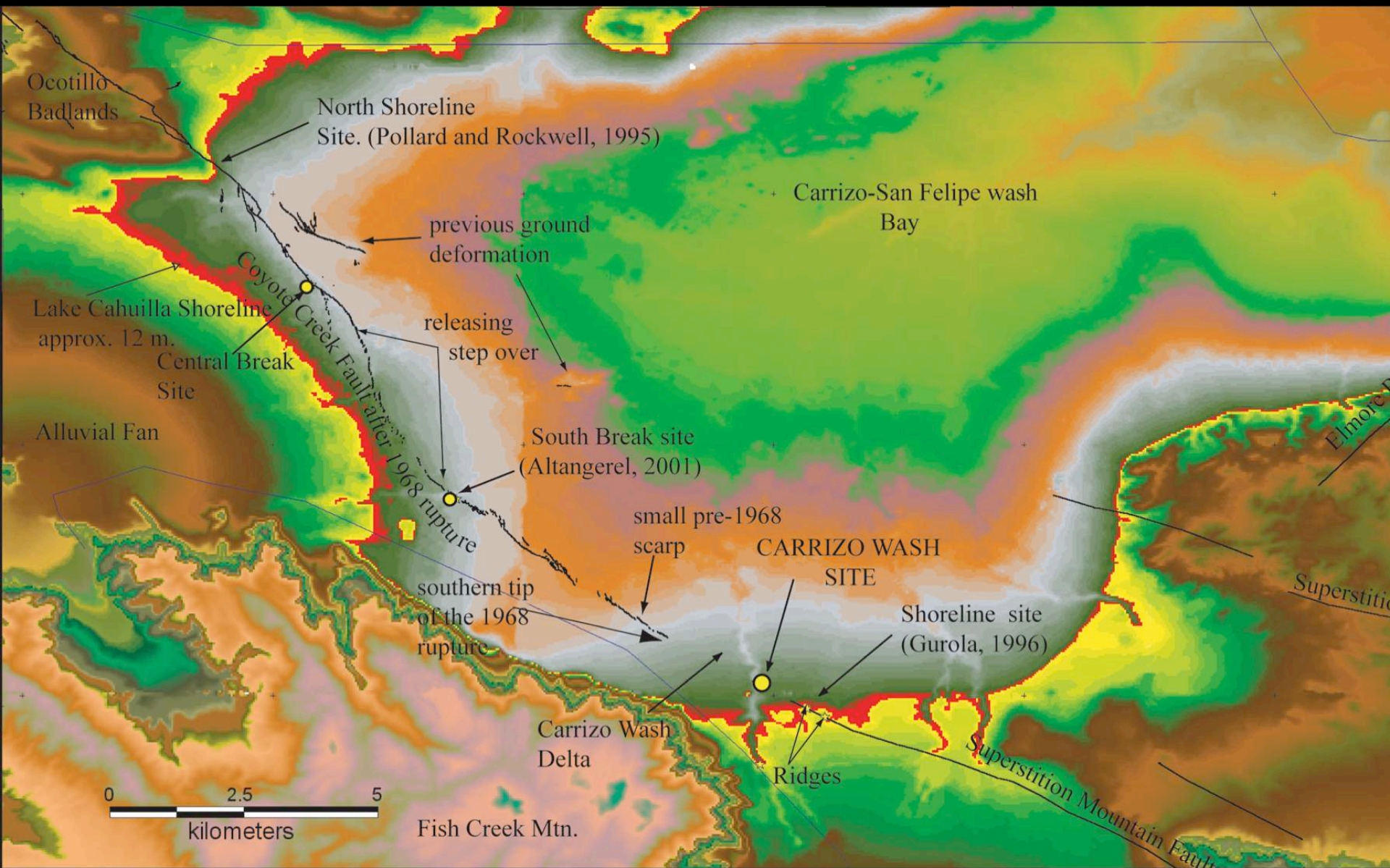
The north margin of the unit E channel is traced into and across the fault zone, yielding ~2.2 m of RL offset in the MRE



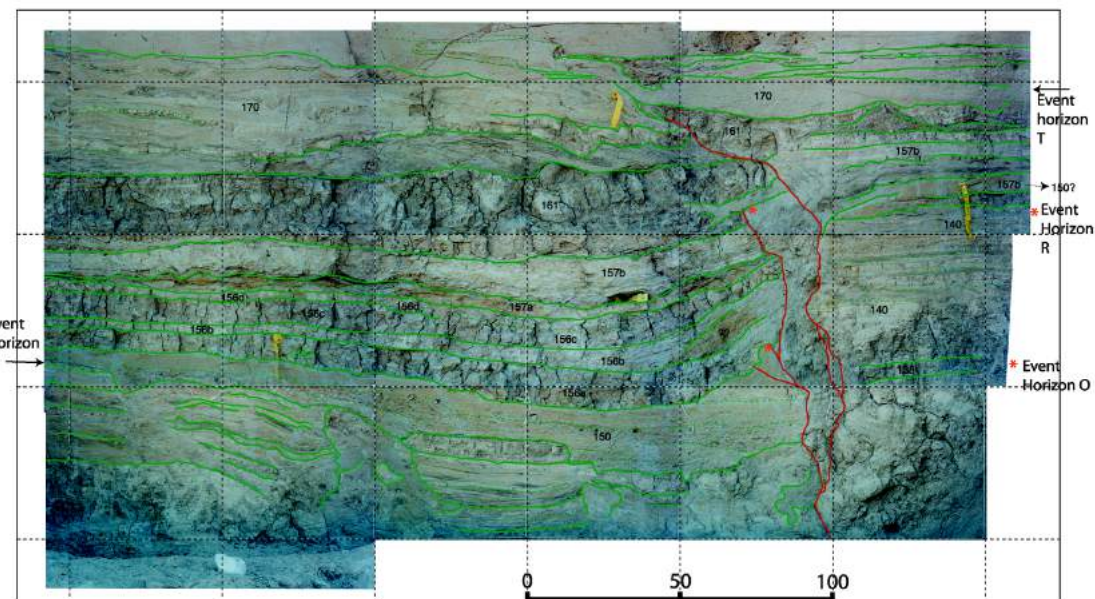
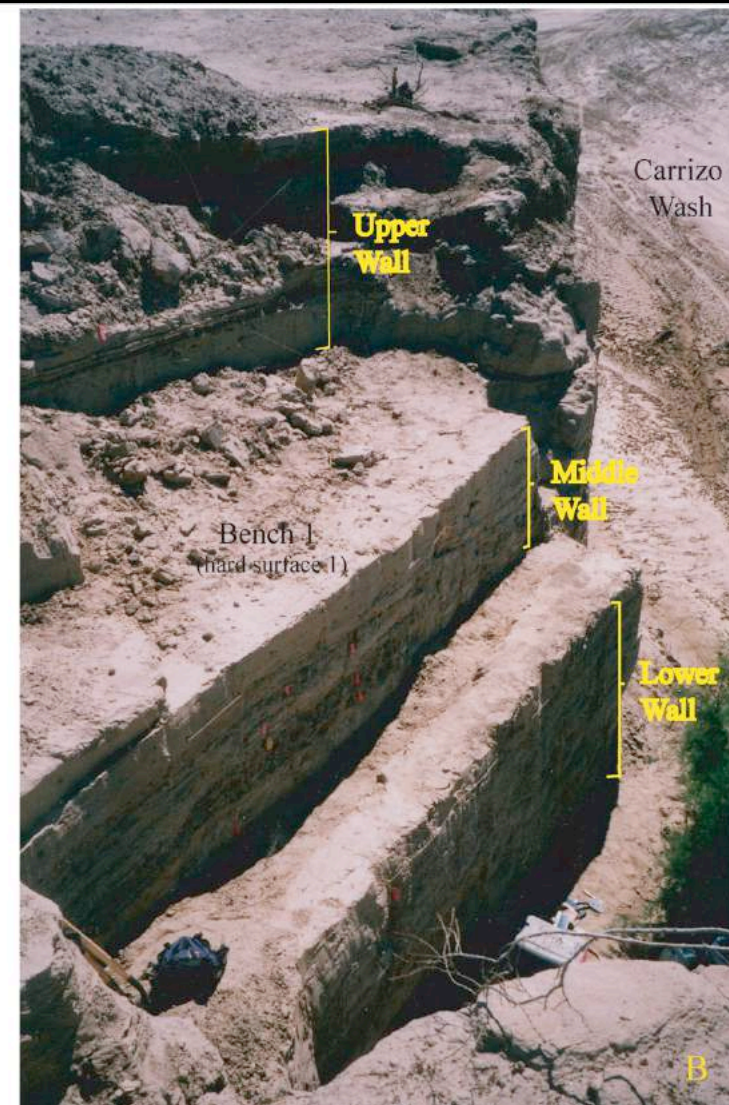
Superstition Mountain Fault, Northern Shoreline Site

Three surface ruptures in past 1100 years

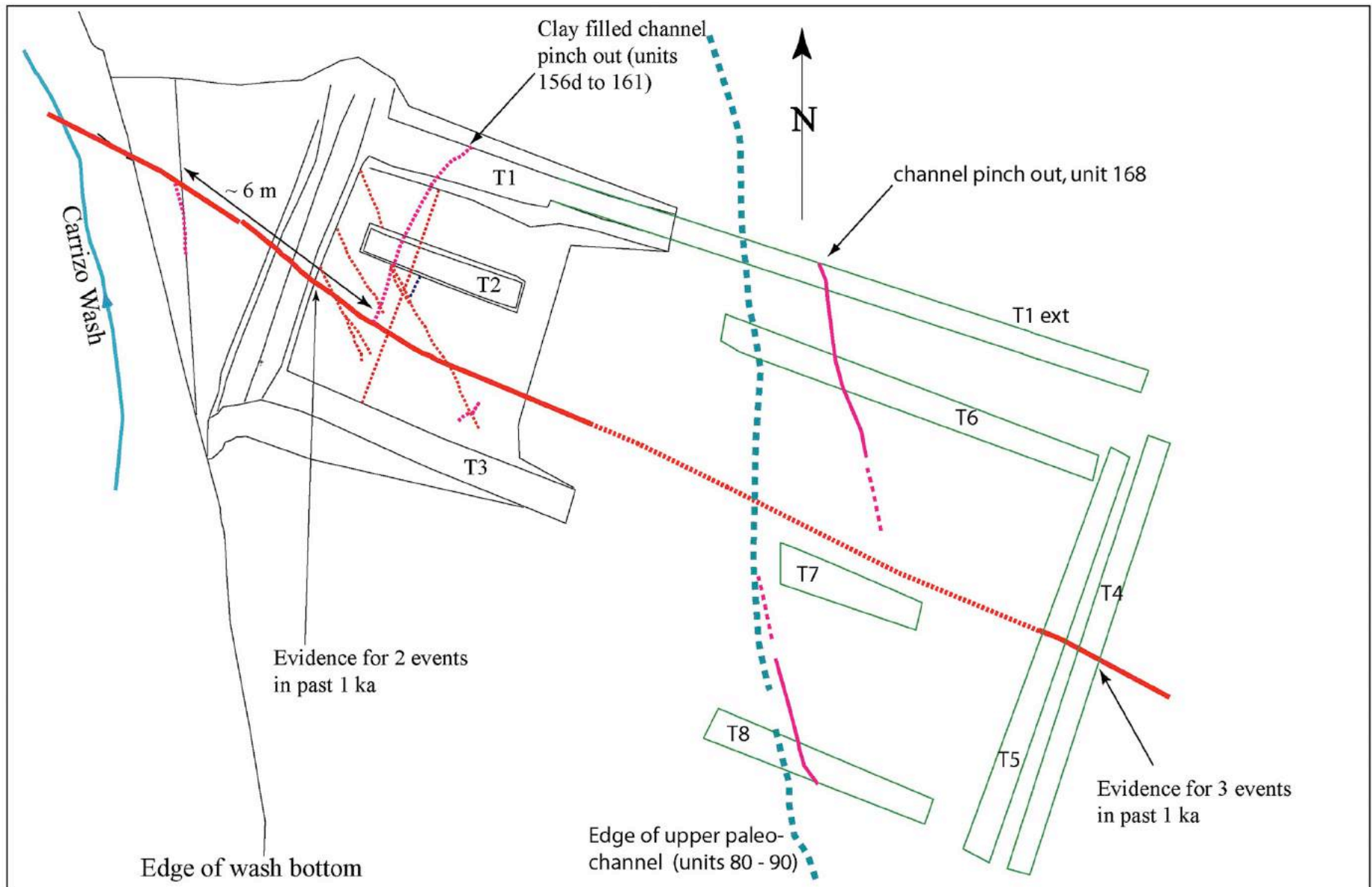
2.2 m in MRE



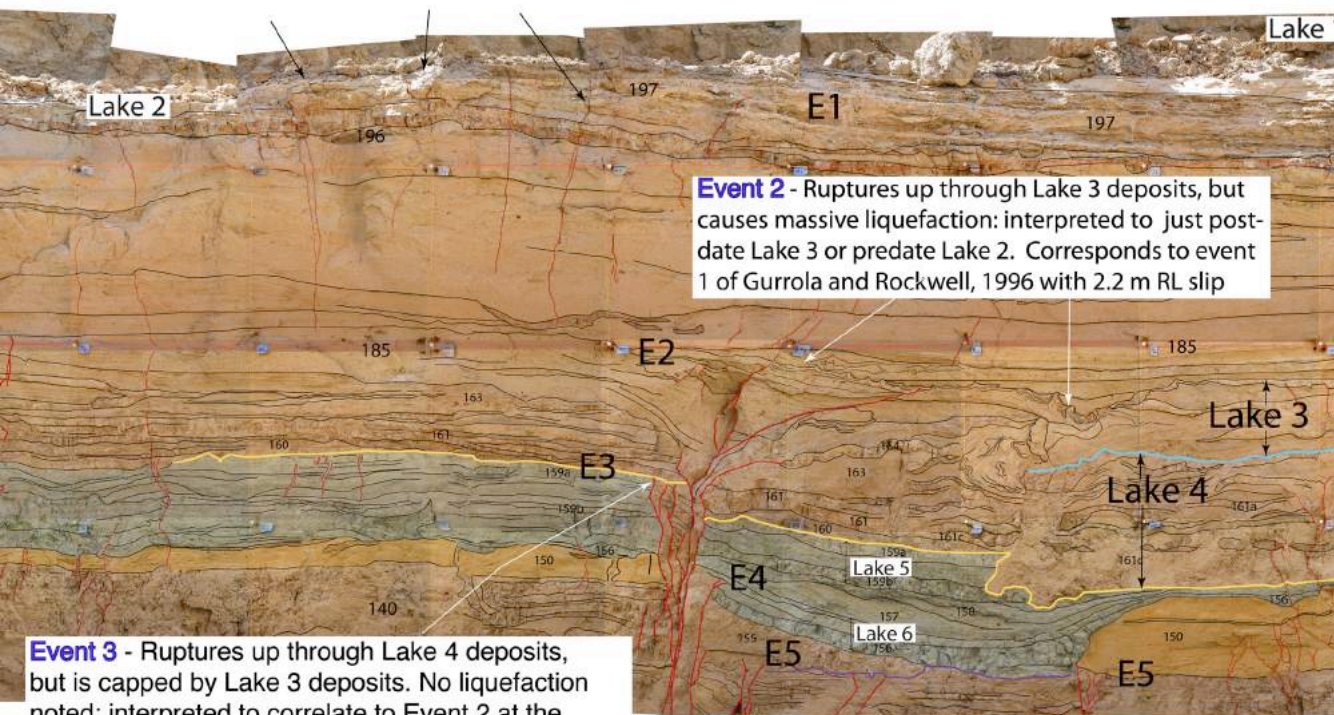
Superstition Mountain Fault, Carrizo Wash Site



Map of trenches, Carrizo Wash Site



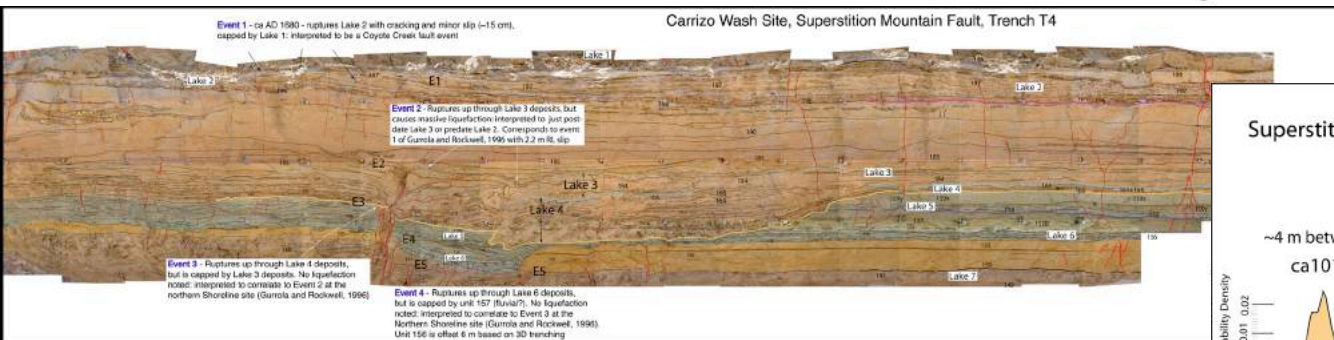
Event 1 - ca AD 1680 - ruptures Lake 2 with cracking and minor slip (~15 cm), capped by Lake 1: interpreted to be a Coyote Creek fault event



Event 2 - Ruptures up through Lake 3 deposits, but causes massive liquefaction: interpreted to just post-date Lake 3 or predate Lake 2. Corresponds to event 1 of Gurrola and Rockwell, 1996 with 2.2 m RL slip

Event 3 - Ruptures up through Lake 4 deposits, but is capped by Lake 3 deposits. No liquefaction noted: interpreted to correlate to Event 2 at the northern Shoreline site (Gurrola and Rockwell, 1996)

Event 4 - Ruptures up through Lake 6 deposits, but is capped by unit 157 (fluvial?). No liquefaction noted: interpreted to correlate to Event 3 at the Northern Shoreline site (Gurrola and Rockwell, 1996). Unit 156 is offset 6 m based on 3D trenching



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.

