Review of the Bird Critique

Seismic Review Team

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Presentation at the Diablo Canyon Independent Safety Committee Public Meeting

June 10, 2025

Seismic Review Team

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Charge to the Seismic Review Team by the DCISC

- Conduct a peer review of reports submitted by Dr. Peter Bird to the DCISC, CPUC, and NRC regarding the seismic hazard at DCPP
  - Main report by Dr. Bird:

    "High Seismic Hazard and Risk at Diablo Canyon Power Plant Due to Thrust Faulting Under the Irish Hills" (27 pp.), submitted to the DCISC on October 30, 2024

- Evaluate Dr. Bird's assertions using the best science available from the published literature, public PG&E reports, and expert knowledge
  - Submit a written report on the SRT findings and recommendations to the DCISC by May 30, 2025

Four Main Assertions of the Bird Critique

a. PG&E (2015, 2024) underestimated the hazard to DCPP from thrust faulting under the Irish Hills because it made four false assumptions. Removing these assumptions increases the thrust-faulting potency rate by a large factor.

b. Three independent analytic methods give values for the total slip rate on shallow-dipping thrust faults under the Irish Hills in the range of 2.0-2.8 mm/yr.

c. January 1, 2024, Noto Peninsula (Japan) earthquake (M7.5) is a good analog for a large thrust event beneath the Irish Hills

d. Recurrence interval of a Noto24-type earthquake involving Irish Hills thrust faulting is 715-1000 yr, posing an unacceptable risk to the DCPP.

Four Main Assertions of the Bird Critique

a. PG&E (2015, 2024) underestimated the hazard to DCPP from thrust faulting under the Irish Hills because it made four false assumptions. Removing these assumptions increases the thrust-faulting potency rate by a large factor.

False Assumptions
1. The Irish Hills are uplifting as a rigid block, with no internal deformation
2. Active thrust faults may dip at any angle
3. Geologic structures older than ~0.33 Ma are irrelevant to seismic hazard estimation
4. GPS geodetic velocities are not useful for site-specific seismic hazard estimation

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b. Three independent analytic methods give values for the total slip rate on shallow-dipping thrust faults under the Irish Hills in the range of 2.0-2.8 mm/yr.

Method	Bird slip rate (mm/yr)
1. Isostatic	2.8
2. Thrust fault heave rate	~2
3. GPS geodetic horizontal shortening rate	2.2

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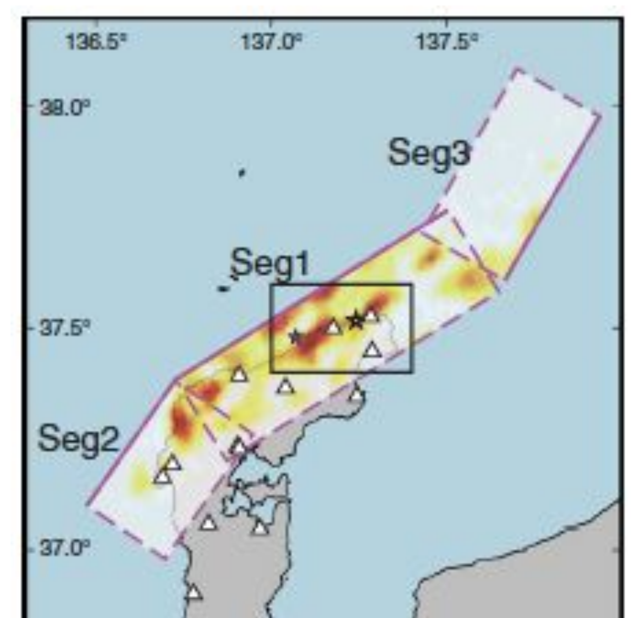
b. Three independent analytic methods give values for the total slip rate on shallow-dipping thrust faults under the Irish Hills in the range of 2.0-2.8 mm/yr.

c. January 1, 2024, Noto Peninsula (Japan) earthquake (M7.5) is a good analog for a large thrust event beneath the Irish Hills

Xu et al. (2024)



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Outline of the SRT Report

1. Introduction
   - SRT charge, review process
2. Annotated summary of the Bird critique
   - Point-by-point commentary on text of Bird critique
3. Technical analyses
   - Gravimetric data
   - Fault reactivation
   - Fault system geometry and kinematics
   - Geodetic data and models
   - 2024 Noto Peninsula analog earthquake
4. Findings and recommendations
   - 15 major findings and 9 recommendations for future work

Review Process by SRT

- Reviewed six of Dr. Bird's filings and evaluated his assertions based on published literature, public PG&E reports, and expert knowledge
  - Began review on February 20, 2025
  - Paced progress with weekly on-line meetings
  - Submitted final report (98 pp.) to the DCISC on May 30, 2025

- Consulted widely with subject-matter experts, including
  - Dr. Peter Bird (on-line March 18, 2025)
  - PG&E representatives (in-person at DCPP on March 28, 2025)
  - IPRP technical team assessing the Bird critique (on-line April 25, 2025)

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Annotated Summary of the Bird Critique

- Point-by-point SRT commentary on text of Bird critique
  - Bird text in **blue font**, taken primarily from 10/30/24 filing with DCISC
  - SRT comments and analysis in **black font**
- We frequently reference technical analyses of Section 3 in support of the commentary

2.2. Four False Assumptions in the Development of SSC15 and SSC24

a. One of the reasons that the SSC15 and SSC24 reports seriously underestimated seismic hazard due to thrust faulting is that they were guided by four assumptions that are actually false.

The assumptions stated by Dr. Bird involve simplifications and generalizations that go beyond the hypotheses that actually guided PG&E in the development of the SSC model, as discussed below.

2.2.1. "The Irish Hills are uplifting as a rigid block, with no internal deformation."

a. PG&E assumed that the Irish Hills are uplifting as a rigid block, with no internal deformation.

While it is true that the fault-based sources used in the SSC are consistent with block uplift of the Irish Hills, it is not correct to say that PG&E assumes that there is no internal deformation. Transpressive internal deformation is modeled by a Local Areal Source Zone that produces 70% strike-slip sources with magnitudes up to 7.0 and dips that range from 90° to 65°, and 30% reverse-slip sources with magnitudes up to 7.1 and dips that range from 70° to 35° (PG&E, 2015, sect. 13.5). The deaggregated hazard curves in Figure 2.1 show that the contribution of the Local Areal Source Zone to the exceedance rate measured at an 5Hz-SA = 1 g is the second largest; only the Hosgri source is larger. At 5Hz-SA = 2 g, Hosgri accounts for 45%, SWBZ for 17%, and the Local Areal Source Zone for 15%, tying with the Los Osos Fault in third place.

b. From this assumption, PG&E concluded that thrust faulting occurs only at the margins (Los Osos thrust, San Luis Bay thrust) with fault throw rates equal to marine terrace uplift rates of ~0.2 mm/year, and that thrust faulting occurs nowhere else.

The statement that thrust faulting occurs nowhere else is not correct, because the Local Areal Source Zone includes widely distributed reverse-slip sources. These sources are consistent with the internal structure of the Irish Hills, where geologic mapping indicates minor inversion of normal faults inherited from an earlier period of crustal extension, producing reverse slip and forced folds above steeply dipping (> 60°) faults. None of these internal structures produces measurable offset of marine terraces or other youthful geomorphic features (Hanson & Lettis, 1994; PG&E, 2014a). Such evidence occurs only at the margins of the Irish Hills along the Los Osos trend and along various onshore and offshore strands of the SWBZ (Lettis & Hall, 1994; Lettis et al., 1994).

c. However, the geologic map of the Irish Hills shows tight folding of Late Miocene sedimentary rocks has occurred since 6 ~ 5 Ma. Therefore, the Irish Hills are not rigid, and additional blind thrust faults are active in the interior.

Tight folds are defined by interlimb angles less than 30°, implying more than 50% shortening. The map-scale folds expressed in the Irish Hills are open folds, with interlimb angles greater than 70° (PG&E, 2014a; Weigers, 2021). Tight folding is present at outcrop-scale, especially within the Monterey formation, and is attributed to shortening as a result of flexural-slip folding. The estimated internal shortening ranges from 3.4% to 8.7% across the axis of the Pismo Syncline (PG&E, 2014a). The uniform elevation of marine-terrace platforms across these fold axes (Figure 2.2) shows that these folds are not presently tightening within the resolution of these reference horizons. Any model to produce the Pismo Syncline via ongoing fault-related folding must account for both the total deformation across the syncline and the ongoing surface deformation evident only at the northern and southern boundary of the Irish Hills (See §3.3). The Local Areal Source Zone is intended to represent the internal deformation of the Irish Hills and the possibility of blind-thrust sources.

d. According to geological mapping, the sedimentary beds in the Pismo have been rotated ~45º. This folding began after deposition of the youngest strata in the core of the fold (Tmpm), and prior to deposition of the Squire Member of the (Pliocene) Pismo Formation (Tpps), probably circa 5 Ma.

This statement is consistent with the geologic map relationships expressed within the Irish Hills and western San Luis Range.

e. This folding implies upper-crustal strains of ~0.8, and mean strain-rates of ~0.8 / 5 Ma = 5×10^{-15} per second, which is ~10× faster than rates of deformation of the modeled faults that are typical in the long-term neotectonics of the western U.S.

The 0.8 / 5 Ma strain estimate is equivalent to 160 nanostrain/yr, which is typical within the plate-boundary deformation zone along the entire length of the San Andreas fault (see Zeng, 2022, fig. 9). In a discussion with Dr. Bird, the SRT clarified that his estimate is a shear strain rate based on the ~40° tilt of the limbs of the Pismo Syncline with respect to horizontal. It should be recognized that the cumulative strain expressed as folding is not identical to the present pattern of strain accumulation evident in geodetic data and patterns of marine-terrace uplift. Reconciling these differences requires a kinematic model of fold growth in relation to underlying fault geometry, and consideration of the differing time frames for each type of measurement (see §3.3). The time-averaged strain rate since 5 Ma is not necessarily the same rate implied by Q2 marine-terrace uplift over the past 124.0 ± 2.5 ka (Marine Isotope Stage 5e highstand age from Simms et al, 2016). The analysis in §3.3 suggests that the 5-Ma rate is greater than the 120-ka rate.

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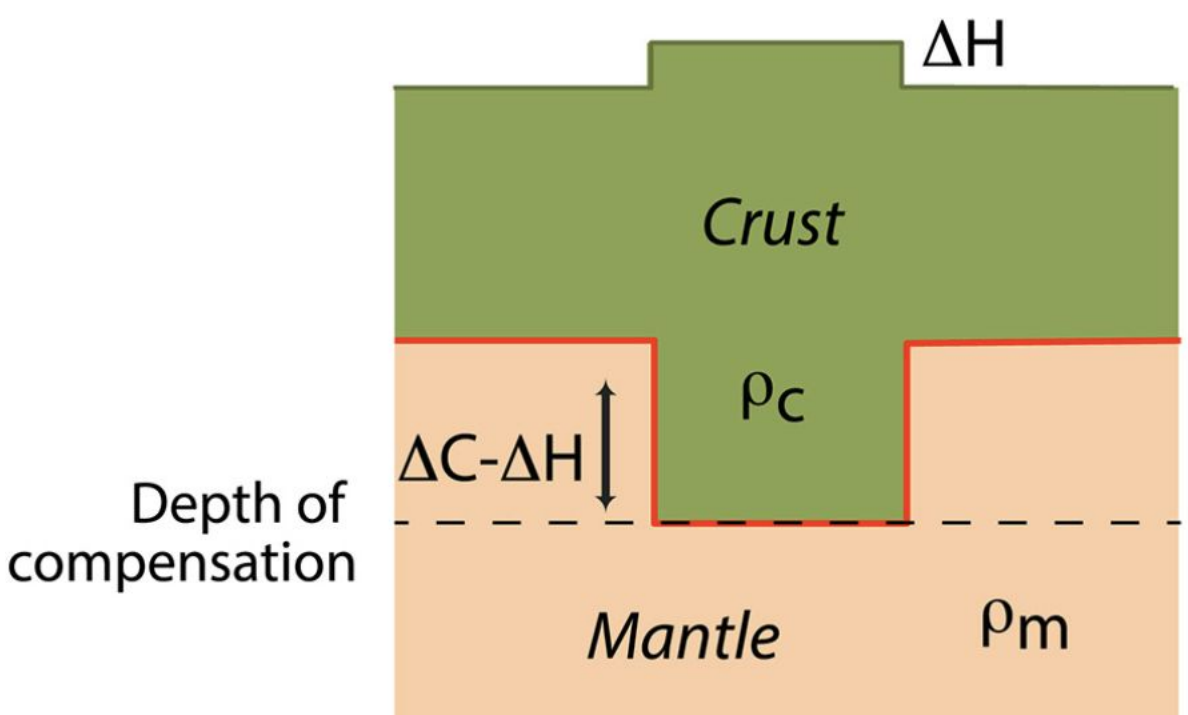
Gravimetric Analysis

- Bird's assertion: Active thrust faulting must explain not only the 0.2 mm/yr uplift rate of the Irish Hills but also a crustal thickening rate about six times larger.
  - Assumes mass compensation mechanism is Airy isostasy, where the local topographic height is balanced by the local Moho depth



Airy Compensation Model

$\rho_c \approx 2.75\ \mathrm{gm/cm^3}$

$\rho_m \approx 3.30\ \mathrm{gm/cm^3}$

$$\Delta C = \frac{\rho_m}{\rho_m - \rho_c} \Delta H \approx 6\ \Delta H$$

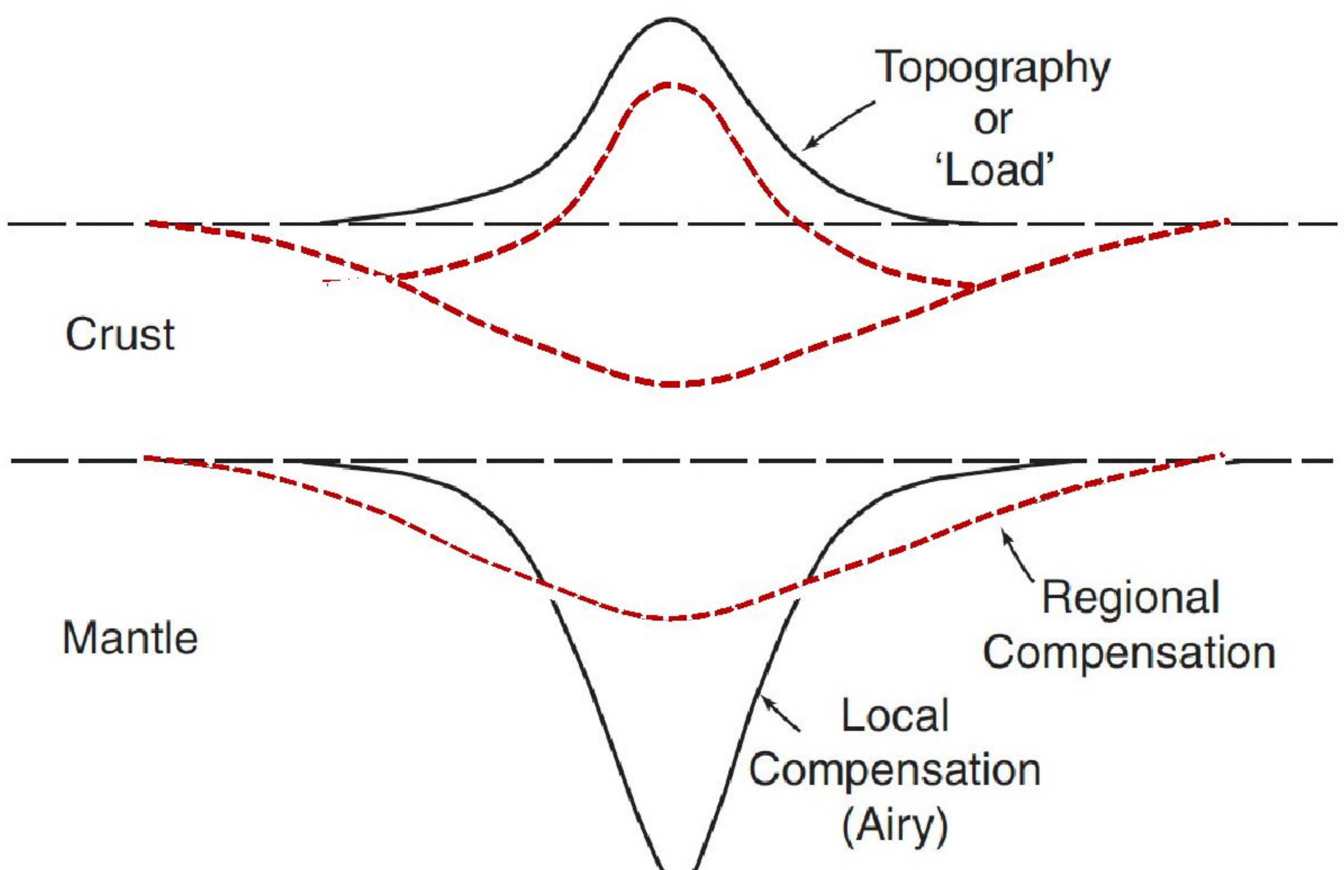
Crustal thickening rate is 6 times the uplift rate

Lamb et al. (2020, fig. 1)

Gravimetric Analysis

- Regional compensation is the most realistic and widely applied isostatic model
  - Loads are supported by the flexural rigidity of the lithosphere, parameterized by T_e

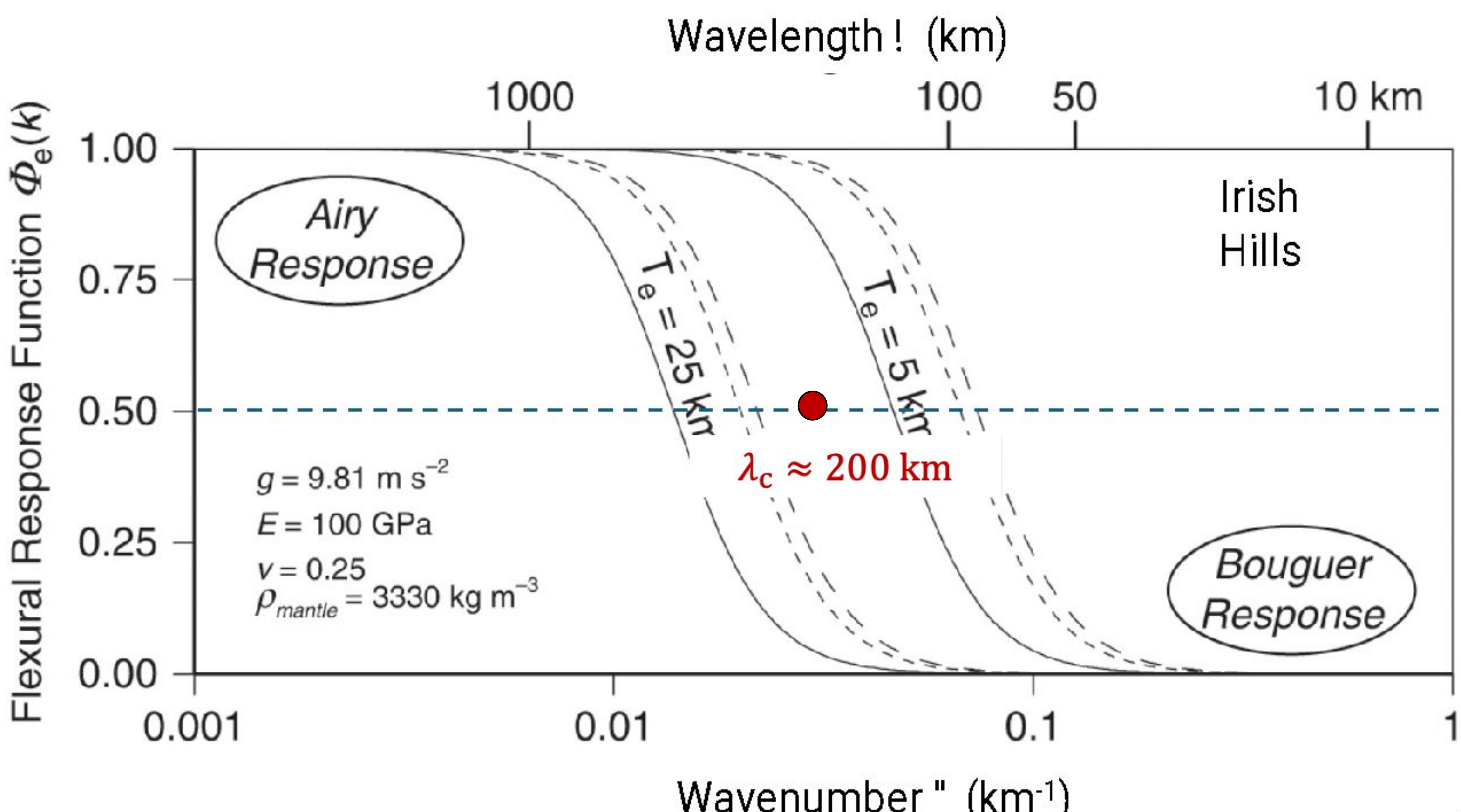
$T_e \to 0$ Airy (weak plate) compensation
$T_e \to \infty$ Bouguer (strong plate) compensation



