Contributions from programs *Slippery* & *NeoKinema* to the UCERF3 fault & deformation models of California

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Pomona, CA
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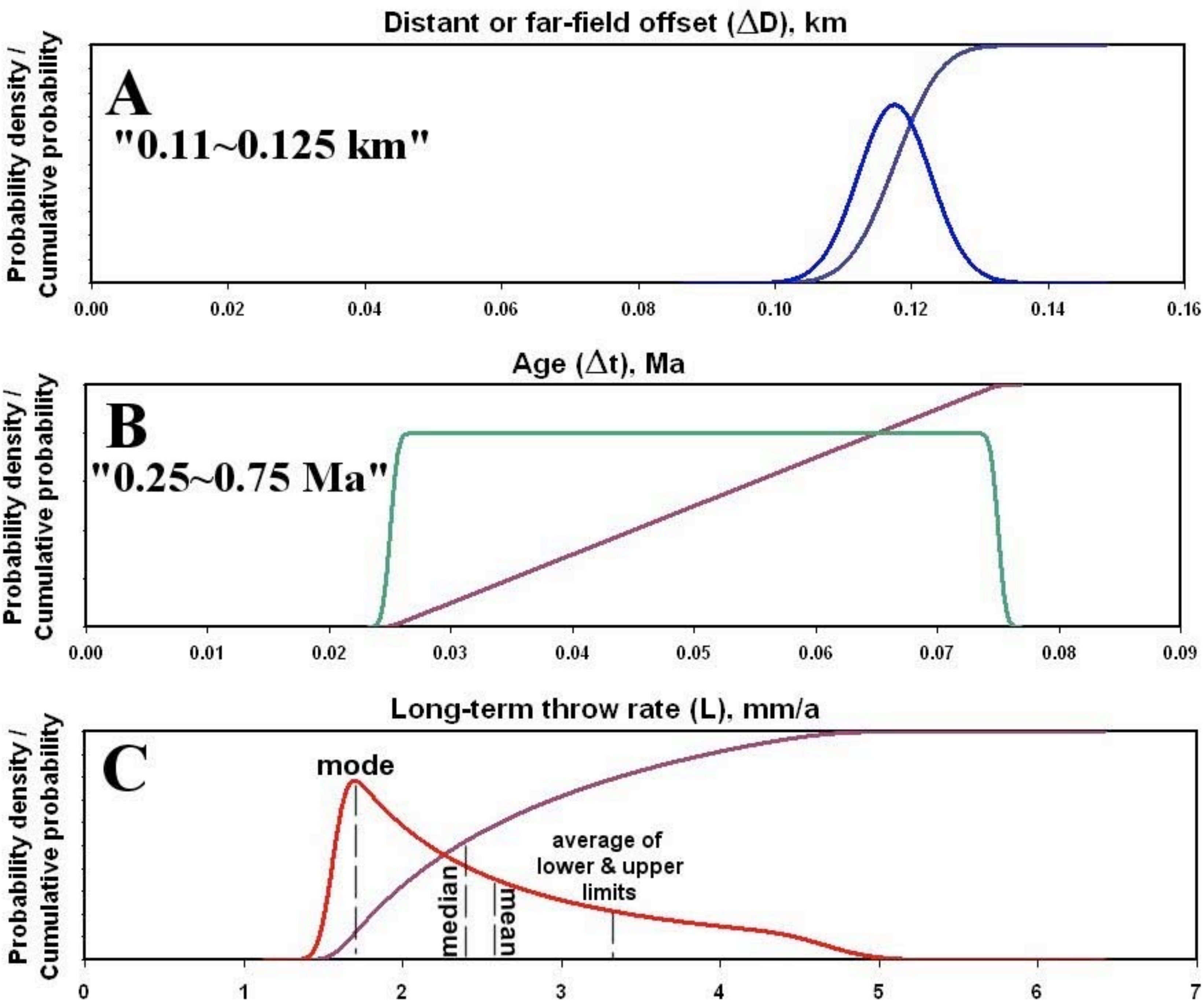
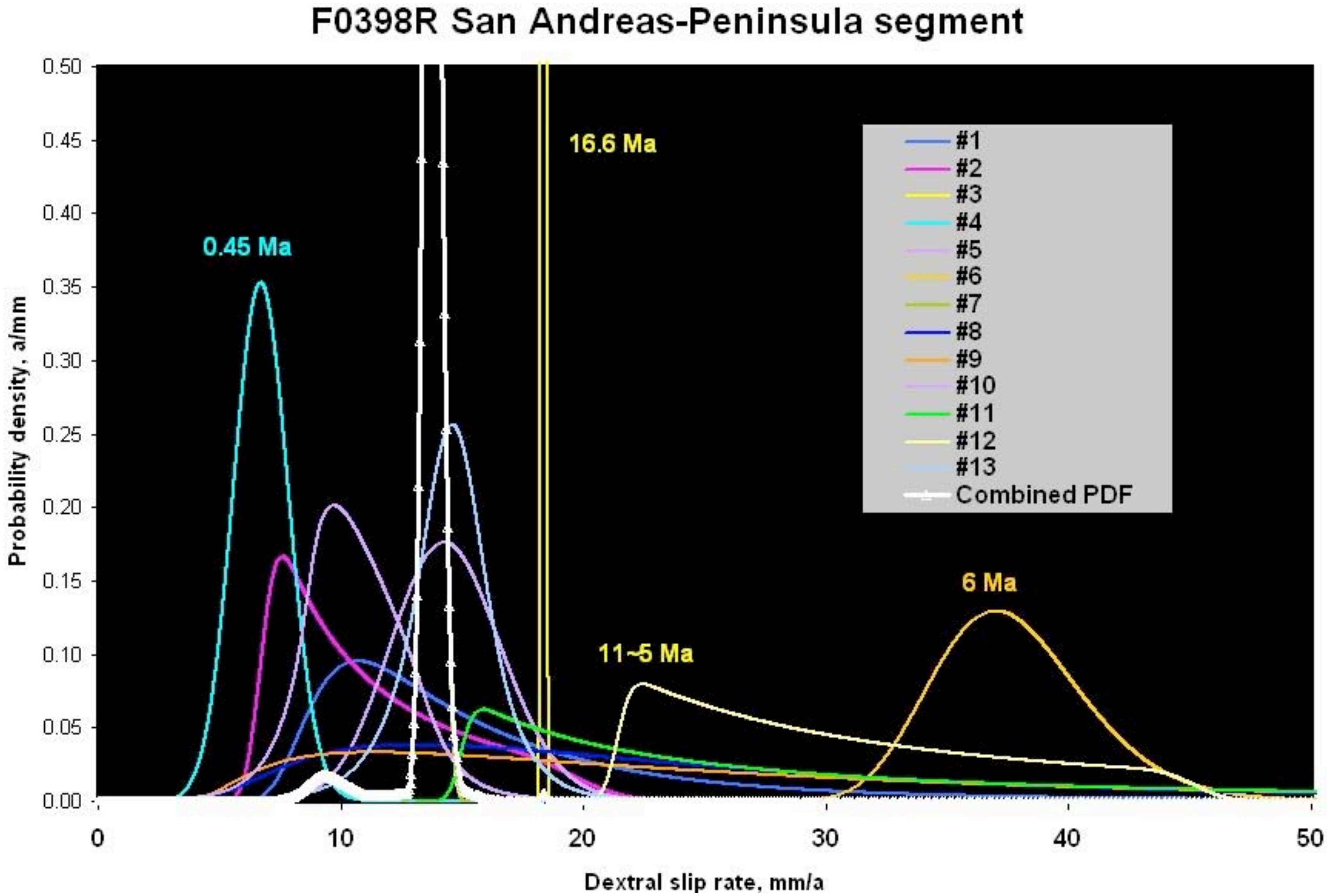
Program ***Slippery.f90*** [*Bird,* 2007, *Geosphere*] for statistical analysis of geologic offsets:

- Suggested PDFs for amount of offset, including elastic uncertainties in far-field offsets;
- Suggested PDFs for age of offset, including cases of inheritance, upper-limit, or lower-limit;
- Convolution formula for PDF of long-term offset rate based on a single feature;
- Formula(s) for combined offset rates based on several offset features along the same fault train.



Distant or far-field offset (ΔD), km
A
"0.11~0.125 km"
Probability density / Cumulative probability
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Age (Δt), Ma
B
"0.25~0.75 Ma"
Probability density / Cumulative probability
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Long-term throw rate (L), mm/a
C
mode
median
mean
average of
lower & upper
limits
Probability density / Cumulative probability
0
1
2
3
4
5
6
7



F0398R San Andreas-Peninsula segment
Probability density, a/mm
Dextral slip rate, mm/a
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
16.6 Ma
0.45 Ma
6 Ma
11~5 Ma
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
#11
#12
#13
Combined PDF

Available tables of rates:

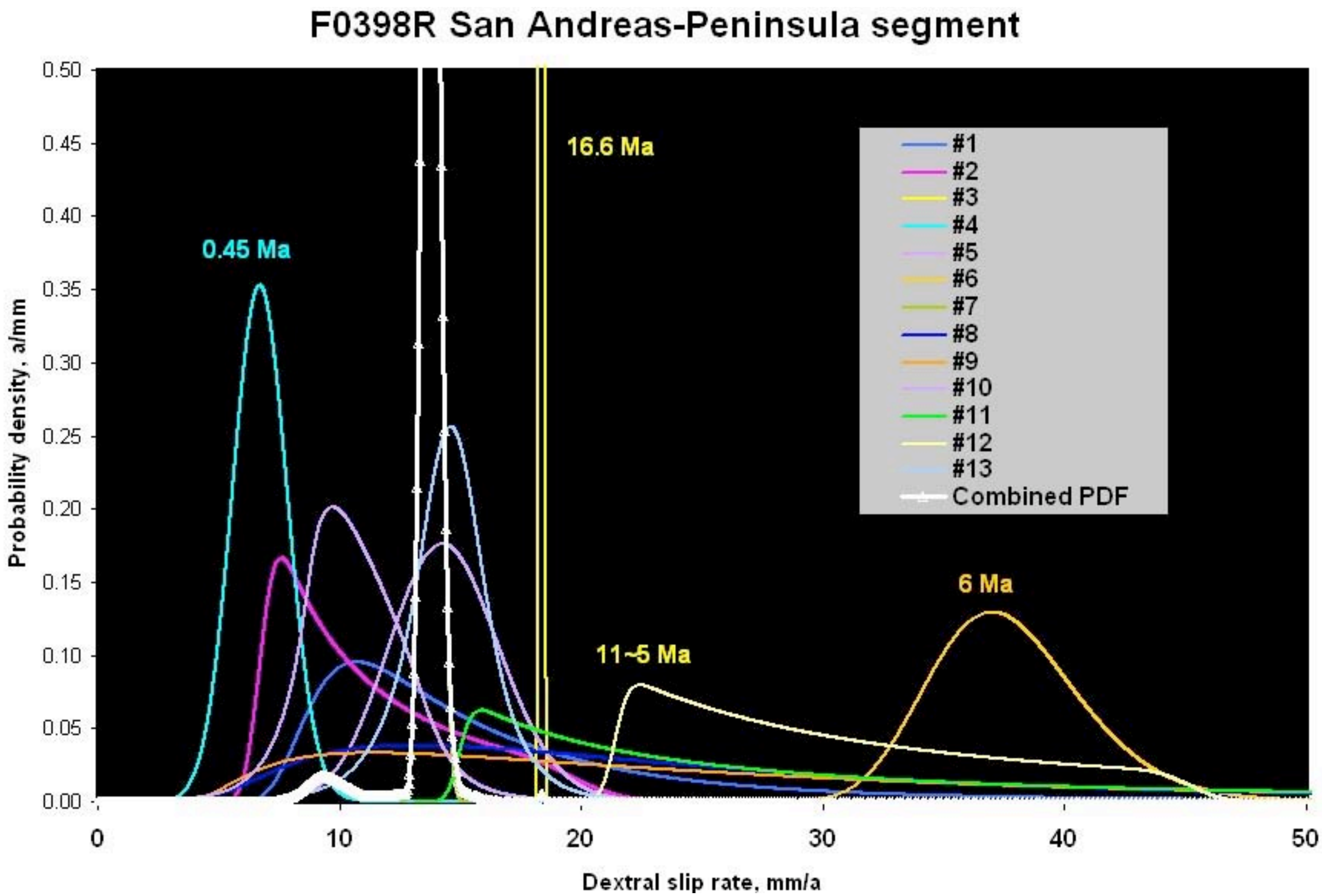
- Table 2 of *Bird* [2007, *Geosphere*]: 264 offsets on 107 WGCEP faults in California;
- Table 1 of *Bird* [2007, *Geosphere*]: 1017 offsets on 487 faults in all western states (including CA), plus generic rate estimates for 362 other faults that lack offsets;
- Table 4 of *Bird* [2009, *JGR*]: 126 additional offset features: 73 on 38 faults in CA, and 53 on 30 faults in other states.

Sample from Table 1:
F0398R San Andreas dextral fault, section C (Peninsula), CA
(Bird's data base for GCN orogen)

Grade	Reference	Kilometers	Since_(Ma)	I:P(L<I)=2.5%	mode of L	MEDIAN L	mean L	I:P(L<I)=97.5%	SIGMA_of_L
A	Cummings, 1968	28	3.0-1.0	8.1	10.7	14	17.4	47.5	13.1
A	Addicott, 1969	32-40	5.3-1.8	6.57	7.6	10.1	11.1	19.4	3.64
B	Graham, 1979	305	16.6	18.3	18.4	18.4	18.4	18.5	0.0629
A	Cummings, 1983	3	0.45	4.52	6.71	6.72	6.73	8.98	1.14
A	Mattinson and James, 1985	900-1400	80	10.1	14.3	14.4	14.4	19.1	2.28
A	Sarna-Wojcicki et al., 1986	225	6	32.2	37	37.5	37.8	44.8	3.21
A	Graham et al., 1989	315-320	23	13.2	13.8	13.8	13.8	14.4	0.309
A	Ward and Page, 1989 (revising Hall, 1984 age)	>0.015	0.002	6.73	13.3	20.8	25.3	69.1	17.3
C	Brown, 1990 (neotectonic rate)	>11	2-0.4	6.45	11.3	22.9	31.1	106	26.4
A	Dieterich et al., 1990 (revising Hall, 1984 age)	0.024	.0028~.0018	6.53	9.7	10.5	10.6	15.1	2.17
C	Stewart and Crowell, 1992 (total slip)	330	<22	15.3	15.8	28.1	43.7	U	38.9
C	Stewart and Crowell, 1992 (partial slip)	240	11.2-5.3	21.6	22.4	29.1	30.4	44.1	6.67
A	Hall et al., 1999 (neotectonic rate)	0.028-0.032	.00219-.00195	10.3	14.6	14.6	14.5	18.5	1.98
S	**combined offset rate (13 GCN data)**			**9.88**	**13.8**	**13.8**	**13.6**	**14.5**	**0.916**