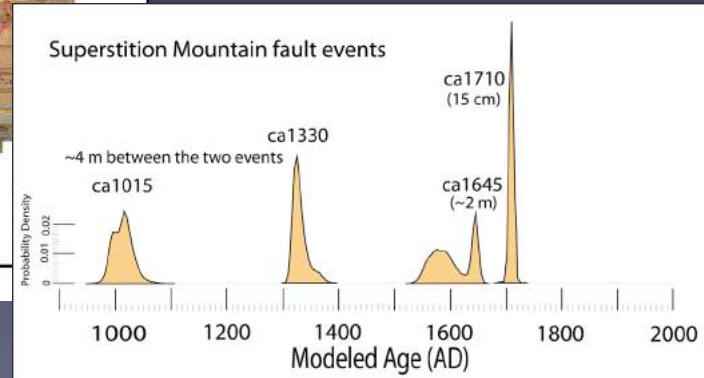
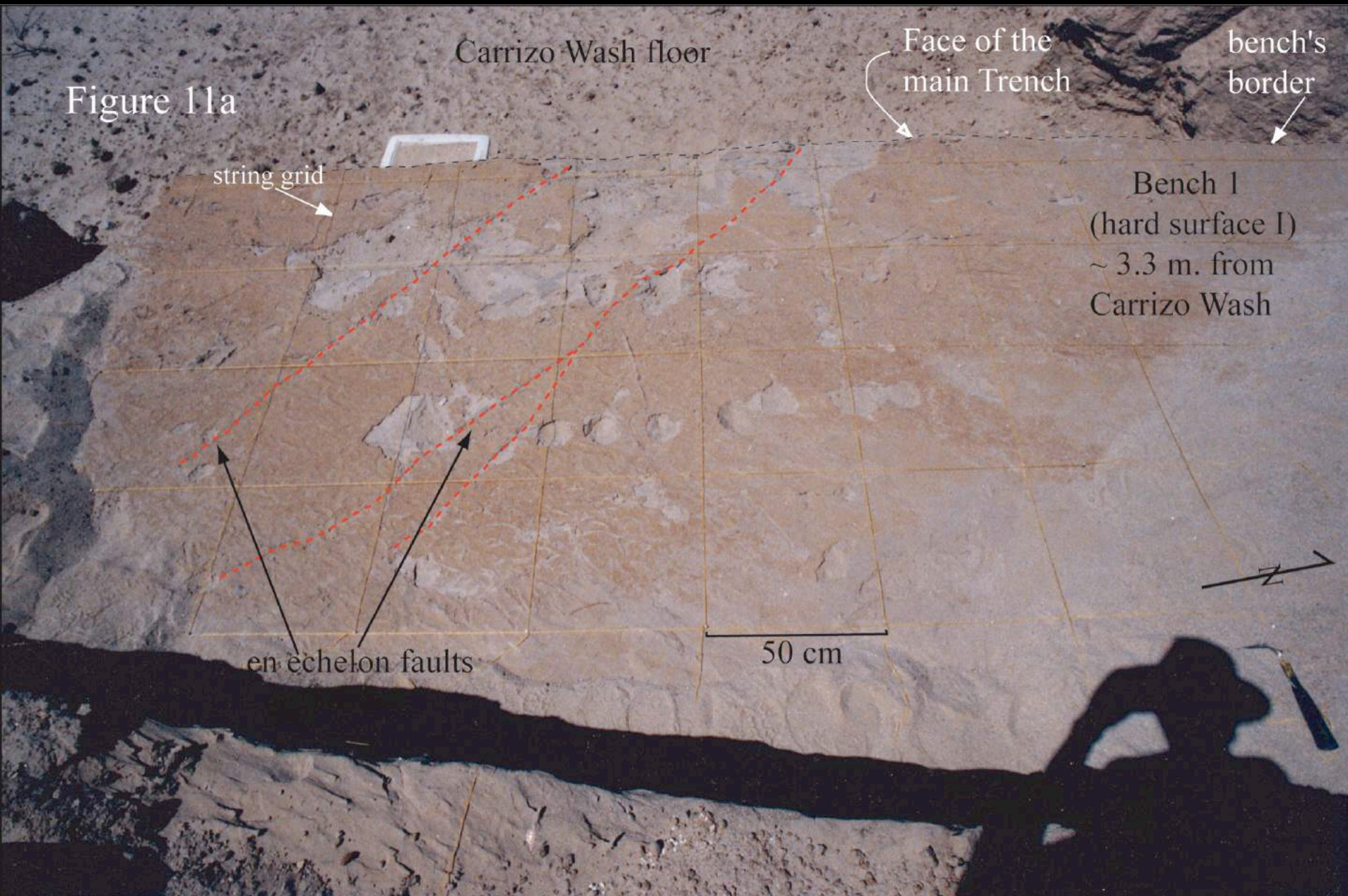
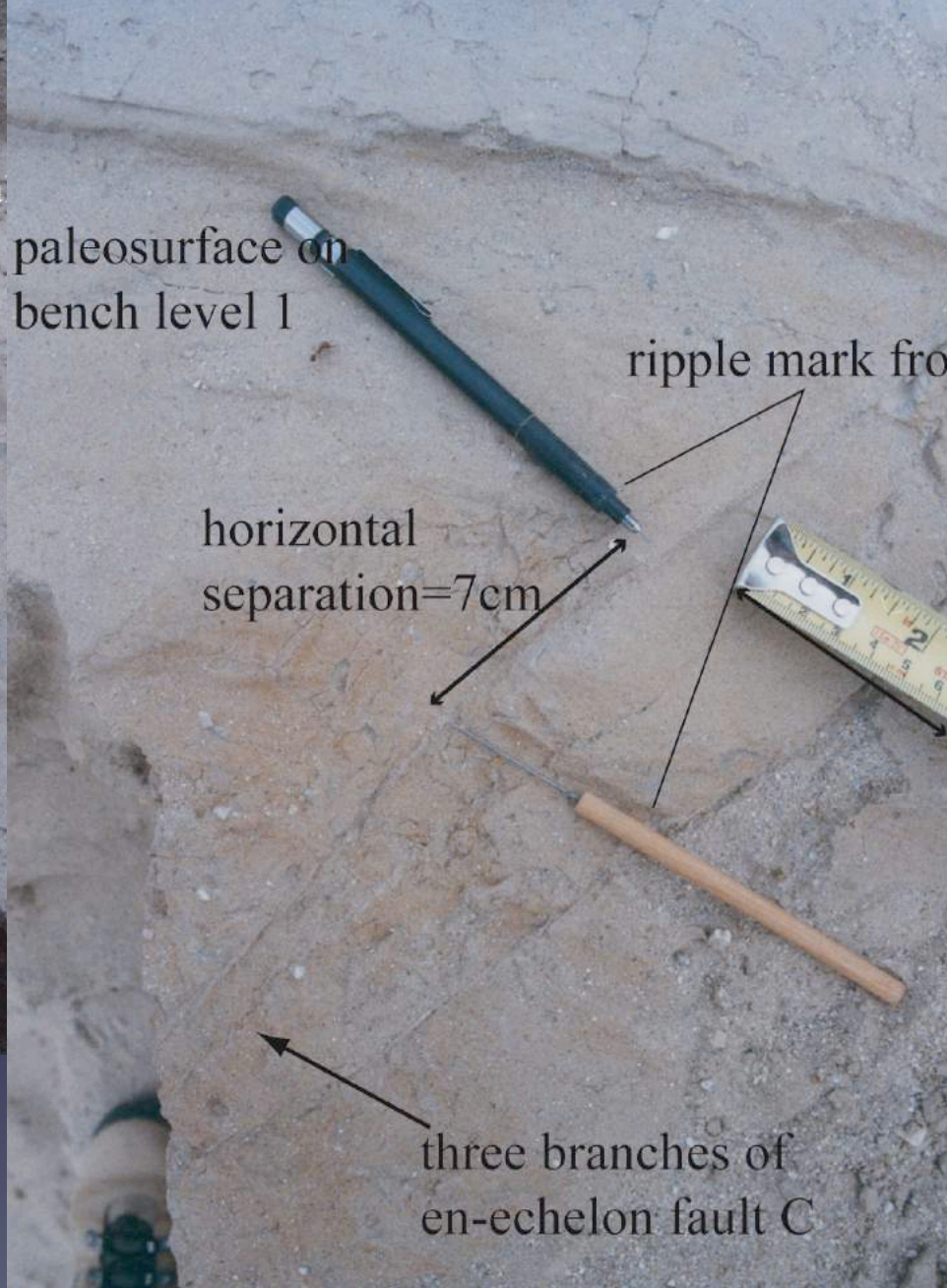
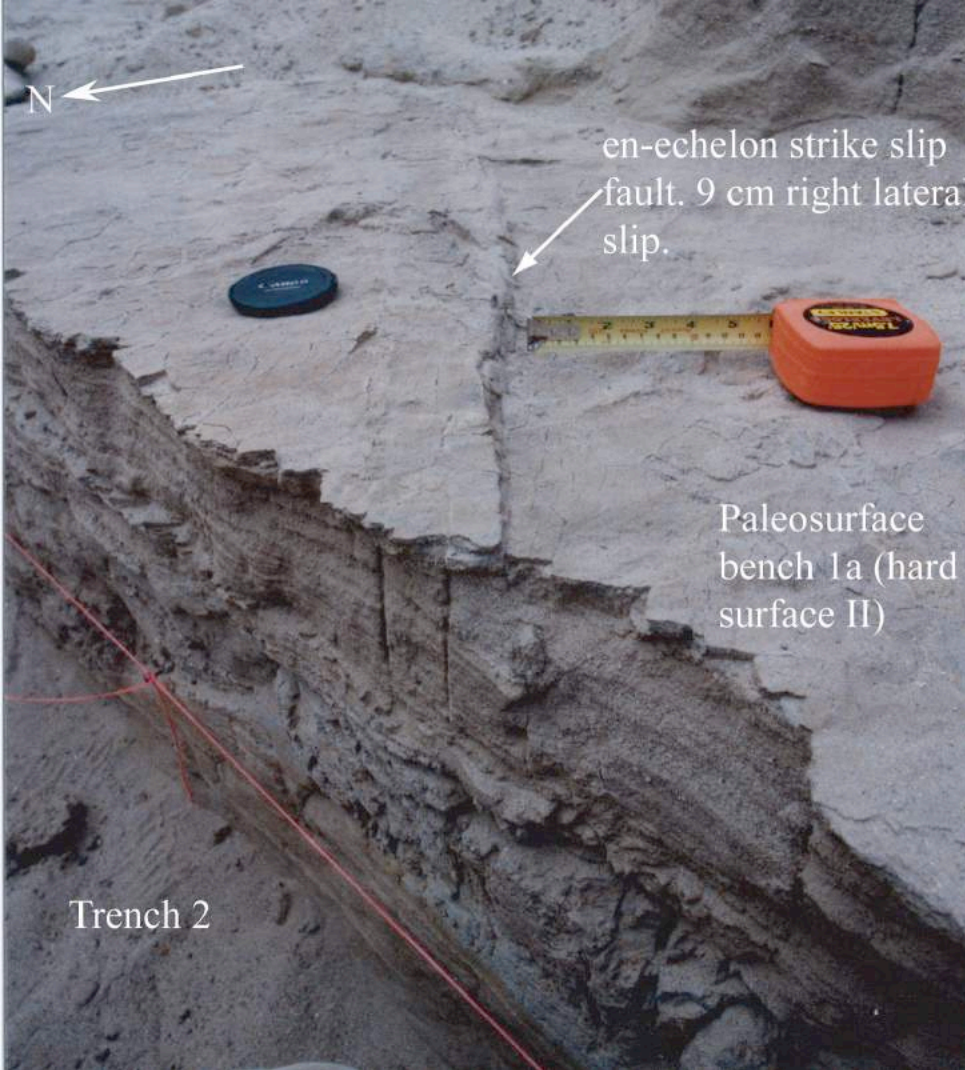


Figure 11a



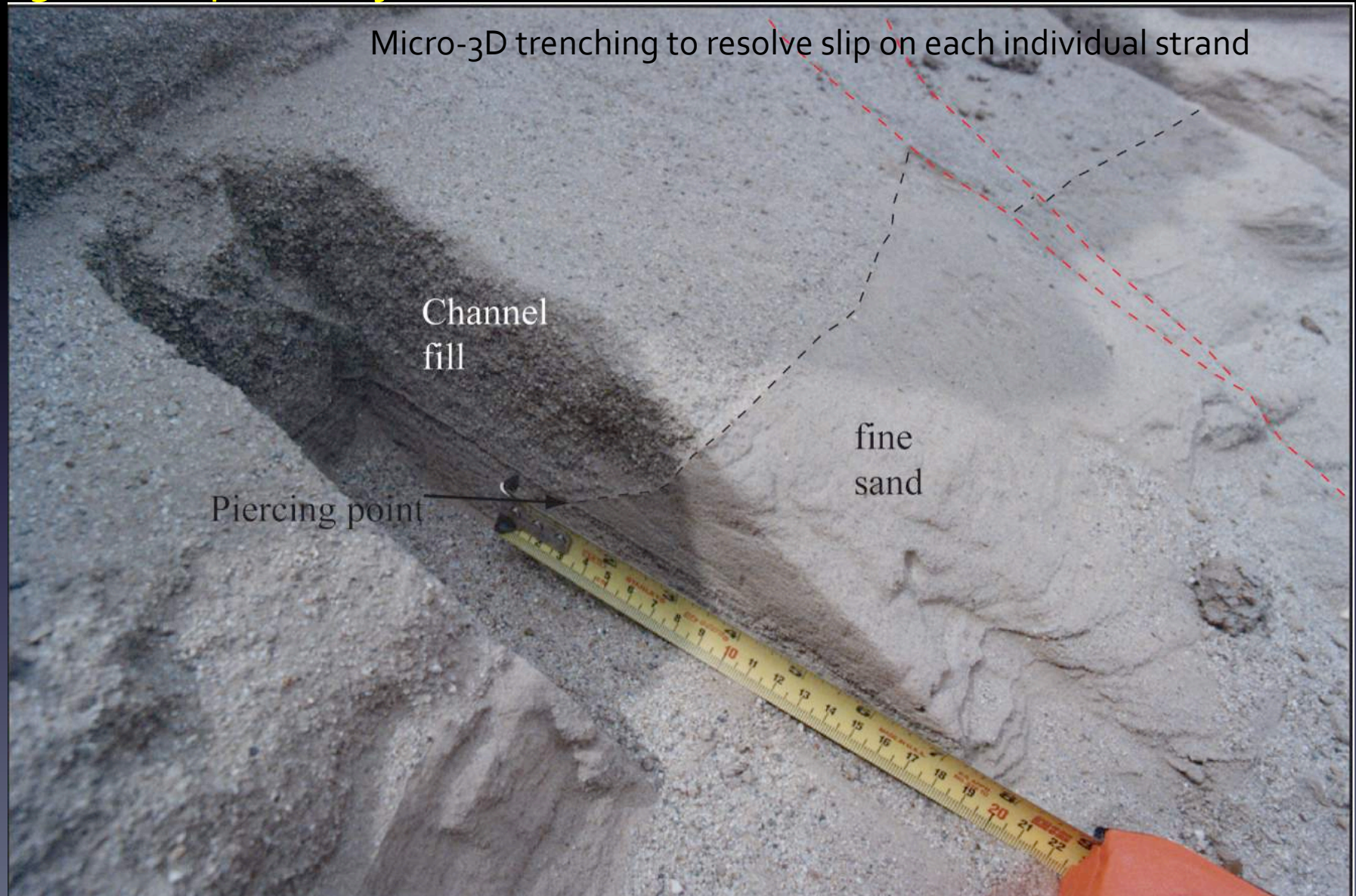


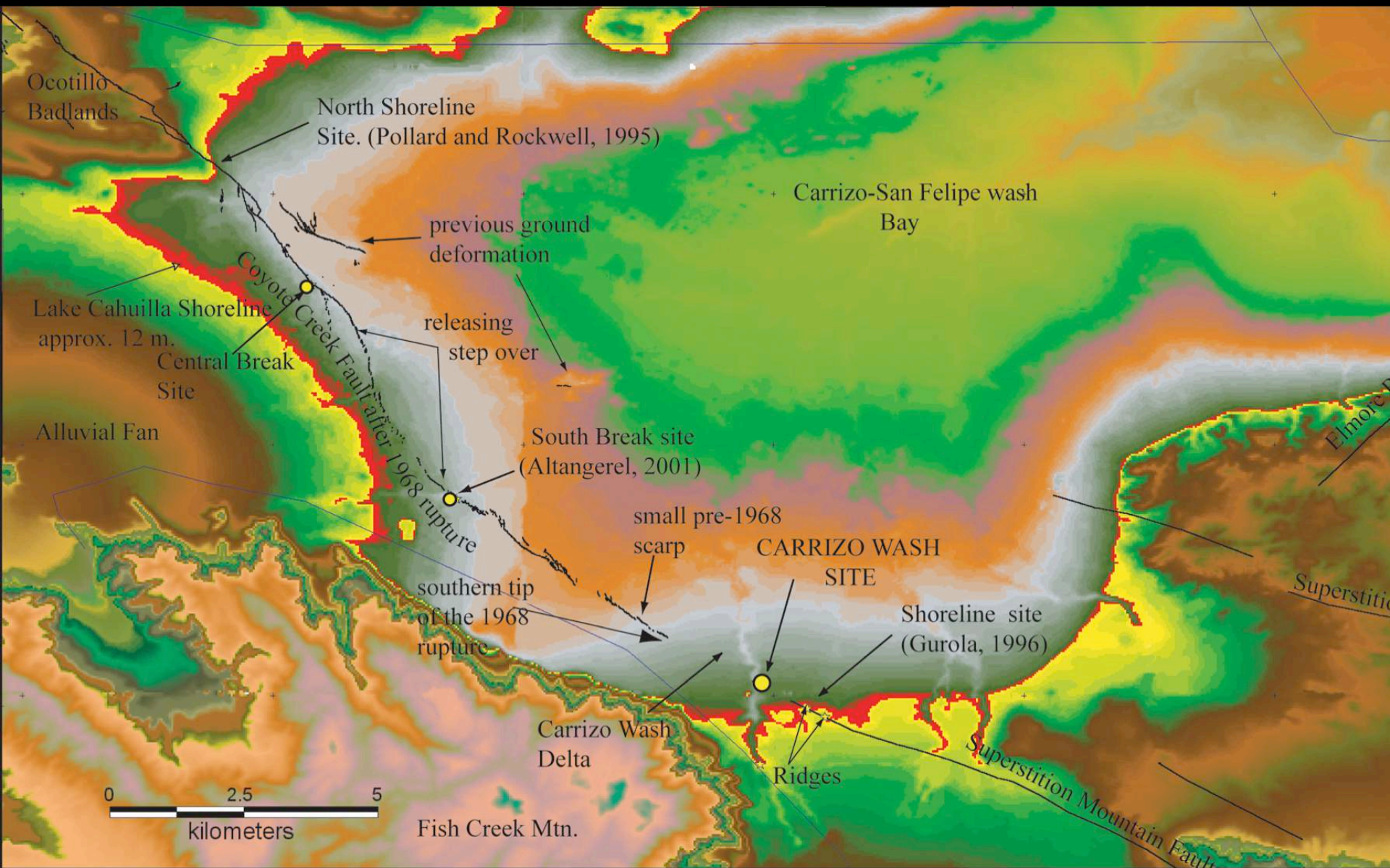


Paleosurface II

En-echelon cracks

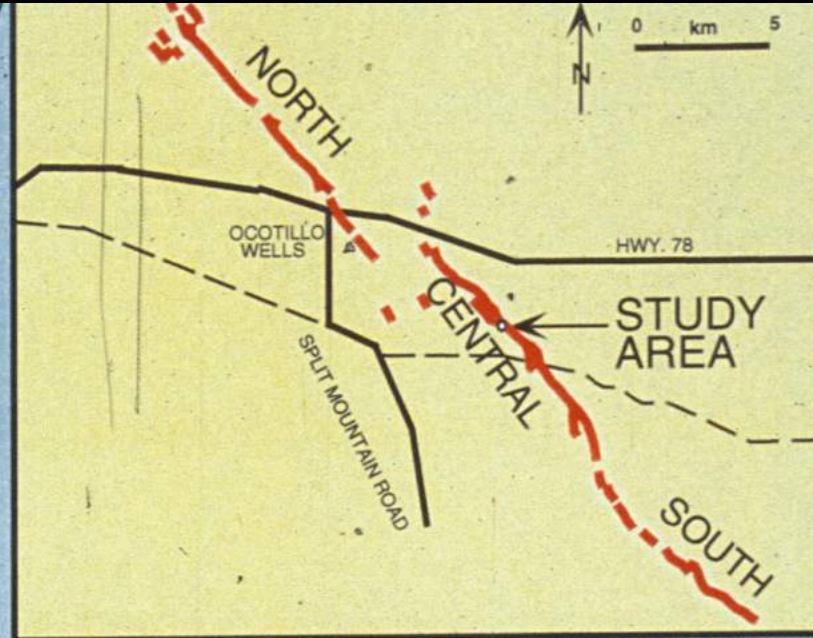
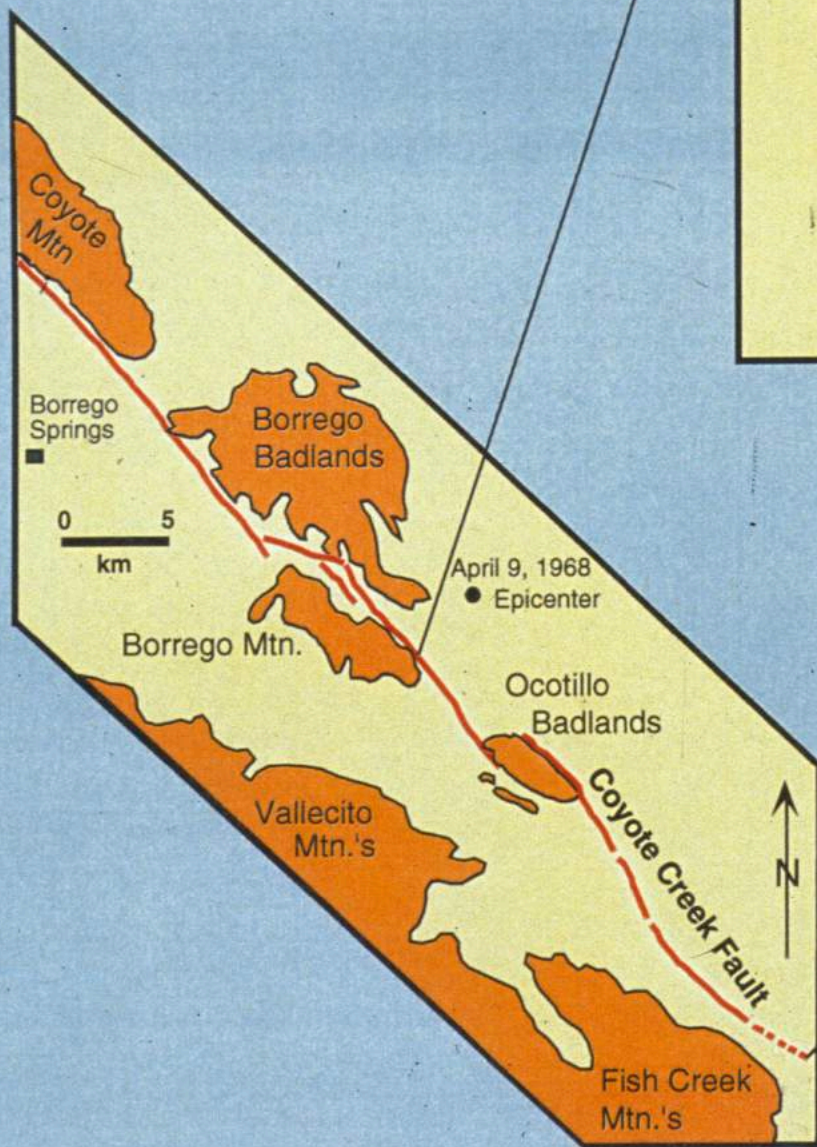
Bottom line – we can resolve both timing and displacement, even for moderate-sized earthquakes, and distinguish moderate from large earthquakes – just takes work!