- Flexural rigidity spreads out compensation and reduces Moho depression
- For Irish Hills:
  $T_e \approx 10$ km
  $\lambda_c \approx 200$ km

Gravimetric Analysis

- From the gravimetric analysis, the SRT concludes that
  a. Airy isostasy cannot be applied to the compensation of loads of as small as the Irish Hills (15 × 25 km)



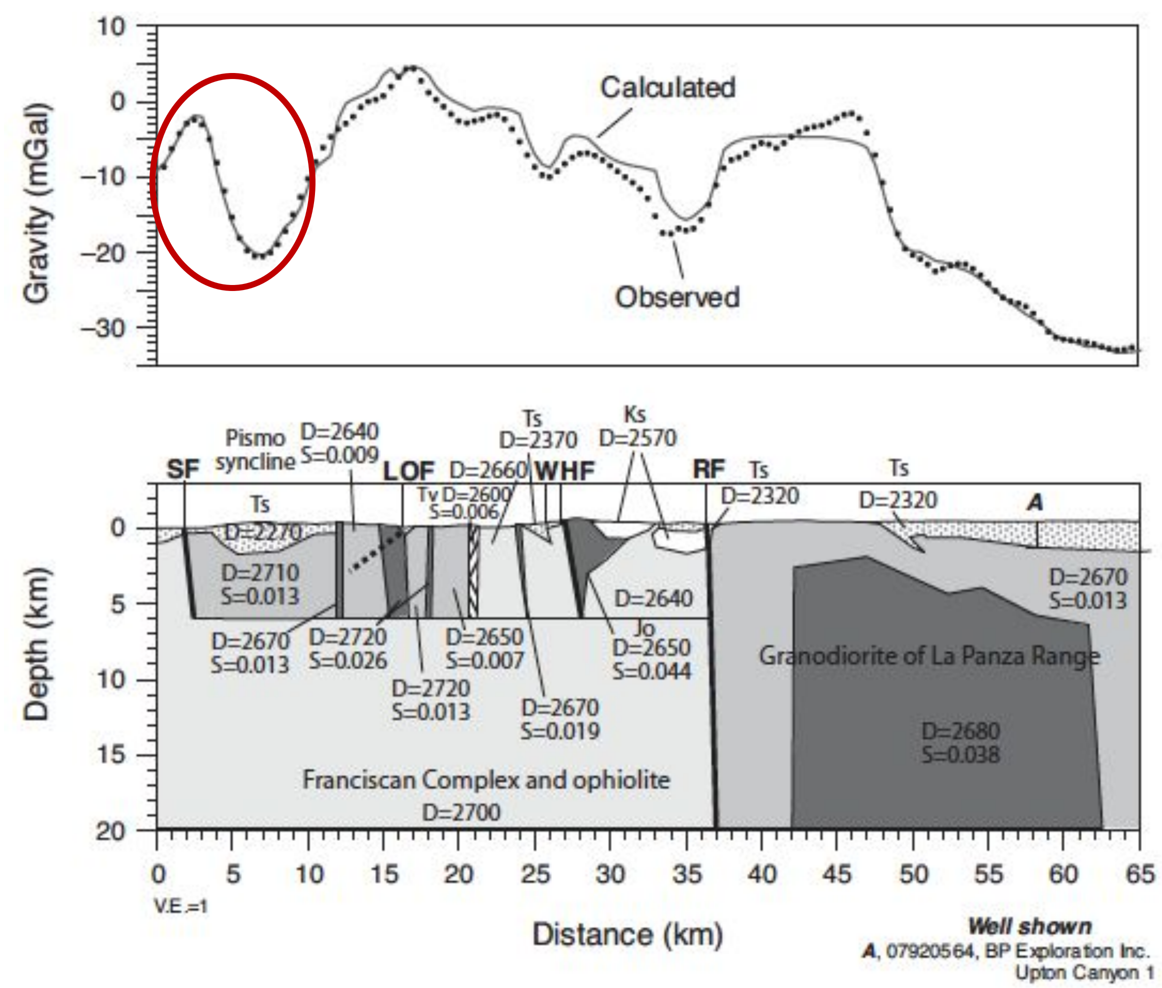
$T_e \approx 10$ km
$\lambda_c \approx 200$ km

Watts (2023, fig. 5.2)

Gravimetric Analysis

- From the gravimetric analysis, the SRT concludes that
  a. Airy isostasy cannot be applied to the compensation of loads of as small as the Irish Hills
  b. Gravity anomalies associated with the Pismo Syncline and Irish Hills can be successfully explained by plausible models based on Bouguer (rigid plate) compensation without Moho variations

"20 mgal Pismo Syncline anomaly"



Langenheim et al. (2012): *"Isostatic residual gravity anomalies reflect density variations in the upper 10-15 km with one of the most prominent density contrasts being that between low-density Neogene sedimentary rocks and dense Mesozoic basement rock types."*

Langenheim et al. (2012, fig. 10)

Gravimetric Analysis

- Bird assertion: Simple Airy isostasy implies that the ratio of crustal thickening to topographic rise is about 6. Therefore, a simple isostatic model for the total rate of thrust-fault slip under the Irish Hills is at least:

  (0.2 mm/yr uplift) × 6 / sin(25°) = 2.8 mm/yr (Bird's Method #1)

- For small areas such as the Irish Hills, the response to surface loading is Bouguer, not Airy. Hence, the factor of six in the above equation reduces to unity, and the slip rate becomes

  (0.2 mm/yr)/sin(25°) = 0.47 mm/yr

- This rate is further reduced if the average SWBZ dip of 38° is used:

  (0.2 mm/yr)/sin(38°) = 0.32 mm/yr

- Best estimate: 0.29 ± 0.07 mm/yr, based on an uplift rate of 0.18 ± 0.03 mm/yr

Fault Reactivation Analysis

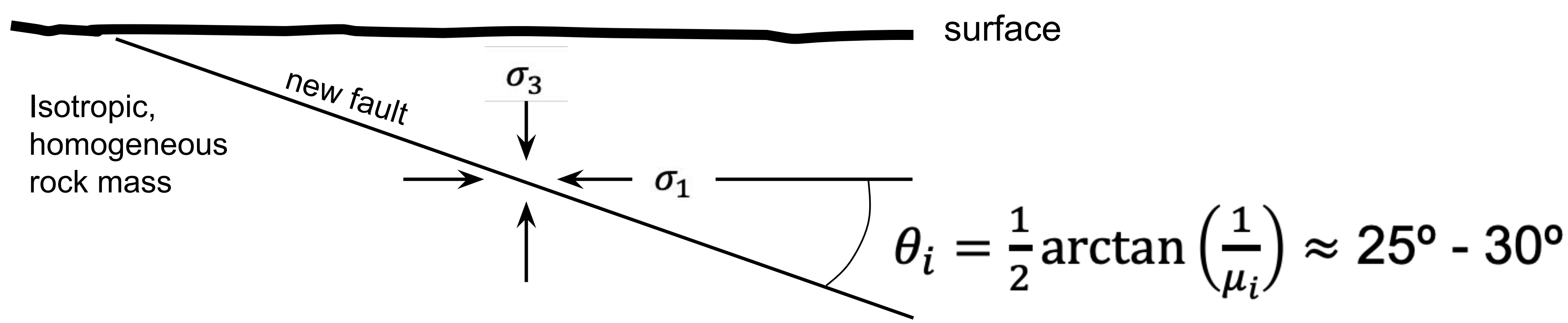
- Bird's assertion: High-angle reverse faulting in the SSC24 model is mechanically infeasible; faults with dips of 50º-80º are mechanically impossible in the present horizontal compressive stress regime

Mohr-Coulomb failure criterion:

$\tau = C + \mu_i(\sigma_n - P_f)$

Byerlee internal friction:

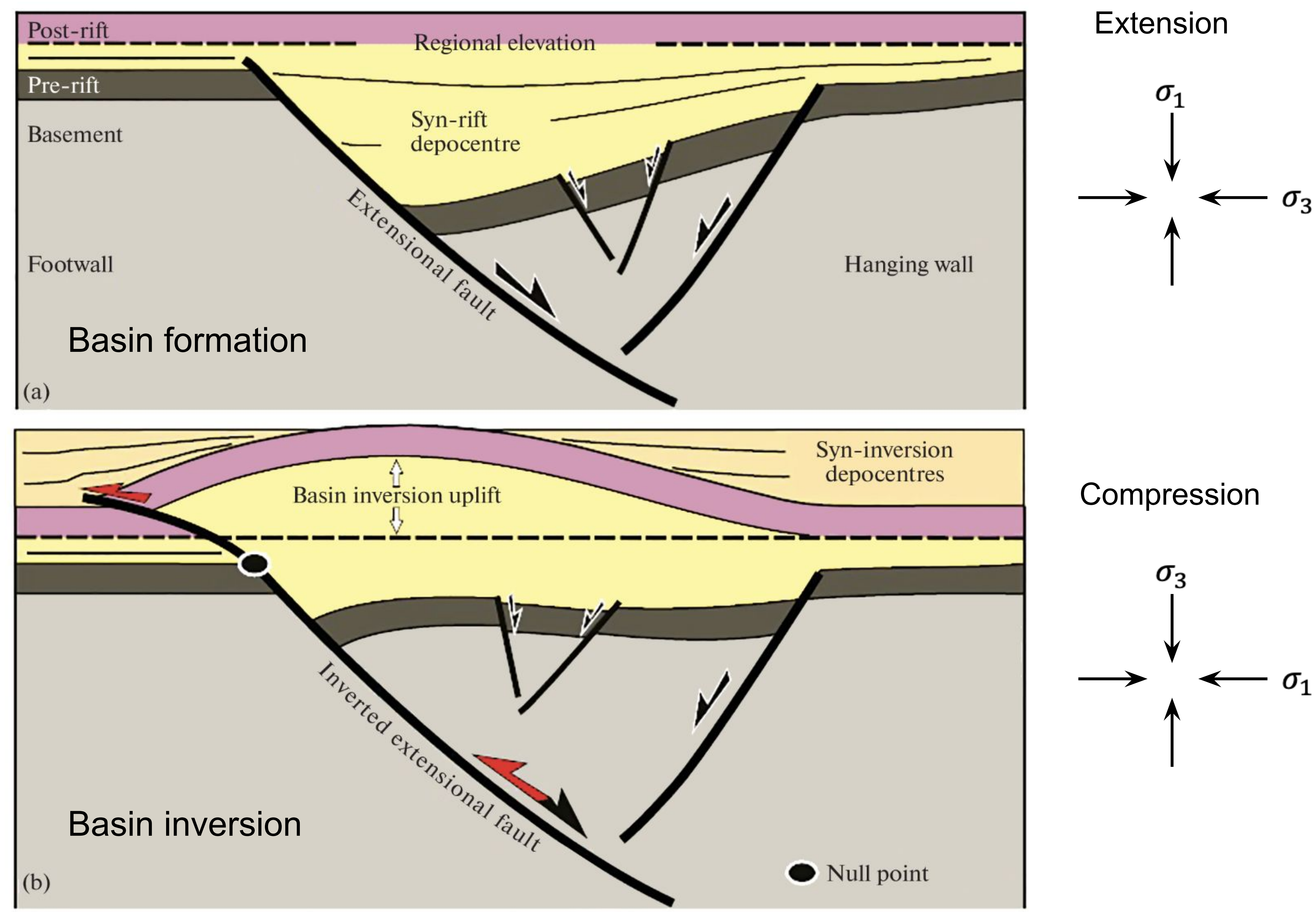
$\mu_i \approx 0.60 - 0.85$



- *The Mohr-Coulomb failure criterion for fault initiation assumes homogeneity and isotropy*
- *Does not apply to active fault systems, where most of the slip occurs on preexisting faults*

Fault Reactivation Analysis

- High-angle reverse faulting is commonly observed in inverted sedimentary basins around the world



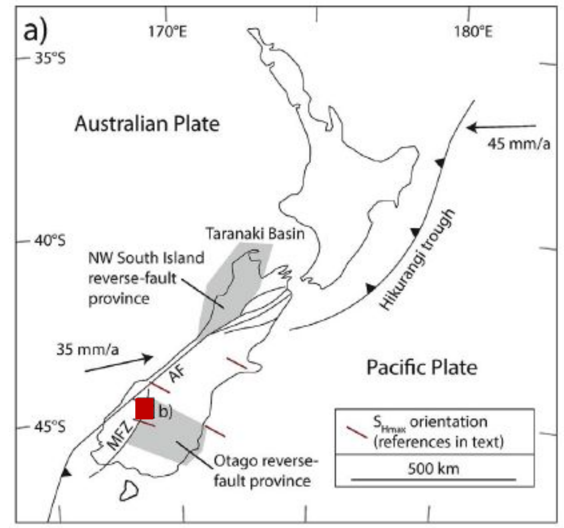
Zaidi & Ahsan (2024, fig. 1)

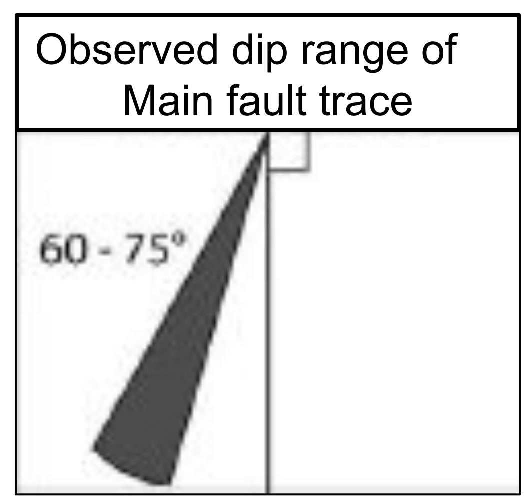
Fault Reactivation Analysis

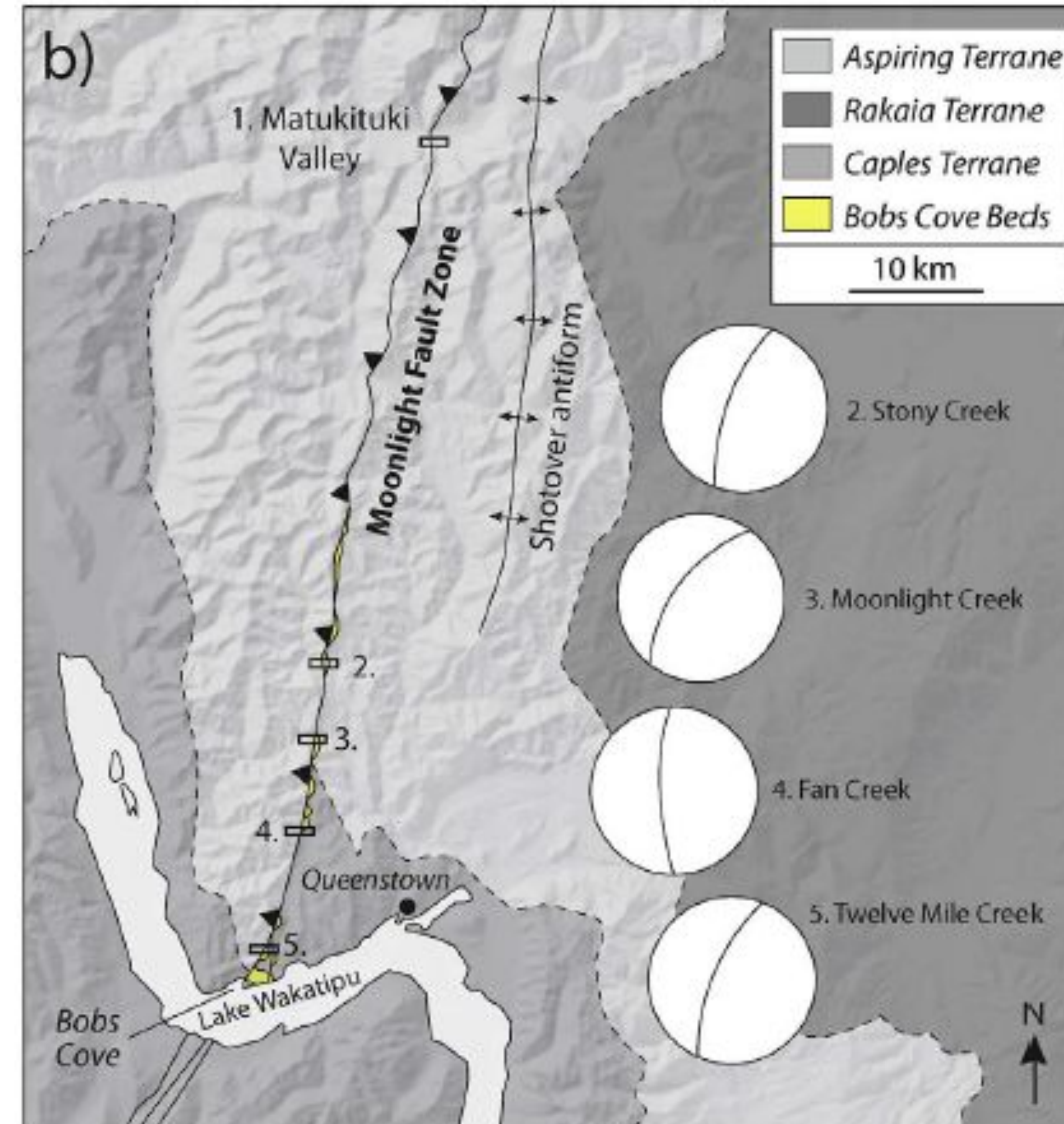
- High-angle reverse faulting is commonly observed in inverted sedimentary basins around the world
- <u>Example</u>:

  Moonlight Fault Zone, NZ (Smith et al., 2017)

  – Transpressional regime similar to the Los Osos domain







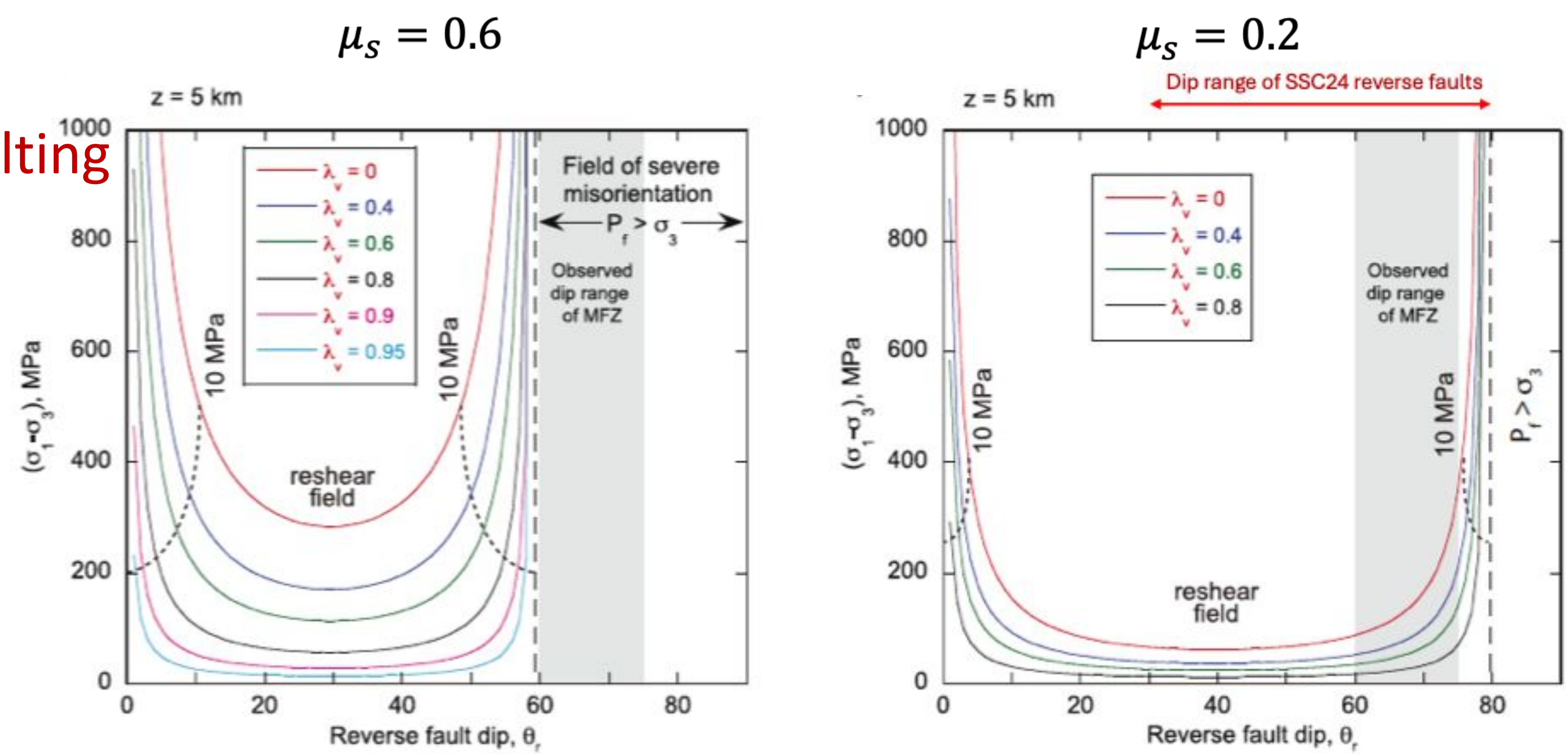
Smith et al. (2017, fig. 1)

Smith et al. (2017) measured the static friction of phyllosilicate-rich fault gouge exhumed from the fault core and obtained very low friction coefficients ($0.19 < \mu_s < 0.25$).