Aside: Could these offsets be used separately as “point rates”? Yes, *but*....

- Large offsets span a finite length of fault.
- Many “rates” are just upper or lower limits, requiring nonlinear programming for separate use.
- Single-offset rates have varying reliabilities due to age of feature and type of publication; this is currently considered in combined rate from ***Slippery***.
- Models fit to “point rates” will be more noisy, less stable, and will have ***even more*** distributed deformation than models fit to combined rates.



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0.45 Ma
16.6 Ma
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#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
#11
#12
#13
Combined PDF
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0
10
20
30
40
50

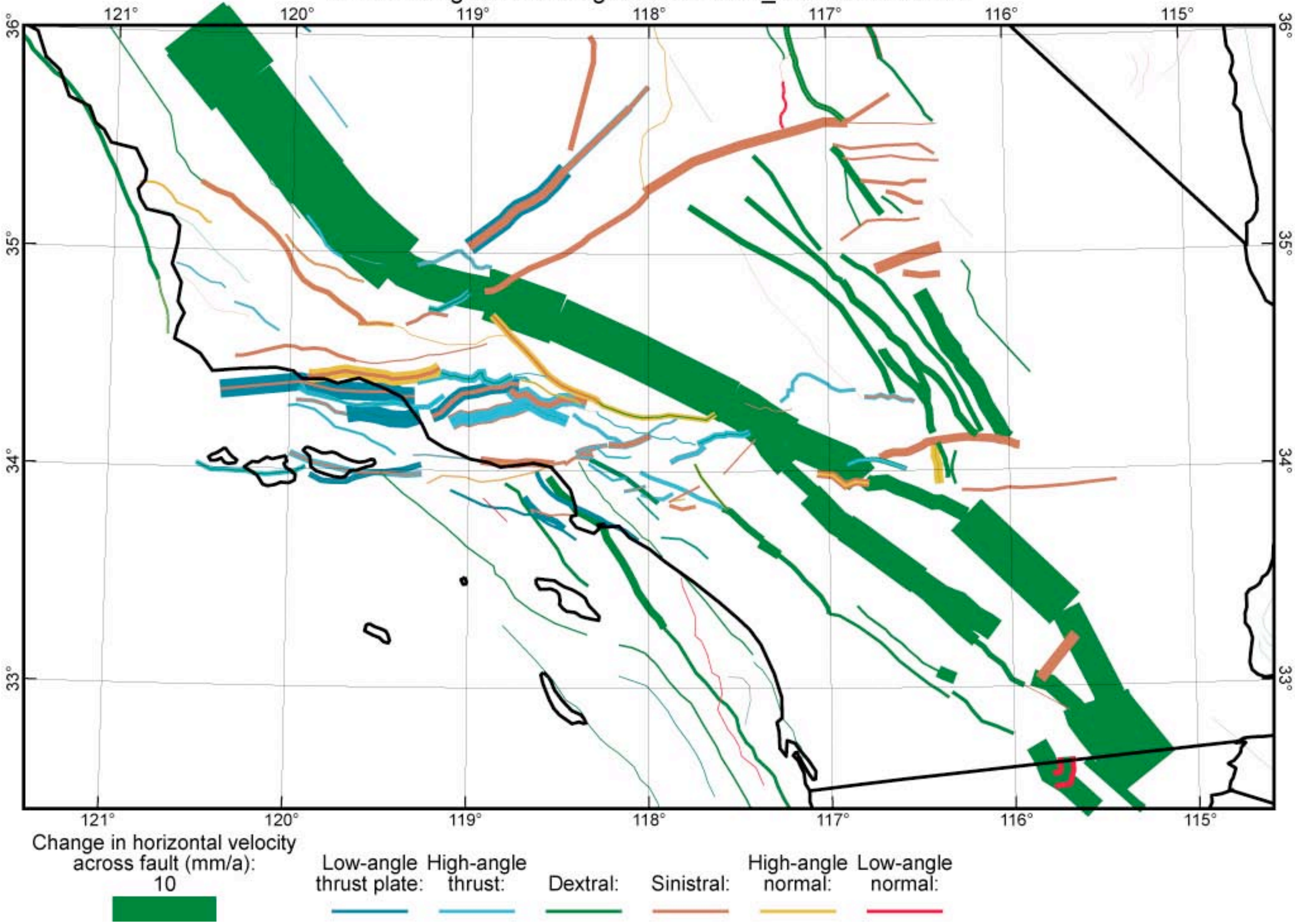
Combined geologic + geodetic + stress + plate-tectonic solutions with ***NeoKinema*** [*Bird*, 2009, *JGR*]:

- Takes combined long-term offset rates & $\mathbf{S}_s$ (or empirical priors) from ***Slippery***;
- Corrects GPS velocities from interseismic to long-term in a self-consistent way;
- Enforces chosen PA-NA Euler pole, and geometric compatibility throughout;
- Minimizes (but also reports) long-term permanent strain rates between faults, which are aligned with interpolated stress-directions.

Output from tuned ***NeoKinema*** models can be used at 3 distinct levels of detail/trust:

- 1) Better trace-averaged long-term offset rate ranges for each fault train (even those with no offset features).

Fault Heave Rates (from model _GCN2008088)
shown using trace-averaged rates from f_GCN2008088.nko



Extract from a table which lists the <u>ranges</u> of offset rates found among 24 ***NeoKinema*** models considered "successful":

F0000X	Trace_name	Encounters	Targets	Sigmas	Results	Range		
F4253P	White Wolf	24	5.09	1.33	5.29~6.78	1.49	f_GCN2008069.nko	f_GCN2008081.r
F4253L	White Wolf (0 data)	24	2.23	4.56	2.6~3.59	0.995	f_GCN2008083.nko	f_GCN2008064.r
F4254T	White Wolf (Extension) (0 data)	24	0.228	0.691	0.619~1.2	0.579	f_GCN2008082.nko	f_GCN2008087.r
F4254L	White Wolf (Extension) (0 data)	24	2.23	4.56	2.1~2.92	0.817	f_GCN2008091.nko	f_GCN2008061.r
F4255R	Earthquake Valley (No Extension) (0 data)	24	6.18	12.6	0.893~1.9	1	f_GCN2008061.nko	f_GCN2008067.r
F4256R	Earthquake Valley (So Extension) (0 data)	24	6.18	12.6	3.4~4.78	1.38	f_GCN2008082.nko	f_GCN2008101.r
F4282R	San Andreas (San Bernardino N)	24	23~23.6	1.01~2.04	16.5~20.6	4.07	f_GCN2008089.nko	f_GCN2008082.r
F4283R	San Andreas (San Bernardino S)	24	16.6~18	1.97~2.82	11.6~15.4	3.8	f_GCN2008061.nko	f_GCN2008082.r
F4284T	San Andreas (San Gorgonio Pass-Garnet Hill(0 data)	10	0.228	0.691	0.518~0.912	0.394	f_GCN2008091.nko	f_GCN2008087.r
F4284R	San Andreas (San Gorgonio Pass-Garnet HIll)	24	15.4	8.47	4.75~11.8	7.03	f_GCN2008067.nko	f_GCN2008086.r
F4285R	San Andreas (Cholame) rev (0 data)	24	6.18	12.6	25.6~26.4	0.811	f_GCN2008087.nko	f_GCN2008100.r
F4286R	San Andreas (Mojave N)	24	59.6	7.5	17.4~20.3	2.93	f_GCN2008081.nko	f_GCN2008091.r
F4287R	San Andreas (Big Bend)	24	45.2	9.95	13.1~16.9	3.76	f_GCN2008090.nko	f_GCN2008061.r
F4289R	San Jacinto (San Jacinto Valley) rev (0 data)	24	6.18	12.6	4.23~5.77	1.54	f_GCN2008082.nko	f_GCN2008063.r
F4290R	San Jacinto (San Jacinto Valley, stepover)(0 data)	24	6.18	12.6	1.11~2.68	1.57	f_GCN2008084.nko	f_GCN2008061.r
F4291R	San Jacinto (Anza, stepover) (0 data)	24	6.18	12.6	4.26~11.5	7.29	f_GCN2008082.nko	f_GCN2008061.r
F4292R	San Jacinto (Clark) rev (0 data)	24	6.18	12.6	6.46~9.35	2.89	f_GCN2008082.nko	f_GCN2008060.r
F4293R	San Jacinto (Anza) rev	24	12.8	2.3	8.97~11.5	2.54	f_GCN2008082.nko	f_GCN2008081.r
F4295R	San Andreas (Coachella) rev	24	18.4	0.475~0.92	14.8~17.9	3.07	f_GCN2008064.nko	f_GCN2008091.r
F4296R	Elsinore (Glen Ivy) rev	24	0.756	2.93	1.37~2.86	1.49	f_GCN2008082.nko	f_GCN2008101.r
F4297R	Elsinore (Glen Ivy stepover) (0 data)	24	6.18	12.6	-3.45~6.13	9.58	f_GCN2008083.nko	f_GCN2008081.r
F4298R	Elsinore (Temecula stepover)	24	17.3	11	-2.01~8.46	10.5	f_GCN2008081.nko	f_GCN2008082.r
F4299R	Elsinore (Temecula) rev	24	0.938	8.6	0.438~2.54	2.11	f_GCN2008067.nko	f_GCN2008087.r
F4300R	San Andreas (Carrizo) rev	24	34.2	1.17	24.7~28.7	4.03	f_GCN2008087.nko	f_GCN2008082.r
F4301R	San Andreas (Mojave S)	24	16.1~21.9	1.37~3.85	16.2~17.7	1.48	f_GCN2008067.nko	f_GCN2008091.r
F4067R	**San Andreas (Peninsula)**	24	9.05	2.28	**12.8~18.7**	5.98	f_GCN2008067.nko	f_GCN2008087.r
F4321N	West Tahoe (0 data)	24	0.183	0.343	0.188~0.217	0.029	f_GCN2008067.nko	f_GCN2008060.r
F4321R	shadow datum, which adds strike-slip flexibility	24	0	0.1	0~0.01	0.01	f_GCN2008067.nko	f_GCN2008061.r
F4322N	North Tahoe (0 data)	24	0.183	0.343	0.177~0.192	0.015	f_GCN2008088.nko	f_GCN2008061.r
F4322L	shadow datum, which adds strike-slip flexibility	24	0	0.1	0~0.003	0.003	f_GCN2008063.nko	f_GCN2008061.r