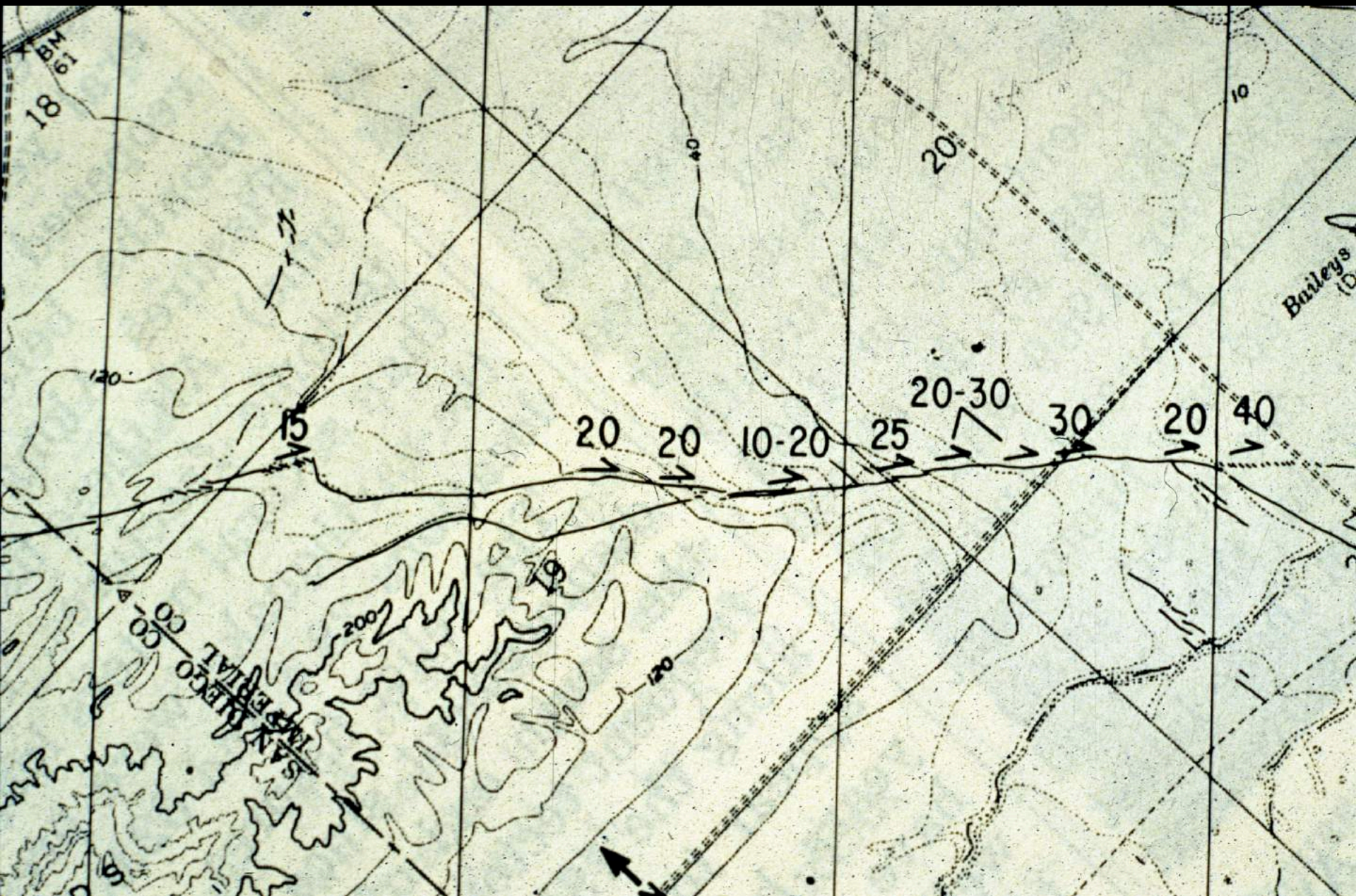




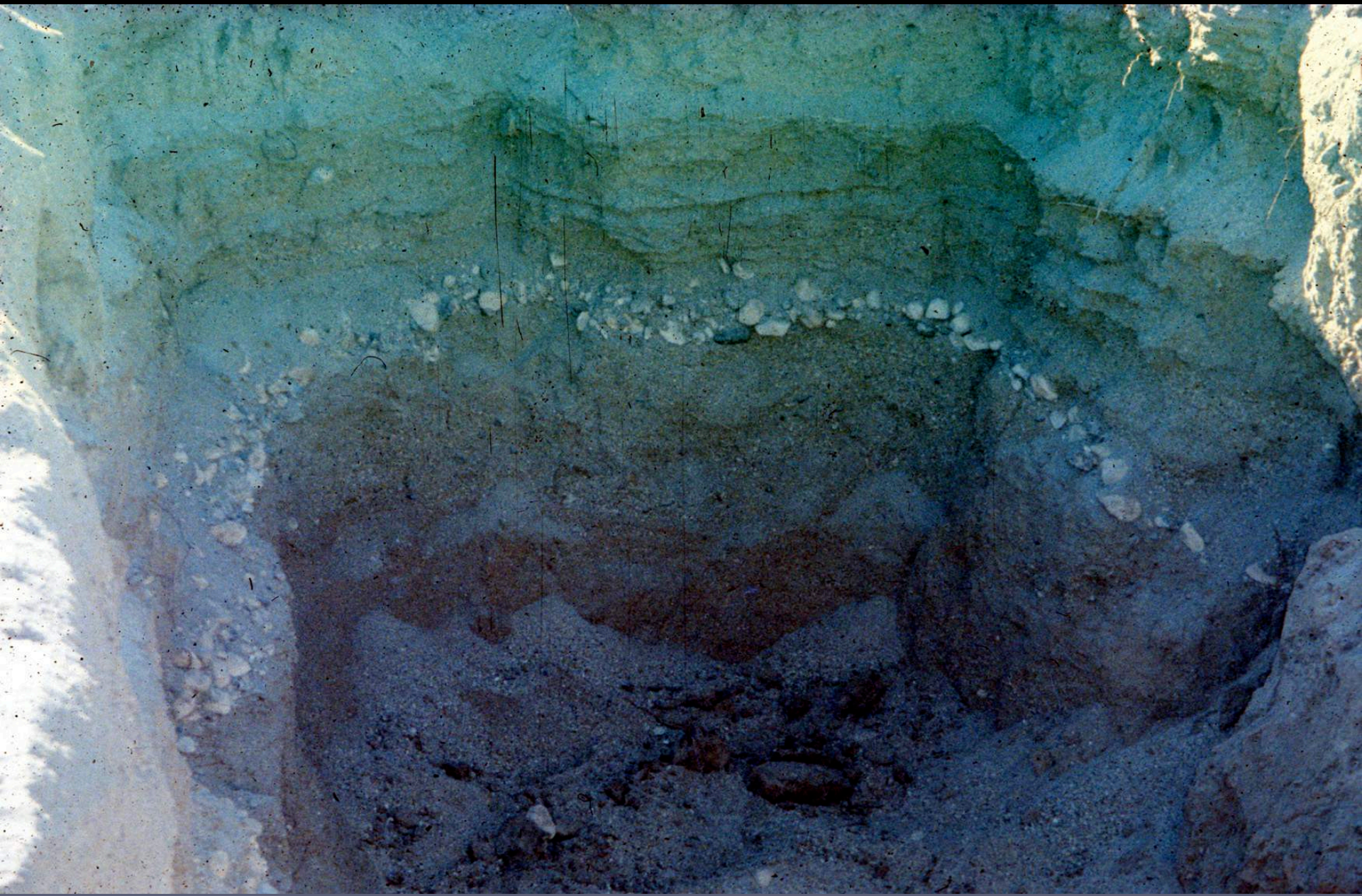
South Break Site on the southern Coyote Creek fault



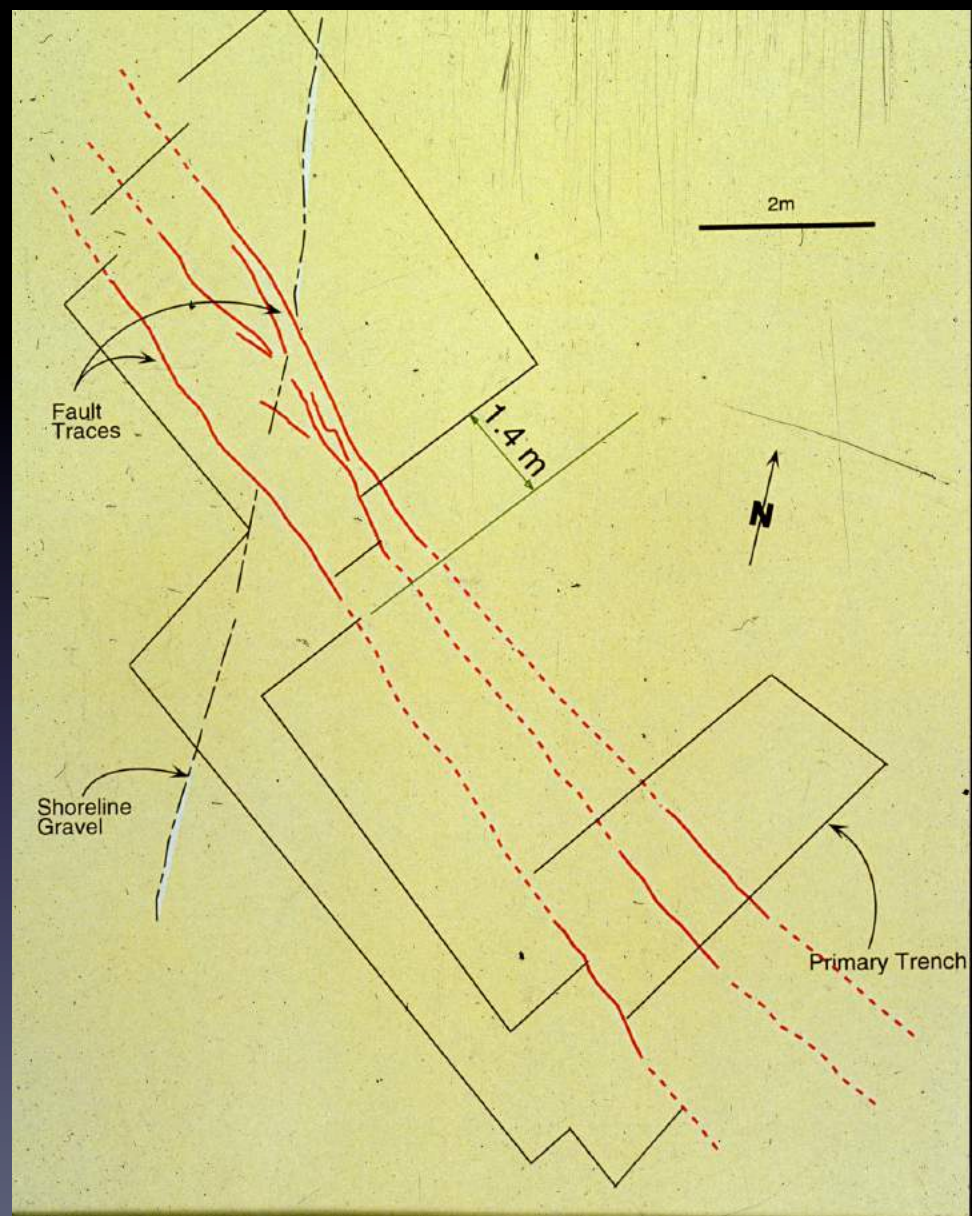
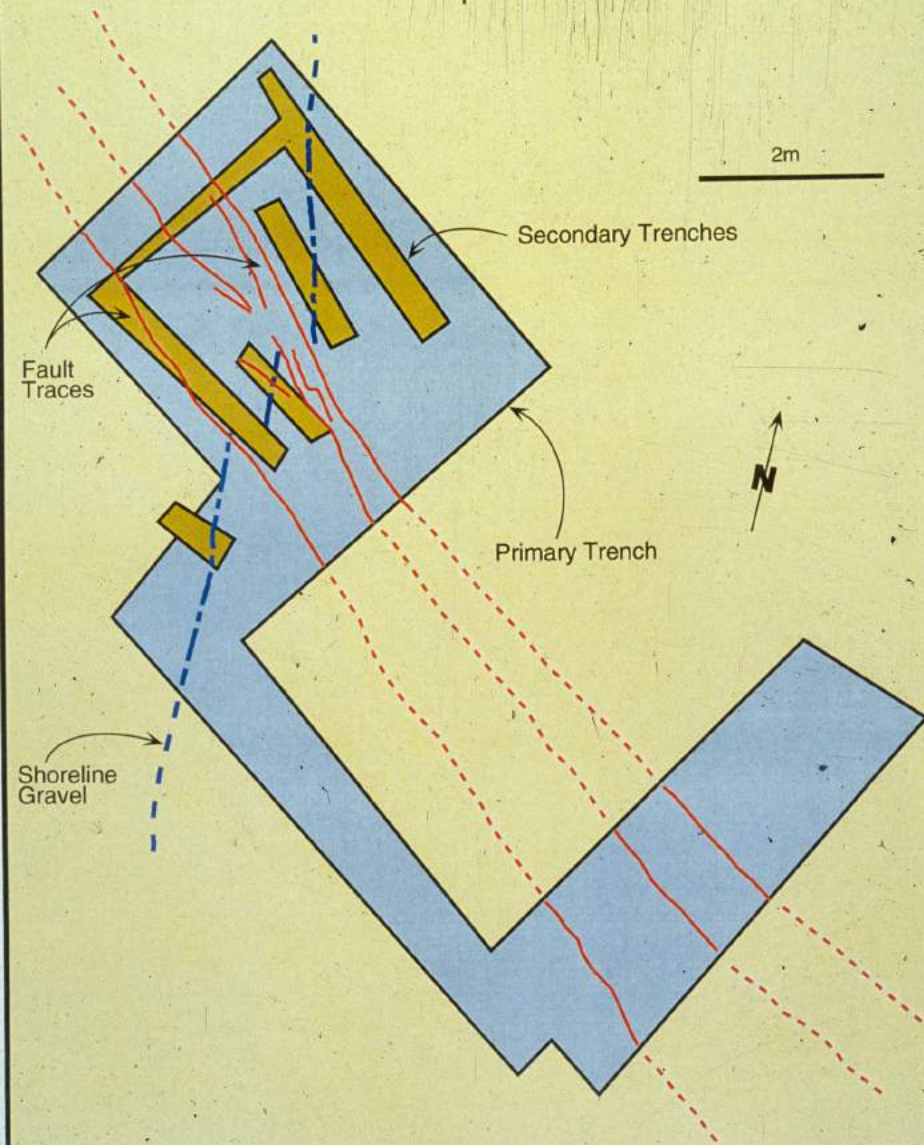




