Recurrence, Rates, and Paleogeodetic Implications: Southern Cascadia Subduction Zone, Northern California

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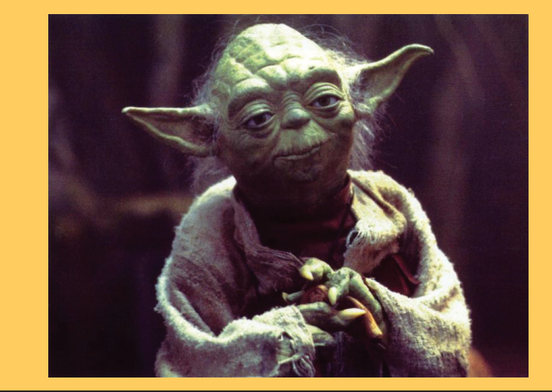
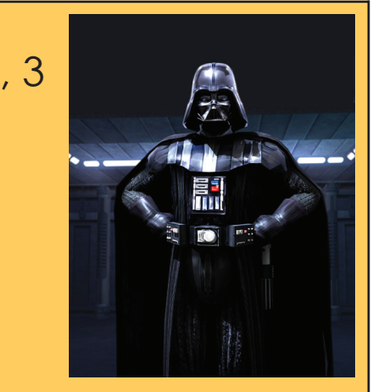


Jason R. Patton [1,2] Tom H. Leroy [2,3]

1. COAS, Oregon State University, Corvallis, OR, United States.
2. Cascadia GeoSciences, McKinleyville, CA, United States.
3. Pacific Watershed Associates, McKinleyville, CA, United States



Earthquake and tsunami hazard for northern California and southern Oregon is dominated by estimates of recurrence for earthquakes on the Cascadia subduction zone (CSZ) and upper plate thrust faults. Site-based terrestrial paleoseismic evidence derived recurrence interval (RI) estimates are inconsistent with the regional marine record of great earthquakes. Reconciling these differences reveals information regarding different sources or magnitudes of coseismic or interseismic deformation in the southern CSZ.

Early paleoseismic investigations utilized bulk peat for 14C age determinations and these early studies were largely reconnaissance work. All terrestrial data sets are compiled, evaluated, ranked, and excluded according to their paleoseismic relevance. We construct an OxCal age model to evaluate the discriminated 14C based space-time relations graphically and statistically. We interpret a regional timing of tectonic deformation that is consistent with the timing of the marine record.

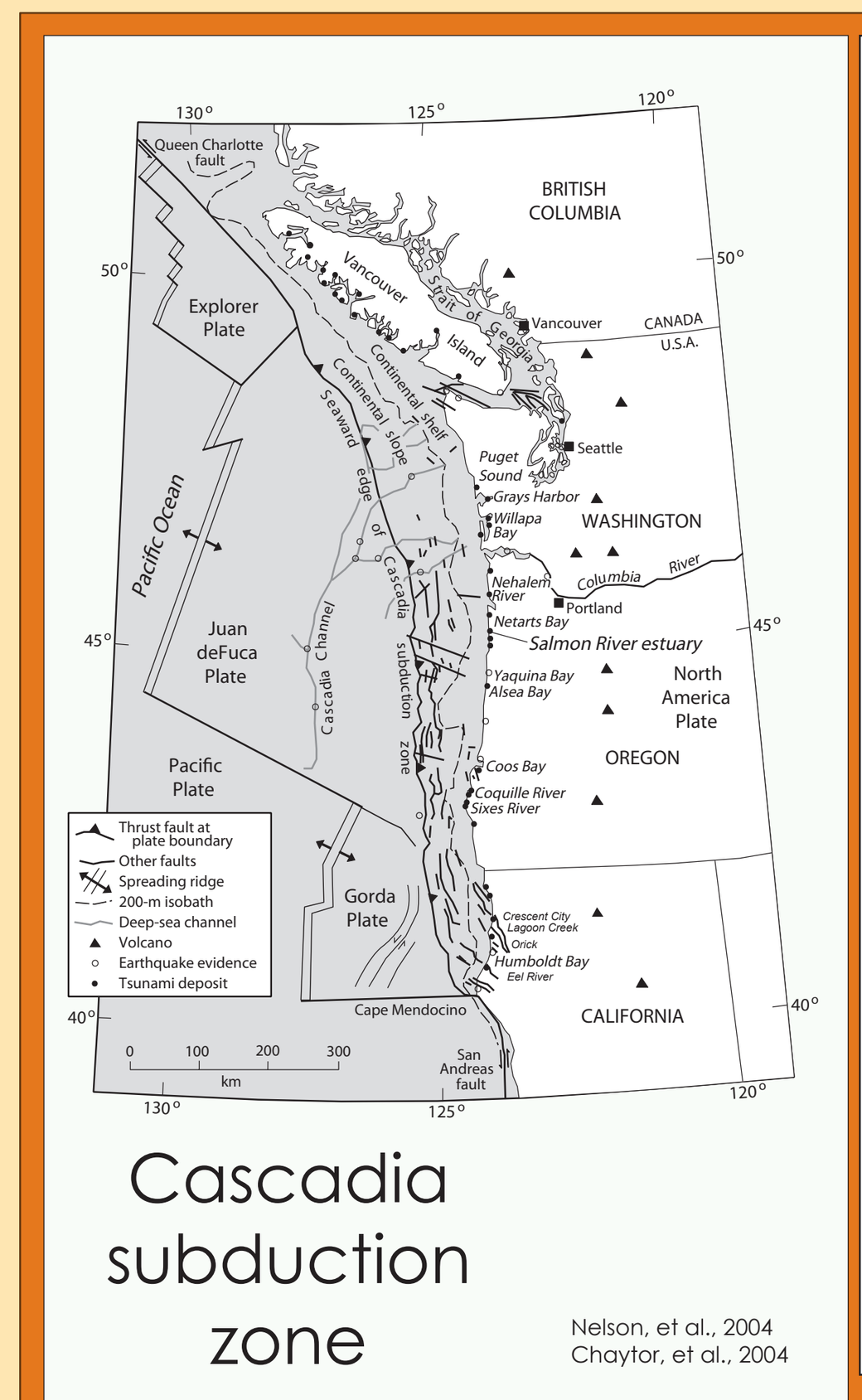
Not all events are observed in each region and not all events have age control. Some regions lack cores representing the complete modern tidal elevation range (biasing the paleoseismic record). For example, when individual sites in the same region are combined, a more complete record of coseismic subsidence can be assumed, reducing the terrestrial RI to 360+-40, yet still longer than the marine RI.