Fault Reactivation Analysis

High-angle reverse faulting promoted by:

1. High pore pressure
2. Weak fault gouge
3. Oblique slip



<u>SRT finding</u>: *Reverse faulting at dips of 50º-80º is mechanically feasible in the transpressive regime of the Irish Hills*

Pore fluid factor: $\lambda_v = P_f/\rho g z$

Sibson (1989) fault reactivation criterion:

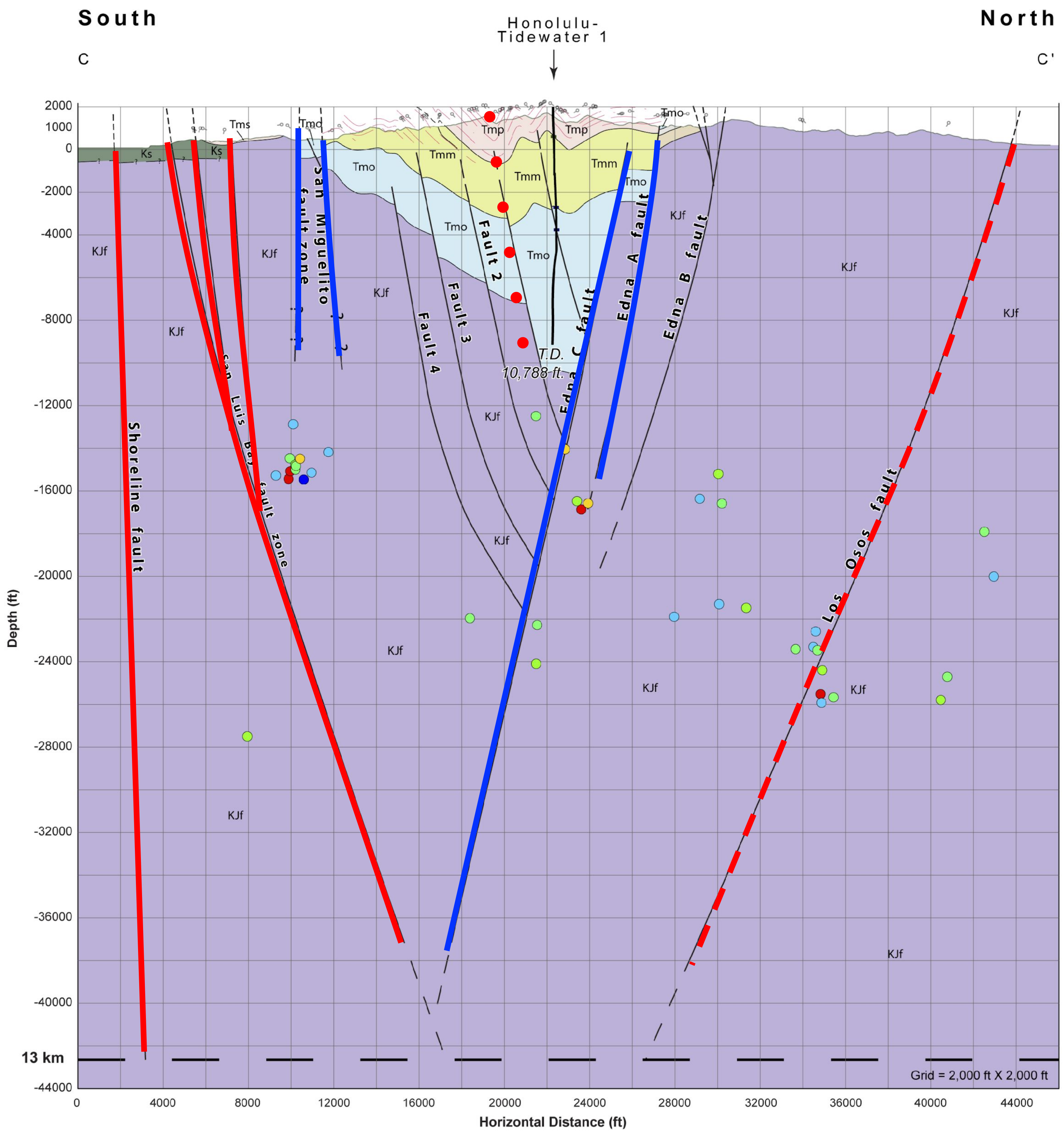
$$\sigma_1 - \sigma_3 = \mu_s \left(\frac{\tan\theta_r + \cot\theta_r}{1 - \mu_s \theta_r} \right) \rho g z (1 - \lambda_v)$$

Smith et al. (2017, fig. 6)

Fault System Analysis

Mike Oskin

Fault System Analysis



Structural Features of the Irish Hills PG&E cross-section C-C'

- Pismo Rift Basin
  - Edna Fault
  - San Miguelito Fault
- Pismo Syncline
- Southwest Boundary Zone (SWBZ)
  - San Luis Bay Fault
- Shoreline Fault
  - Intersects SWBZ along strike
- Los Osos Trend

Fault System Analysis

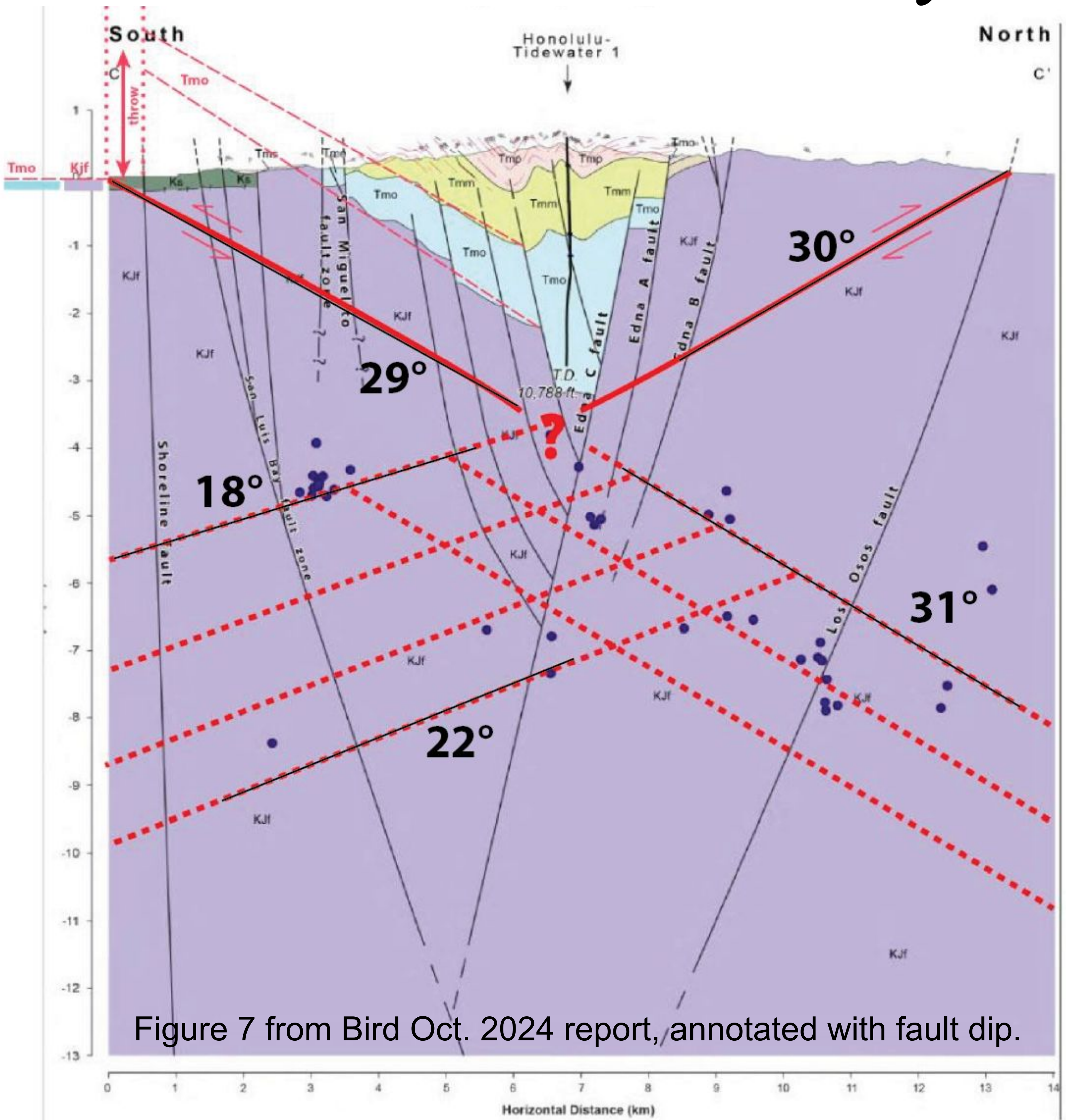
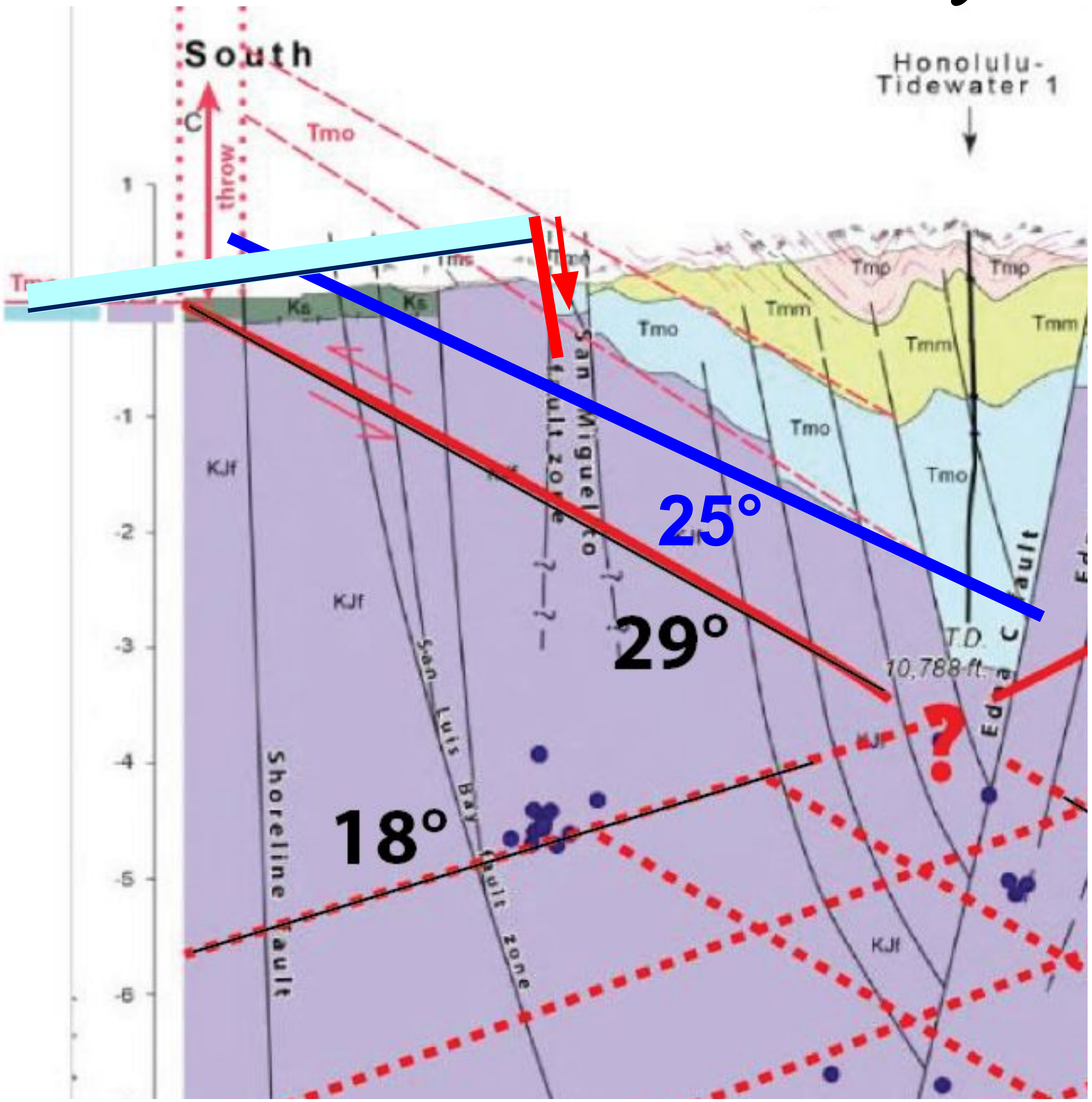


Figure 7 from Bird Oct. 2024 report, annotated with fault dip.

Bird Assertions:

- Thrust faults should dip 25° beneath the Irish Hills.
- Throw of the Obispo Formation at the San Luis Bay thrust fault is 1.6-2.2 km, implying 0.76-1.04 mm/yr.
- If thrusting has been symmetrical, then a minimum total thrust slip-rate would be 1.52-2.08 mm/year.
- This neglects internal blind thrusts,

Fault System Analysis



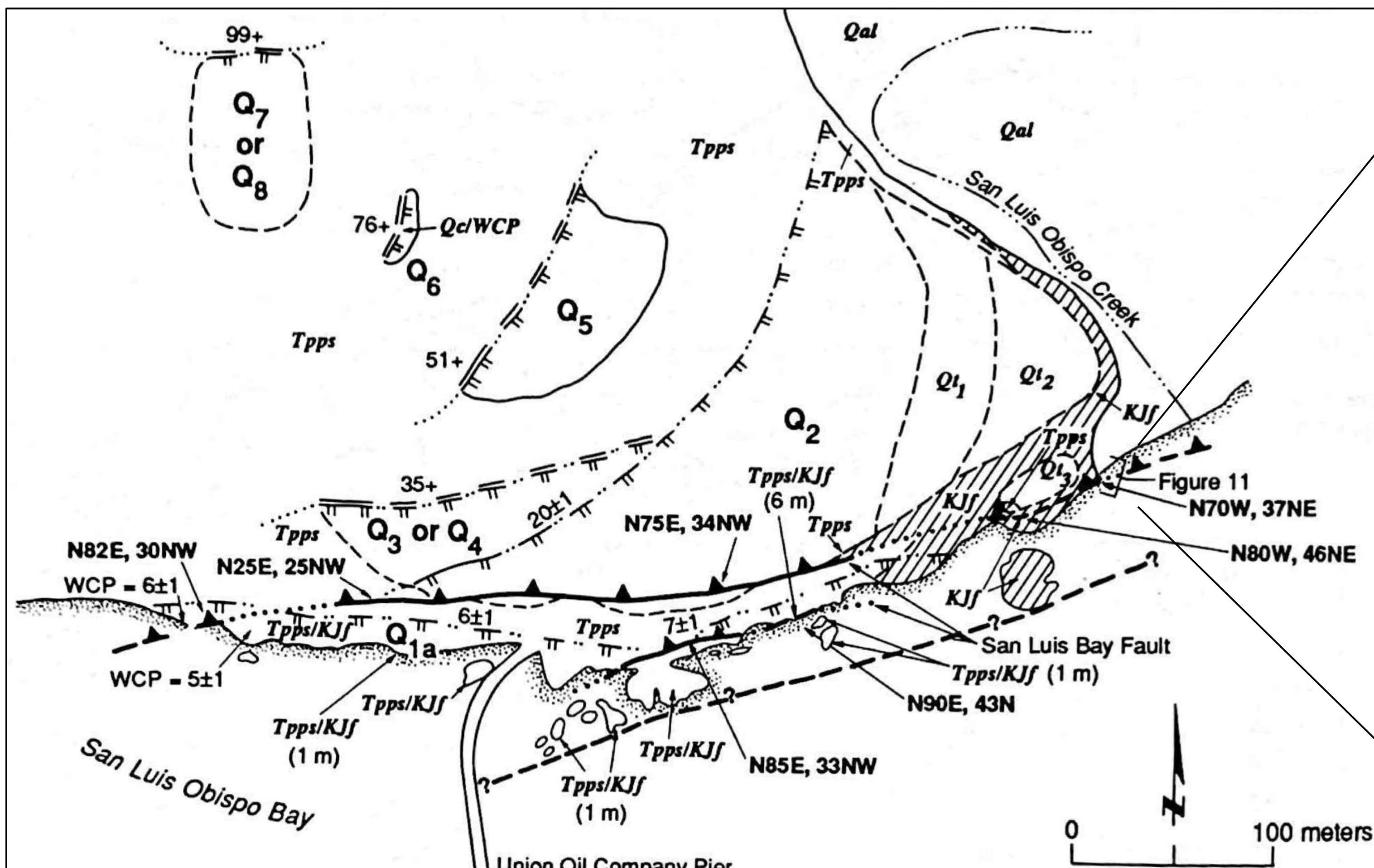
Excerpt from Figure 7 from Bird Oct. 2024 report, annotated with fault dip.