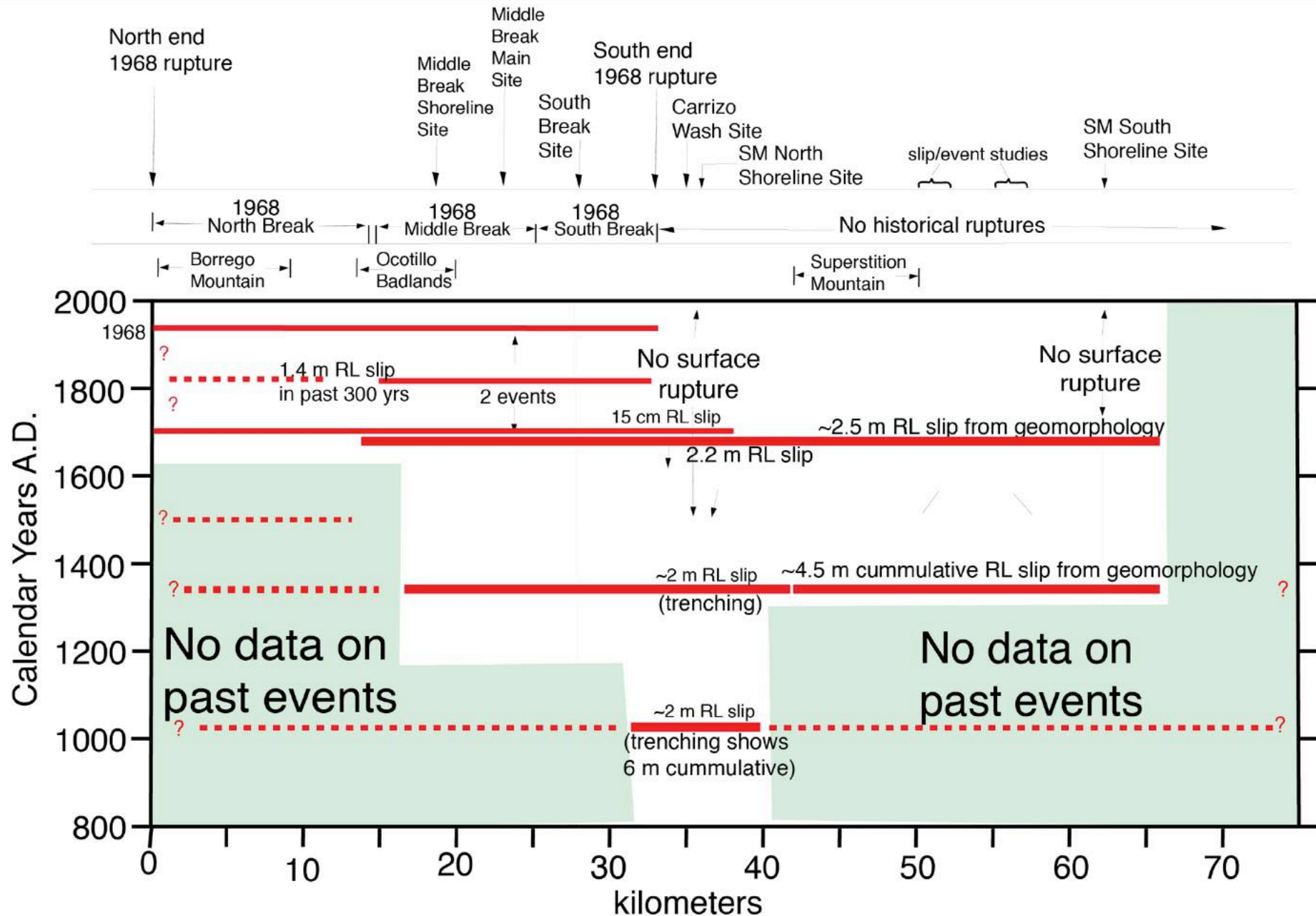




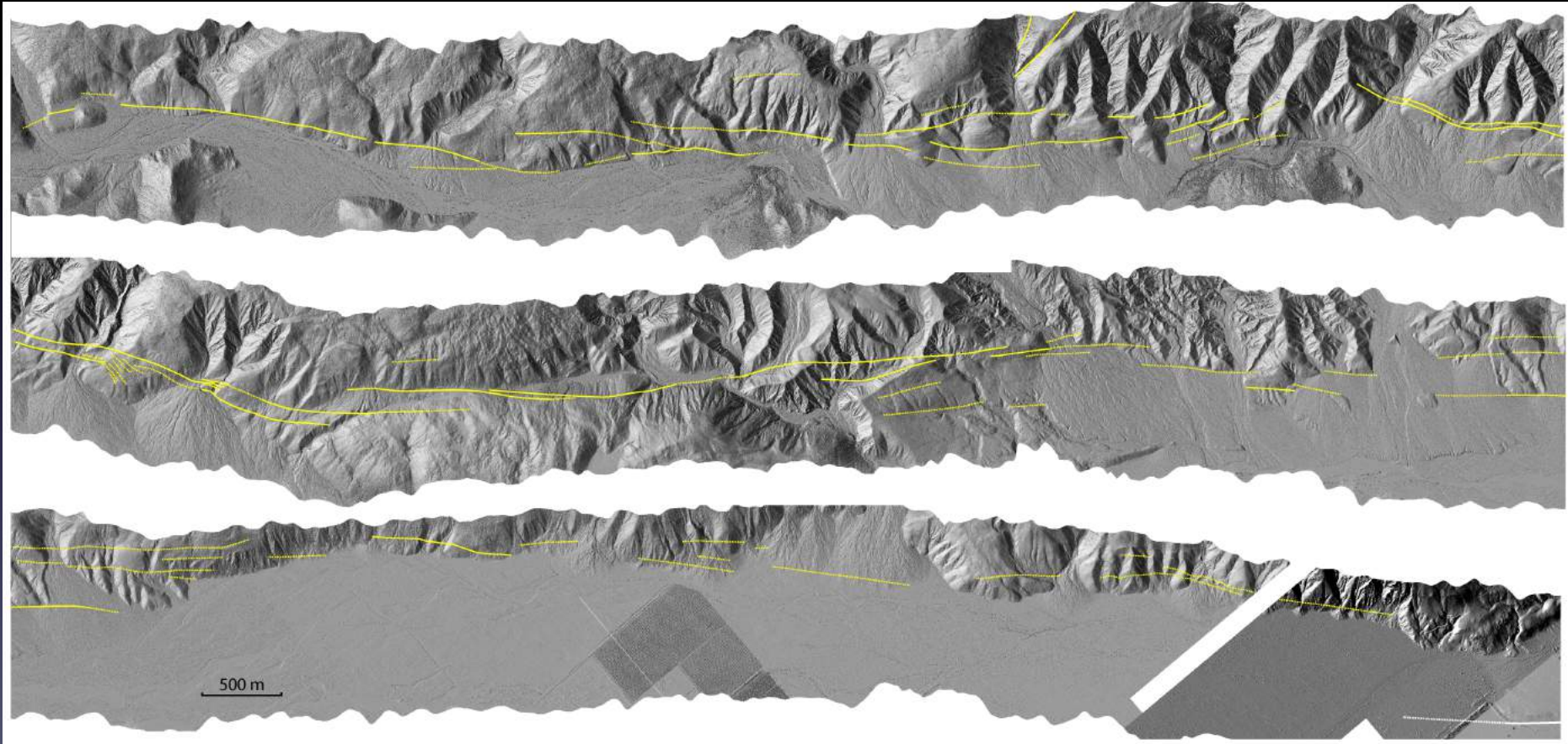
Map View of T -1



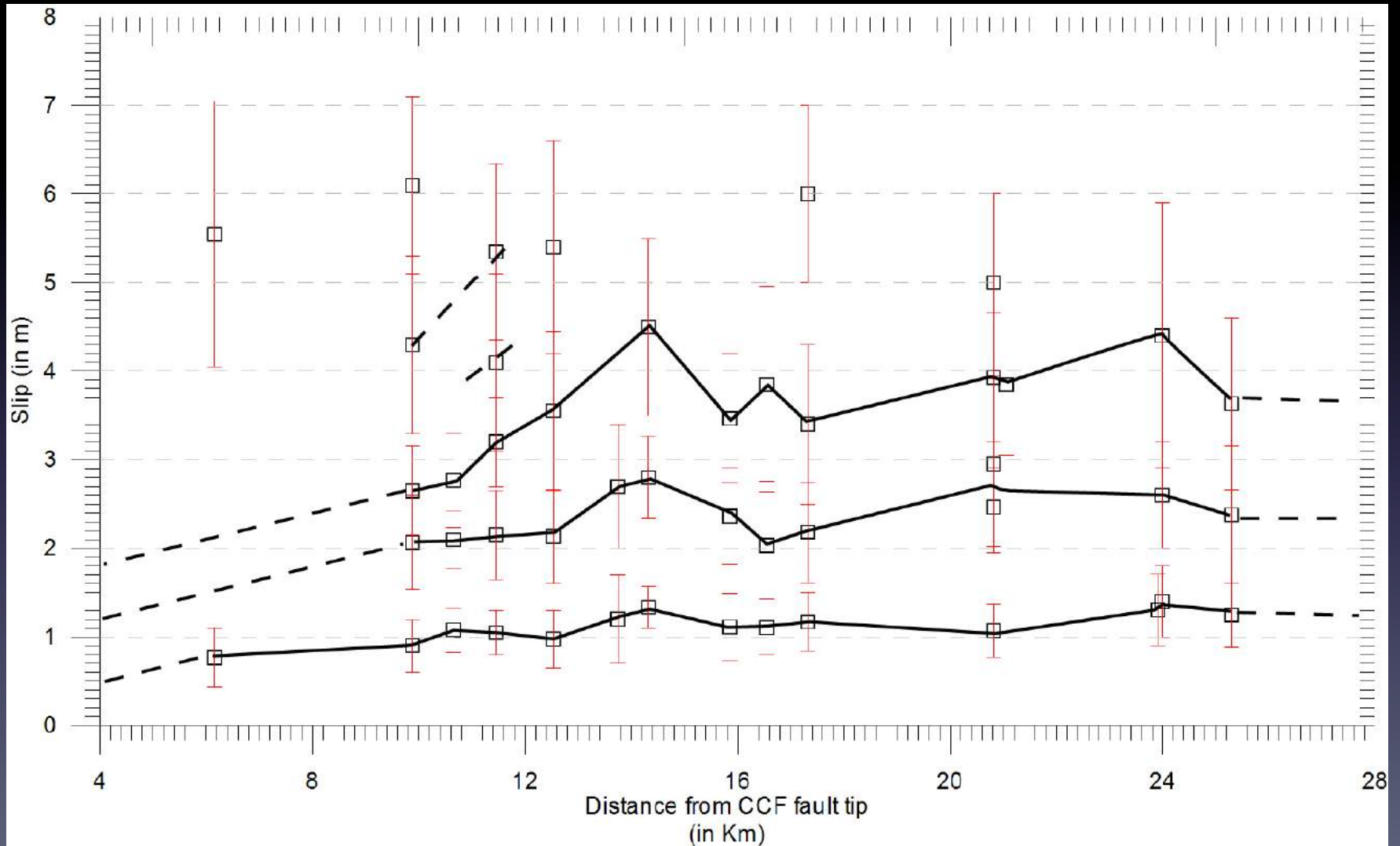
Construct rupture history of the southern San Jacinto fault zone



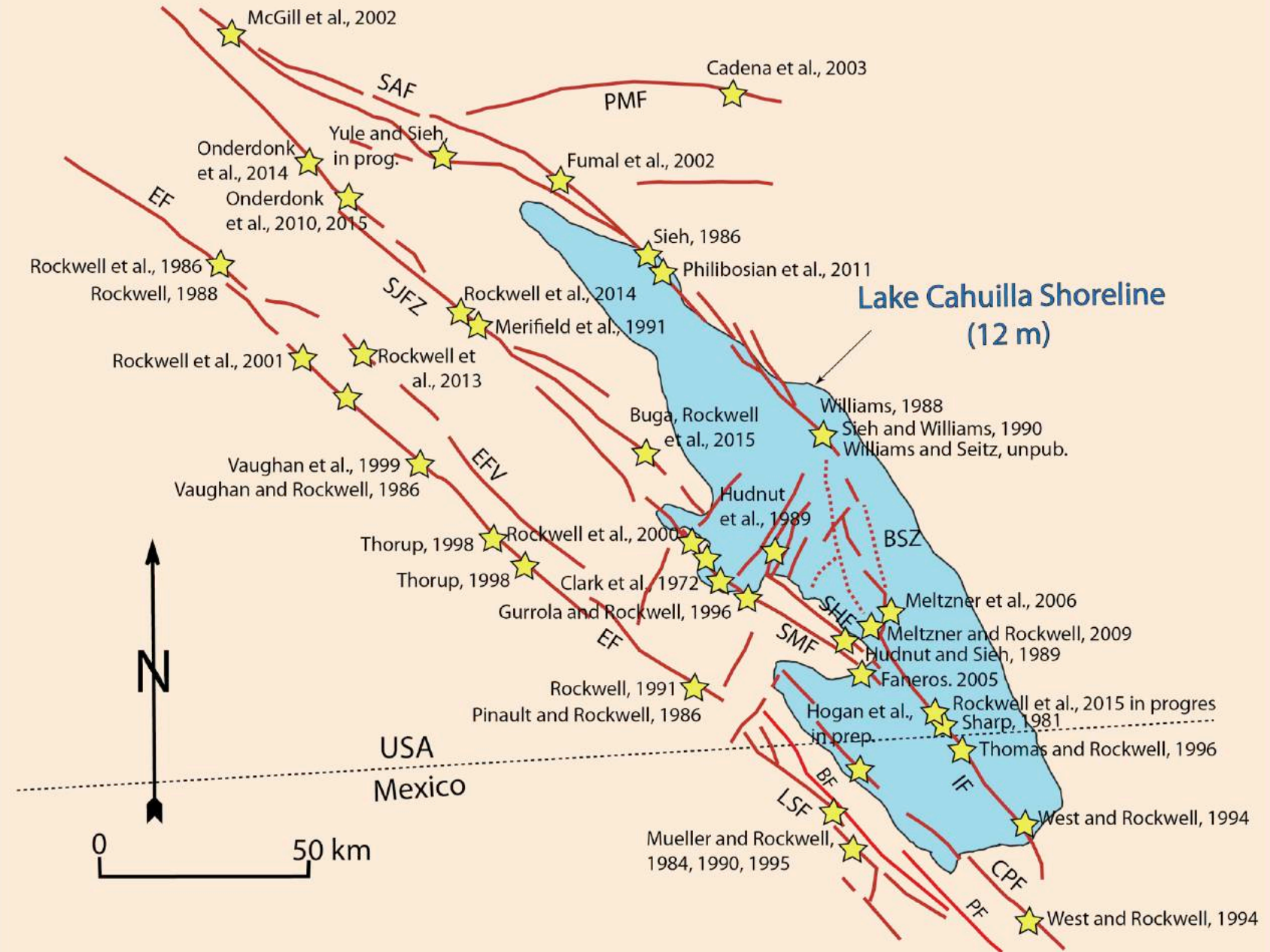
New LiDAR and field mapping results on slip distribution from the Coyote Creek Fault

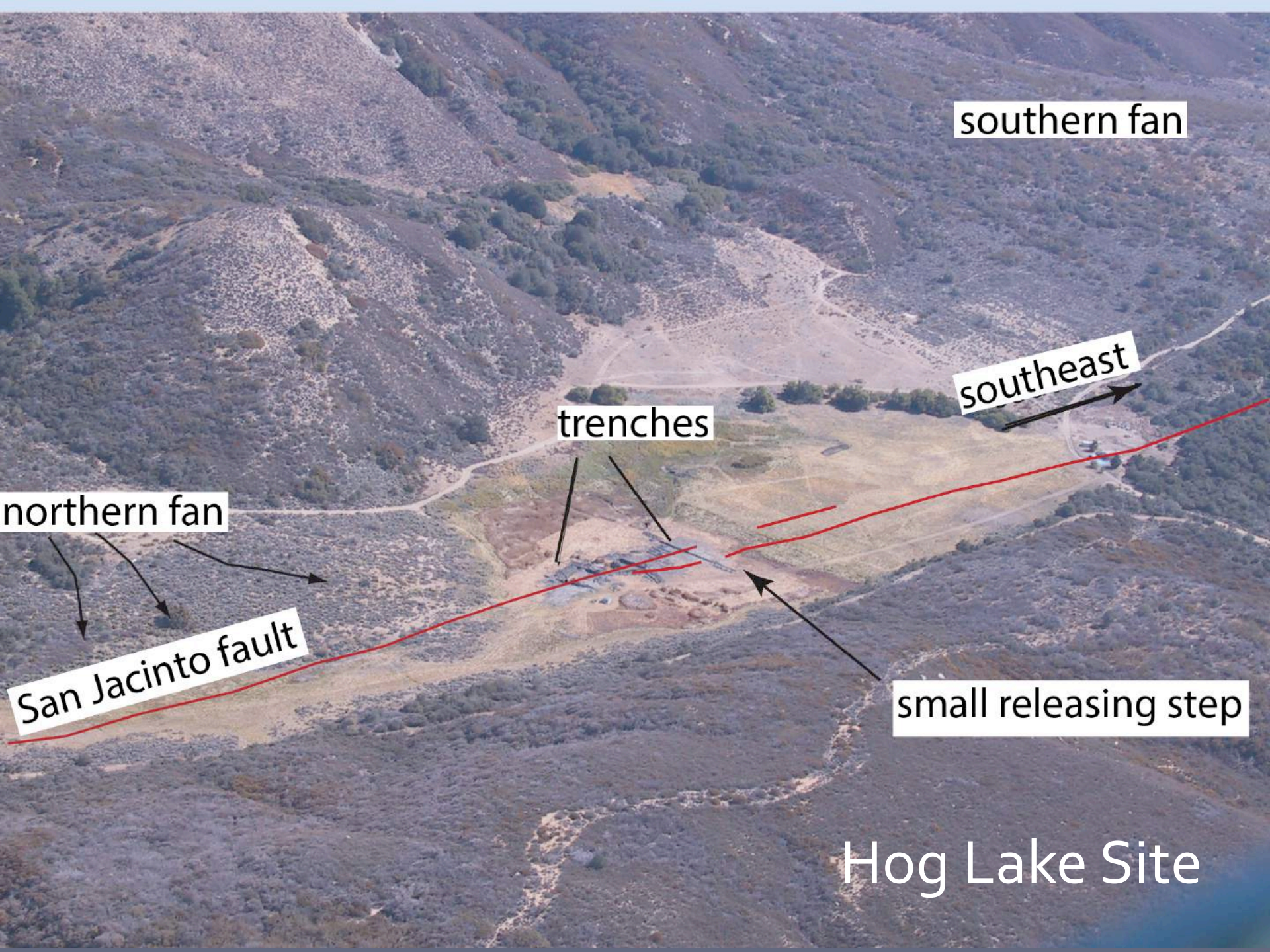


Northern Coyote Creek Fault: ~1-1.5m slip per event



Okay, what about the south central San Jacinto fault?