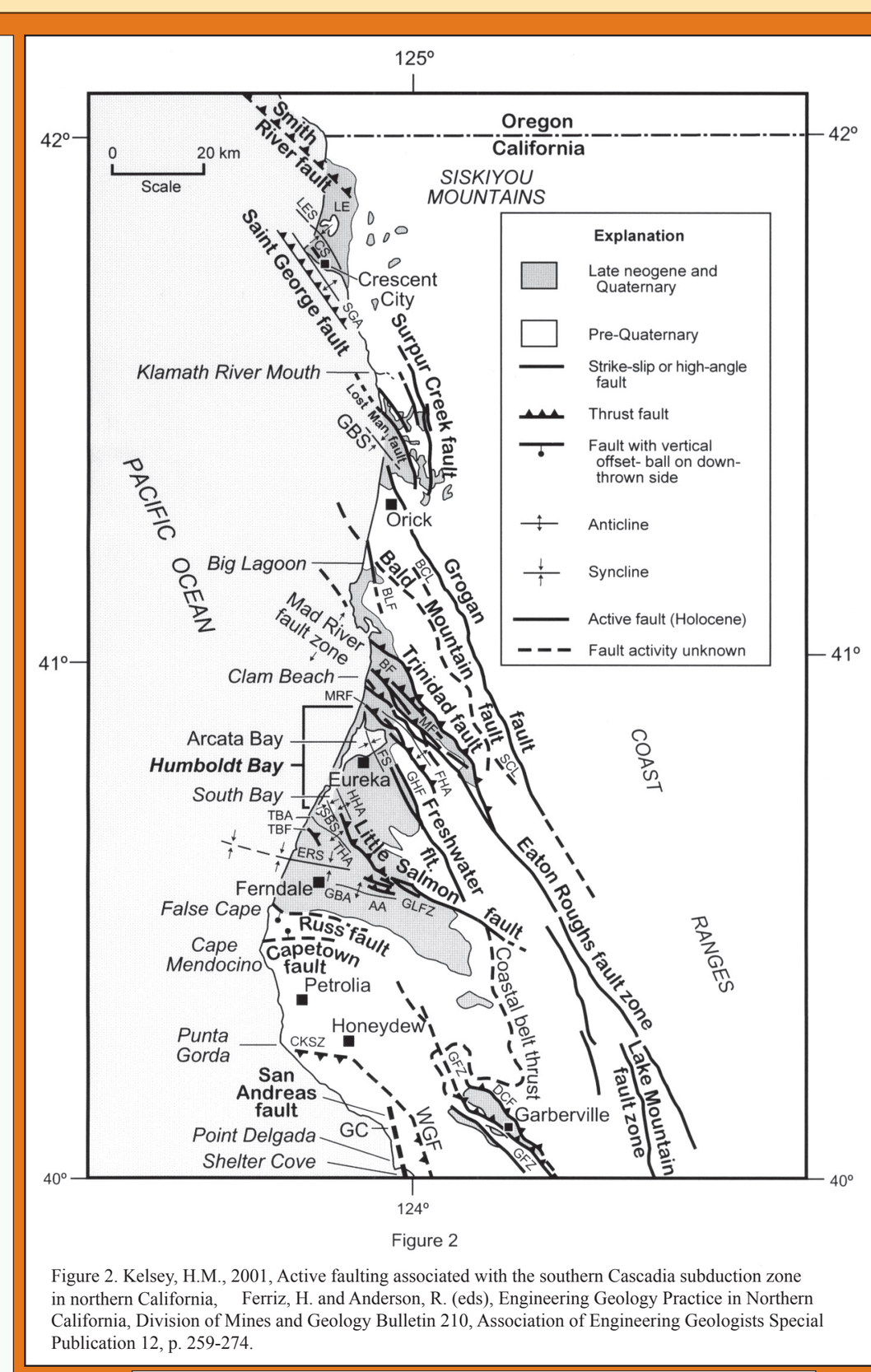
We consider relative sea-level (RSL), as the relation between land-level and sea-level and we find that chronologically distinct buried soils are found in settings segregated by elevation. Subsidence in southern Humboldt Bay occurred in positions of higher RSL at ~1,500, ~2,200, and ~3,500 cal yrs BP. We pose that the RSL position does not relate to the time preceding the earthquake, but may relate to the accumulated strain at the time of the earthquake. RSL with a higher position would correspond with more accumulated strain in the upper plate. We evaluate the various factors that may confound this relation.

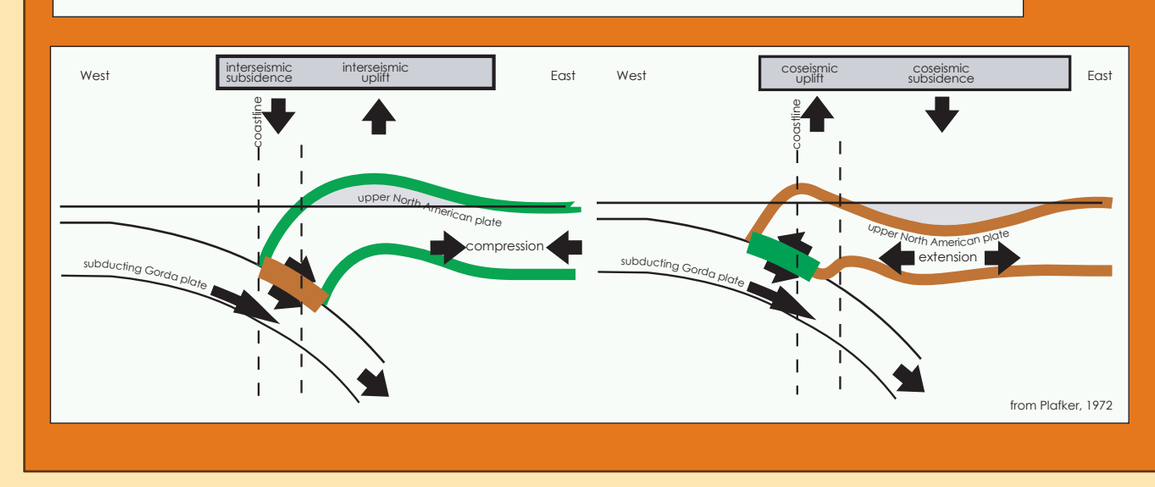
We also compare the estimates of subsidence for cores in locations that share the sea-level / land-level relations as today as these may be a modern analogue to what subsidence we might expect if the CSZ earthquake were to occur tomorrow.

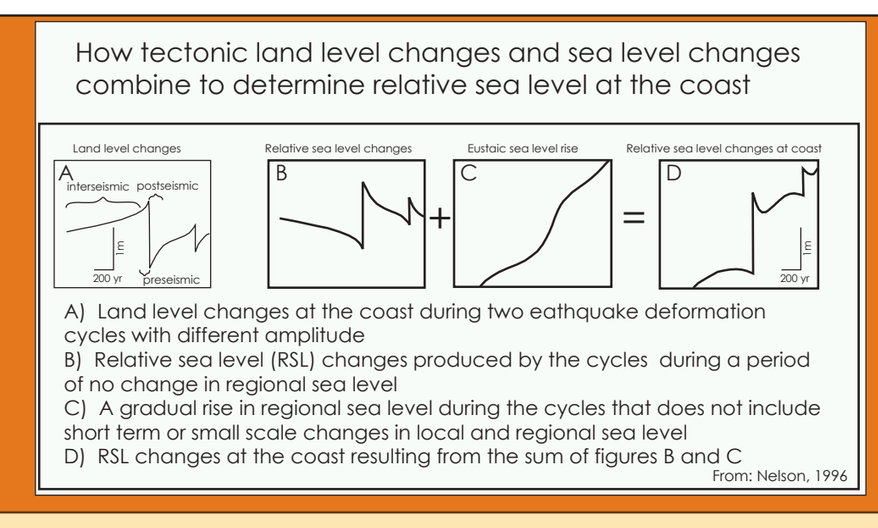
Some important unknowns that are required to complete this analysis include down-core diatom paleoecologic interpretations based upon correlations (transfer function) with modern biogeochemical transects, neither of which currently exist. There also remain several buried soils that lack 14C age determinations.