Bird Assertions:

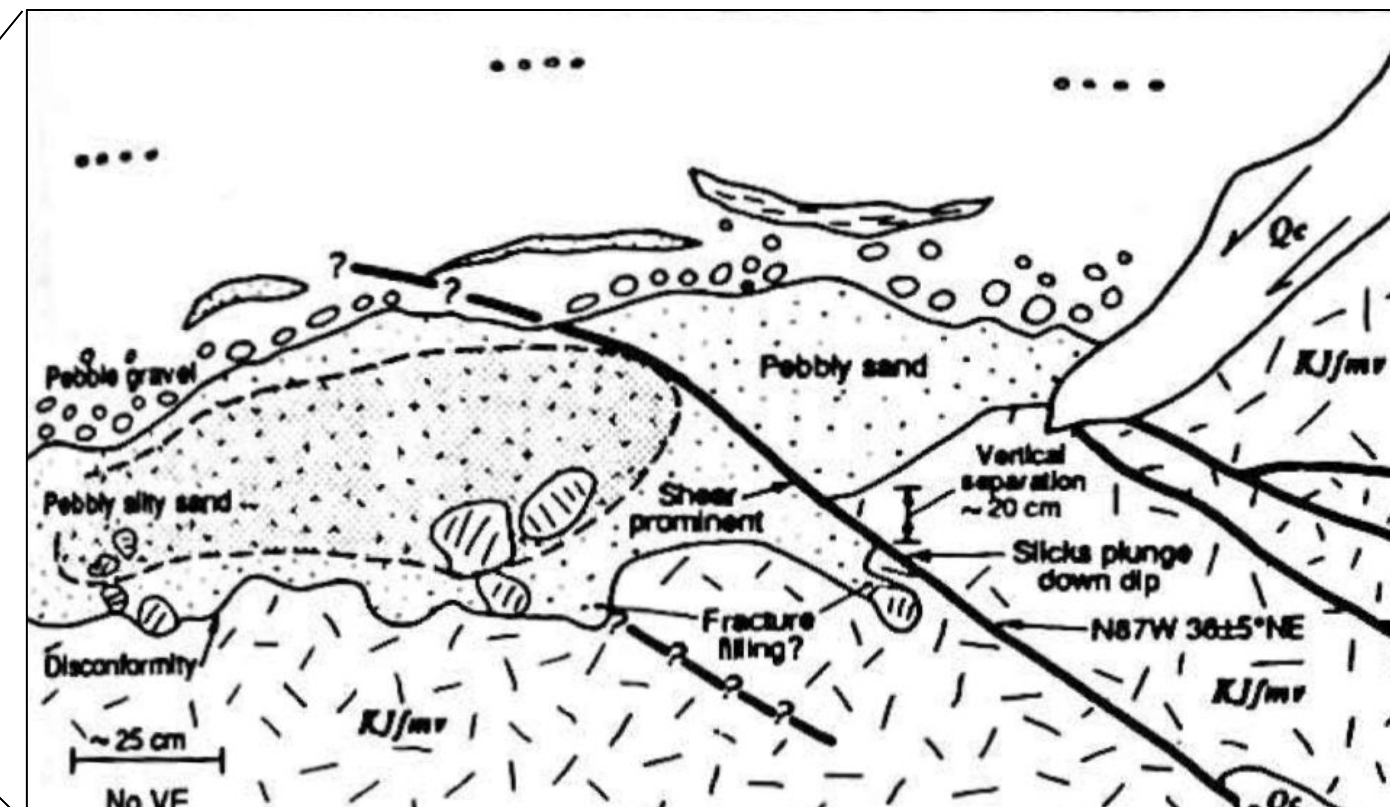
- Thrust faults should dip 25° beneath the Irish Hills.
  - A correctly positioned 25° fault dips less than the fold limb and would intersect well control within the Pismo basin.
- Throw of the Obispo Formation at the San Luis Bay thrust fault is 1.6-2.2 km, implying 0.76-1.04 mm/yr.
  - Normal slip across San Miguelito fault can explain this offset.

Fault System Analysis

- Field observations indicate Southwest Boundary Zone is moderately inclined, parallel to south limb of Pismo Syncline, dipping 38 ± 3° (standard error of mean)



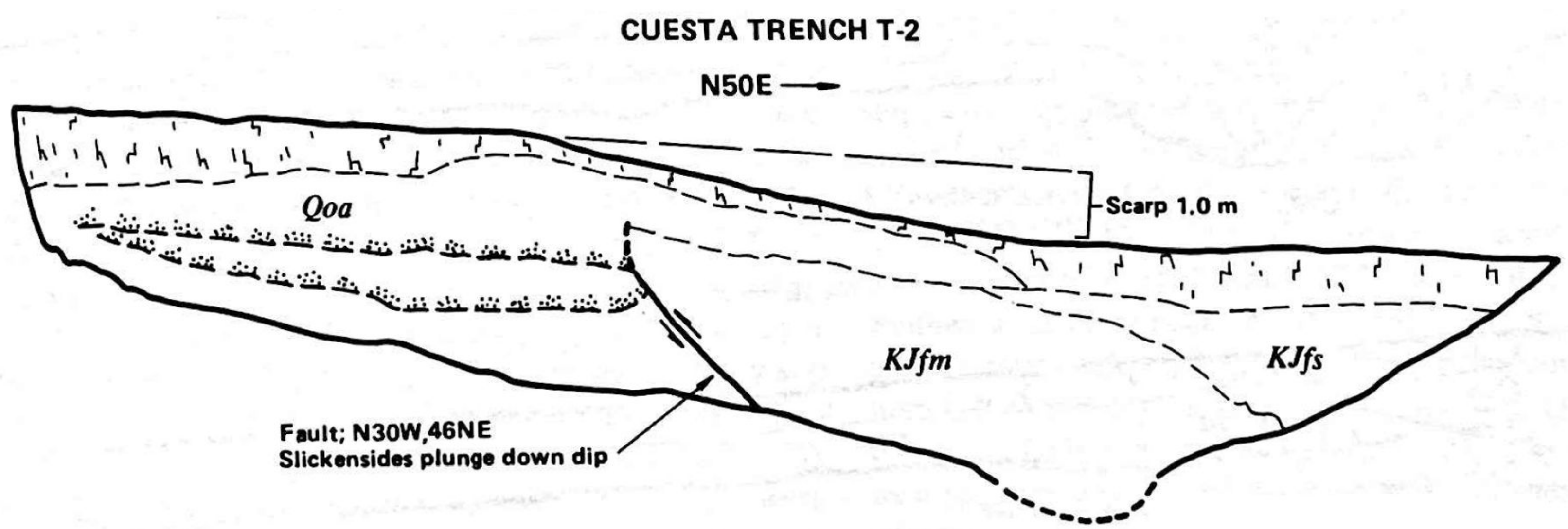
Map of San Luis Bay fault near Avila Beach
Dip measurements: 25, 30, 33, 34, 37, 43, 46°
Figure 10 from Lettis et al. (1994)



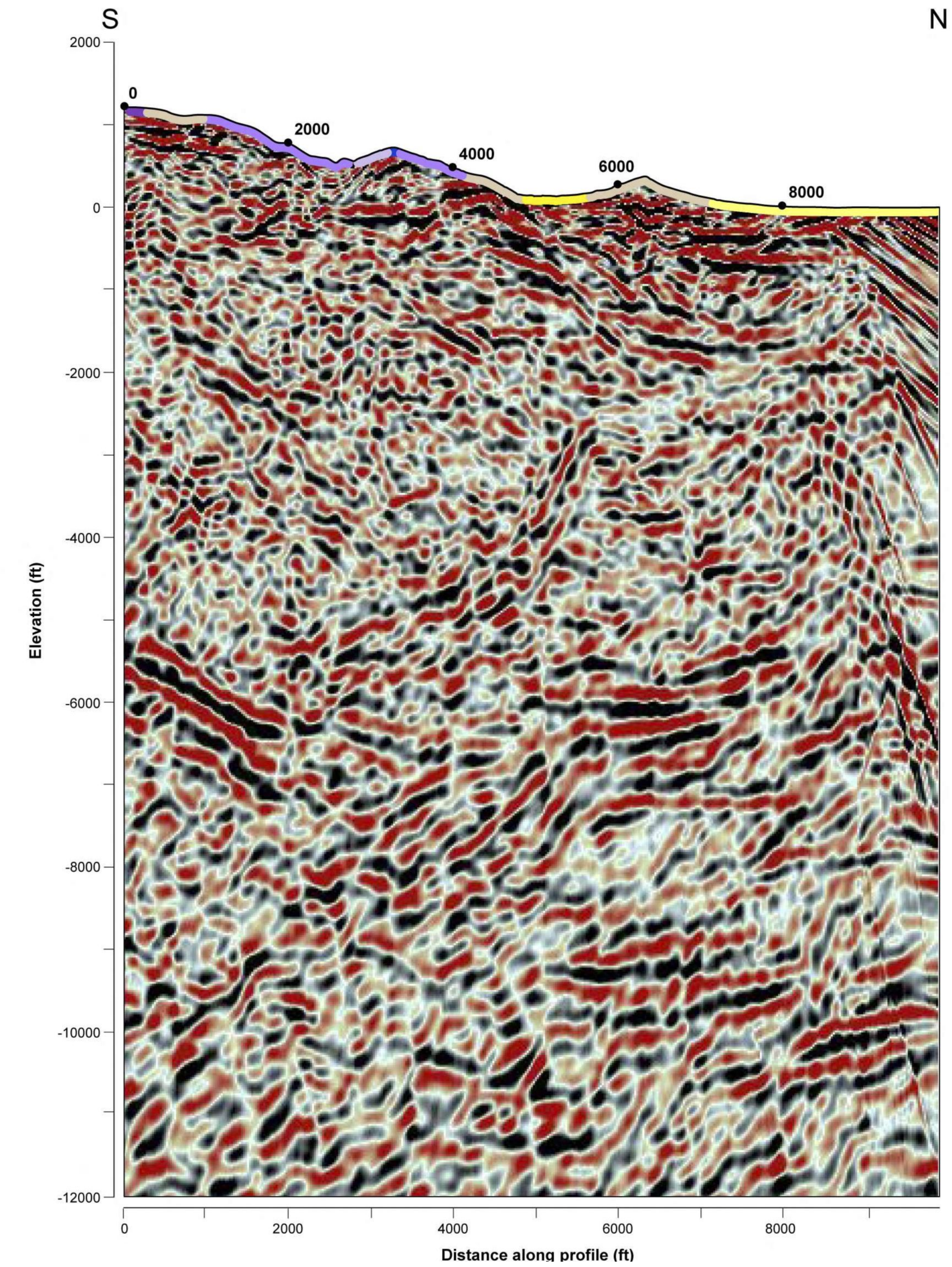
Outcrop log of San Luis Bay fault exposure,
San Luis Obispo Creek. Dip: 38±5°
Figure 11 from Lettis et al. (1994)

Fault System Analysis

- Uplift associated with Los Osos Trend is not accompanied by clear evidence of thrust faulting. Evidence favors hinge line interpretation.



Trench exposures from Lettis and Hall (1994) reveal NE-dipping faults underlie NE-facing scarps, opposite expected thrust dip direction. NE-dipping faults may be formed due to folding-related flexure.



PG&E ONSIP imaging does not clearly reveal faults within Franciscan Melange.

Fault System Analysis

- Marine terraces constrain uplift pattern and slip rate of Southwest Boundary Zone

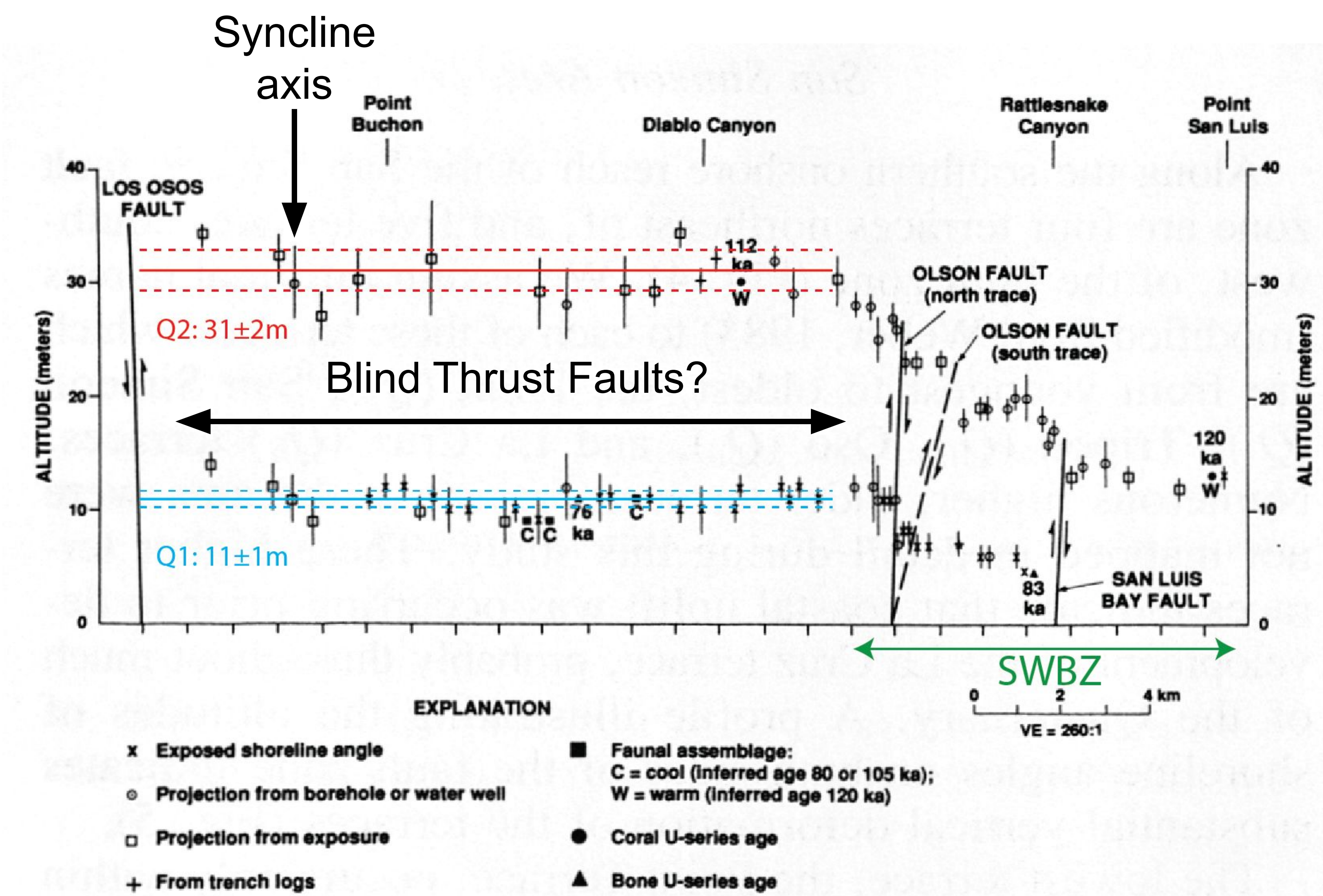


Figure 3 from Lettis & Hanson (1992), annotated to highlight uniform uplift of Irish Hills and warping associated with the Southwest Boundary Zone.

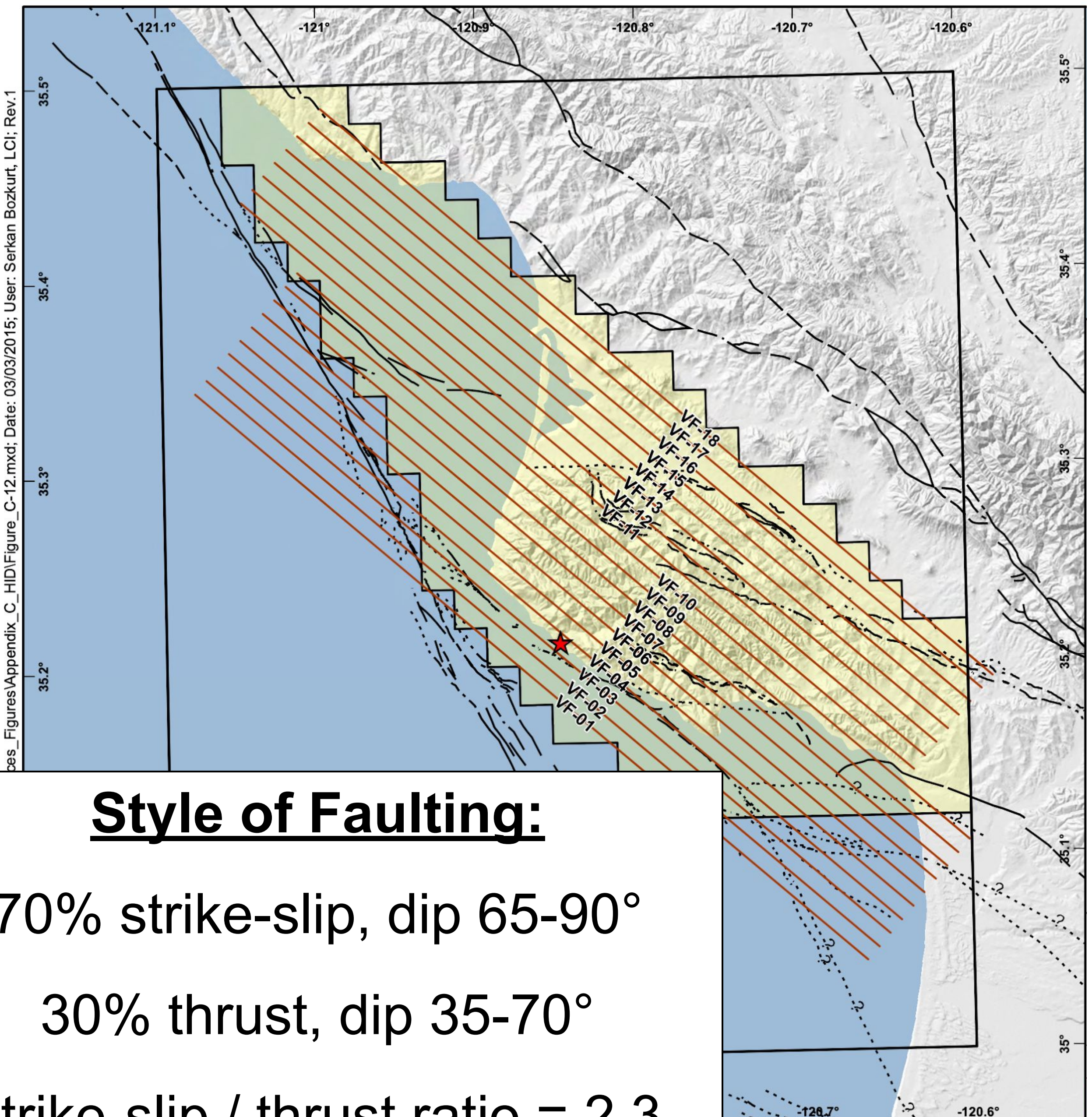
<u>Q2 terrace constraints</u>
Age: **124.0±2.5 ka**
Paleo-sea level:
6.0±1.5 m or **13.0±1.5 m**
(weighted equally)

<u>Uplift rate</u>: **0.18±0.03 mm/yr**

<u>SWBZ slip rate</u>: **0.29±0.07 mm/yr**
(38±3° fault dip)

Fault System Analysis

- The Local Areal Source Zone model accounts for possibility of a blind thrust rupture within the interior of Irish Hills, with a significant hazard contribution.