southern fan

southeast

trenches

northern fan

San Jacinto fault

small releasing step

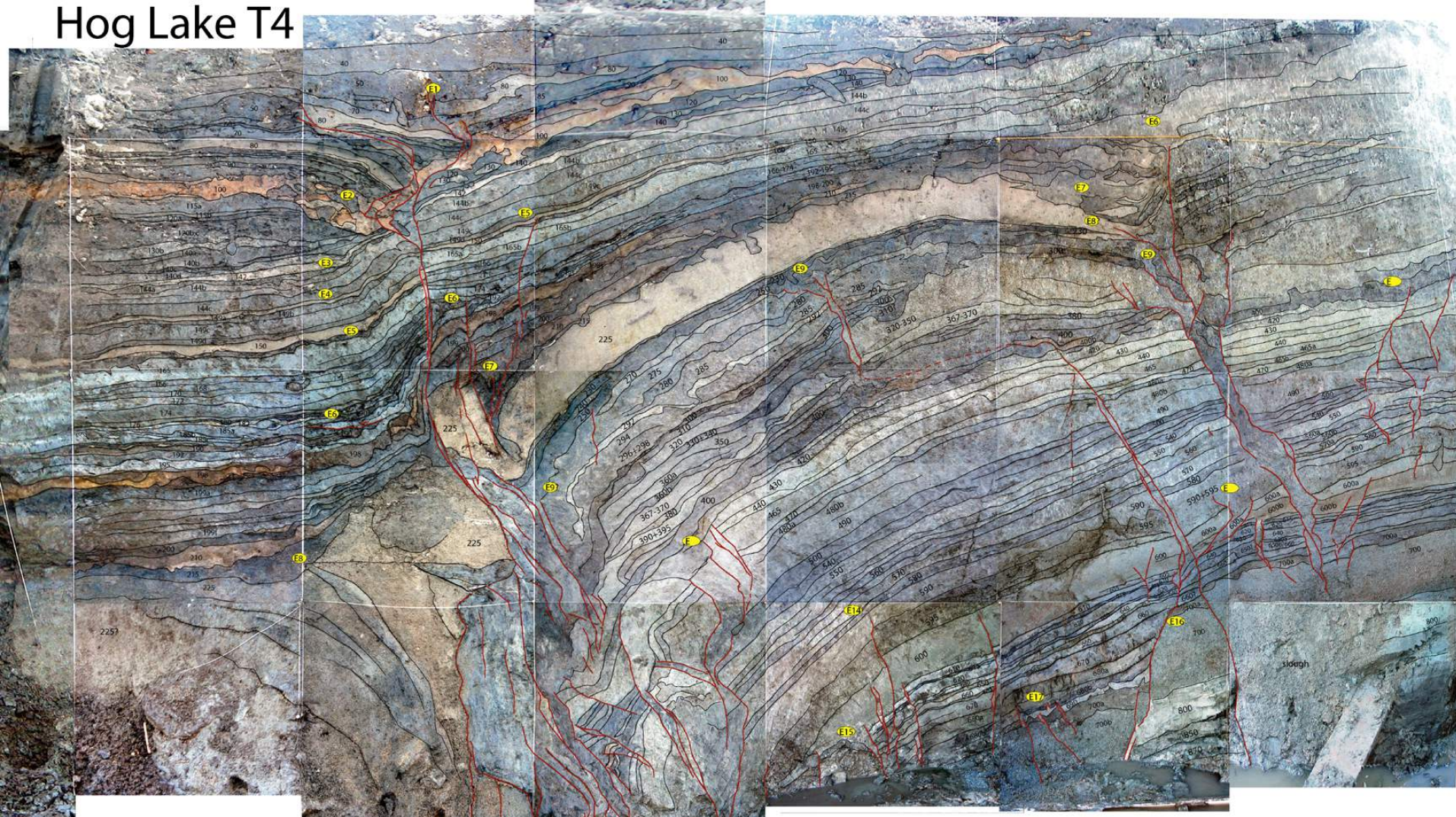
Hog Lake Site

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

Hog Lake T4



Signature of a past earthquake surface rupture

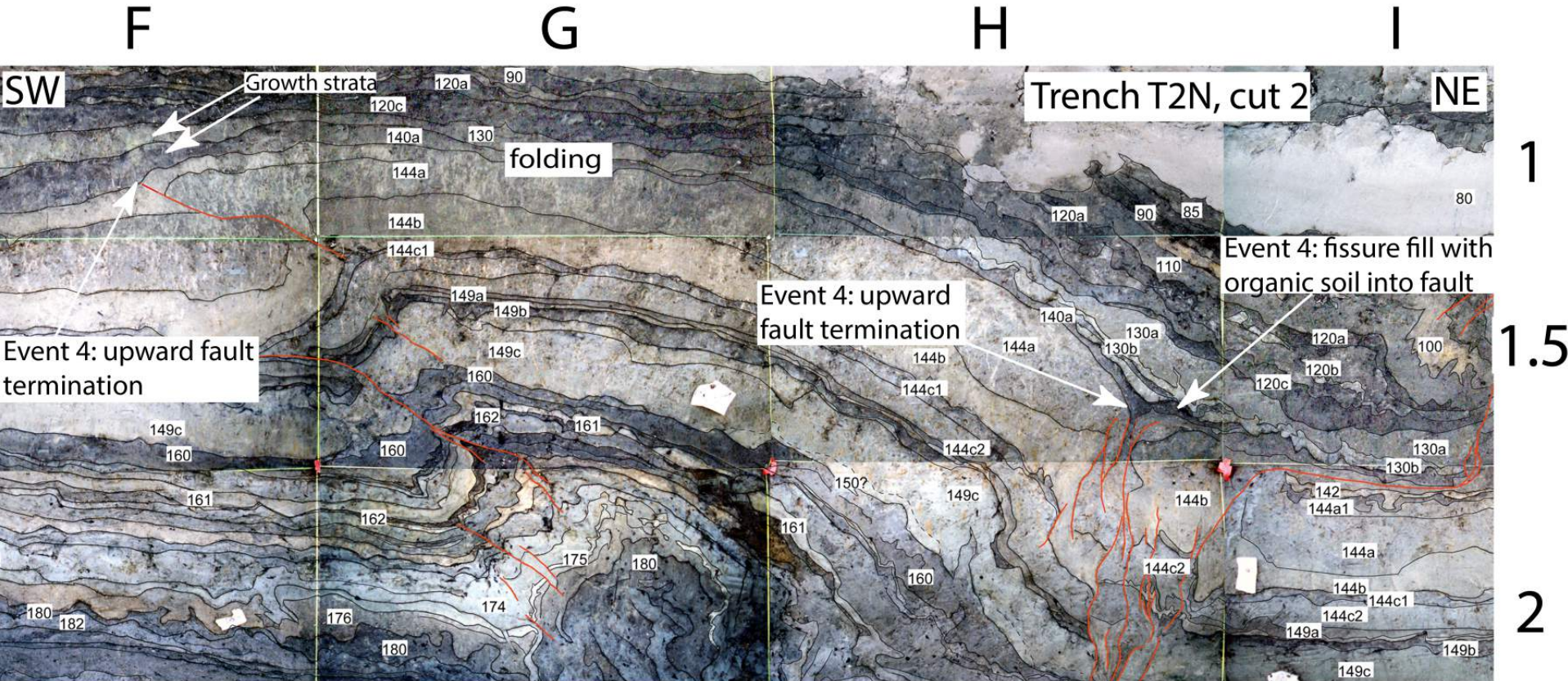
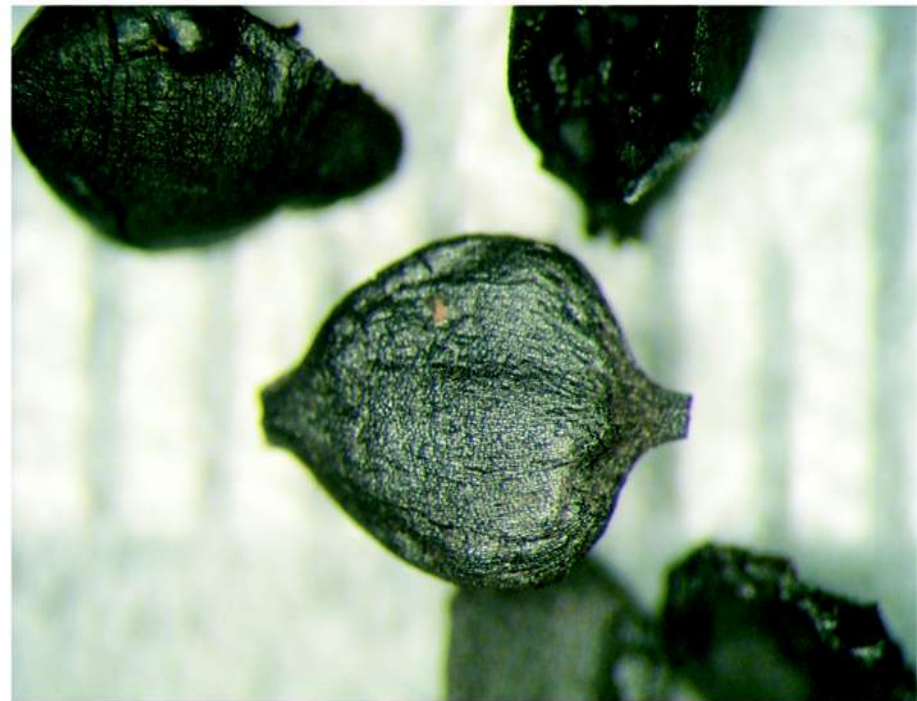
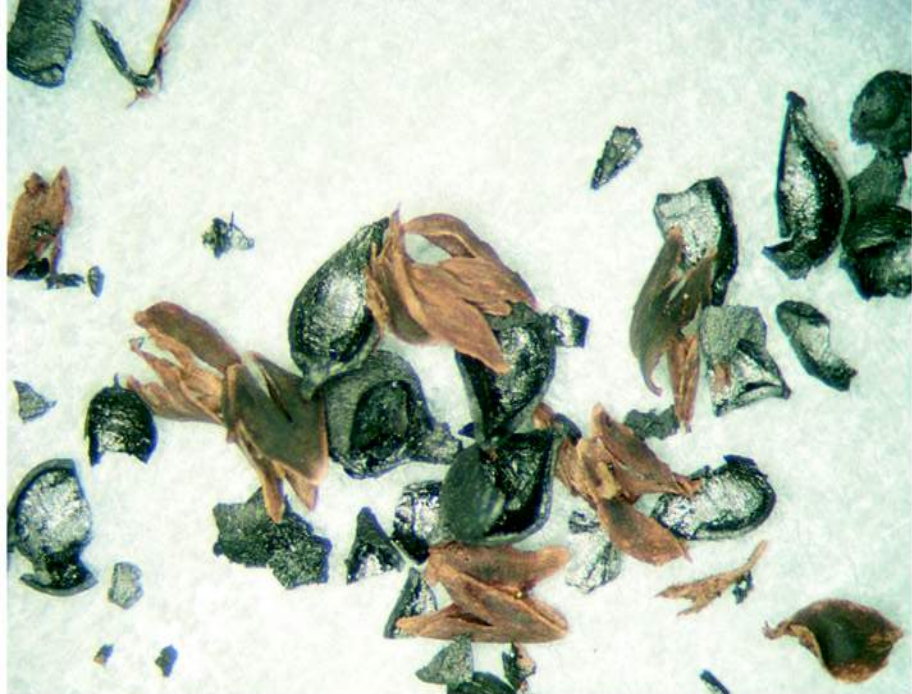


Figure 10. Rockwell et al.

Primary fault breaks to a paleo-ground surface, and is capped by undeformed strata



Section taken from SW side of fault in trench T2N, cut 3



Unit

Unit Descriptions (primarily from trench T2N)

0-40 Massive fine sandy silt interpreted to be well mixed by bioturbation

50 Organically enriched fine sand interpreted to be a weak soil developed on unit 57

57 Clean fine sand identical to unit 80. May represent a liquefaction ejecta deposit

60 Organically enriched fine sand interpreted to be a weak soil developed on unit 80

80 Clean fine, well-sorted sand; fines towards deponenter

85 Finely laminated fine sand and organic layers

90 Dense accumulation of organics interpreted to represent a significant pond surface

100 Oxidized fine silty sand interpreted to represent a burning of the pond surface

110 Stratified silt and fine sand deposits with organic peat-like layers developed on some strata that are interpreted as pond surface organic accumulations. Unit 120 is a single layer near the pond margin and splays into multiple layers towards the depo-center.

120a, 120b, 120c, 120d, 120e, 120f, 120g, 120h, 120i, 120j, 120k, 120l, 120m, 120n, 120o, 120p, 120q, 120r, 120s, 120t, 120u, 120v, 120w, 120x, 120y, 120z

140b, 141 Stratified silt and clay deposits with organic peat-like layers developed on some strata that are interpreted as pond surface organic accumulations. Unit 140 is a single layer near the pond margin and splays into at least two layers towards the depo-center.

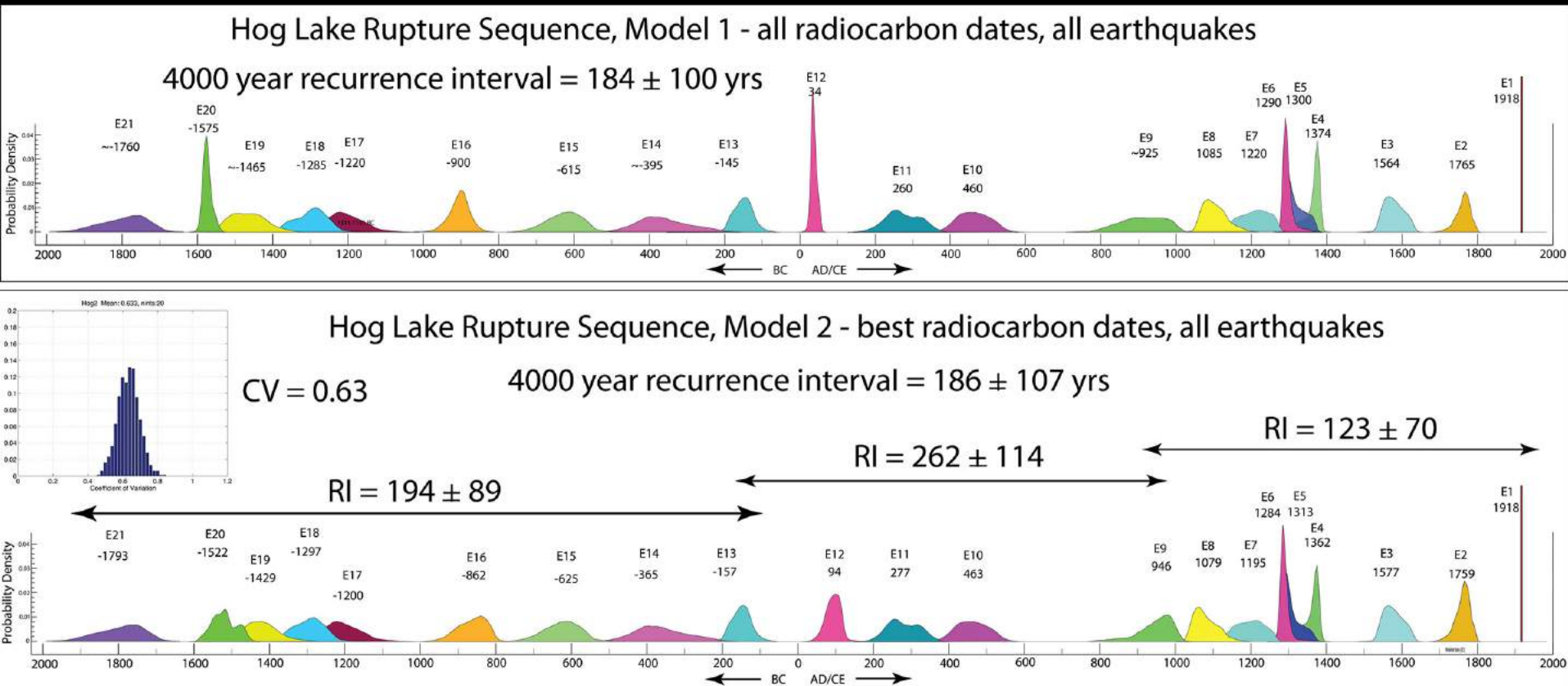
142, 143a, 144a, 144b, 144c, 144d, 144e, 144f, 144g, 144h, 144i, 144j, 144k, 144l, 144m, 144n, 144o, 144p, 144q, 144r, 144s, 144t, 144u, 144v, 144w, 144x, 144y, 144z

149b Organic peat-like layers developed in stratified silt and fine sand deposits, interpreted as pond surface organic accumulations. These are a single layer near the pond margins, and splay into multiple layers towards the depo-center.

150, 155, 160, 161, 162, 167, 172, 173, 174, 175, 176, 180, 182, 185, 188, 192, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845

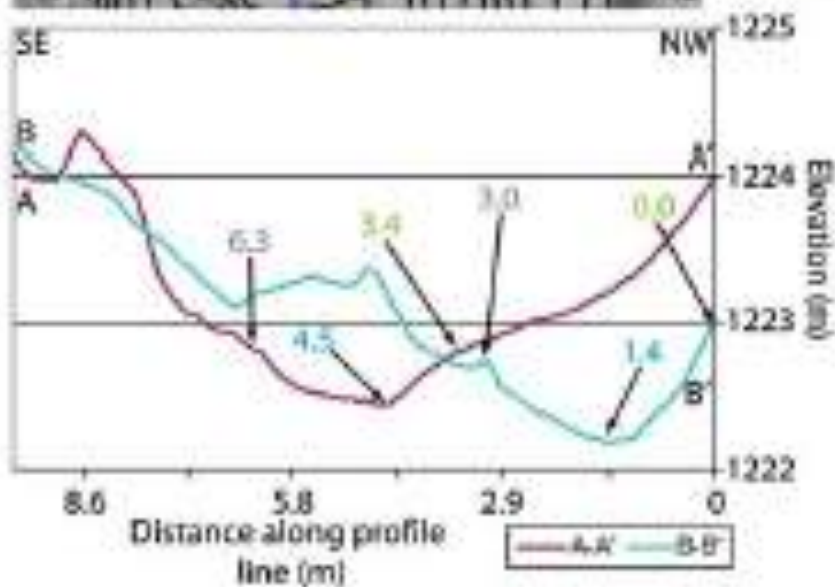
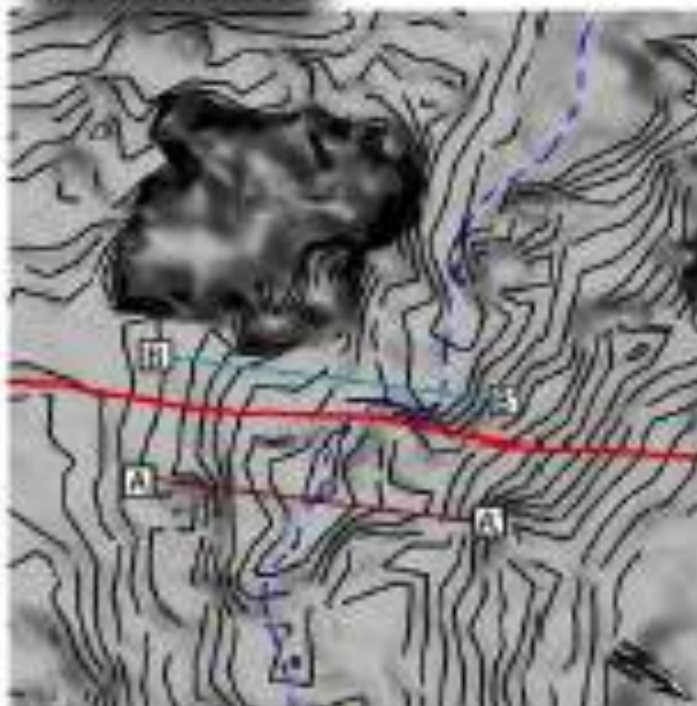
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Earthquake occurrence is quasi-periodic

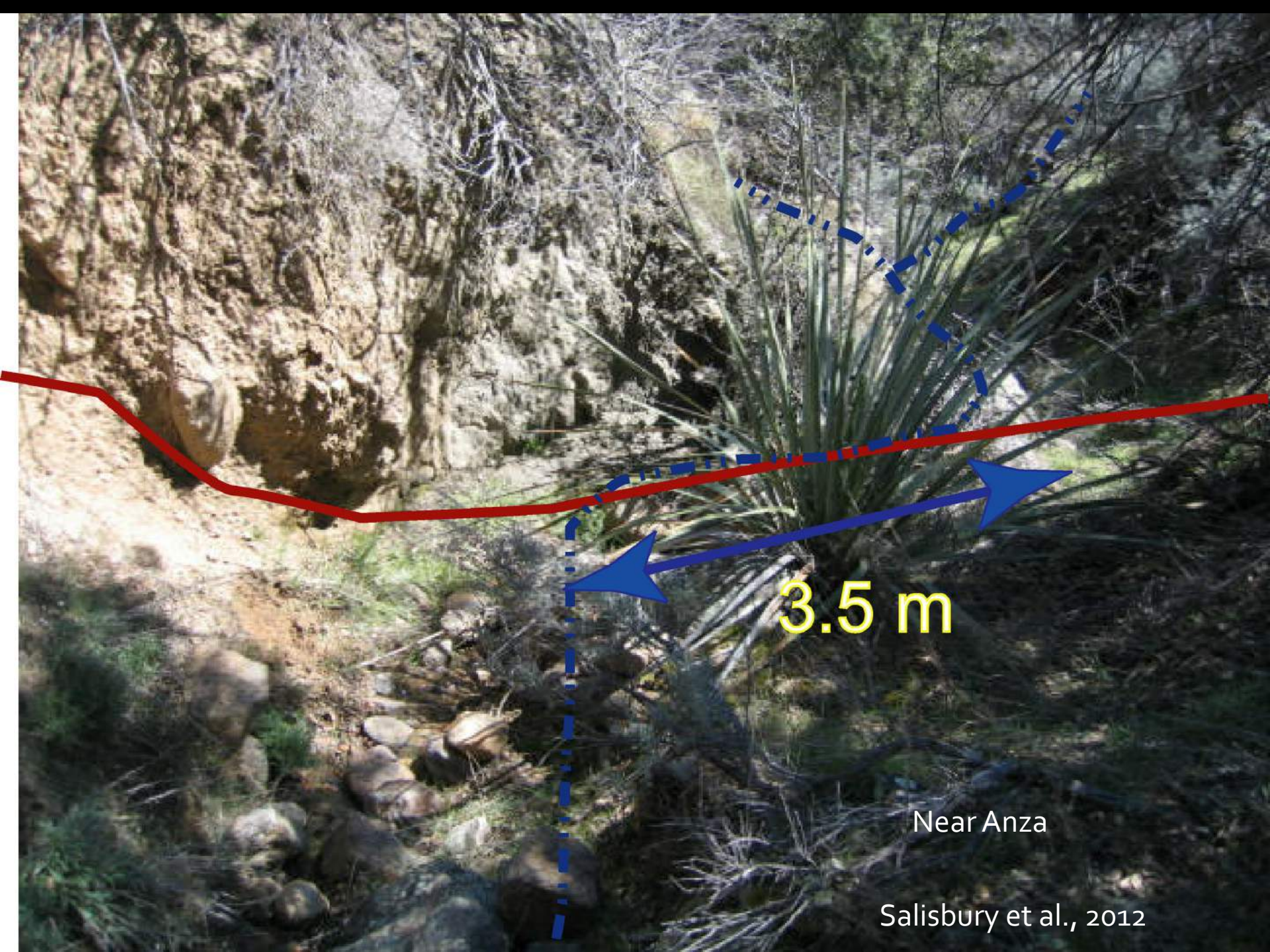


Note relatively high CoV – this is typical for all long Paleoseismic records in California