PART I PLATE SETTING







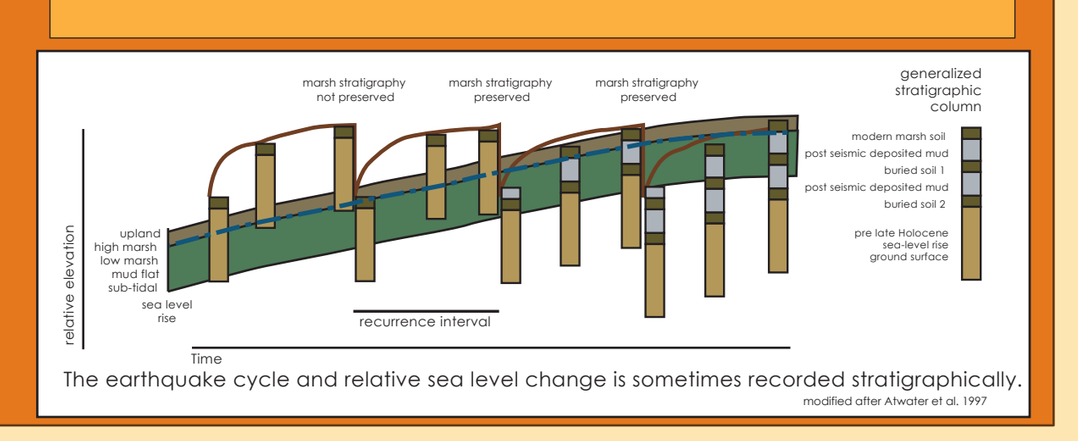


What is the Problem?

RI estimates for earthquakes on the southern Cascadia subduction zone are inconsistent. We evaluate the terrestrial record.

Terrestrial Record: what are the problems?
1) stratigraphy is not directly correlable (rely on 14C)
2) 14C ages have issues
   a) conventional vs. ams
   b) bulk samples vs. identifiable plant mat'l.
3) secondary evidence cannot be directly attributed to any particular source.

Marine Record: what are the problems?
1) secondary evidence cannot be directly attributed to any particular source.