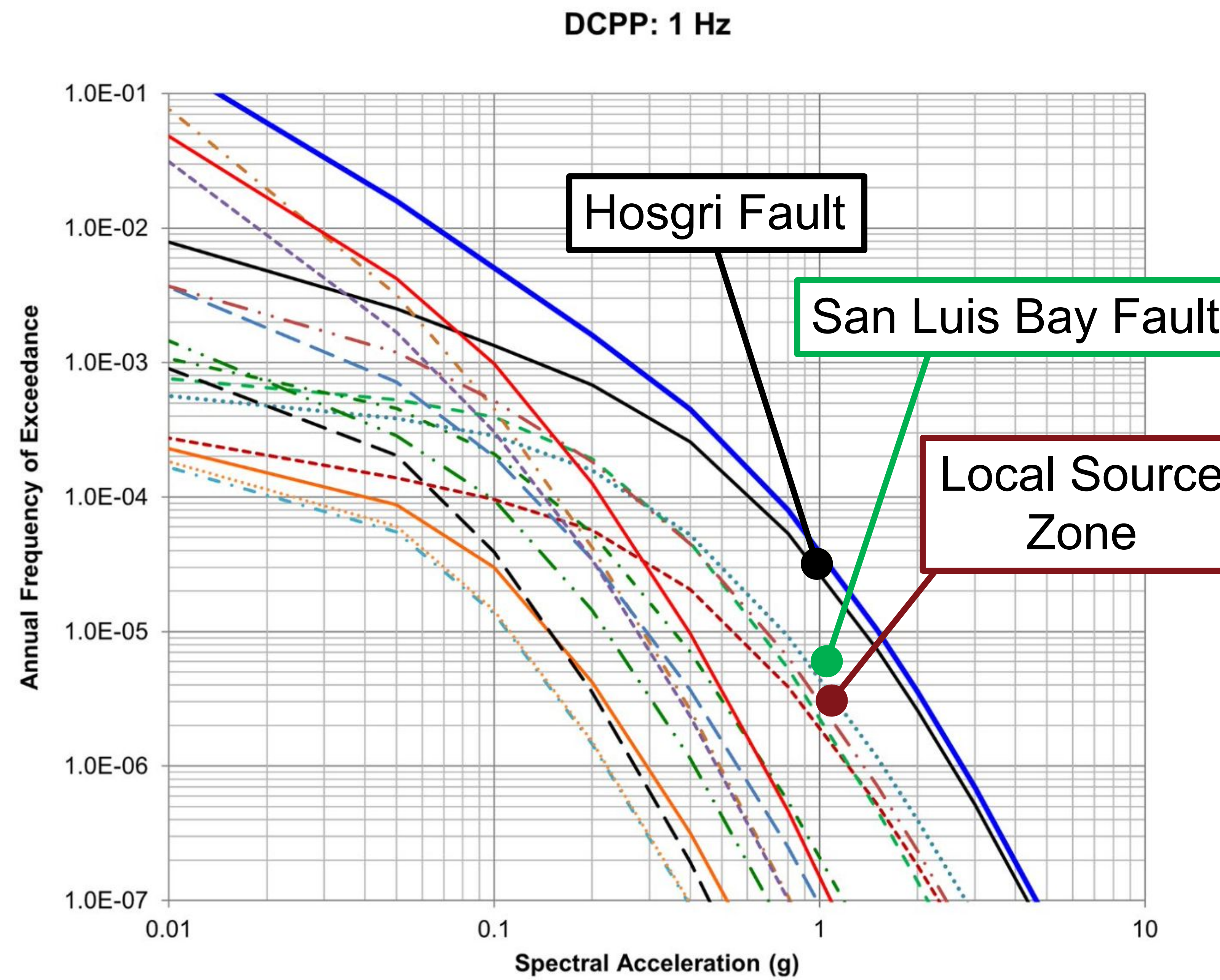


Style of Faulting:

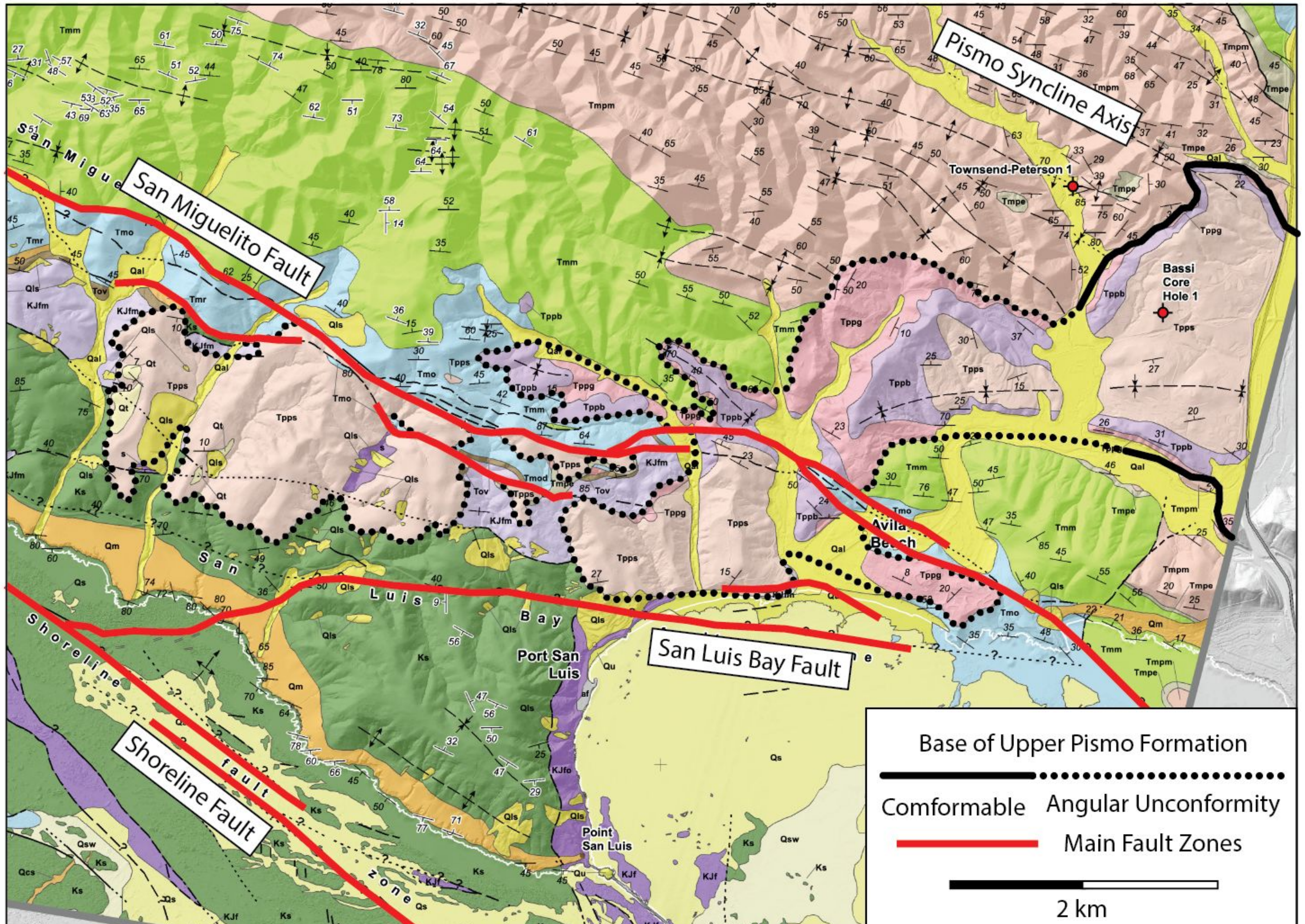
70% strike-slip, dip 65-90°

30% thrust, dip 35-70°

strike-slip / thrust ratio = 2.3

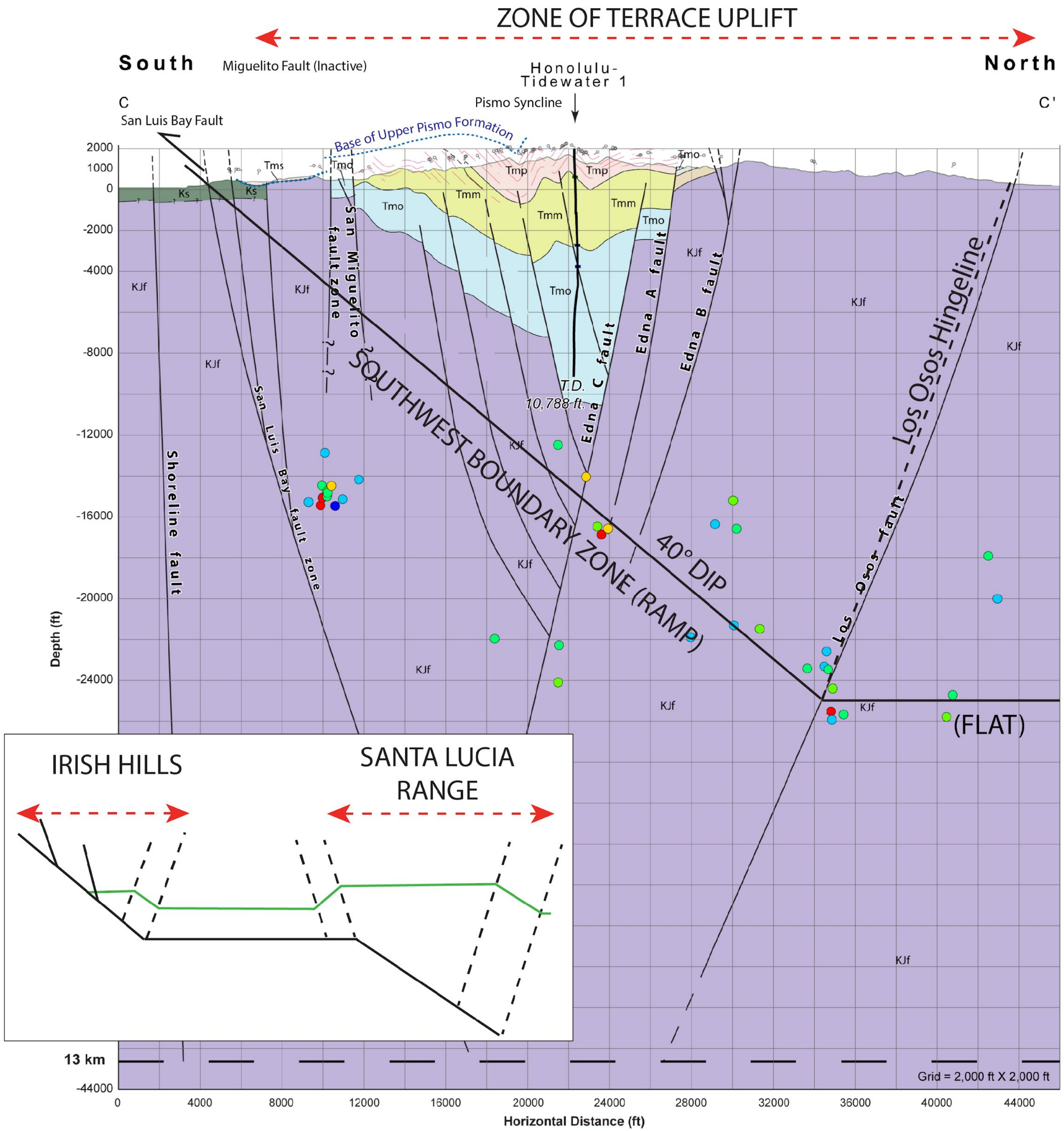


Fault System Analysis



Geologic Map Constraints

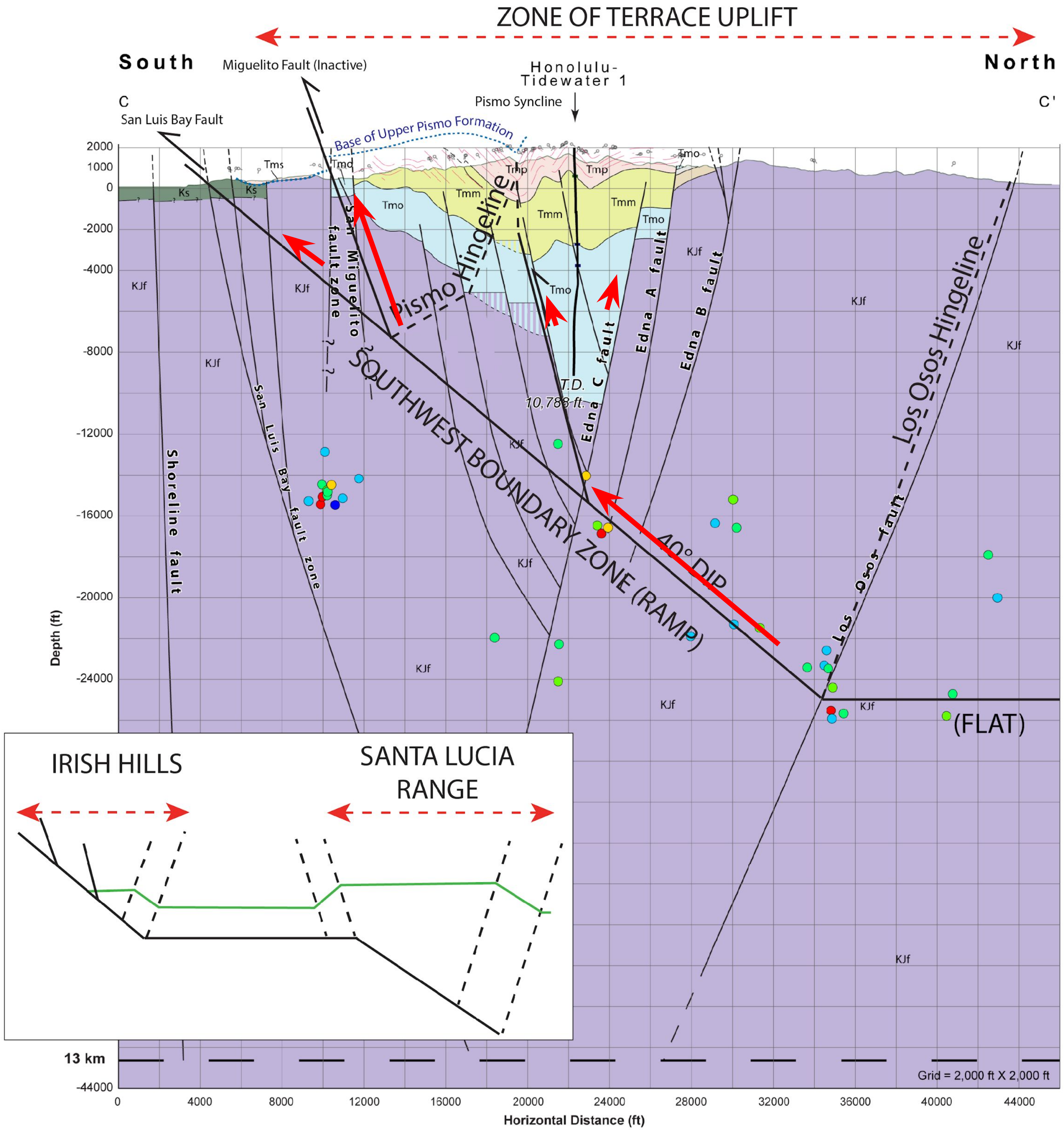
- Unconformity at base of Upper Pismo Formation records onset of folding at 5.1±0.4 Ma.
- San Miguelito fault is an inverted normal fault that bounds Pismo Syncline
- San Luis Bay fault cuts footwall of San Miguelito fault
- Preservation of these relationships implies limited SWBZ slip.



Fault System Analysis

Example Kinematically Constrained Fault Model, part I

- 40º Dipping Southwest Boundary Zone
- Los Osos Hingeline formed by ramp-flat transition.
- Explains block-like uplift evident from marine terrace record.
- SWBZ may root beneath Santa Lucia Range, forming a second zone of marine terrace uplift.



Fault System Analysis

Example Kinematically Constrained Fault Model, part II

- 1.8 ± 0.2 km reverse slip on San Miguelito fault forms south limb of Pismo Syncline.
- San Luis Bay thrust, with 0.3-0.6 km slip, forms shortcut thrust, bypassing San Miguelito fault.
- North limb of Pismo syncline absorbs 0.3-0.4 km of slip.
- 2.6±0.3 km slip / 5.1±0.4 Myr yields 0.5±0.1 mm/yr slip rate.

Fault System Analysis

From fault system analysis, the SRT concludes:

- The geological structure of the Irish Hills indicates a moderate ($38^o \pm 3^o$) dip of the SWBZ, consistent with fault-outcrop observations and reactivation of steeply dipping normal faults in its hangingwall to fold the Pismo Syncline.
- The best estimate of the SWBZ slip rate during the last 124.0 ± 2.5 ka, inferred from the uplift rate of the MIS 5e marine terrace and the SWBZ dip, is 0.29 ± 0.07 mm/yr, which is about an order of magnitude smaller than the rates proposed by Dr. Bird.
- The long-term (5 Ma) slip rate of 0.50 ± 0.10 mm/yr inferred for the SWBZ from the kinematically constrained fault analysis is marginally higher than the short-term (120 ka) rate and significantly less than Bird's long-term rate of 2 mm/yr.

Fault System Analysis

From fault system analysis, the SRT recommends:

- Development of a set of kinematically constrained structural models for reverse faults underlying the Irish Hills that can explain the folding observed since 5 Ma.
- Dating of low-stand abrasion platforms offshore, south of the Irish Hills, to further constrain the rate of footwall subsidence and its contribution to the SWBZ slip rate.
- Monitoring of IRSL-dating efforts and reassessment, if necessary, of the MIS 5 age assignments for the Q1 and Q2 terraces surrounding the Irish Hills.
- Further investigation of potential strike-slip faulting along the Los Osos trend and its impacts on the pattern of marine-terrace uplift.