BV-8 0.25 m Contours



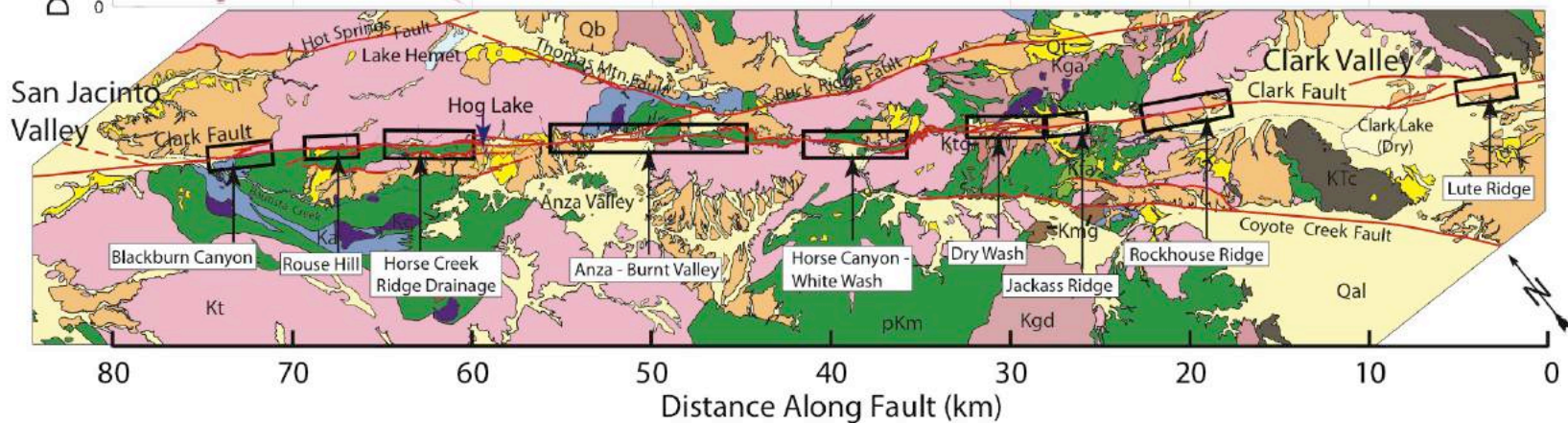
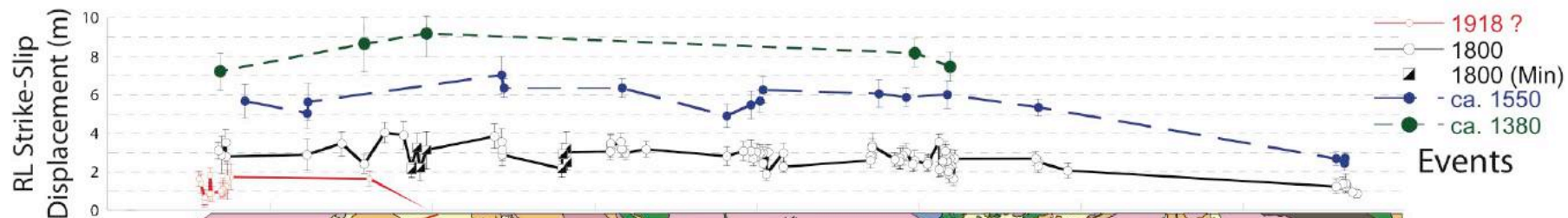
Method	Southeast Margin	Thalweg	Northwest Margin
Field	3.2 ± 0.4	3.3 ± 0.3	2.6 ± 0.4
LIDAR	3.4 ± 0.4	3.1 ± 0.3	3.3 ± 0.4



3.5 m

Near Anza

Salisbury et al., 2012



Metamorphic Rocks

Pre-Mid-Cretaceous

- pKm Banded gneisses, gabbros, pegmatites, and other intrusives

Mid-Cretaceous

- Kgd Inequigranular granodiorite and adamellite
- Kfa Fine- to medium-grained biotite adamellite
- Kt Medium-grained tonalitic rocks
- Kga Medium- to coarse-grained garnetiferous adamellite
- Kmg Medium-grained granodioritic rocks

Plutonic Rocks

Pre-Mid-Cretaceous

- Ka Medium-grained adamellite rocks
- Ktg Fine- to medium-grained biotite tonalite and granodiorite

Cataclastic Rocks

Cretaceous or Tertiary

- KtC Adamellite/Tonalitic augen gneiss and mylonite

Sediments

Tertiary Quaternary

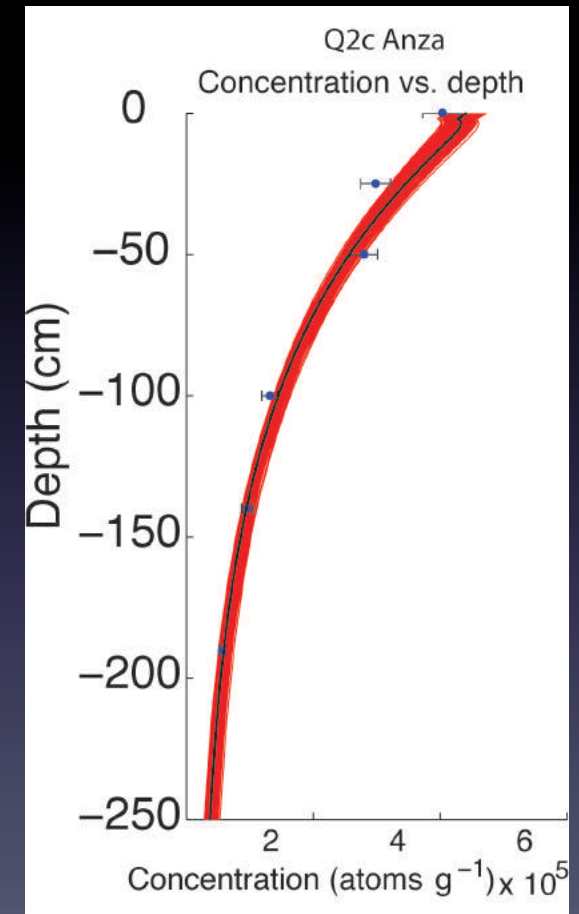
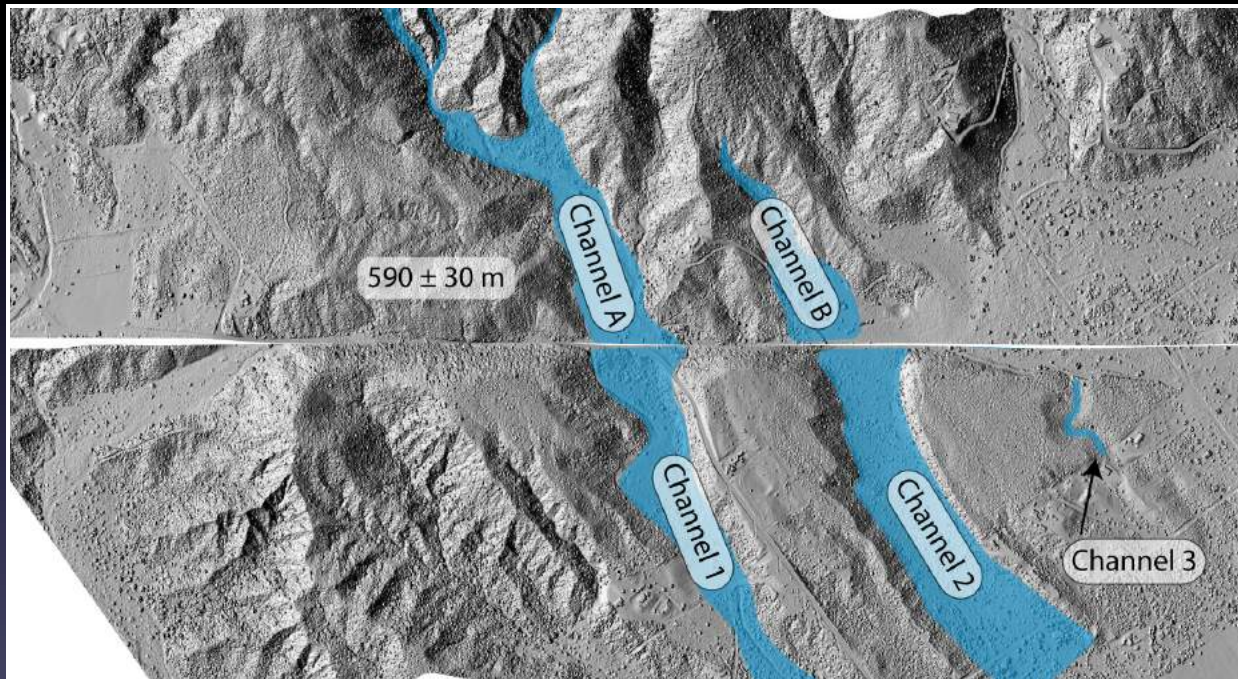
- Qal Alluvium
- Qt Terrace sands and gravels
- Qb Bautista beds
- Unconformity

Geology (Simplified from Sharp, 1967)

Salisbury et al., 2012

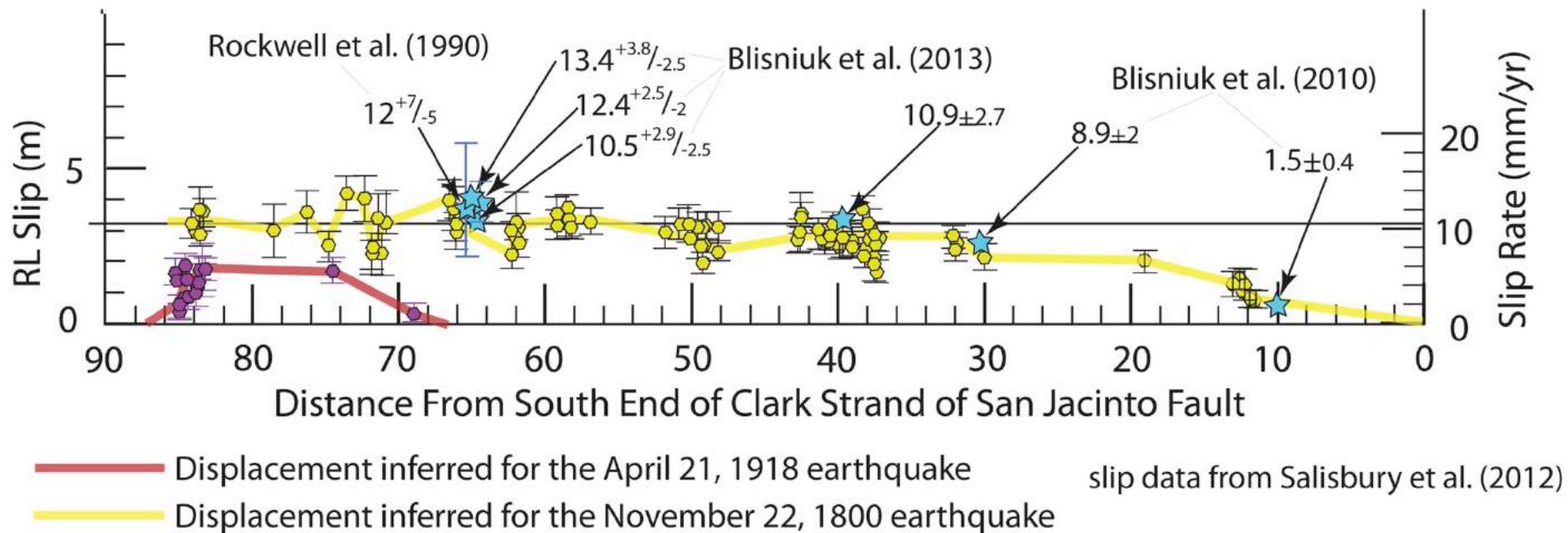
Clark strand of the San Jacinto fault (main strand)

590 ± 30 m offset since 45 ± 10 ka $\rightarrow 13.2^{+4.3}_{-2.9}$ mm/yr



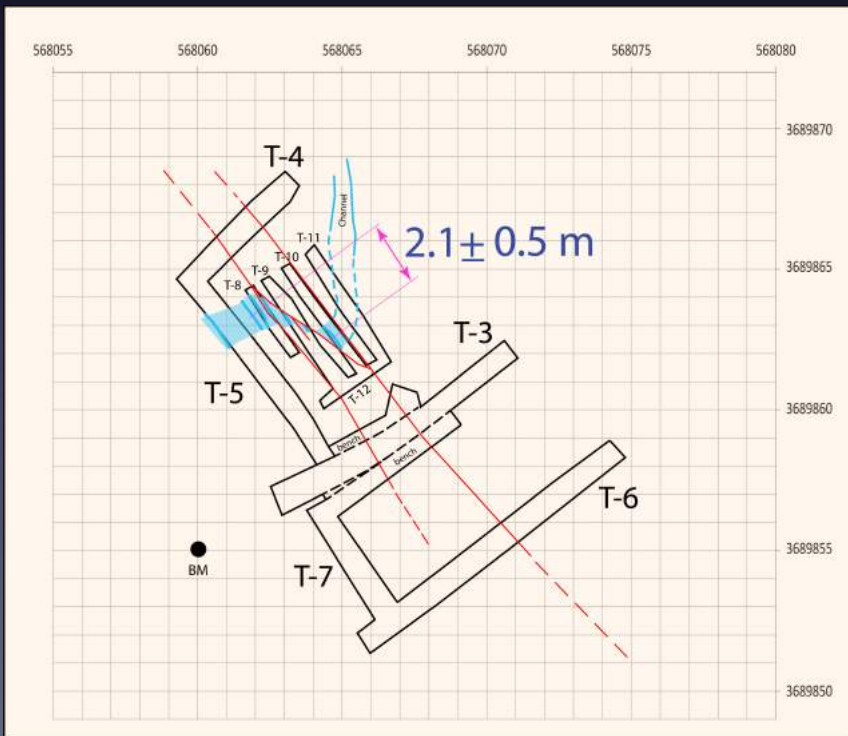
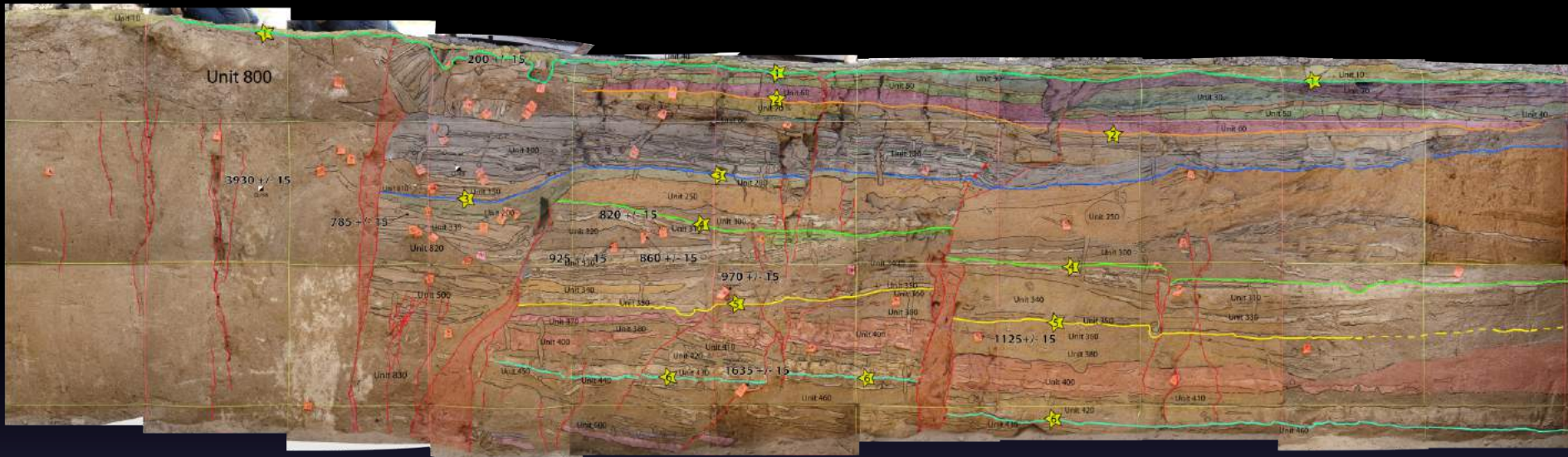
Blisniuk et al., 2012.

Slip Rate can be built by repeated ruptures similar to the November, 1800 earthquake

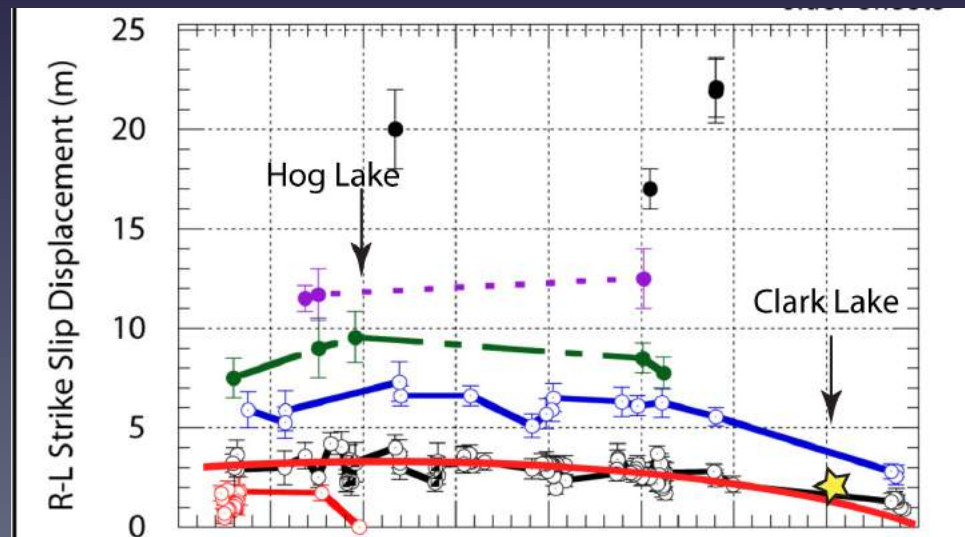


So the paleoseismic record combined with the slip per event record should predict the long-term slip rate