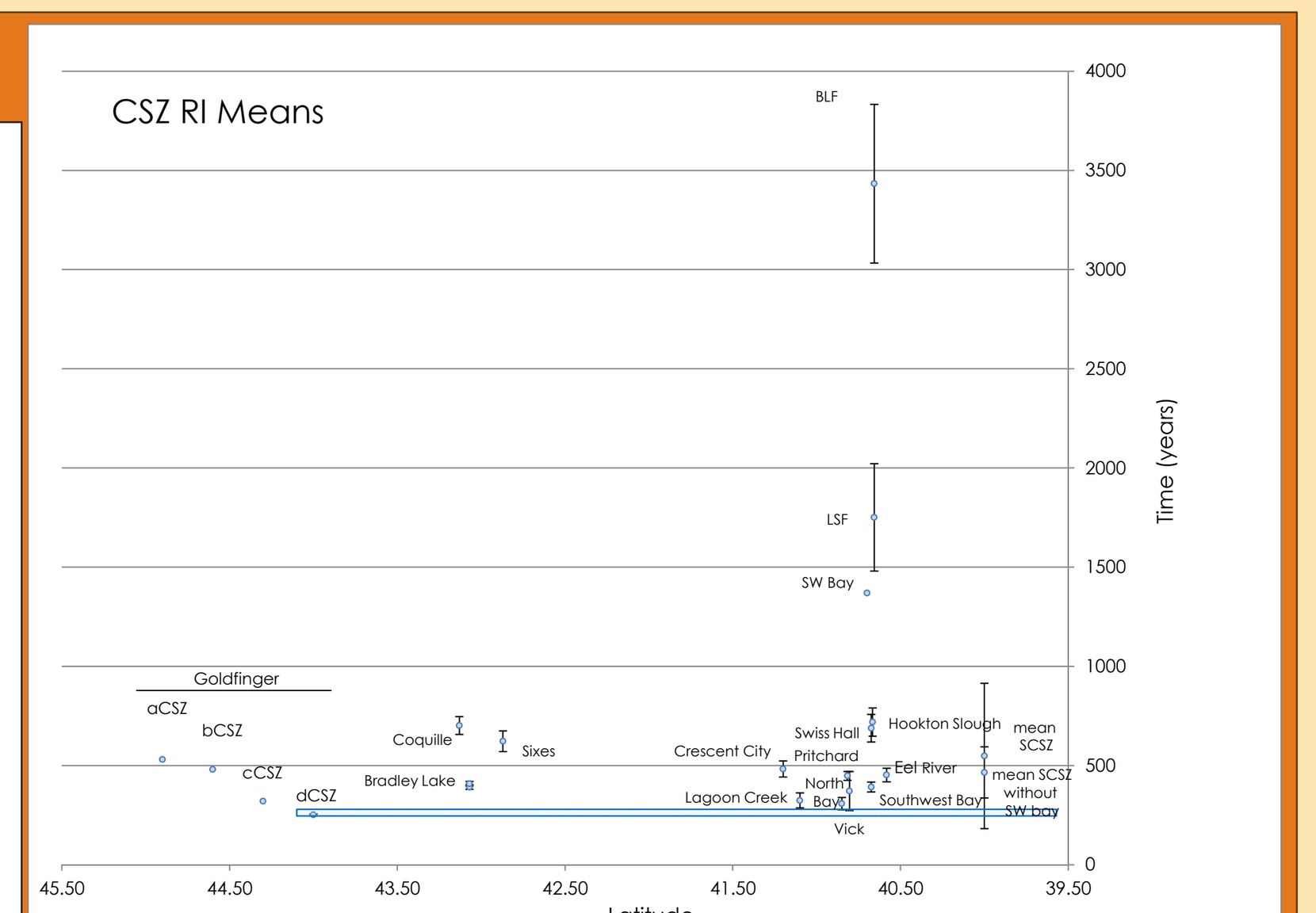


PART II RECURRENCE

Recurrence Intervals

reference	region	oldest age ^ min	oldest age ^ max	events included *	events total ++	RI mean @	Std Error +/-	R. I. rounded #	RI reported $	EQ missing %	RI new
Goldfinger, et. al., 2008	aCSZ			19	19	530		530	530	0	530
Goldfinger, et. al., 2008	bCSZ					480		480	480	0	
Goldfinger, et. al., 2008	cCSZ					320		320	320	0	
Goldfinger, et. al., 2008	dCSZ	10010	9650	38	38	251	5	**250**	220	0	250
Nelson, et. al., 2006	Bradley Lake	4700	4700	12	12	392	12	390	440	6	260
Kelsey, et. al., 2005	Bradley Lake	4630	4460	12	12	408	12	410	390	5	289
Witter, et. al., 2003	Coquille	6720	6500	12	12	702	45	700	580	15	311
Kelsey, et. al., 2002	Sixes	5600	5050	11	11	623	52	620	510	10	325
Carver, et. al. 1998	Crescent City	3060	2760	1, 2, 4, 5, 6	6	483	41	480		5	262
Abramson, et. al., 2007	Lagoon Creek	3440	3164	2, 4, 5, 6, 7, 8	8	324	38	**320**		1	284
Vick, et. al., 1988	North Bay	1568	1390	4, 5	5	308	31	**310**		1	258
Pritchard, et. al., 2004	North Bay	1684	1410	2, 3, 4	4	448	23	450		3	257
Valentine, 1992	North Bay	4290	4087	1, 2, 4, 6, 7, 8, 9, 10	10	371	99	370	320	4	264
Carver, et. al. 1998	Southwest Bay	1695	1542	2	2	1369		1370		8	274
Valentine, 1992	South Bay	3366	2946	1, 2, 4, 5, 6, 7, 8	8	391	25	390	320	4	260
Witter, et. al., 2002	Swiss Hall	2289	1954	2, 3, 4	4	719	71	720		6	288
Patton, et. al., 2006	South Bay	3631	3474	3, 4, 5	5	688	70	690	900	8	265
Li, 1992	Eel River	1990	1739	2, 3, 4, 5	5	452	34	450		3	281
Carver Burke, 1988	Little Salmon fault	7178	7000	1, 2, 3, 4	4	1751	271	1750		23	259
Carver Burke, 1988	Blue Lake fault	25074	24481	2, 4	4	8103	73	8100		120	261
Carver Burke, 1988	Mad River fault	12085	11415	4, 5	5	3433	400	3430		61	260
			without SW bay	mean		465	129	460			
			all events	mean		548	366	550	494		

^ cal yrs BP, years before 1950.
* events included in RI estimate.
++ total events at site.
@ Mean of clalculated Ris determined for each aged event.
# Recurrence Interval (RI) based on events with radiocarbon based age control.
% number of earthquakes required to shorten RI to match marine RI (result in the next column over).



PART III RADIOCARBON ANALYSIS

What did we do?

\+ We evaluate all 14C data associated with paleoseismic and paleotsunami research in northern California.

\+ We establish criteria to rank 14C samples in order to
1) obtain new age control for strata that have none
2) obtain new age control for strata that have 'bad' ages

\+ We further determine which region needs more coring. In addition, we found only some core studies incorporated biostratigraphic control. Local transfer functions have not yet been developed, so estimates of subsidence based on diatom paleoecology are not well constrained.

Radiocarbon Ommission Rationale

1) For maximum limiting ages: keep only ages within 2 sigma error of the youngest age.

2) Inverted ages are removed.

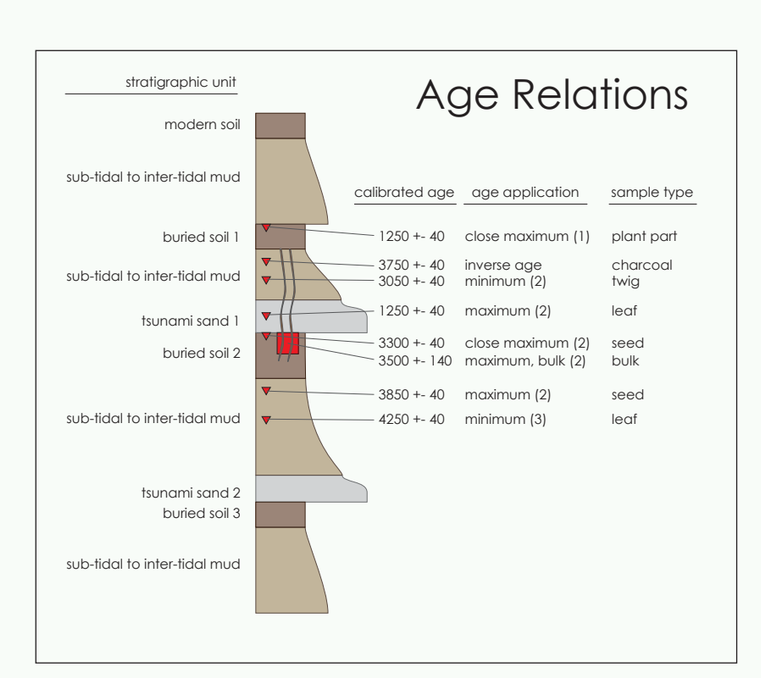
3) Bulk peat ages carry less weight than identifiable plant material, yet are in times the only age control available.

Site Evaluation and Ranking

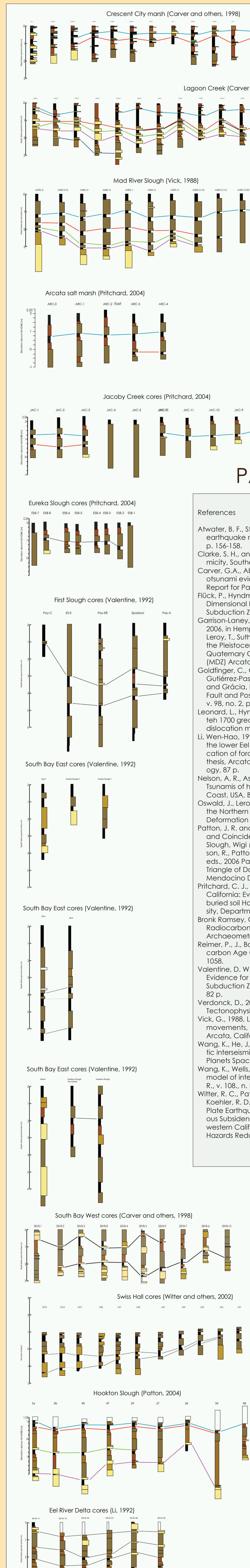
Table 1. Data limitations and priorities for conducting additional paleoseismic and paleotsunami studies at site specific locations in Northern California.