Geodetic Analysis

Scott Marshall

Geodetic Analysis

- **Bird Assertion:** PG&E assumes that GPS geodetic velocities are not useful for site-specific seismic hazard estimation.
- **SRT Finding:** "Whereas geodesy-based model slip rates are interpreted to be unreliable for use as direct inputs in the SSC model for DCPP, they are useful for comparison and to document whether there are large differences between results" (SSC24, p. 116).
- SSC15 analysis and review of geodetic data: sections 4.3.2.5 and 5.1.6

Table 5-11. Comparison of Fault Source Slip Rates, 2015 SSC Model and WUS ERF-2023 Deformation Models

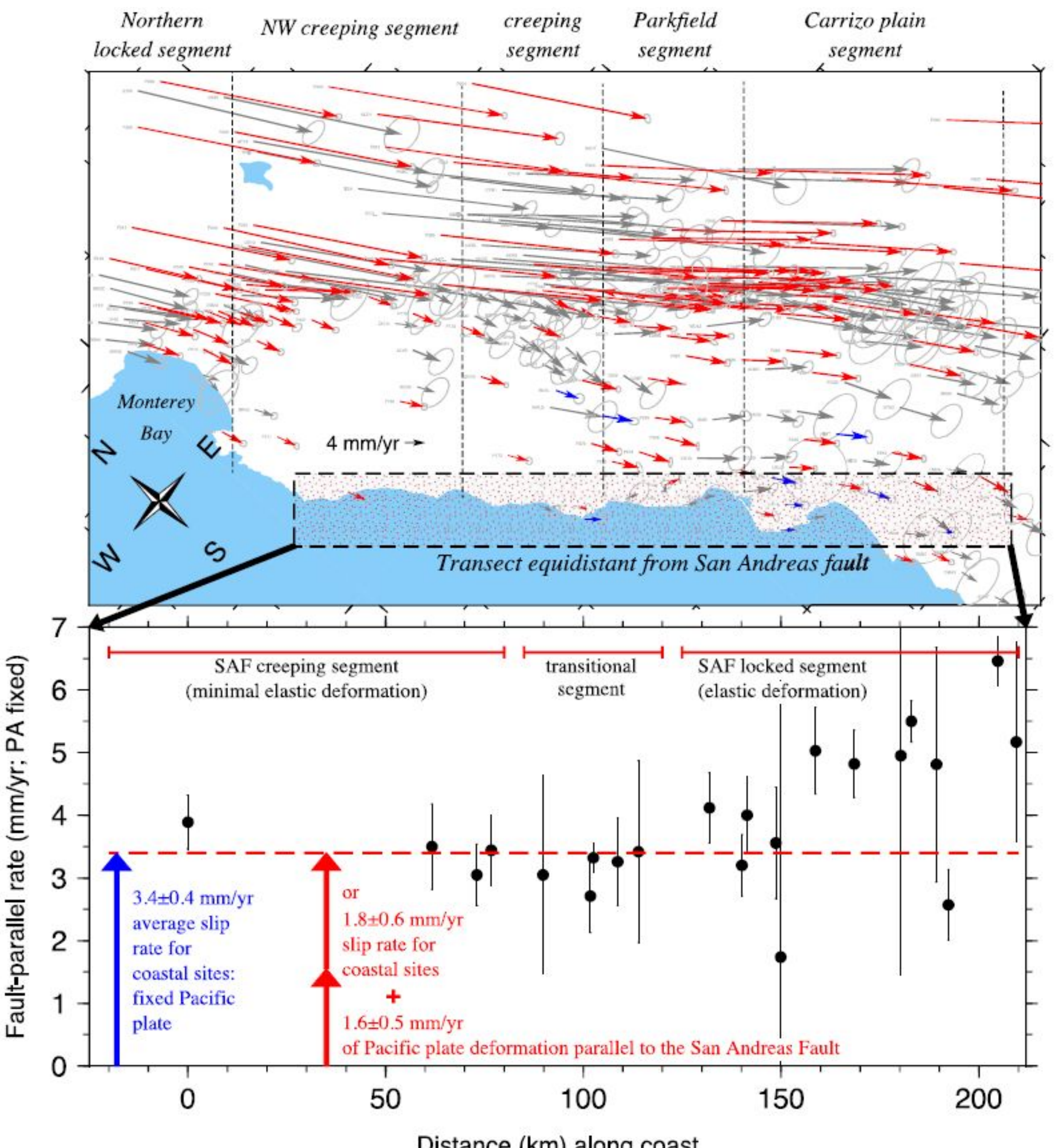
Fault Source	2015 SSC Model Rates (mm/yr)	WUS 2023-ERF Deformation Model Slip Rates (mm/yr)			
		Geologic	Pollitz	Shen-Bird	Zeng
Hosgri (all FGMs)	1.7 (0.6-3.0)	2.5 ± 1.0	3.8 ± 1.3	1.0 ± 0.5	2.8 ± 0.7
Shoreline (all FGMs)	0.07 (0.03-0.16)	0.1* ± 0.125	0.01 ± 0.08	0.05 ± 0.10	0.11 ± 0.90
Los Osos OV	0.26 (0.17-0.39)				
Los Osos SW	0.19 (0.13-0.27)	0.39* ± 0.2	0.25 ± 0.07	0.24 ± 0.08	0.21 ± 0.91
Los Osos NE	0.42 (0.31-0.55)				
San Luis Bay OV	0.16 (0.10-0.24)				
San Luis Bay SW	0.22 (0.13-0.32)	0.2*† ± 0.125	0.20† ± 0.10	0.12† ± 0.09	0.13† ± 0.7
San Luis Bay NE	0.16 (0.10-0.24)				

* A category slip rate; not based on site-specific data

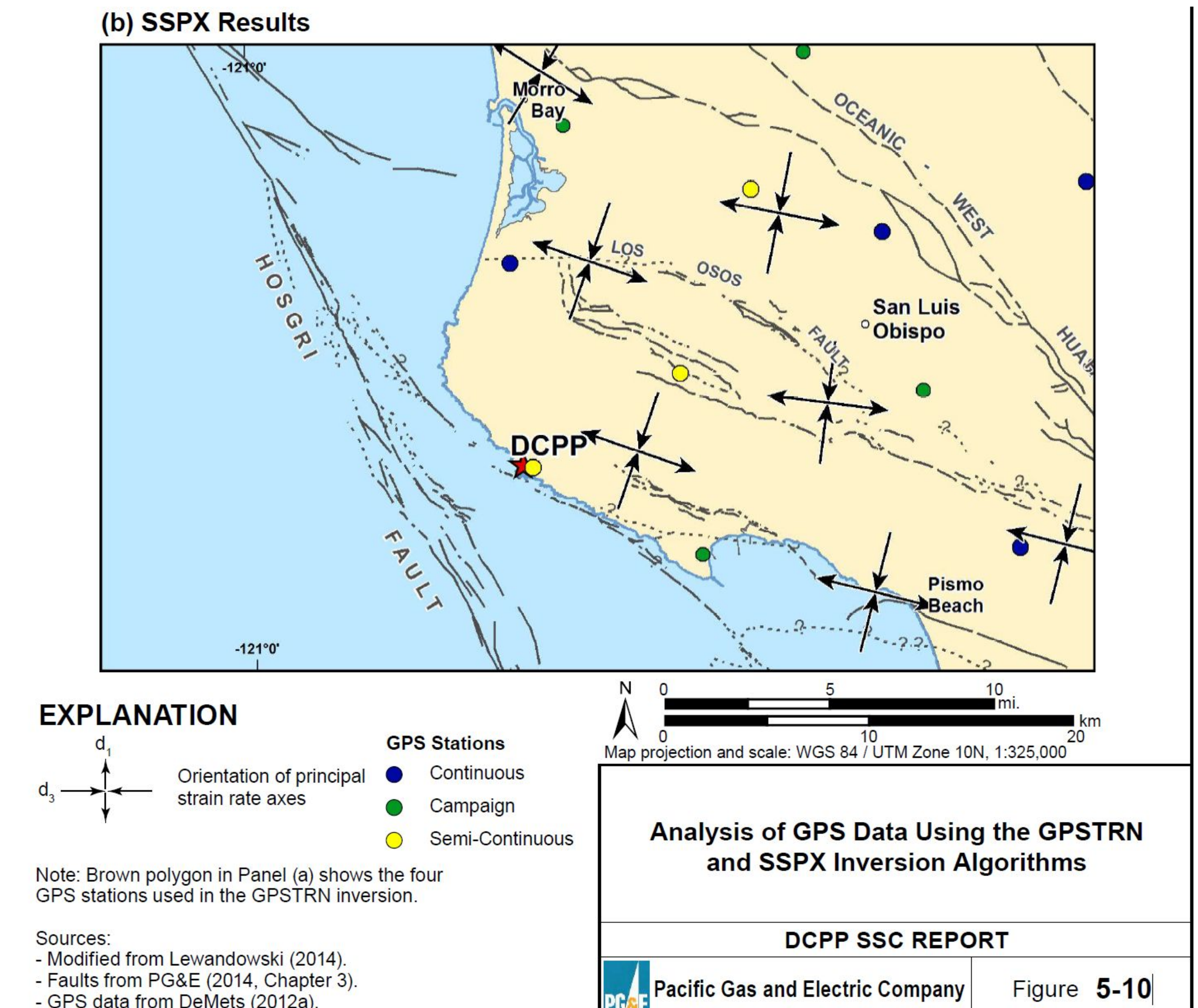
† Slip rate listed for the 45° San Luis Range (extended) source, which has a higher slip rate than the vertical San Luis Bay source in the ERF-2023 model.

Table 5-11 from SSC24

SSC15 Geodetic Analysis



SSC15 Analysis of 1D profiles through GPS
(SSC15, Figure 5-13, data from DeMets et al., 2014)

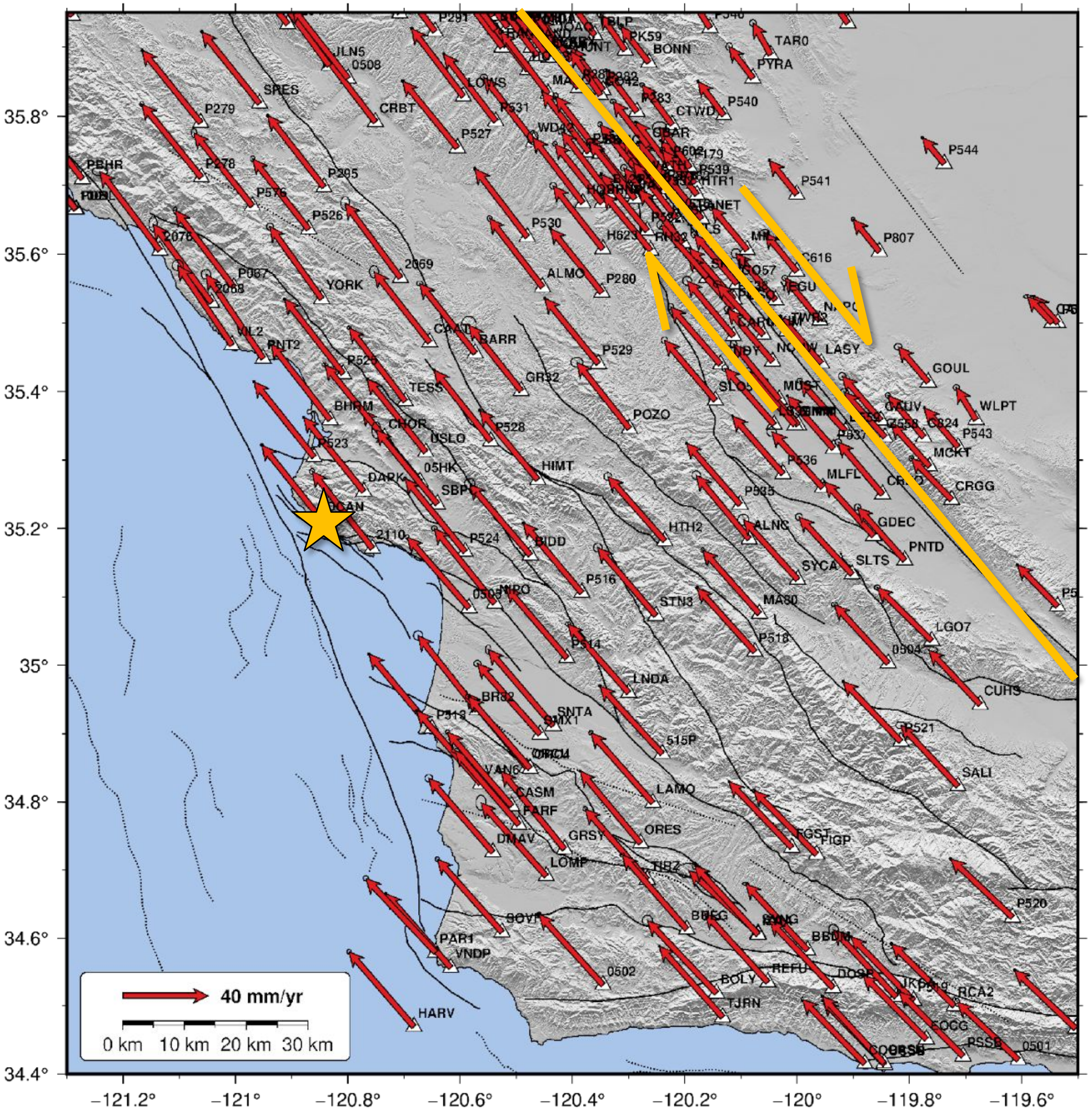


SSC15 Analysis of principal strain orientations from GPS
(SSC15, Figure 5-10, data from DeMets et al., 2012)

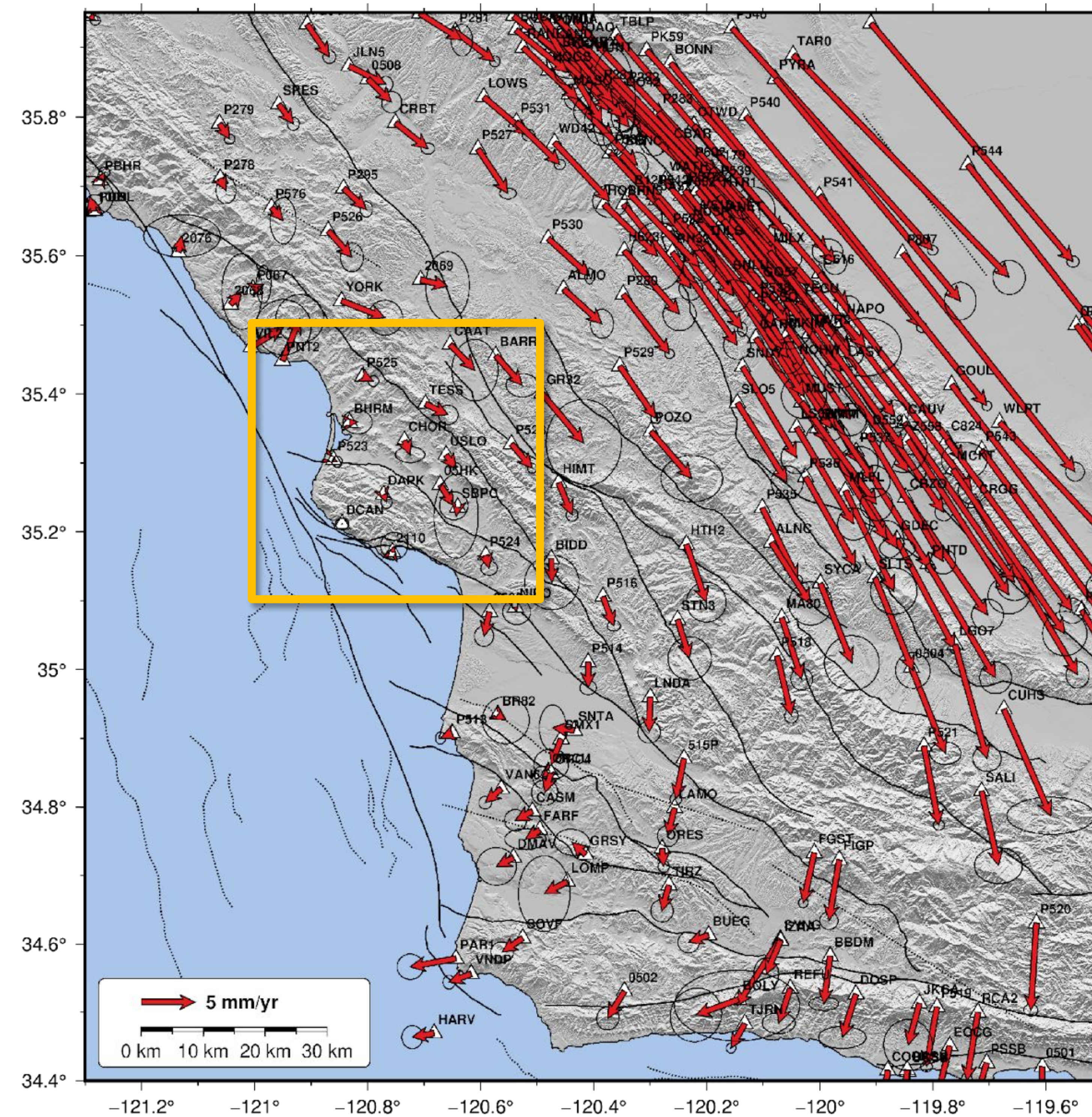
Geodetic Analysis

- **Bird Assertion:** PG&E operated a GPS receiver at DCPP, and SSC15 reported the shortening direction across the Irish Hills as ~N15ºE but did not report the shortening rate.
- **SRT Finding:** We agree that the shortening rates should have been included. Our analysis addresses this.
- **Bird Assertion:** The SSC24 update added no new geodetic information, even though an additional 9 years of data should have greatly reduced all uncertainties!
- **SRT Finding:** The east and north standard deviations of the DCAN velocity vector are 1.97 and 1.88 mm/yr, respectively, for the Murray-Moraleda et al. (2011) dataset and 0.25 and 0.23 mm/yr, respectively, for the Zeng (2022) dataset—an eightfold reduction of uncertainty. This motivated a new analysis.

Zeng (2022) GPS Velocities



Zeng (2022) GPS velocities relative to the North American plate. Faults from the SCEC Community Fault Model v7.0