(These models have different Euler poles, fault sets, geologic datasets, and/or weightings of geologic *vs.* geodetic data.)

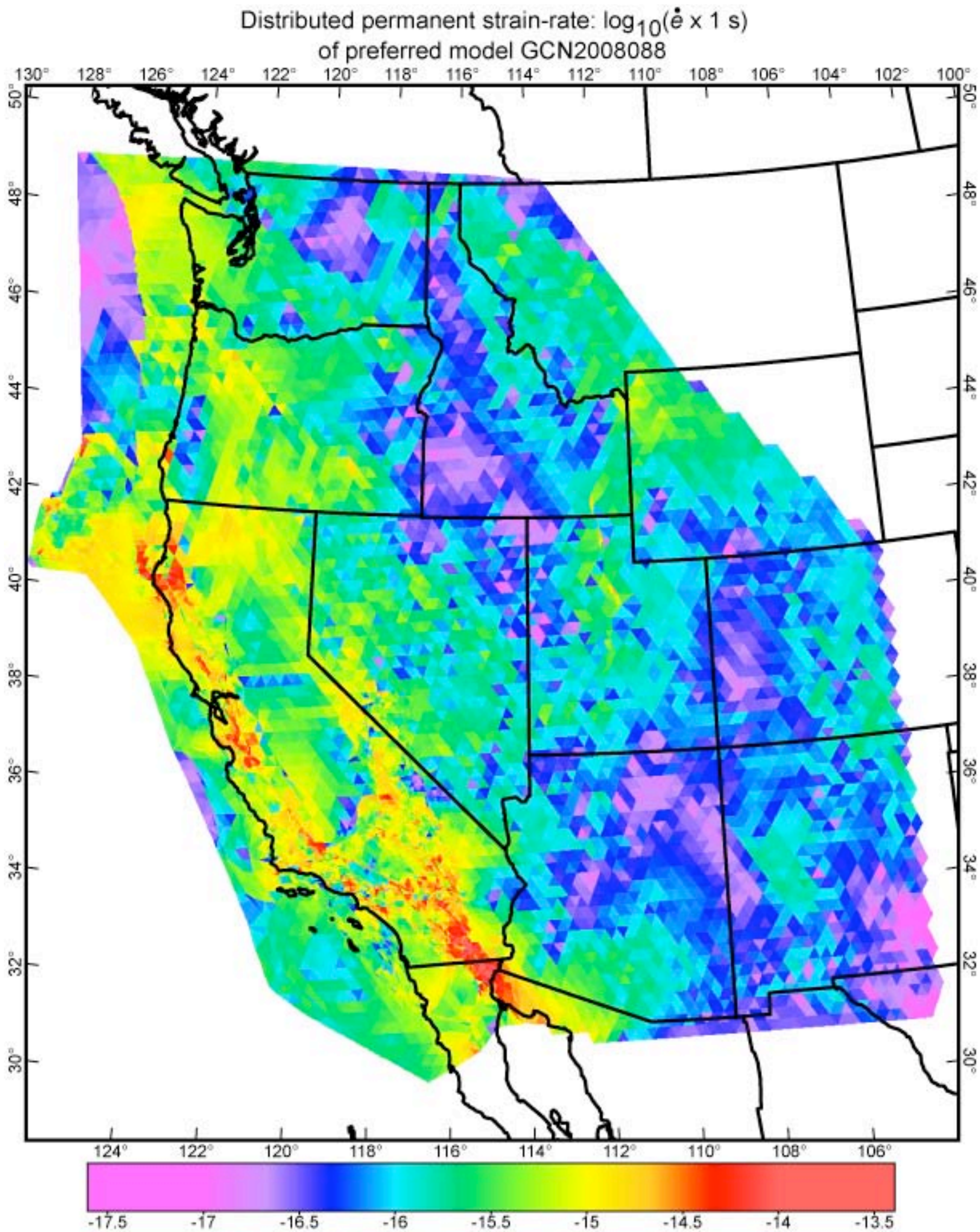
Caveat:

- These long-term fault slip rates only “add up” to 2/3 of PA-NA relative motion in the latitudes of California & Nevada.
- The rest is expressed as distributed permanent deformation, which may also be seismic.
- Using only the fault slip rates could seriously underpredict seismicity.

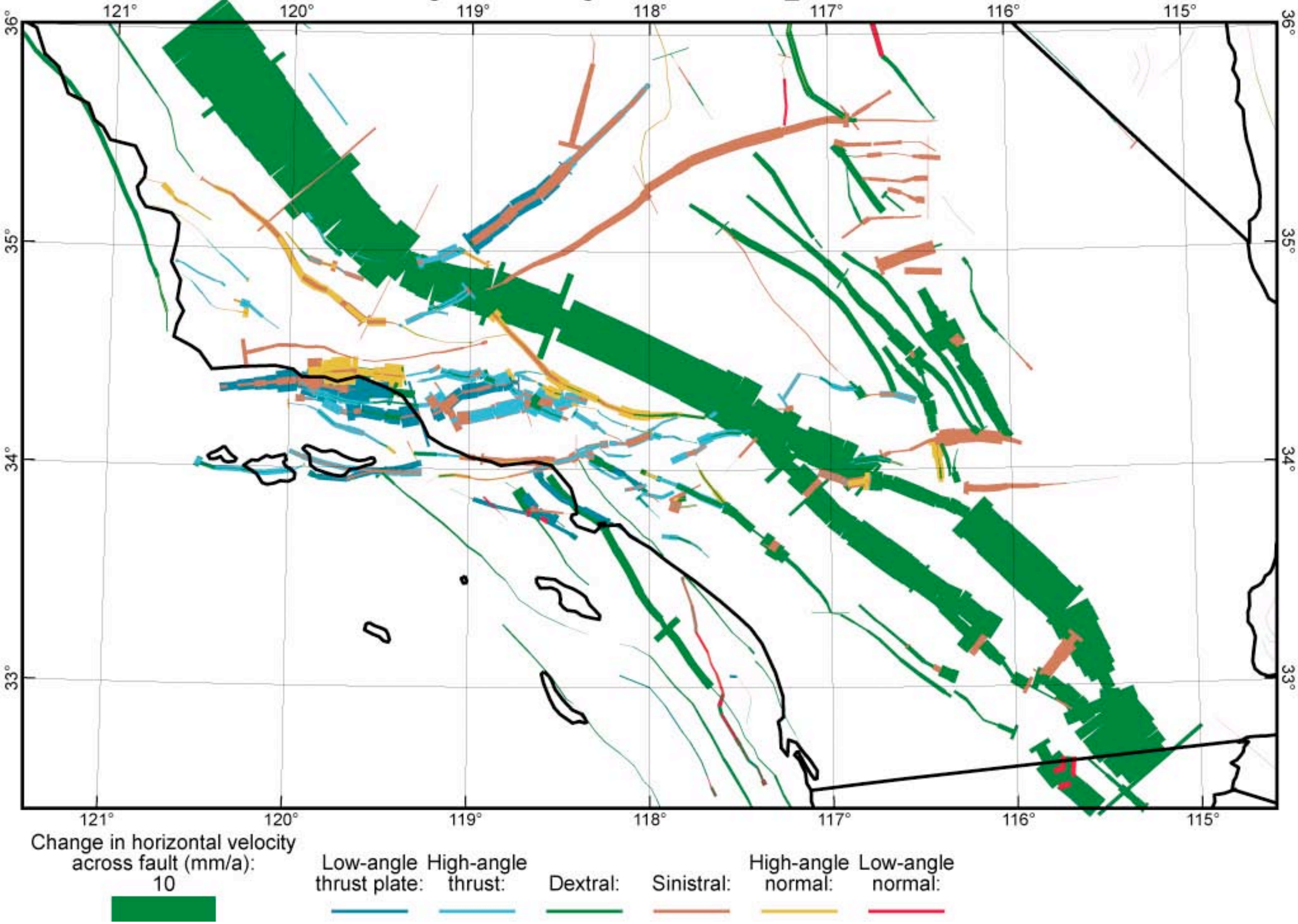
Output from tuned ***NeoKinema*** models can be used at 3 distinct levels of detail/trust:

- 1) Better trace-averaged long-term offset rate ranges for each fault train (even those with no offset features).
- 2) Detailed ("noisy") long-term offset rate ranges and permanent deformation rate ranges in each small finite element.