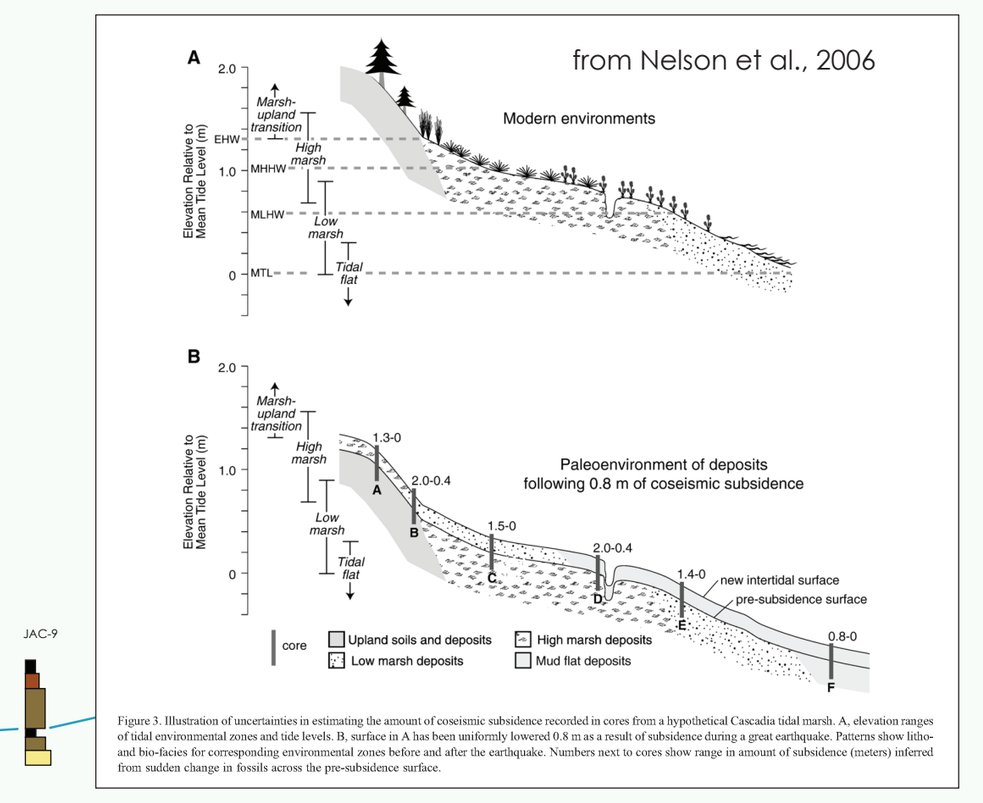
Project Location	Surveyed Elevation Control?	Biostratigraphy?	All Events Dated and Correlated?	^{14}C Limitations[1]	Descriptive Limitations[2]	Scientific Value of the Site[3]	Prioritization for Conducting Additional Studies	Notes
Crescent City marsh	no	diatoms	no	N,L	A	1	5	The event horizons at the Crescent City marsh are poorly constrained. There is a high likelihood that the marsh archives teletsunami evidence.
Lagoon Creek	no	diatoms	yes	I	A	3	12	The data there is mostly sufficient and the lagoon was found to contain dangerous levels of dioxin.
Mad River Slough	no	radiolarians	yes	B,L,I	S	1	1	Mad River Slough, Arcata Marsh and Jacoby Creek occupy an area subject to repeated Late Holocene coseismic subsidence, the timing and magnitude of the associated land level changes is poorly understood. This location is also occupied by critical transportation infrastructure and a public water treatment facility vulnerable to relative sea-level changes.
Arcata Marsh	yes	diatoms	yes	A,L	A	1	2	
Jacoby Creek	yes	no	yes	A,L	A	1	3	
Eureka Slough	no	no	yes	B,L	S	2	6	Eureka Slough, First Slough and Fay slough occupy an area subject to repeated Late Holocene coseismic subsidence, the timing and magnitude of the associated land level changes is poorly understood. This area is also occupied by critical transportation infrastructure and an airport protected by tidal levees.
First Slough	no	no	yes	B,L	S	2	7	
Fay Slough	no	no	no	B,L	S	2	8	
South Bay (west)	no	diatoms	yes	A	A	3	10	The data here is mostly sufficient, occupying a new site would be more prudent.
South Bay (east)	no	no	no	B,L,N,D	S	2	9	South Bay (east) occupies an area subject to repeated Late Holocene coseismic subsidence, the timing and magnitude of the associated land level changes is poorly understood. This location is also occupied by critical transportation infrastructure and a community college.
Swiss Hall	yes	no	yes	A	A	3	11	The data here is mostly sufficient, occupying a new site would be more prudent.
Hookton Slough	yes	diatoms	yes	A	A	3	13	The data here is mostly sufficient, occupying a new site would be more prudent.
Eel River	no	forminifera	yes	B,L,N	S	1	4	The Eel river valley lies just north of the triple junction and has the potential to record paleosiesmic and paleotsunami evidence at the southern most Csz. This data would be valuable in understanding how the southern Csz transitions to the San Andreas fault zone.

[1] ^{14}C limitations include: **B**-bulk samples of organic material were submitted for analysis; **I**- Inverse dates were encountered after analysis of the data; **N**- Not all of the disturbance events had ^{14}C determinations; **L**- several or all event horizons have a limited number of samples to statistically verify age determinations; **D**-Anomalous age determination within data set; **A**-^{14}C sample collection techniques and analysis meet current scientific standards.
[2] Descriptive limitations include: **A**- Lithologic descriptions of core logs meet current scientific standards; **S**- Lithologic descriptions of core logs are simplified compared to modern scientific standards.
[3] Scientific value of site is a subjective determination based on the specific attributes of the site including: ability to archive disturbance events, the value of the existing data, proximity to large human populations or valuable infrastructure, if it spatially or temporally occupies a known or important data gap, or if the data collected at the site meets current scientific standards and does not currently need further analysis. The sites are evaluated on a scale from 1-3 with 1 assigned to locations that are a top priority for further investigation and 3 being locations that do not merit further investigation at this time.