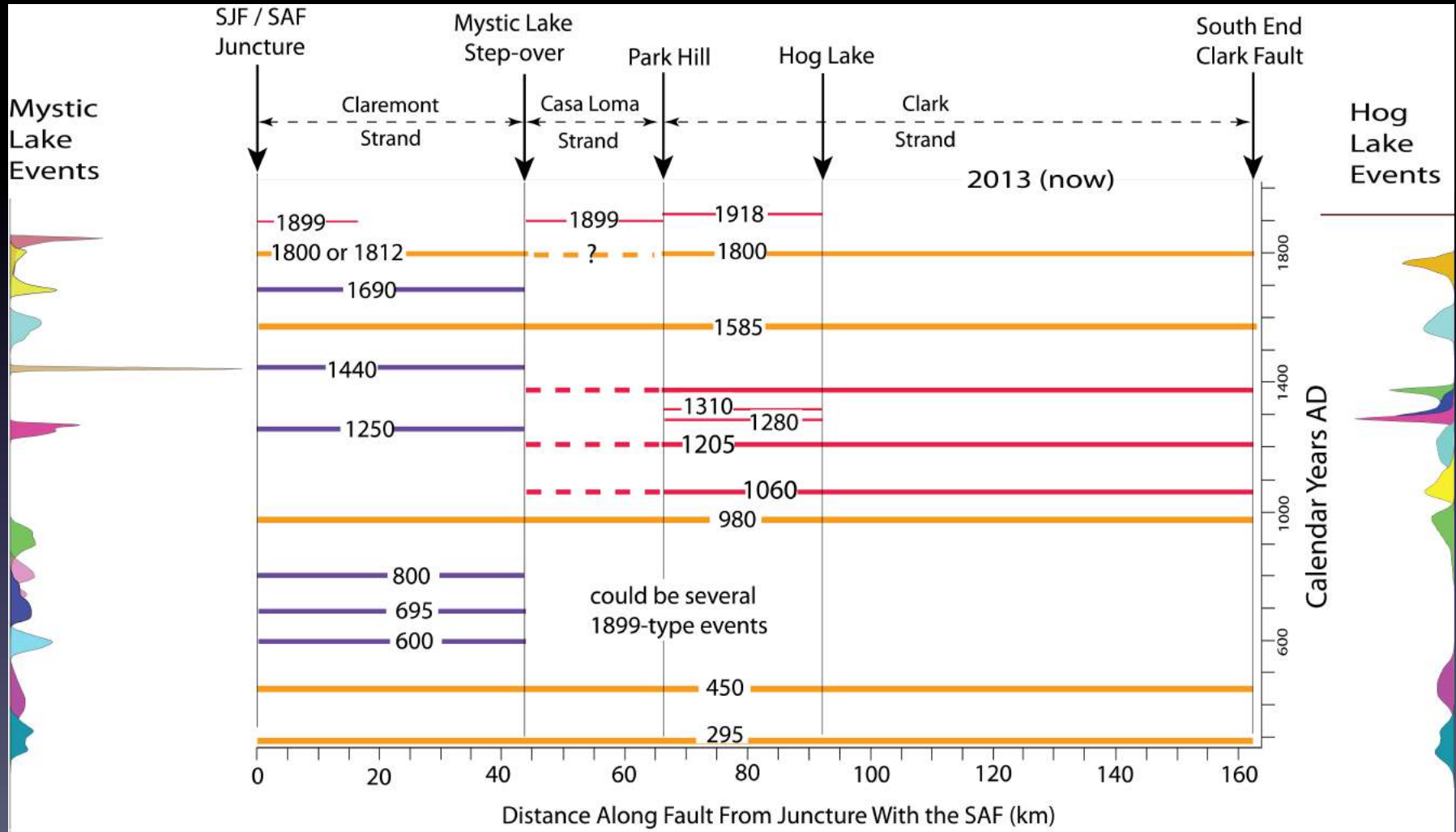
Clark Lake Paleoseismic Site

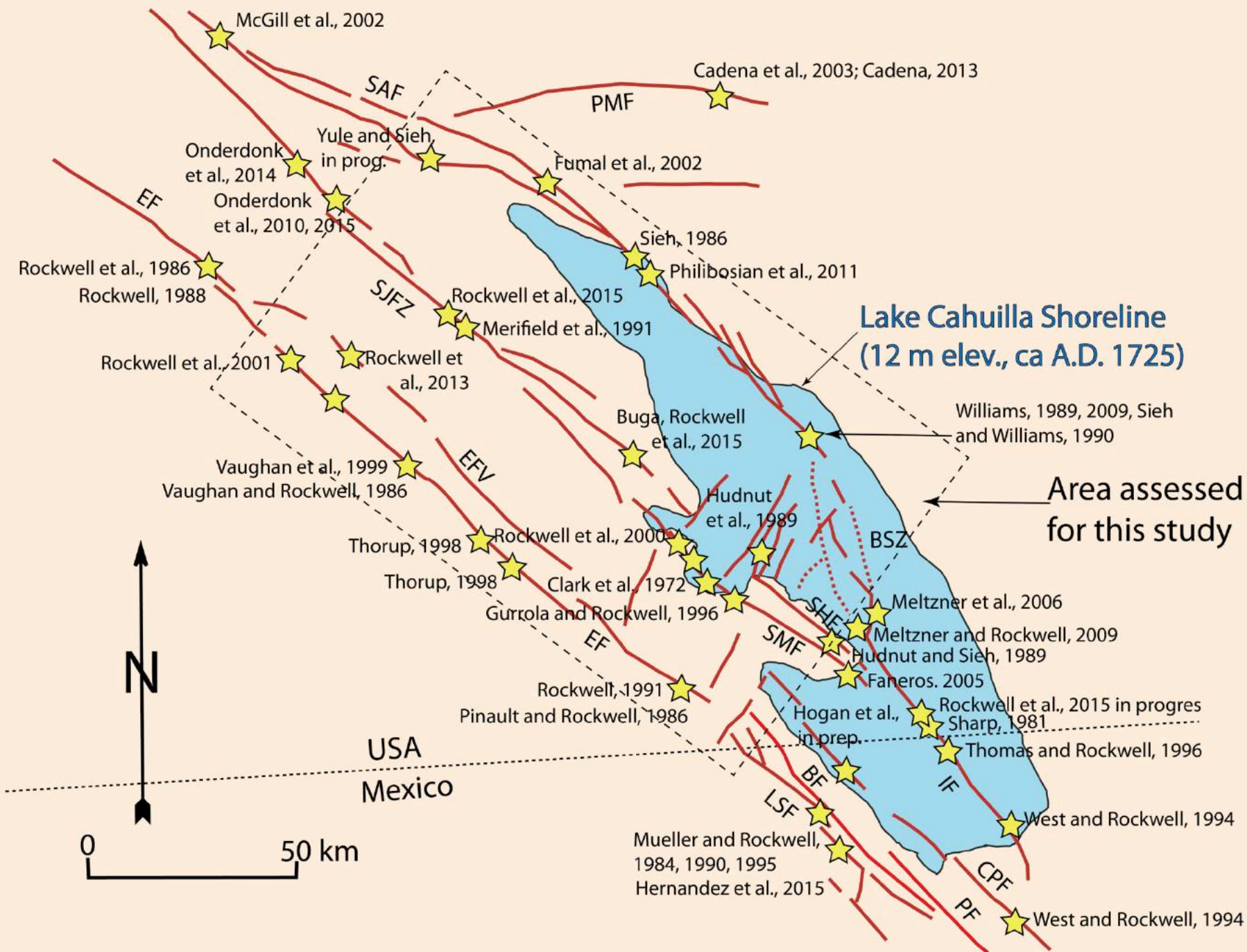


MRE is same as at Hog Lake, with 2.1 m slip. Similar recurrence interval as Hog Lake large events



Rupture history of the San Jacinto fault





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

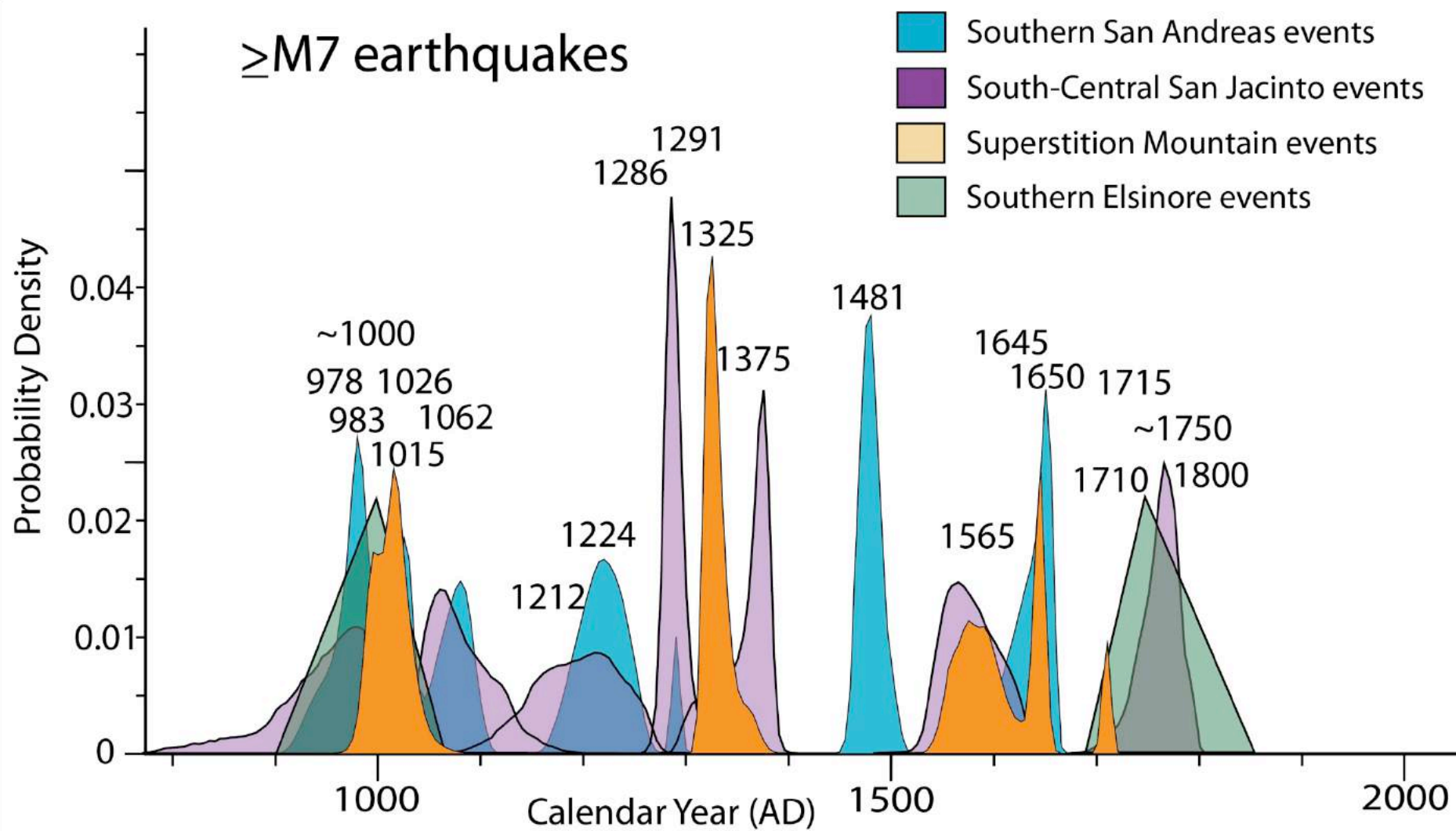
Build a catalogue that includes estimated magnitudes based on displacement data. Estimate seismic moment based on displacement and the same locking depth used to estimate expected long-term moment accumulation.

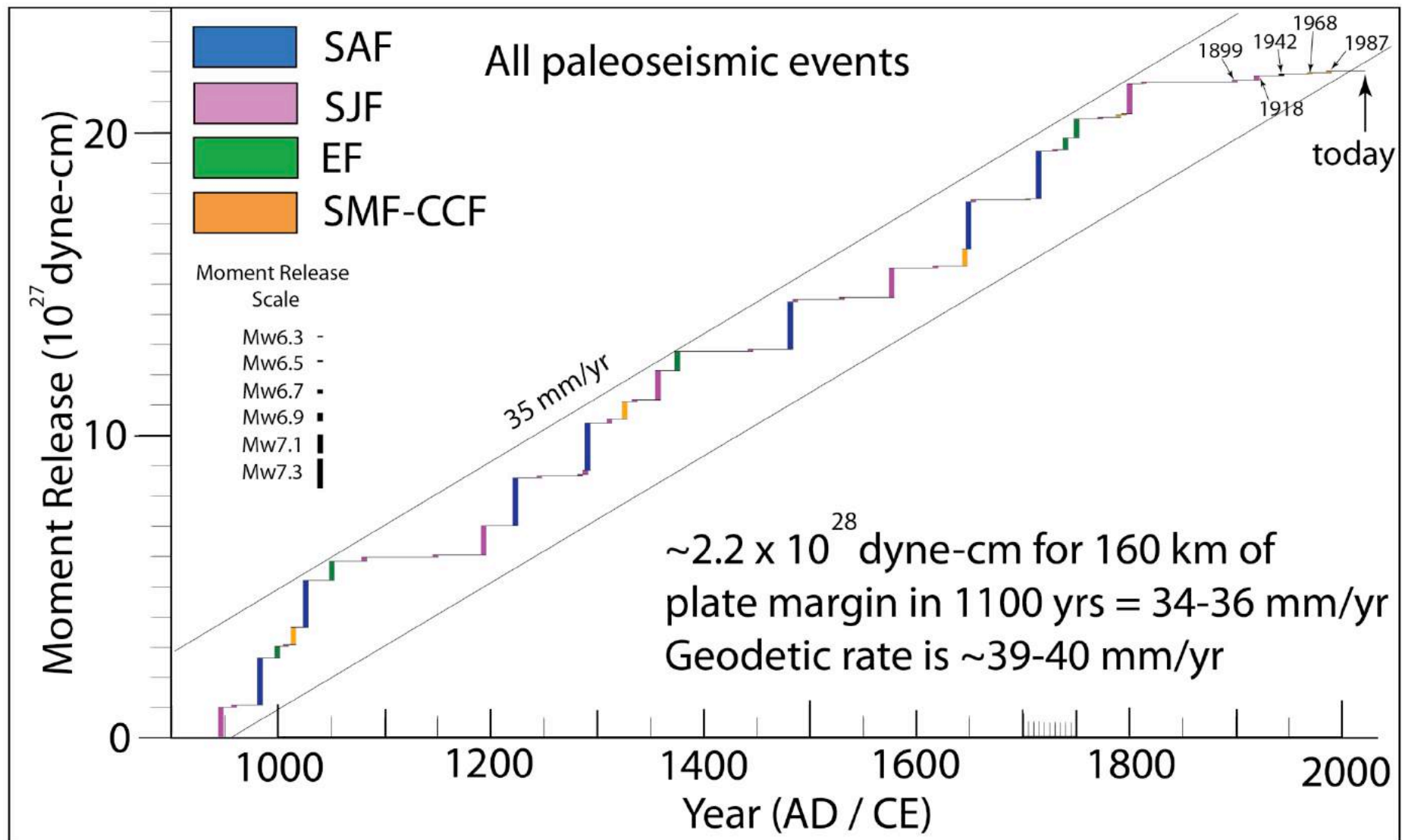
Compare inferred moment release to expected moment release for the past 1100 years

Table 1. Catalog of Paleoseismic Events in the southern 150 km of the San Andreas fault system

Fault	EQ date (AD)	uncertainty range (95%)	EQ date (2) (AD)	uncertainty range (95%)	Magnitude Estimate	Inferred Average Slip (m)	Rupture length (km2)	Rupture depth (km)	Inferred Seismic Moment (dyn-cm)	References and notes
San Andreas F										
Event 1	1715	1706-1722	1690	>1520-1680	7.4	3	150	12	1.53E+27	Philibosian et al. (2011); Coachella site on the SAF south of the juncture between the Banning and Mission Creek faults; event 3 is questionable; ages recalculated based on new Lake Cahuilla model of Rockwell et al. (2016 in progress). (2) Fumal et al. (2002);Thousand Palms site on the Mission Creek fault Also used Sieh (1986) from the Indio shoreline site, and Williams unpublished data from the Salt Creek site Yields about 19 mm/yr for SAF between Banning Pass and Salton Sea
Event 2	1650	1592-1664			7.4	3	150	12	1.53E+27	
event 3	1481	1459-1503	1502	1450-1555	7.4	3	150	12	1.53E+27	
event 4	1291	1281-1300			7.4	3	150	12	1.53E+27	
event 5	1224	1174-1259	1231	1170-1290	7.4	3	150	12	1.53E+27	
event 6	1026	1010-1100			7.4	3	150	12	1.53E+27	
event 7	983	931-1008	982 825	840-1150 770-890	7.4	3	150	12	1.53E+27 1.07E+28	
Clark strand, SJF										
Event 1	1918				6.7	1.25	26	13	1.30E+26	Rockwell et al. (2015) Buga et al (2015); Inferred to be same events as at Hog Lake based on geomorphology and radiocarbon dating of event stratigraphy Salisbury et al. (2012); slip distribution and average slip in past 3 large Clark F. earthquakes, plus slip in 1918 Moment estimates from Rockwell et al. (2015) Needed to decrease average slip estimate by 10 % to match slip rate Yields 12.6 mm/yr for Clark fault in past 1100 years
Event 2	1800				7.3	2.5	90	14	9.76E+26	
event 3	1577	1535-1627			7.3	2.5	90	14	9.76E+26	
event 4	1357	1303-1389			7.3	2.5	90	14	9.76E+26	
event 5	1311	1280-1362			6.7	1.25	26	13	1.30E+26	
event 6	1289	1267-1315			6.7	1.25	26	13	1.30E+26	
event 7	1193	1118-1267			7.3	2.5	90	14	9.76E+26	
event 8	1080	1028-1144			6.7	1.25	26	13	1.30E+26	
event 9	947	842-1020			7.3	2.5	90	14	9.76E+26 5.40E+27	
Casa Loma strand, SJF (assume it ruptures with most or all Clark fault or Clairmont fault events)										
Event 1	1899				6.5	0.6	20	18	6.70E+25	Topozzada et al. (1980) Most events are inferred to have possibly ruptured with either the Clark fault or the Claremont fault when they move (Onderdonk et al., 2013; Rockwell et al., 2015). The Casa Loma fault should rupture about every 50 years with a fault slip rate of 12 mm/yr if it breaks on its own. Assuming rupture with either the Clark or Claremont strands accounts for over half of expected moment release. The other half is assume to be released in 1899-type short segment ruptures.
Event 2	1800 or 1812?				6.5	0.6	20	18	6.70E+25	
Event 3	1698	1665-1820			6.5	0.6	20	18	6.70E+25	
Event 4	1577	1535-1627			6.5	0.6	20	18	6.70E+25	
Event 5	1428	1403-1445			6.5	0.6	20	18	6.70E+25	
Event 6	1357	1303-1389			6.5	0.6	20	18	6.70E+25	
Event 7	1342	1273-1419			6.5	0.6	20	18	6.70E+25	
Event 8	1311	1280-1362			6.5	0.6	20	18	6.70E+25	
Event 9	1289	1267-1315			6.5	0.6	20	18	6.70E+25	
Event 10	1193	1118-1267			6.5	0.6	20	18	6.70E+25	
Event 11	1080	1028-1144			6.5	0.6	20	18	6.70E+25	
Event 12	947	842-1020			6.5	0.6	20	18	6.70E+25 8.04E+26	
Superstition Mtn - Coyote Creek F										
CCF-1	1968				6.3	0.3	30	12	3.35E+25	Rockwell et al. (2000); Ragona et al. (2003); Verdugo et al. (2007) Gurrola and Rockwell (1996), Altangerel and Rockwell (2005) CCF likely ruptures every Yields 6.8 mm/yr for the Coyote Creek - Superstition Mountain fault, 1100 yrs
CCF-2	1795	1720-1850			6.7	1.1	35	12	1.43E+26	
CCF-3	1710	1701-1719			6.3	0.3	30	12	3.35E+25	
SMF-2 (SMF-CCF)	1650	1547-1655			7.1	1.7	90	12	5.70E+26	
SMF-3 (SMF-CCF)	1323	1310-1365			7.1	1.7	90	12	5.70E+26	
SMF-4 (SMF-CCF)	1017	980-1046			7.1	1.7	90	12	5.70E+26 1.92E+27	
Carrizo Mtn cross fault										
	1942				6.5				6.70E+25	
Superstition Hills F.										
Event1	1987				6.5	0.7	26	12	6.77E+25	Slip rate is poorly constrained. At 4 mm/yr, should generate a Mw6.5 about every 175 years Moment sum assumes a Mw6.5 every 175 years, 5 events in 1100 years
Event2	ca 1790	1680-1892			6.5	0.7	26	12	6.77E+25	
									3.38E+26	
Southern Elsinore F										
Event 1	ca 1750	1680-1800			6.9	1.8	34	12	2.28E+26	Rockwell (1991); Rockwell, unpublished C14 data Assumes rupture of entire EF within the "box" Yields 3.6 mm/yr for past 1100 years based on 2 events - unreliable for rate
Event 2	ca 1000	800-1200			6.9	1.8	34	12	2.28E+26	
									4.56E+26	
Central Elsinore F										
No ruptures in past 1200 years										Thorup (1998)
Northern Elsinore F.										
Event 1	ca 1750	1680-1810			7.1	2.1	80	12	6.25E+26	Vaughan et al. (1999); Rockwell et al. (1986); Rockwell et al (2001) (from Whittier/Chino bifurcation to Palomar Mtn) Yields 5.7 mm/yr for past 1100 years. Short record (3 events)
Event 2	1375	1274-1474			7.1	2.1	80	12	6.25E+26	
event 3	1050	1015-1104			7.1	2.1	80	12	6.25E+26	
									1.88E+27	
Sum of moments on major faults									2.16E+28	equates to 33 mm/yr, includes most faults with incomplete records