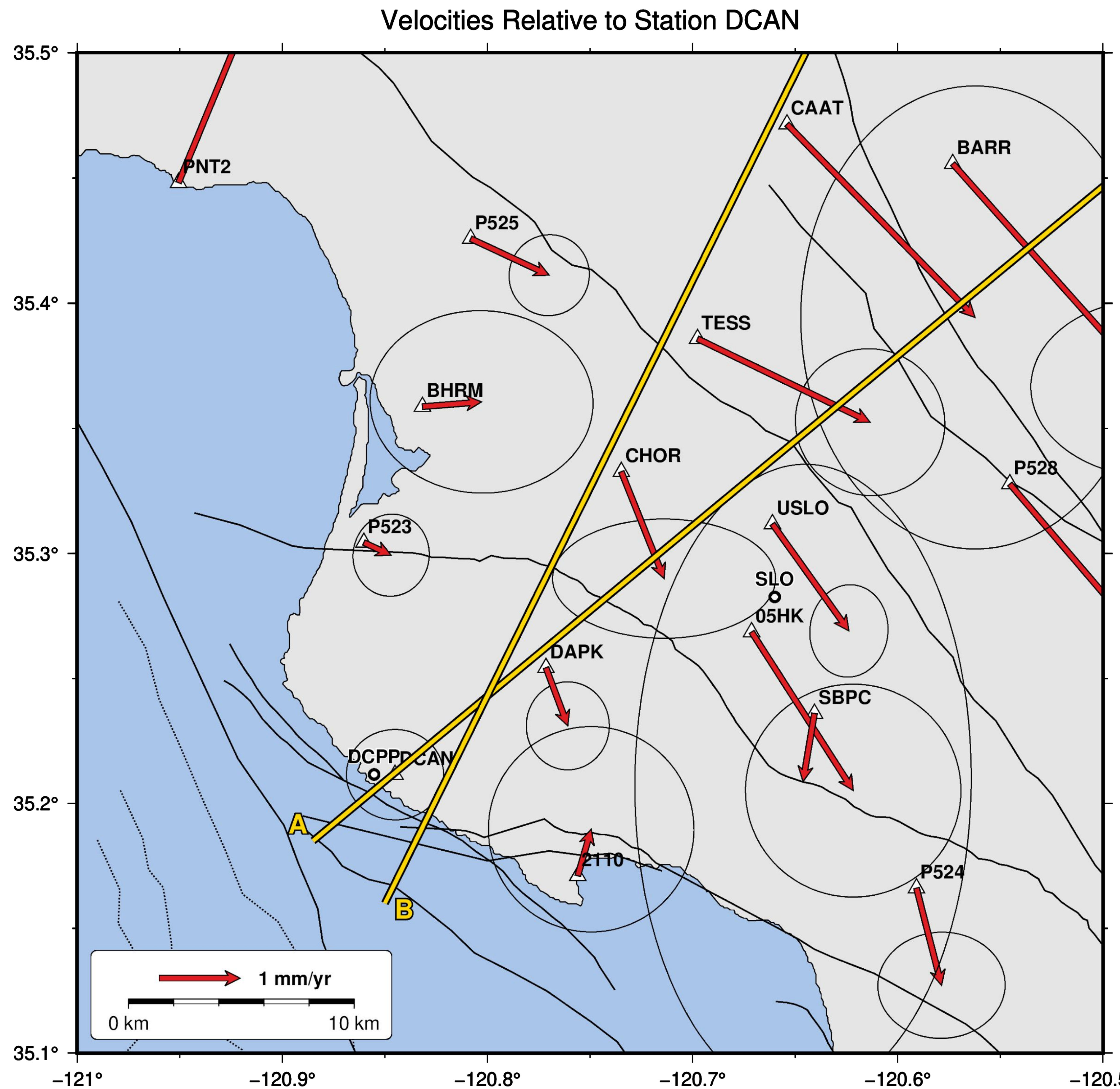


Zeng (2022) GPS velocities relative to station DCAN

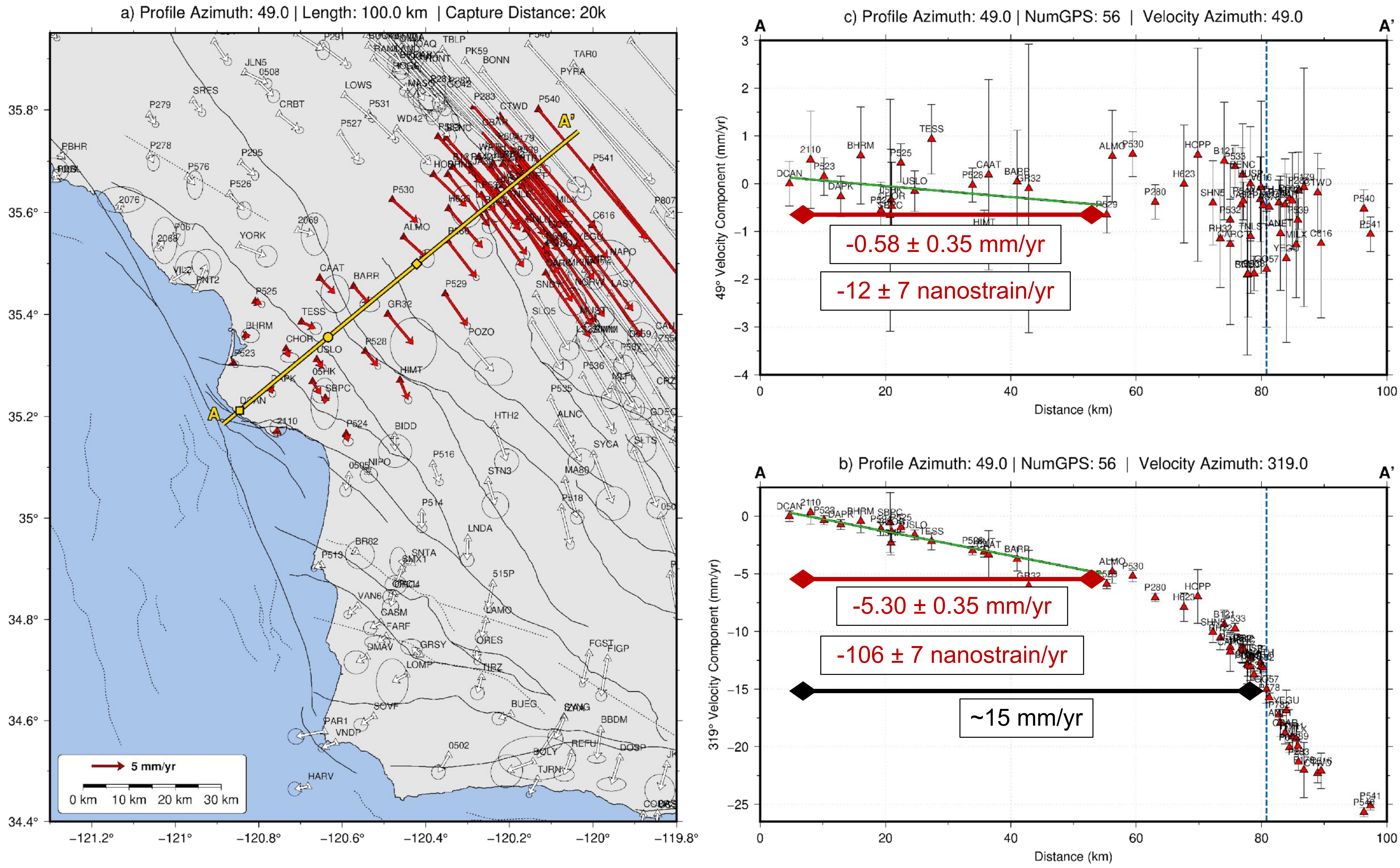
GPS Station Velocities

Bird Assertions:

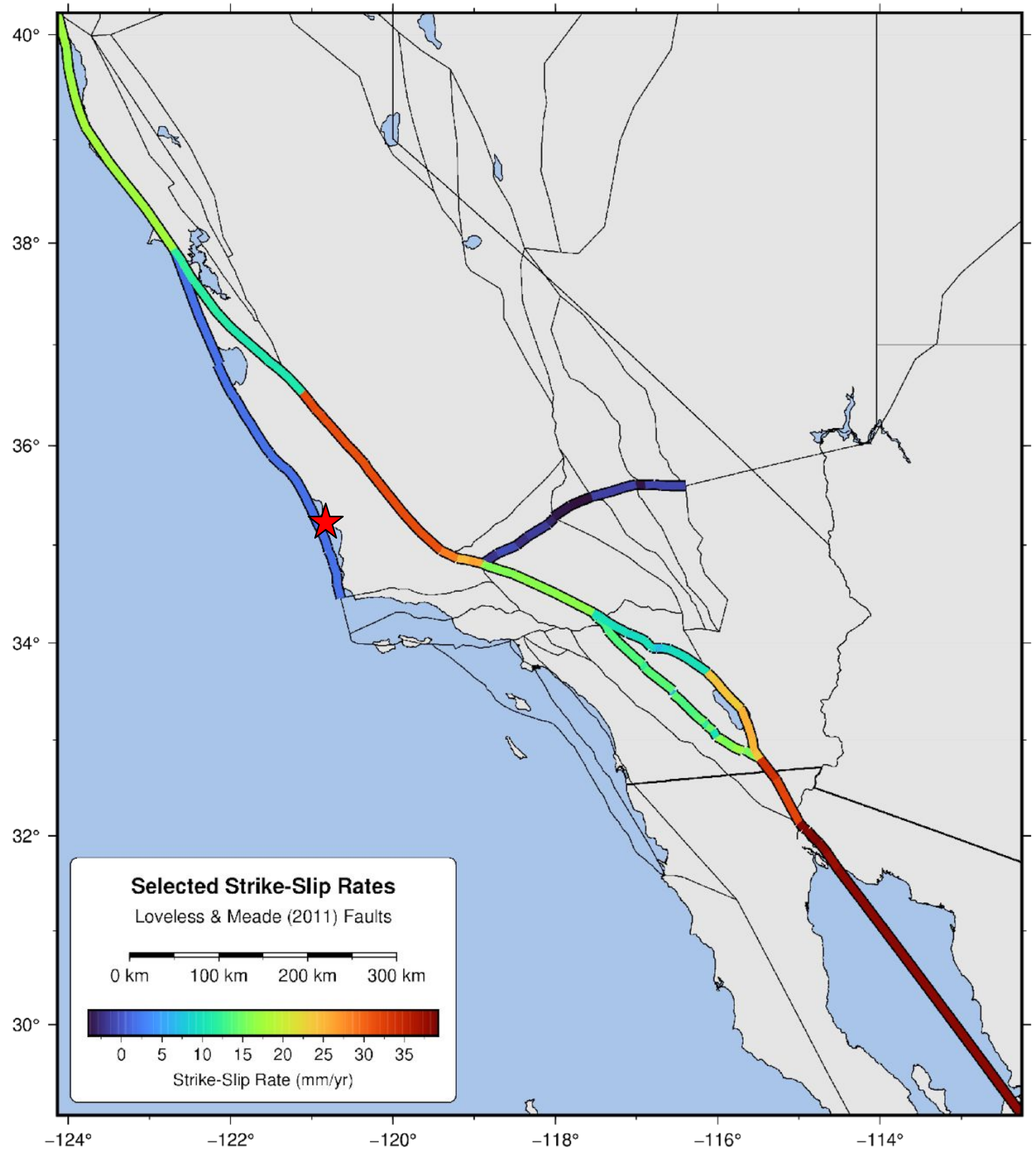
- DCAN is converging at 0.4 mm/yr with respect to DAPK and converging at 1.1 mm/yr with respect to CHOR.
- Site 2110 is converging at 1.7 mm/yr with respect to DAPK (half-way across the Irish Hills) and converging at 2.4 mm/yr with respect to CHOR.
- Bird Summary: The average of the DCAN-CHOR and 2110-CHOR interseismic shortening rate is 1.8 mm/yr.
- **SRT Findings:** 1) We cannot reproduce these velocities. 2) Velocities and station locations should be projected in a consistent direction to evaluate deformation.



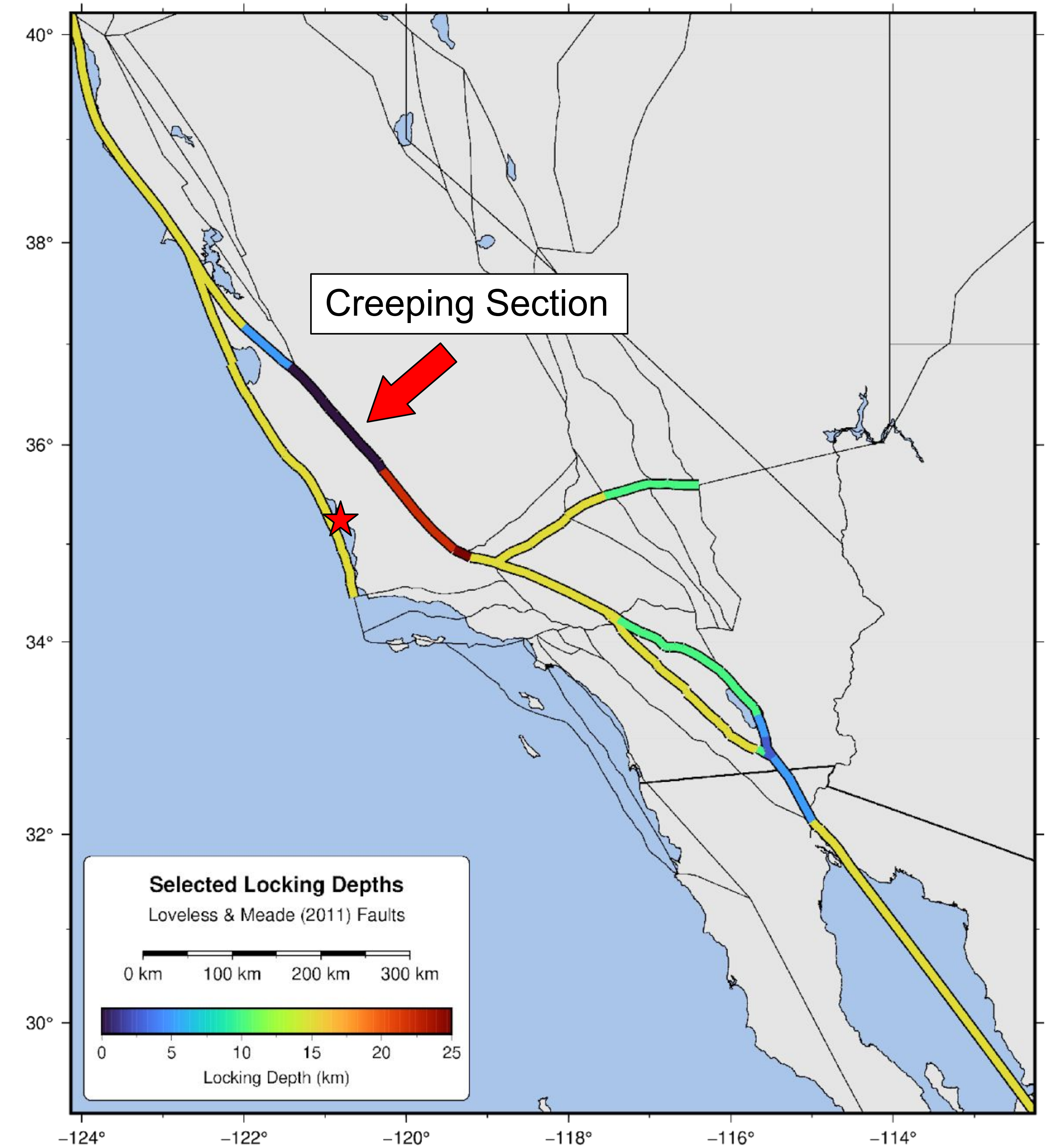
San Andreas fault-Normal Profile



Removing San Andreas and other Deformation

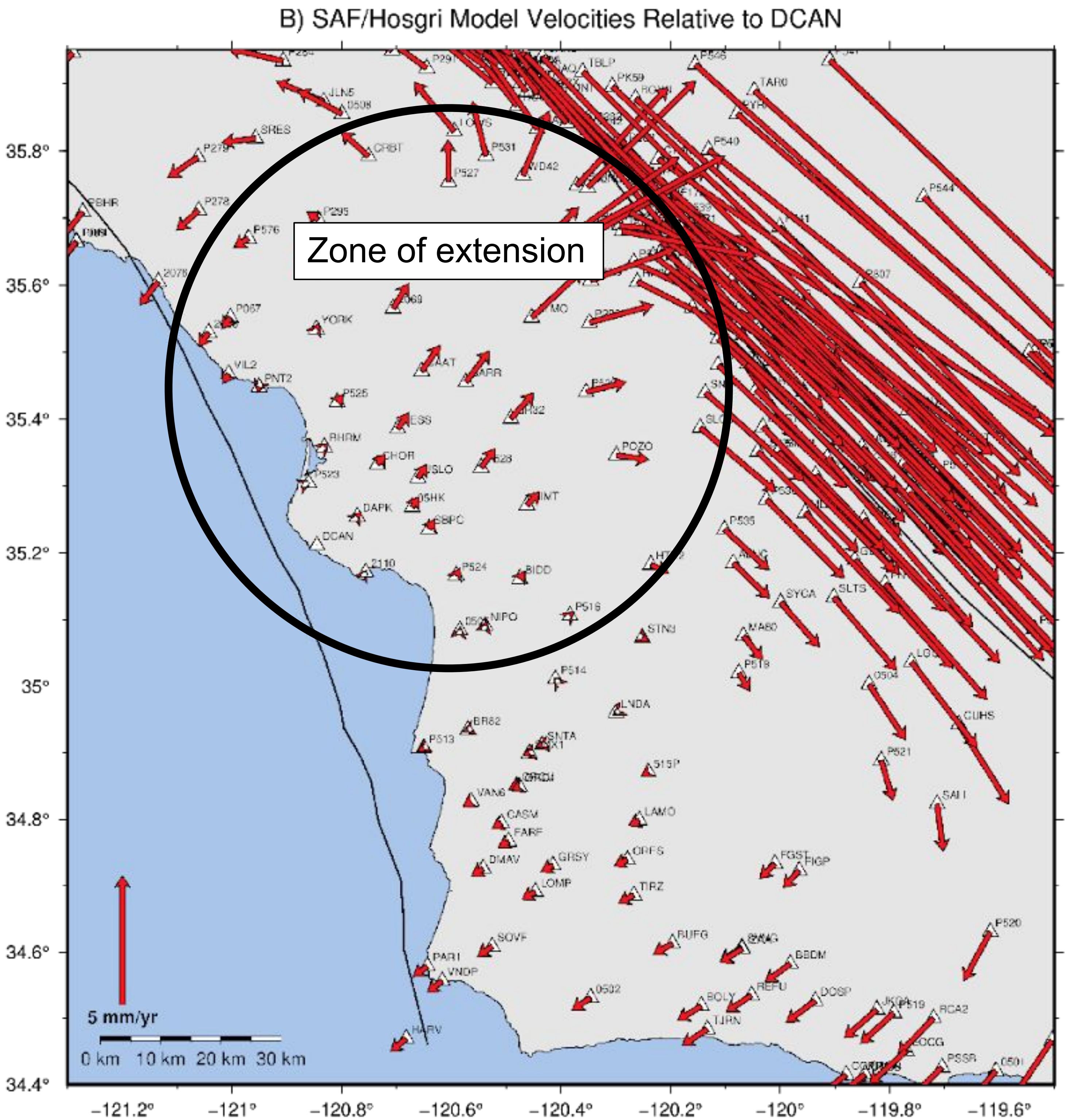


Fault geometry and slip rates from Loveless & Meade (2011). All faults are vertical. The Hosgri-San Gregorio fault is assigned the SSC24 average slip rate of 1.7 mm/yr

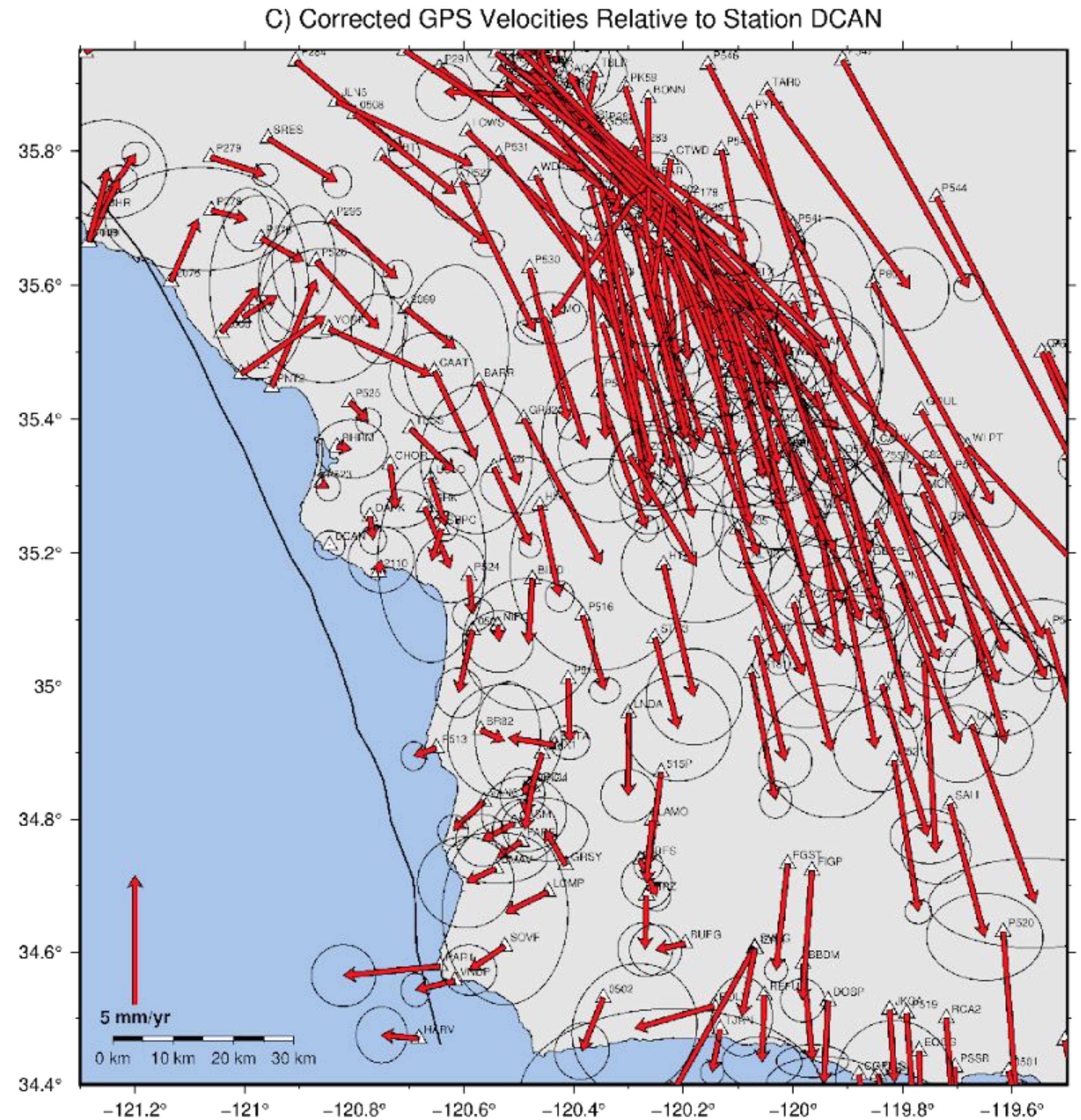


Locking depths from Loveless & Meade (2011). Note the SAF creeping section has a locking depth of zero.