PART IV STRATIGRAPHY





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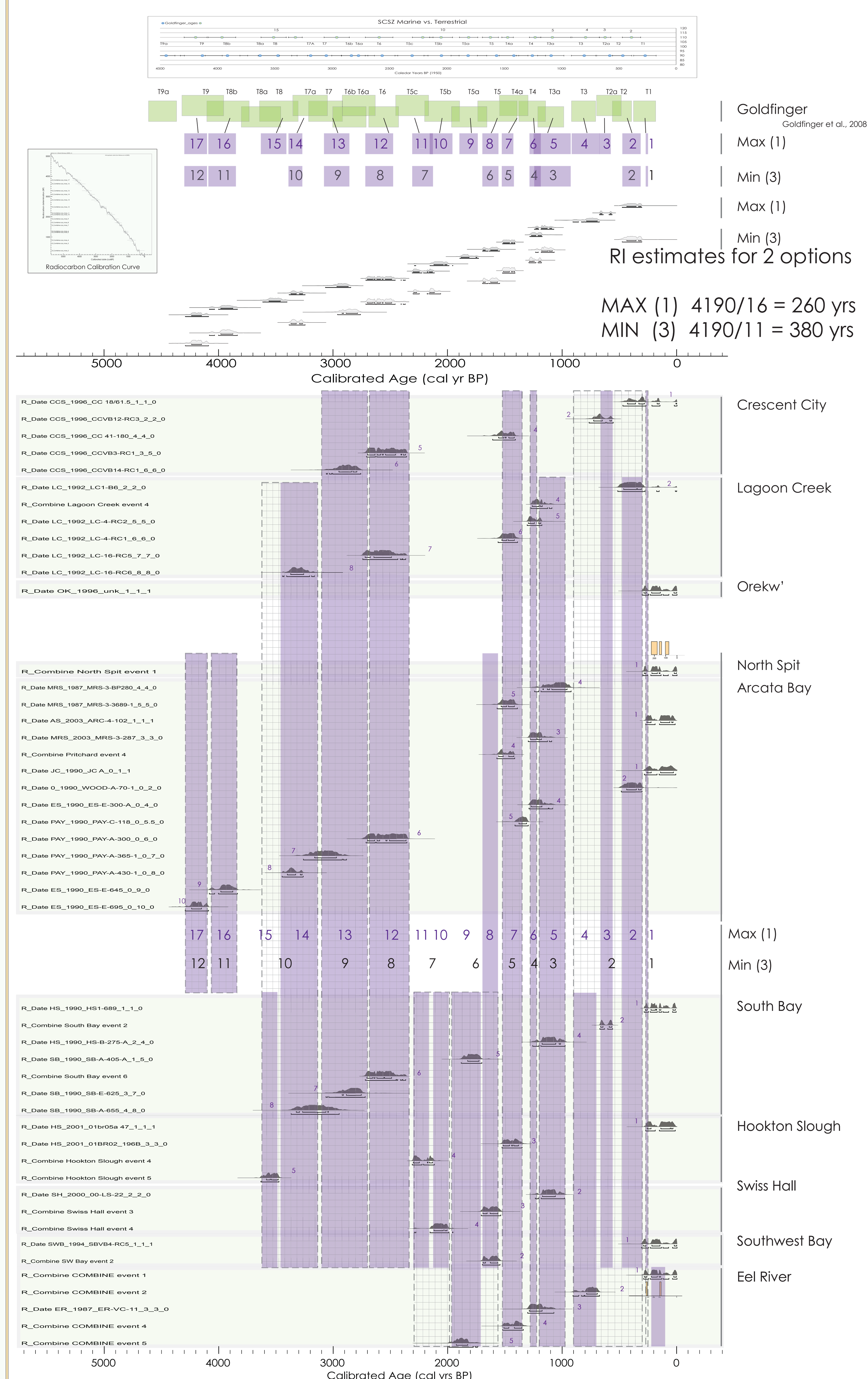
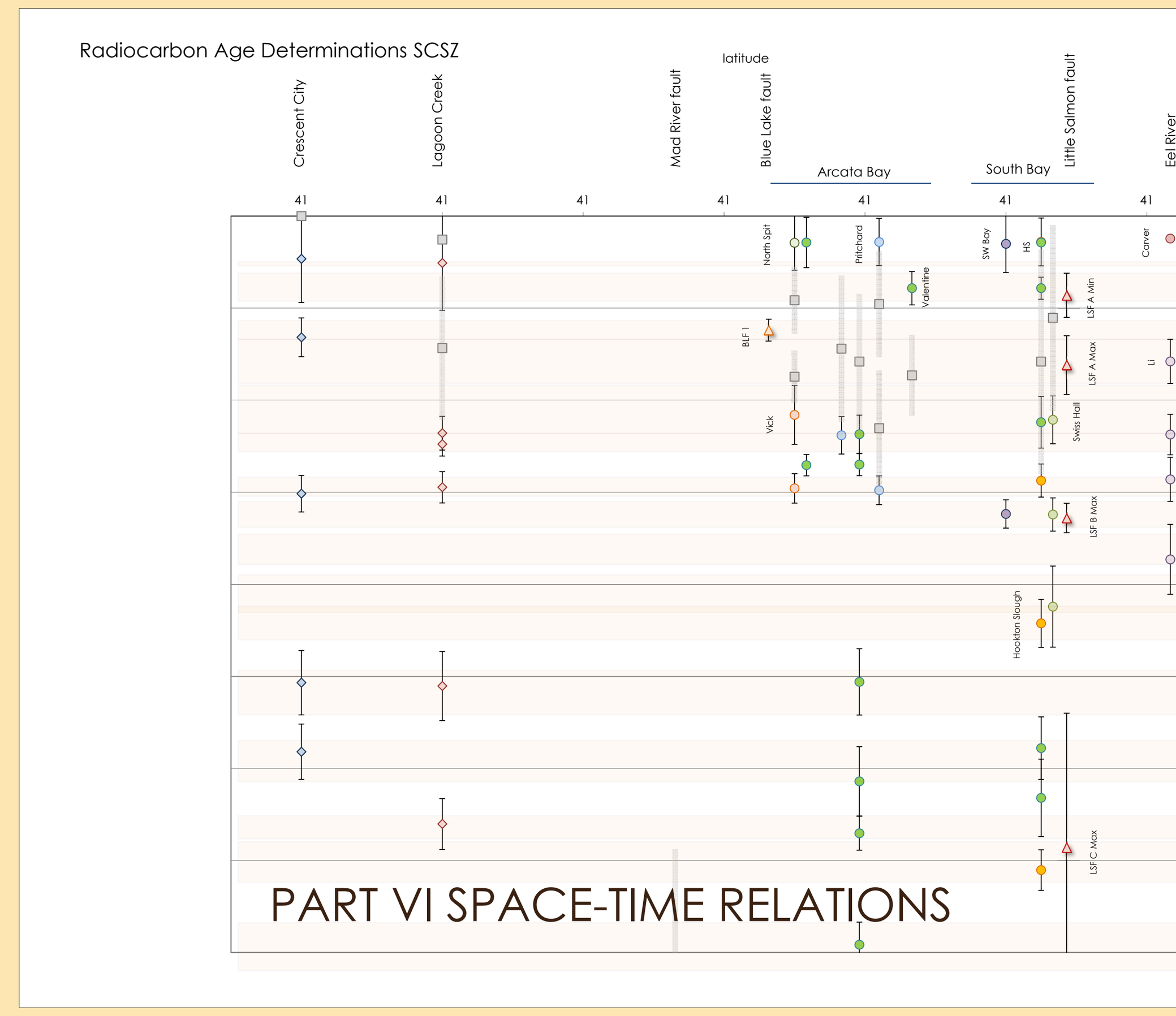
MAX events (1):
the maximum number of events, limited by 1. stratigraphic control, 2. number of ages per event, 3. non-overlap for 2 sigma error

MIN events (3)
the absolute minimum events permissible given stratigraphic relations, regardless of abundance of good acceptable 14C ages.