$\geq M7$ earthquakes

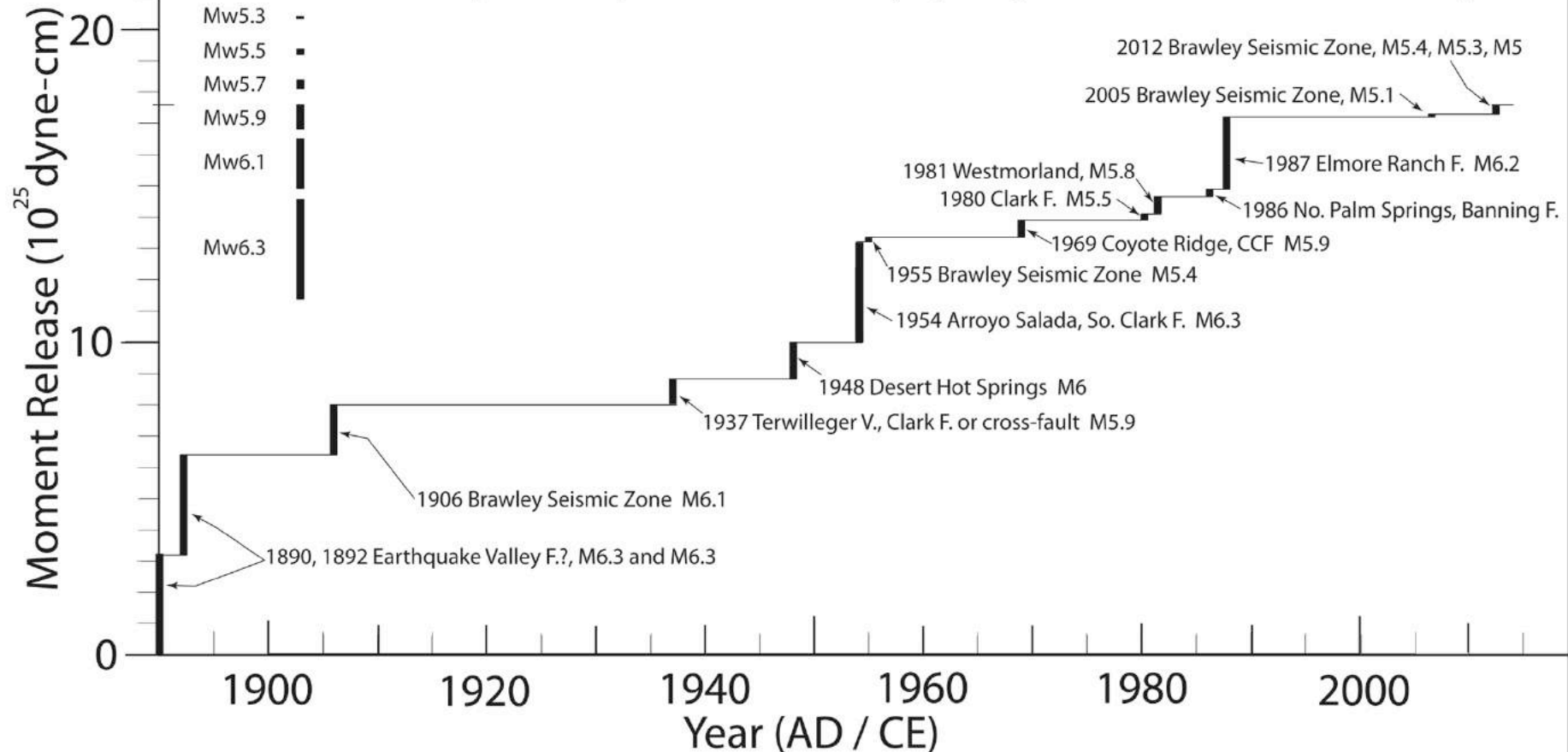




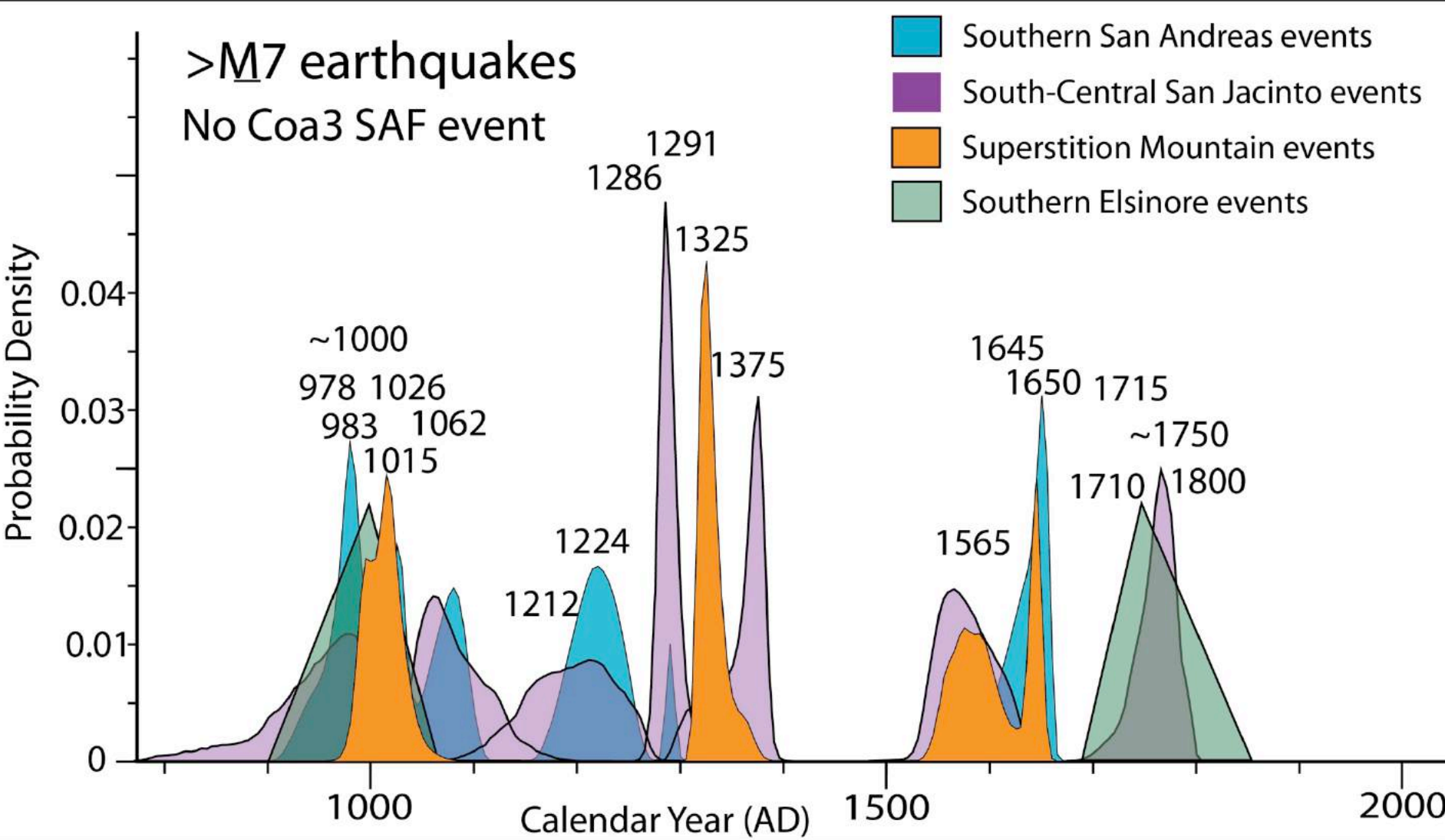
Moment Release
Scale

Mw5.1 -
Mw5.3 -
Mw5.5 -
Mw5.7 -
Mw5.9 -
Mw6.1 -
Mw6.3 -

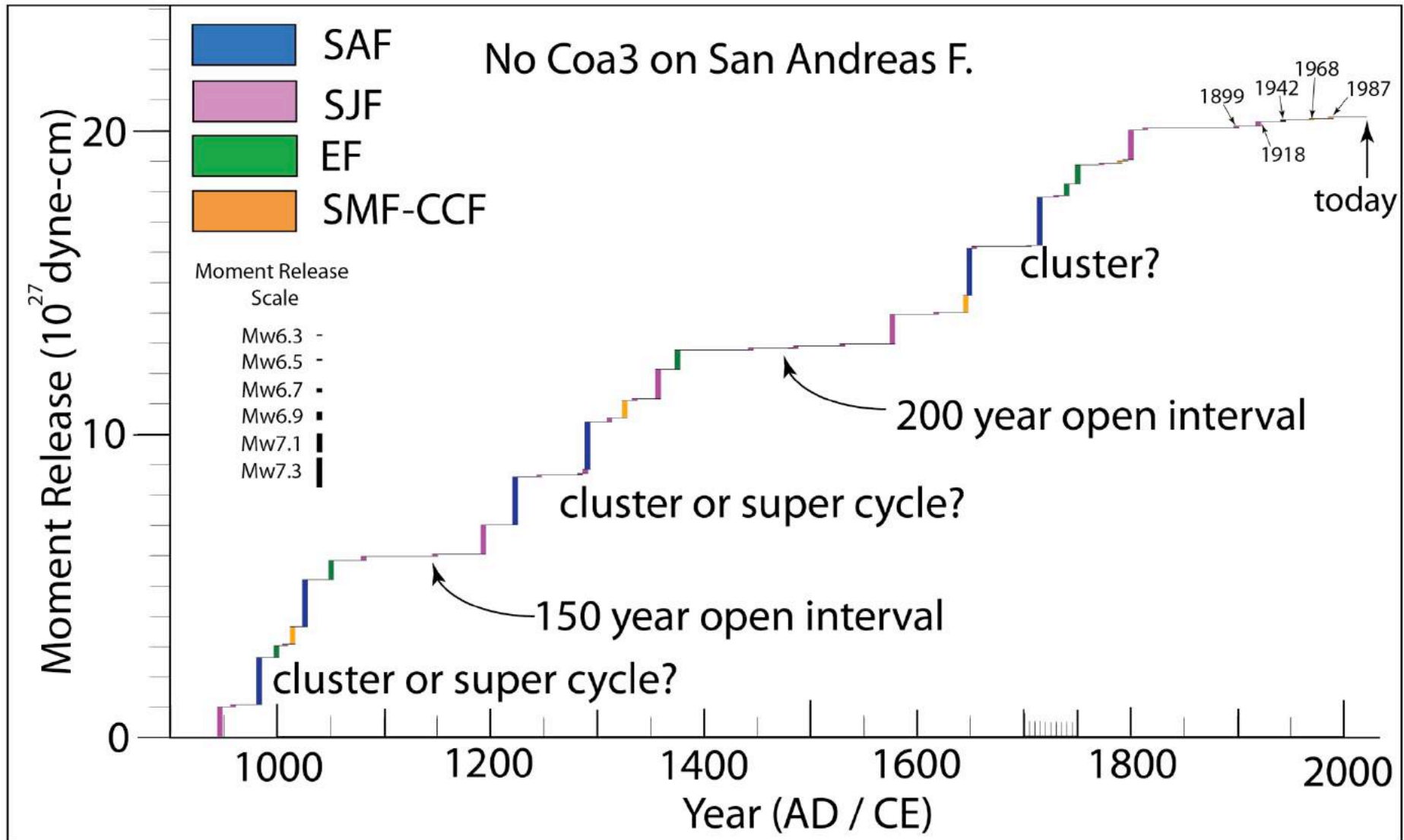
1.76×10^{26} dyne-cm of moment release in past 125 years in M5-M6.3 sized earthquakes equates to 2.3 mm/yr (5.8%) of southern San Andreas slip rate



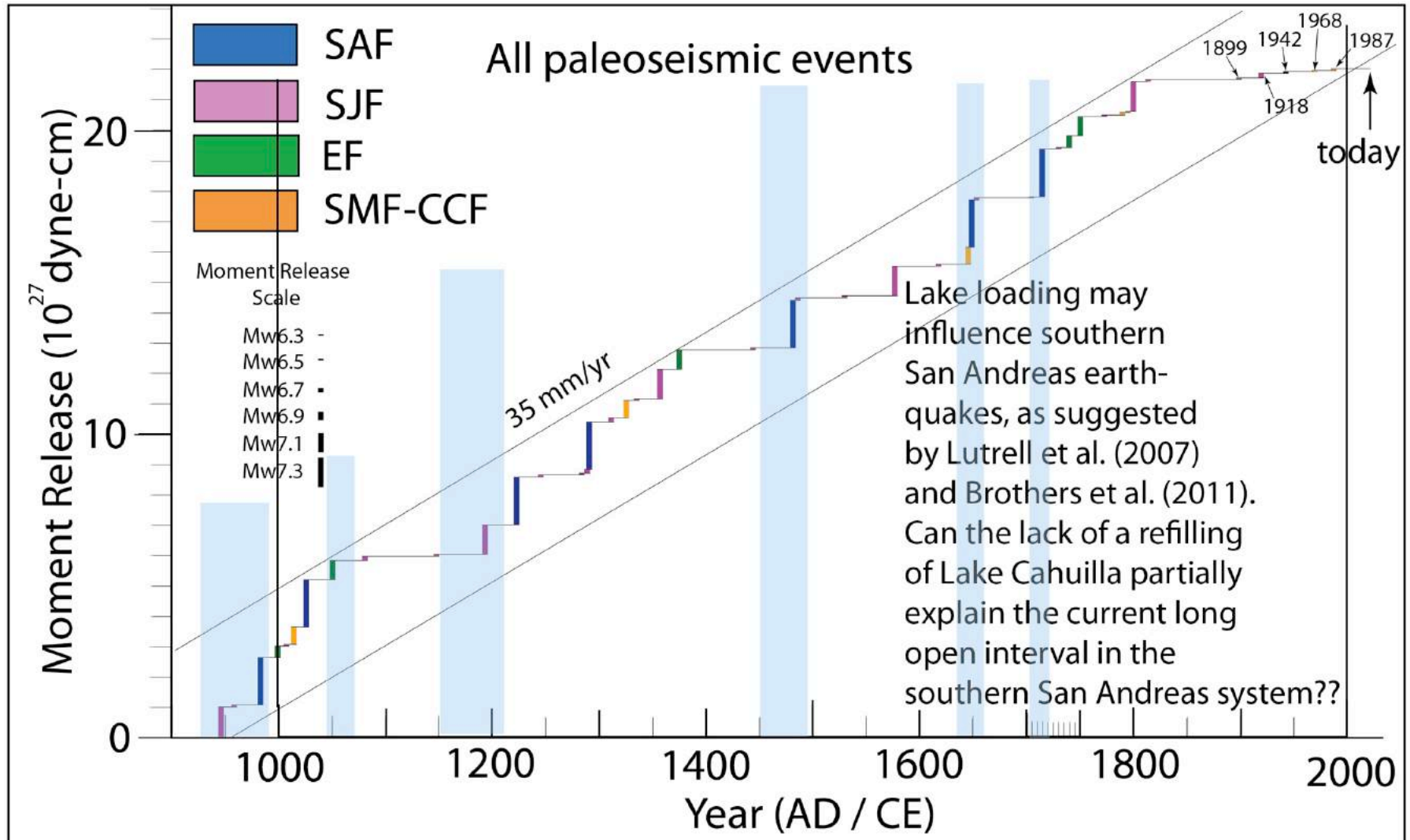
Evidence for Coa-3 on the SAF was weak – what if this was not an Earthquake? (Philibosian actually describes it as only a possible event!)



Results in a more “clustered” behavior



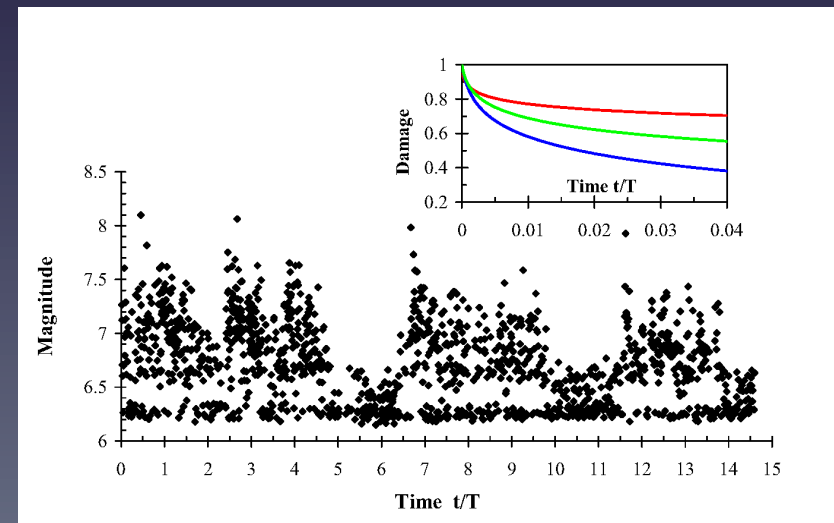
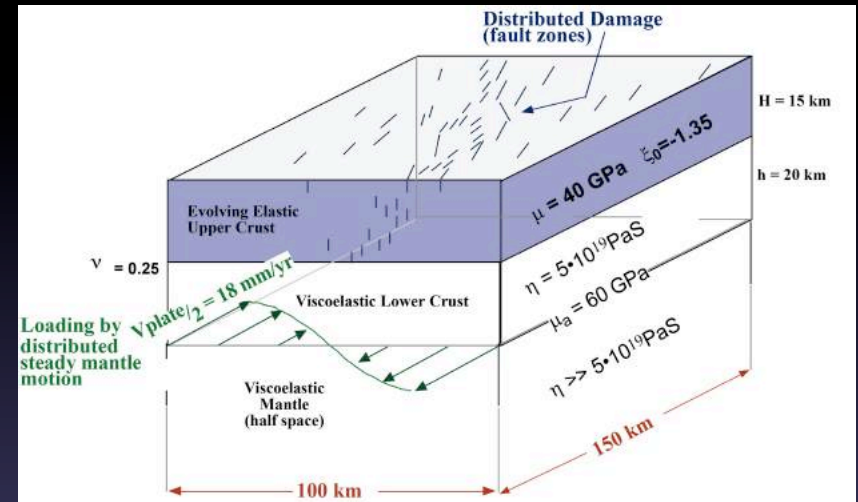
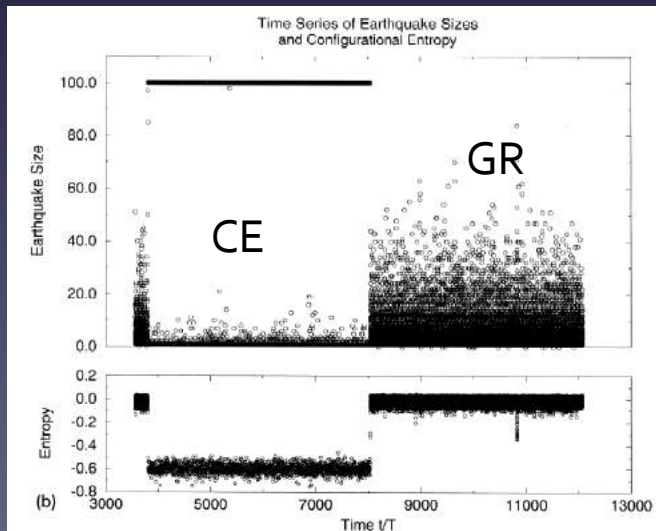
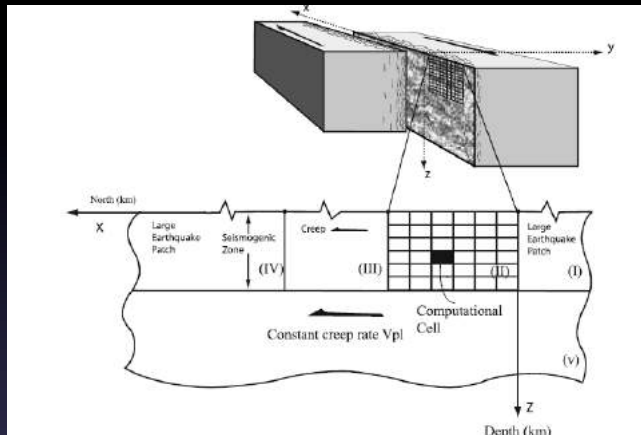
Is there a relationship between Lake Cahuilla highstands (water loading) and earthquakes? **Maybe so...**



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?