N.B.
These long-term permanent strain-rates do ***not*** include any strain due to slip on the modeled set of faults.



Fault Heave Rates (from model _GCN2008088)
shown using individual segment rates from h_GCN2008088.nko



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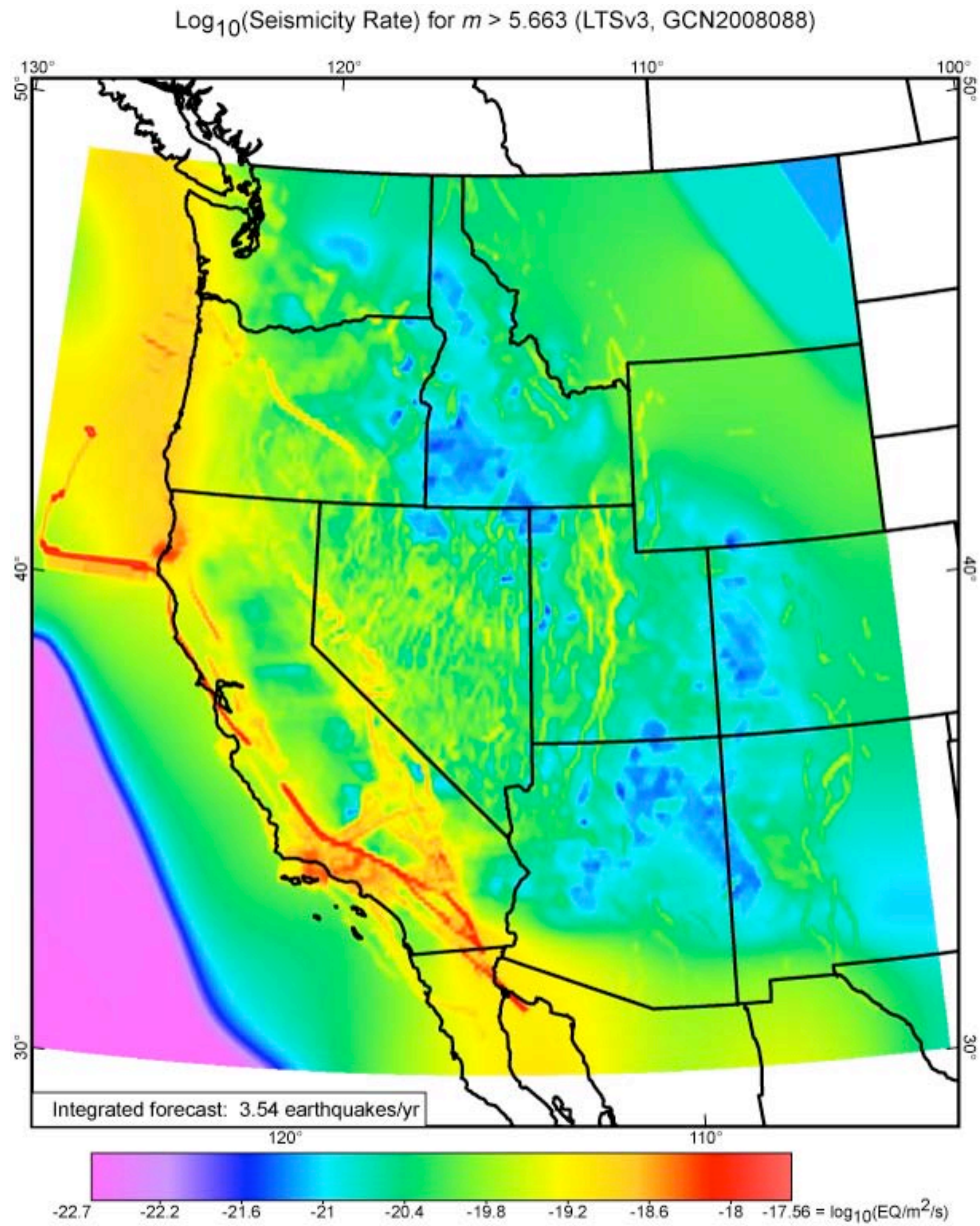
- 1) Better trace-averaged long-term offset rate ranges for each fault train (even those with no offset features).
- 2) Detailed ("noisy") long-term offset rate ranges and permanent deformation rate ranges in each small finite element.
- 3) Long-term seismicity map(s) derived by applying the assumptions of the SHIFT method [*Bird & Liu*, 2007, *SRL*].



Two tasks remain:

(1) Convert epicentral rates to discrete ruptures (while conserving model moment rates);

(2) Consider adding time-dependence(?).

(end)