PART V TIME-SPACE RELATIONS



PART VI SPACE-TIME RELATIONS

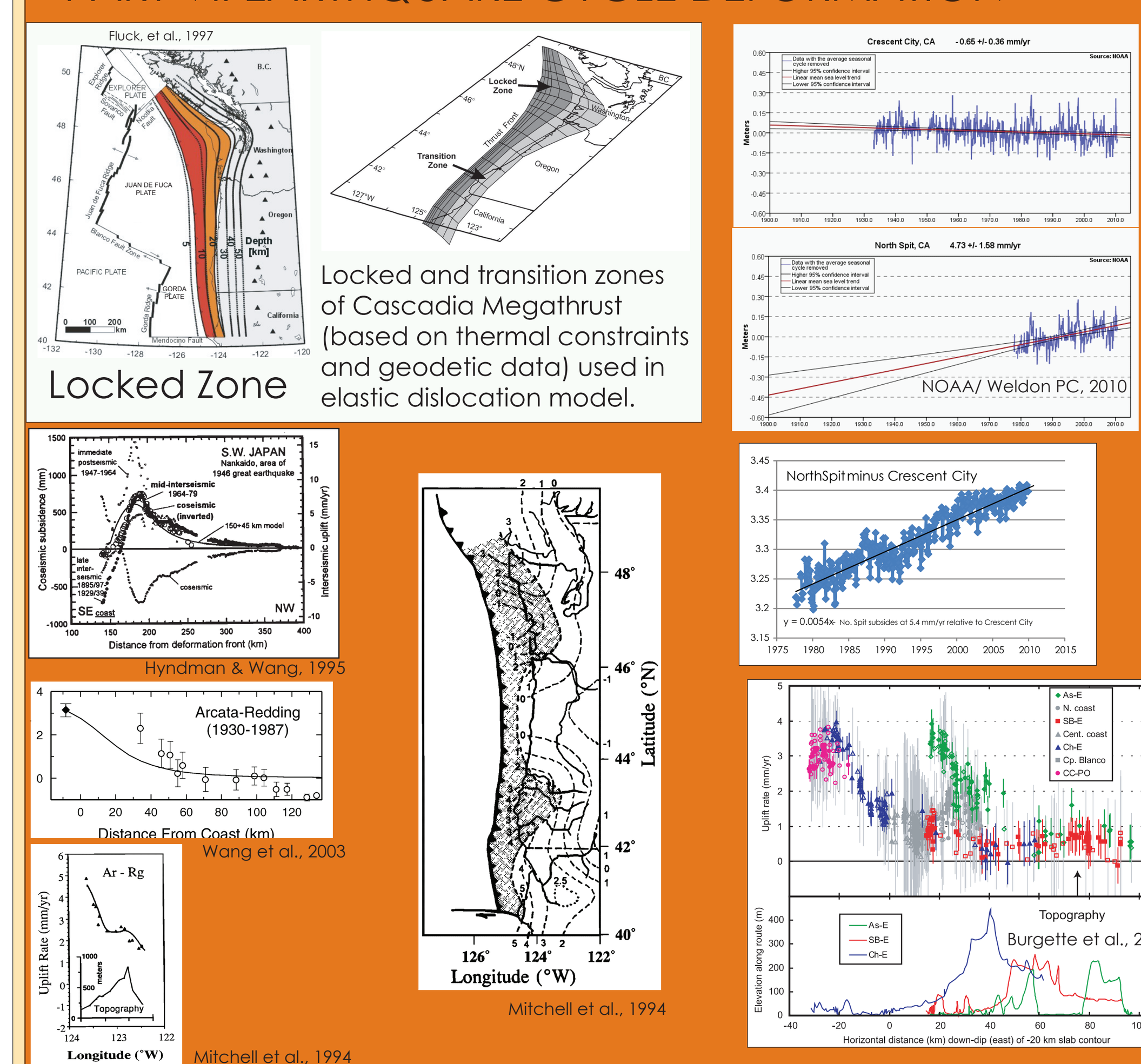


What can we conclude?

Option A: All terrestrial events are unique.

Option B: Fewer events recorded on land, possibly selectively archiving the largest events. What is the Mw threshold for recording an event? (Nelson et al, 1996 suggest we need ~1m subsidence in order to detect the subsidence)

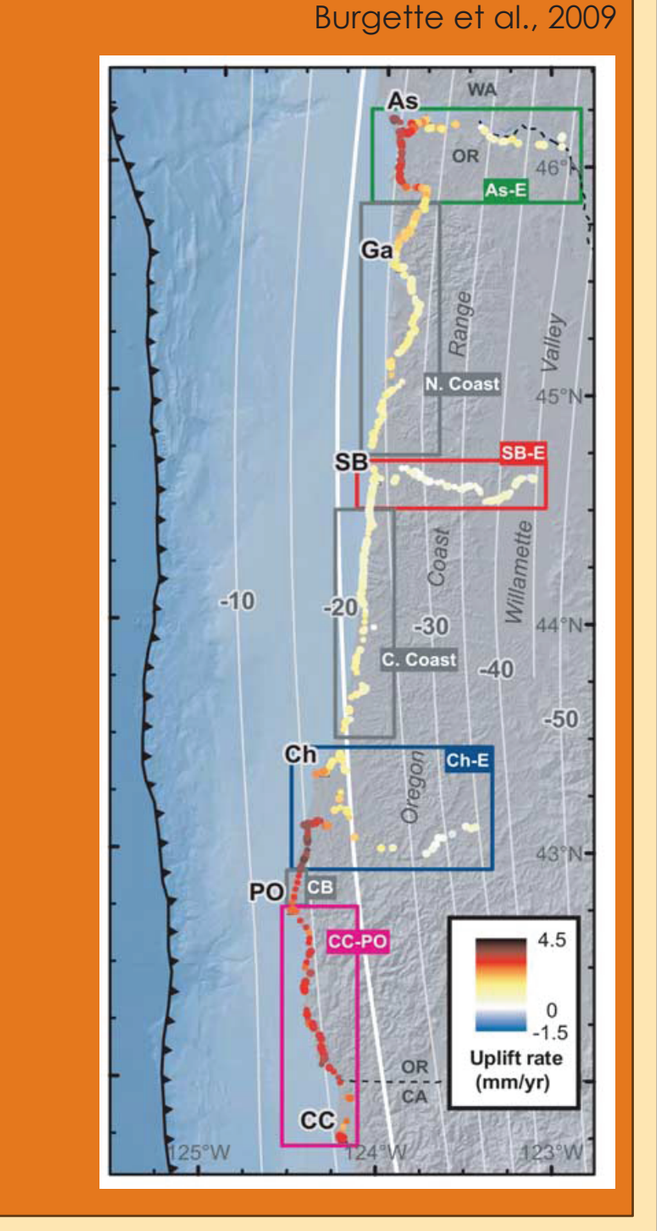
PART VII EARTHQUAKE CYCLE DEFORMATION



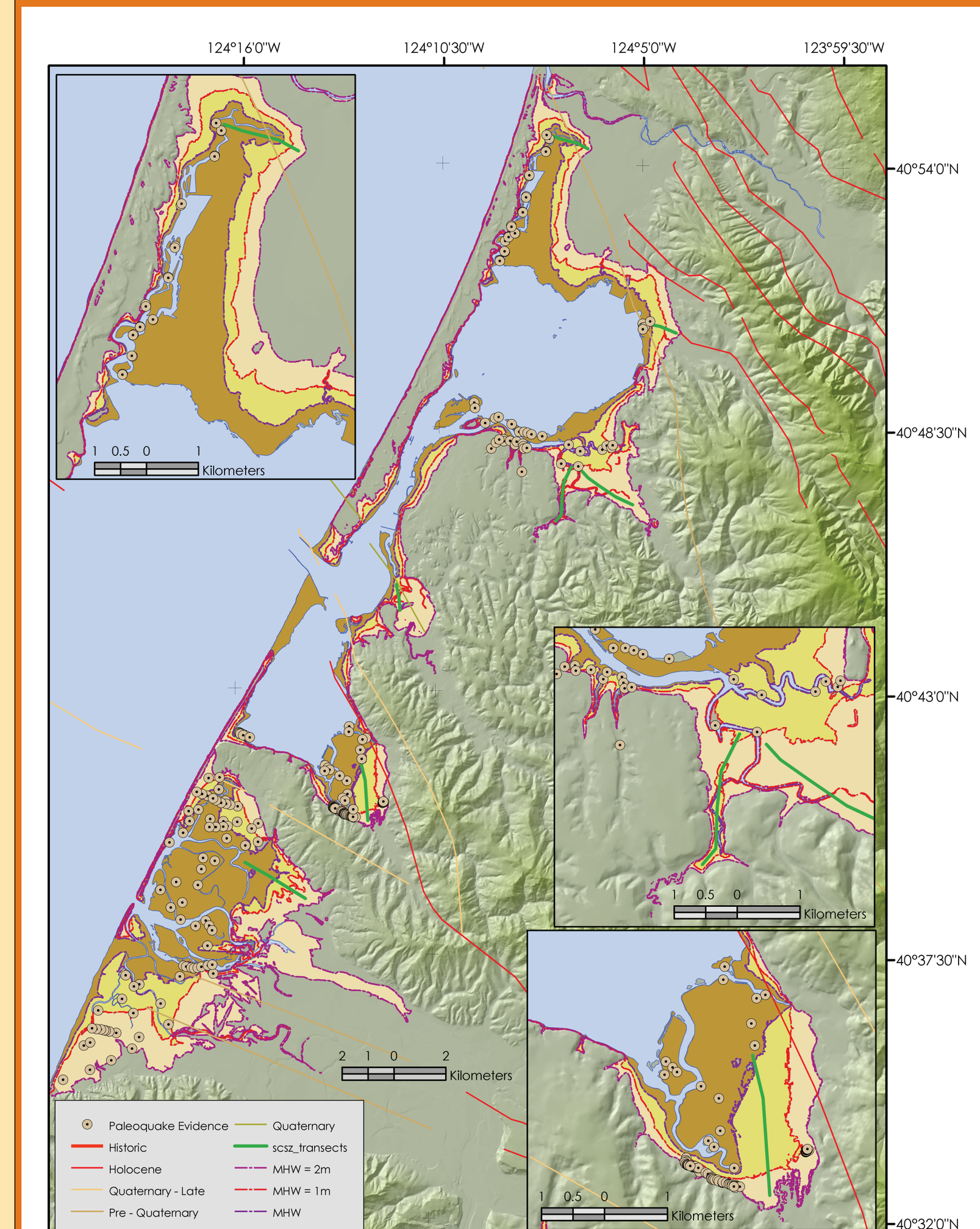
Conclusions

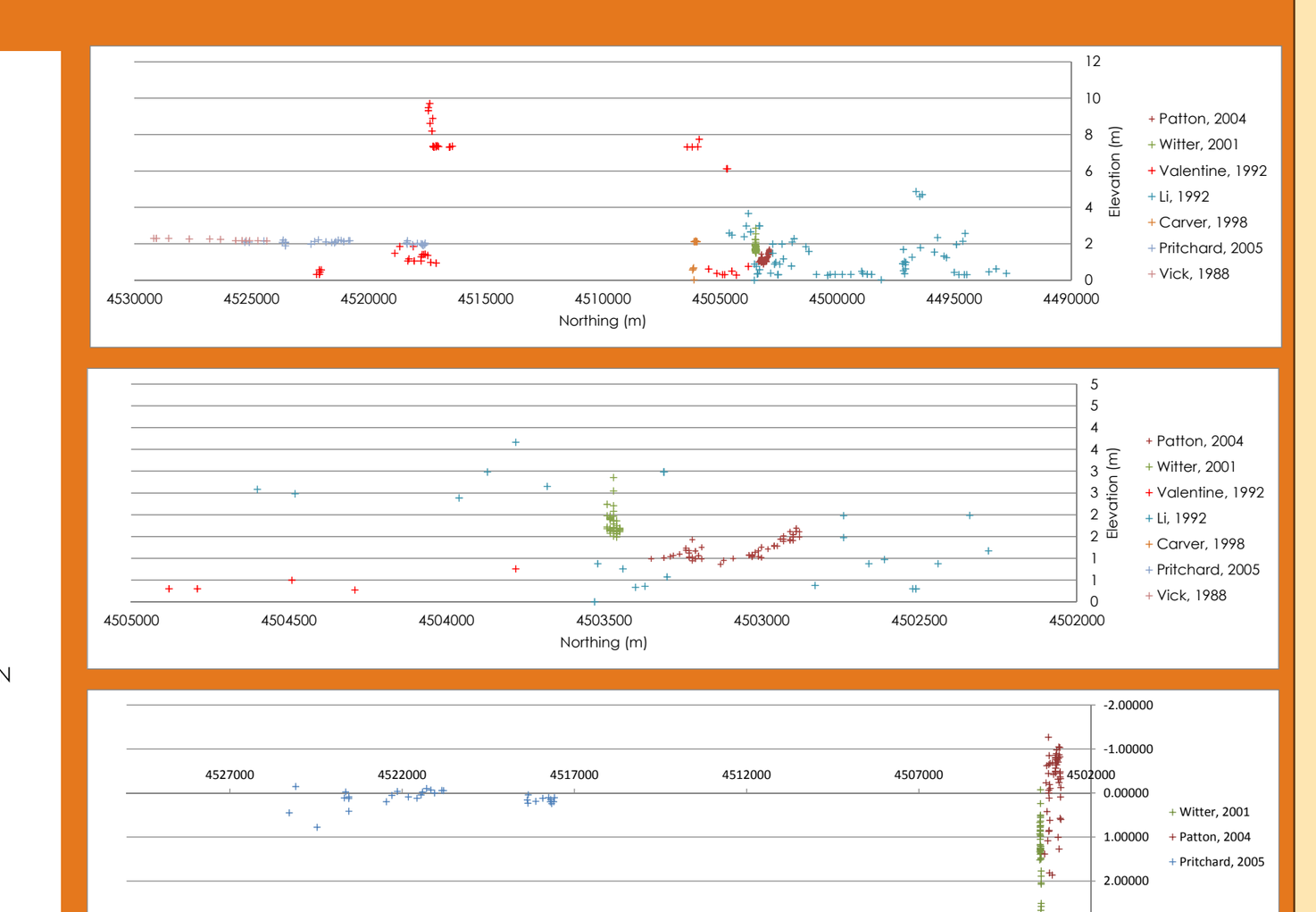
1) interseismic deformation suggests upper plate deformation is complex in northern CA (locked zone boundaries are probably more easterly than Fluck/Wang models)
2) subsidence is likely due to upper plate deformation (while we may expect CSZ coseismic uplift south of CC)
3) upper plate ruptures are likely coincident with CSZ rupture, so records of upper plate subsidence can be used as a proxy for CSZ recurrence

Burgette et al., 2009



PART VIII CORE SITE ELEVATIONS





Conclusions

1) at least one earthquake may be limited to the Eel River region.
2) at least one earthquake may be limited to north of the Eel River region.
3) not all paleoenvironmental elevation ranges have been sampled.
4) not all earthquake related strata have age control (or age control is of low quality).
5) Terrestrial RI estimates from individual paleoseismic investigations need to be combined in order to evaluate the entire record.