“Corrected” GPS Velocities

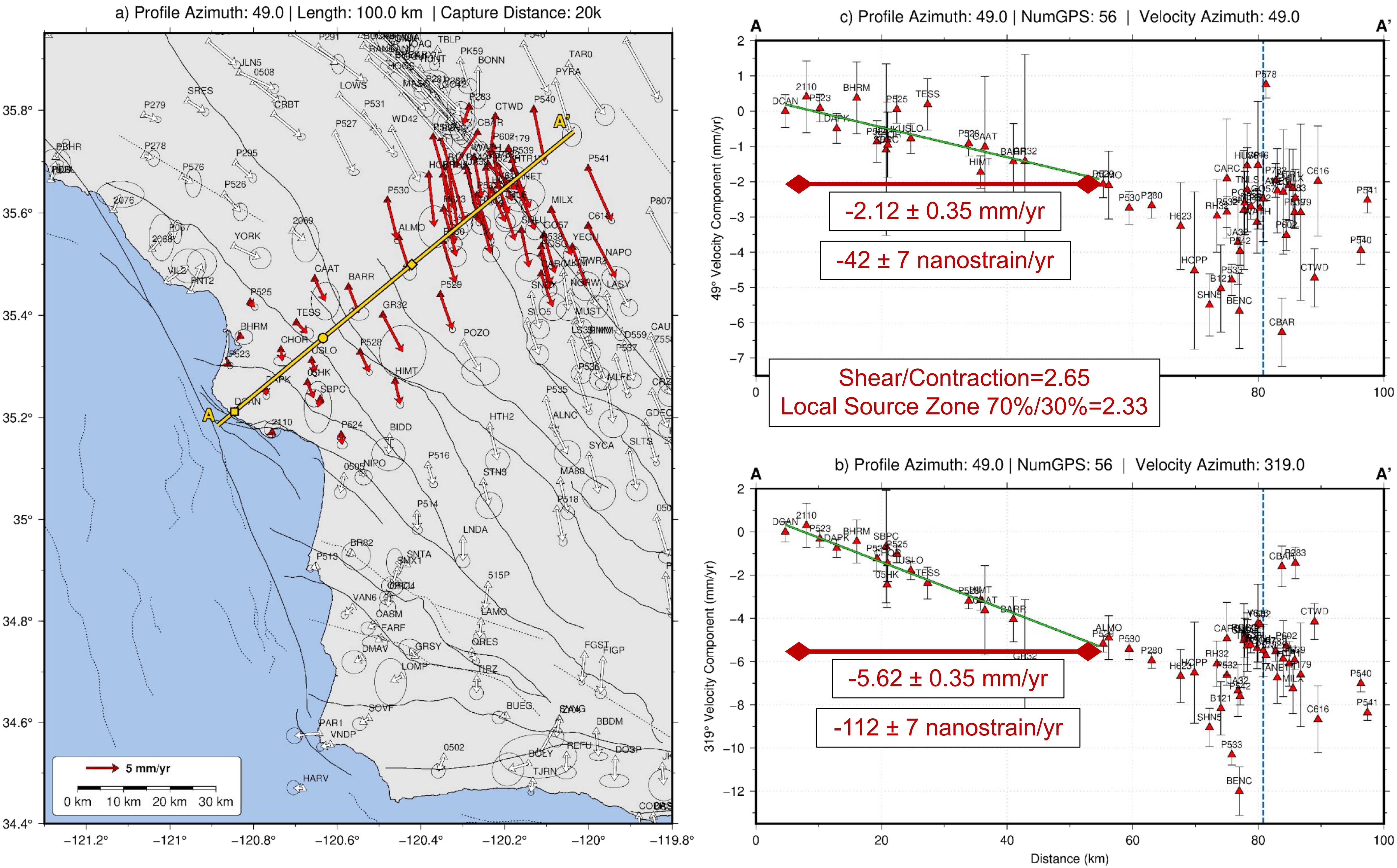


Interseismic velocities from the regional model of the San Andreas, Hosgri, and other faults. Note the regional extension.



The “corrected” GPS is calculated by subtracting the SAF-Hosgri model from the Zeng (2022) GPS velocities.

Corrected GPS: SAF-Normal Profile



Strain Rate Inversion Methods

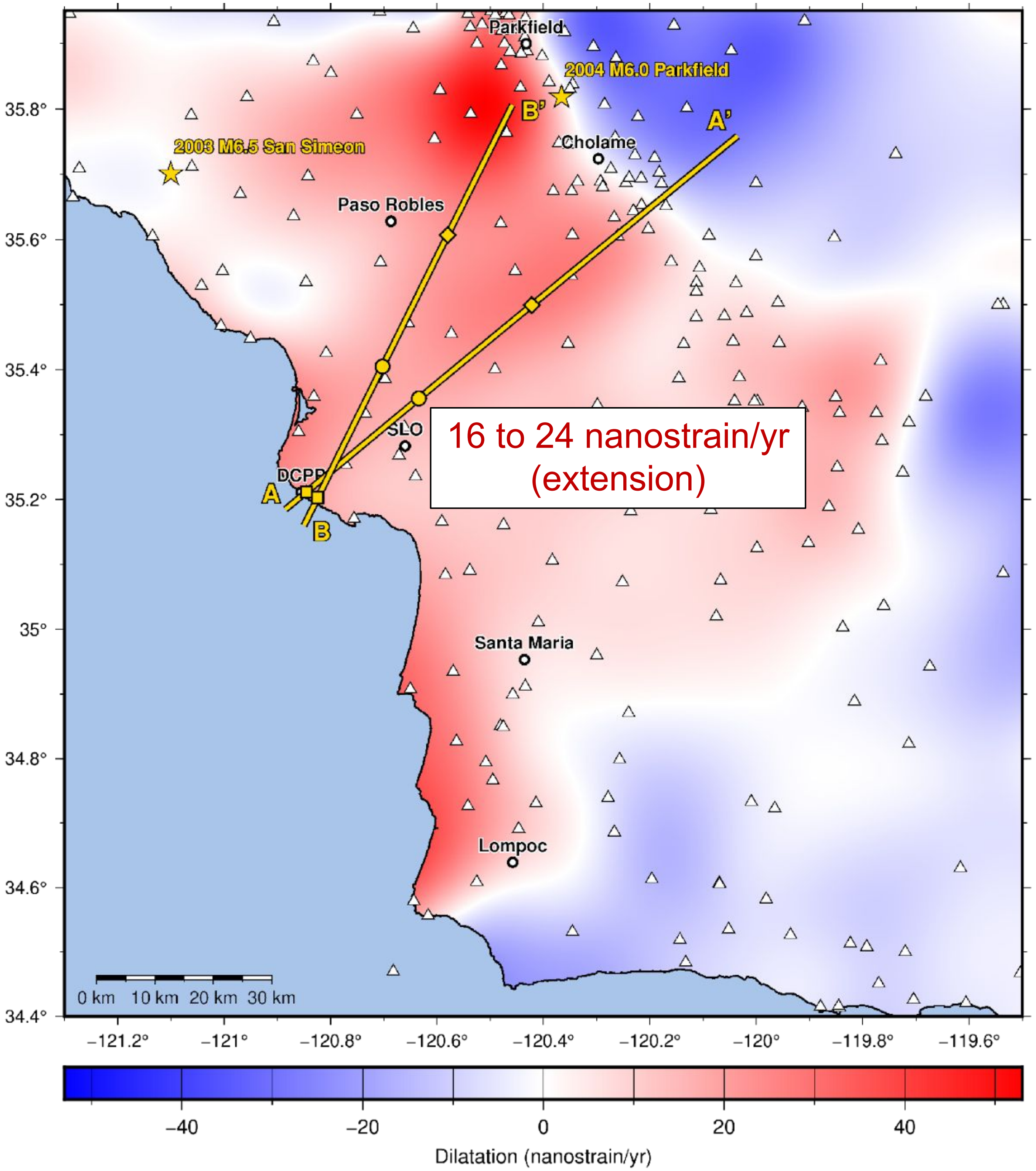
- Strain rates can be calculated from GPS velocities using inverse methods
  - We follow established methods (Allmendinger et al., 2007; 2009; Marshall et al., 2013)
- Because GPS velocities often contain inelastic motions, we follow Sandwell & Wessel (2016) and interpolate the GPS data before inversion
  - Interpolates using 2D elastic constraints
  - Smooths velocities; removes inelastic motions
- To visualize results, we decompose the strain rate tensor, $\dot{e}_{ij}$, into two invariants
  - I_1 = **Dilatation**: Areal contraction/extension

$$I_1 = \dot{e}_{11} + \dot{e}_{22}$$

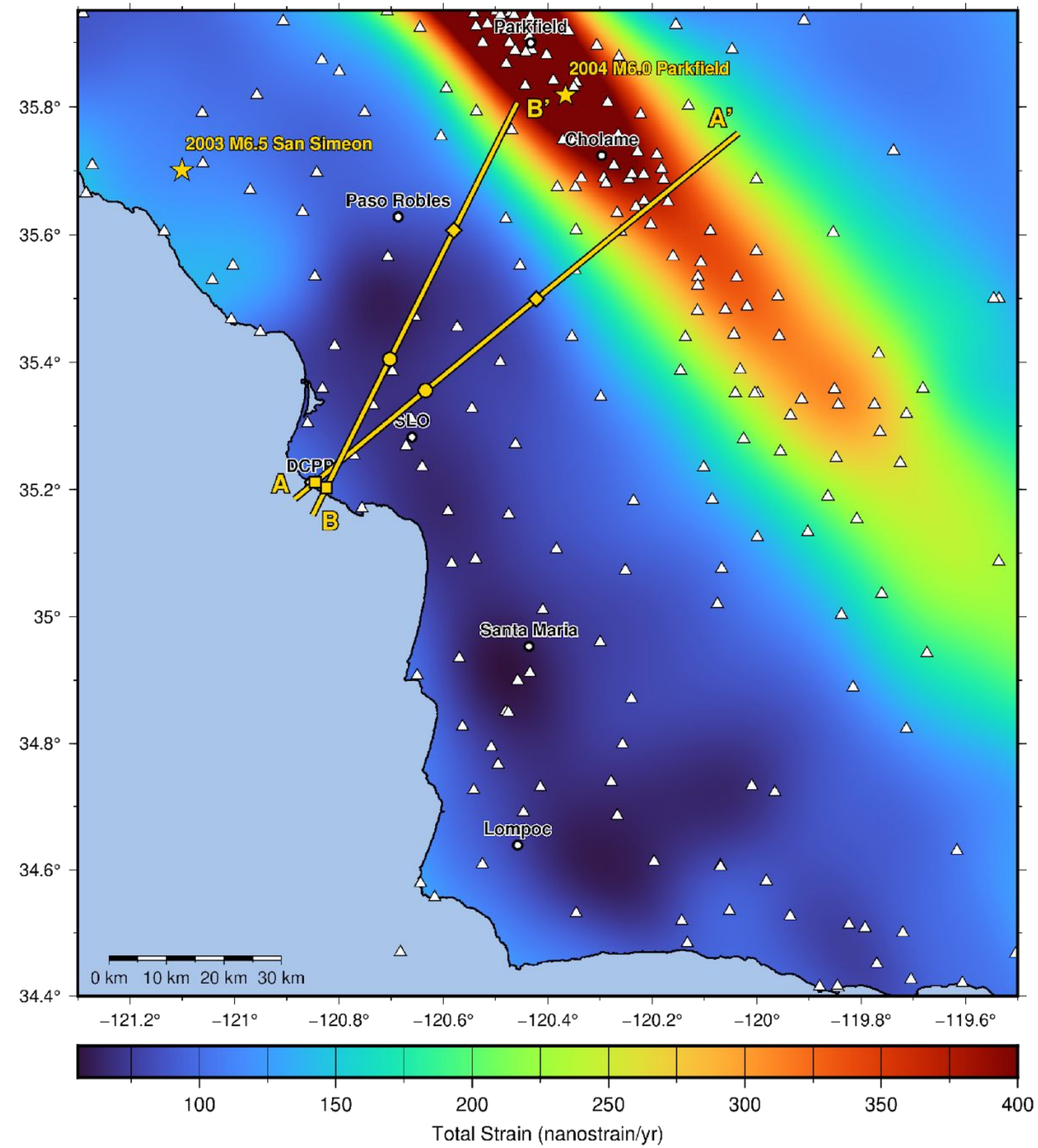
  - $\|\dot{e_{ij}}\|$ = **Total strain**

$$\|\dot{e_{ij}}\| = \sqrt{\dot{e}_{11}^2 + \dot{e}_{22}^2 + 2e_{12}^2}$$

Raw GPS Strain Rate Inversion

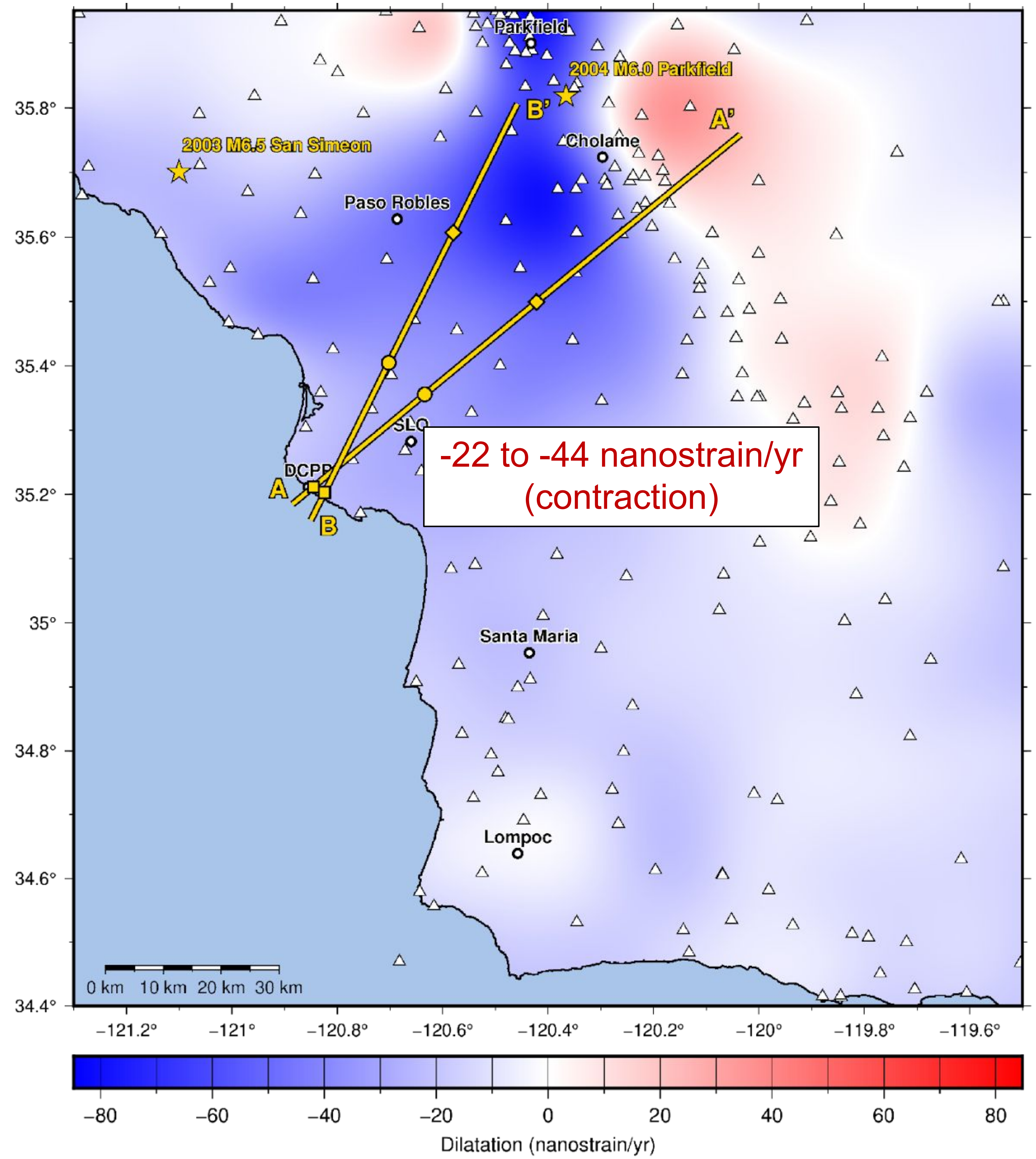


Extensional dilatation is found throughout the greater Irish Hills region.

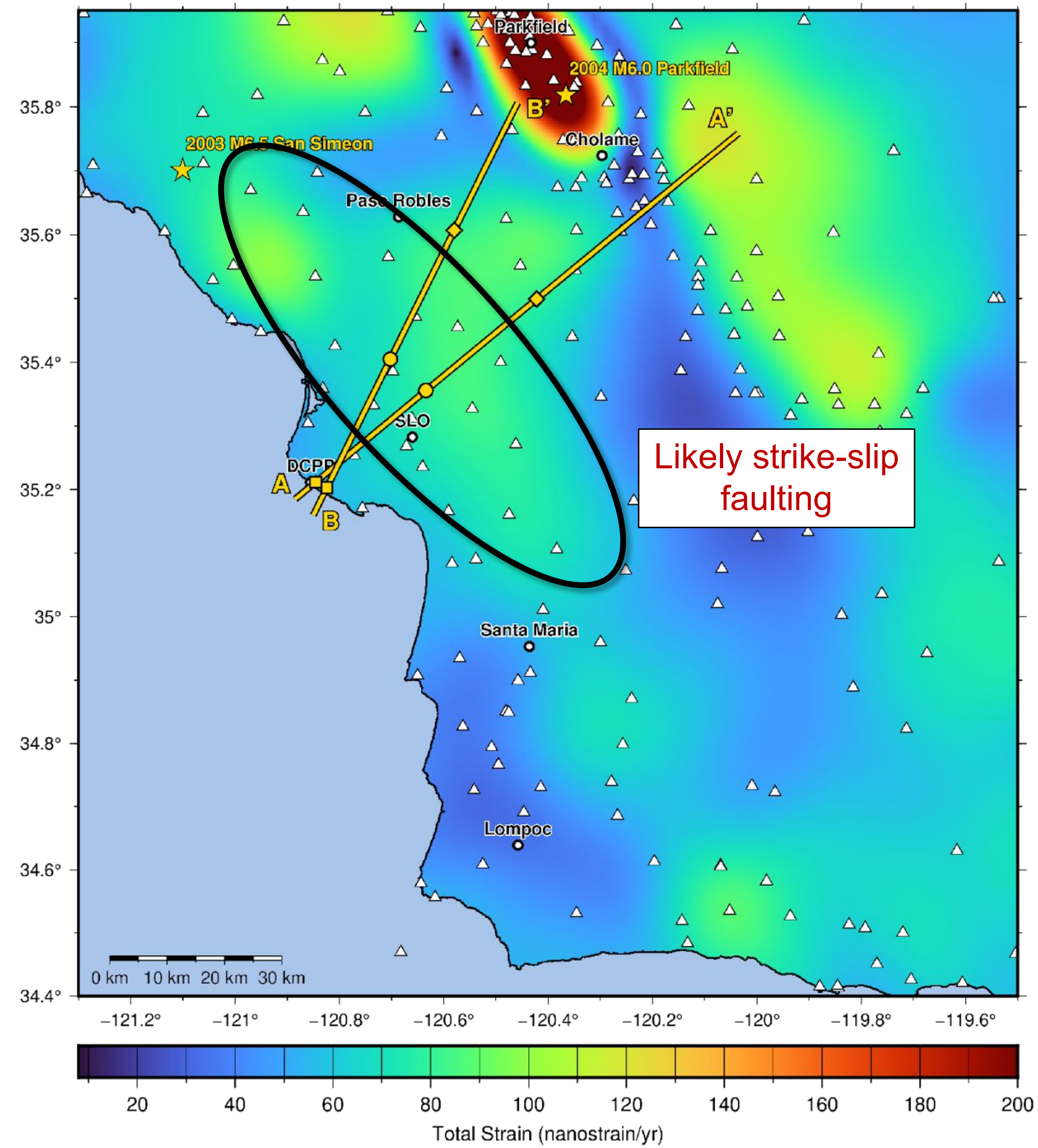


Total strain is focused along the SAF. Plot is truncated at 400 nanostrain/yr.

Corrected GPS Strain Rate Inversion



Data shows contractional dilatation throughout the greater Irish Hills region.



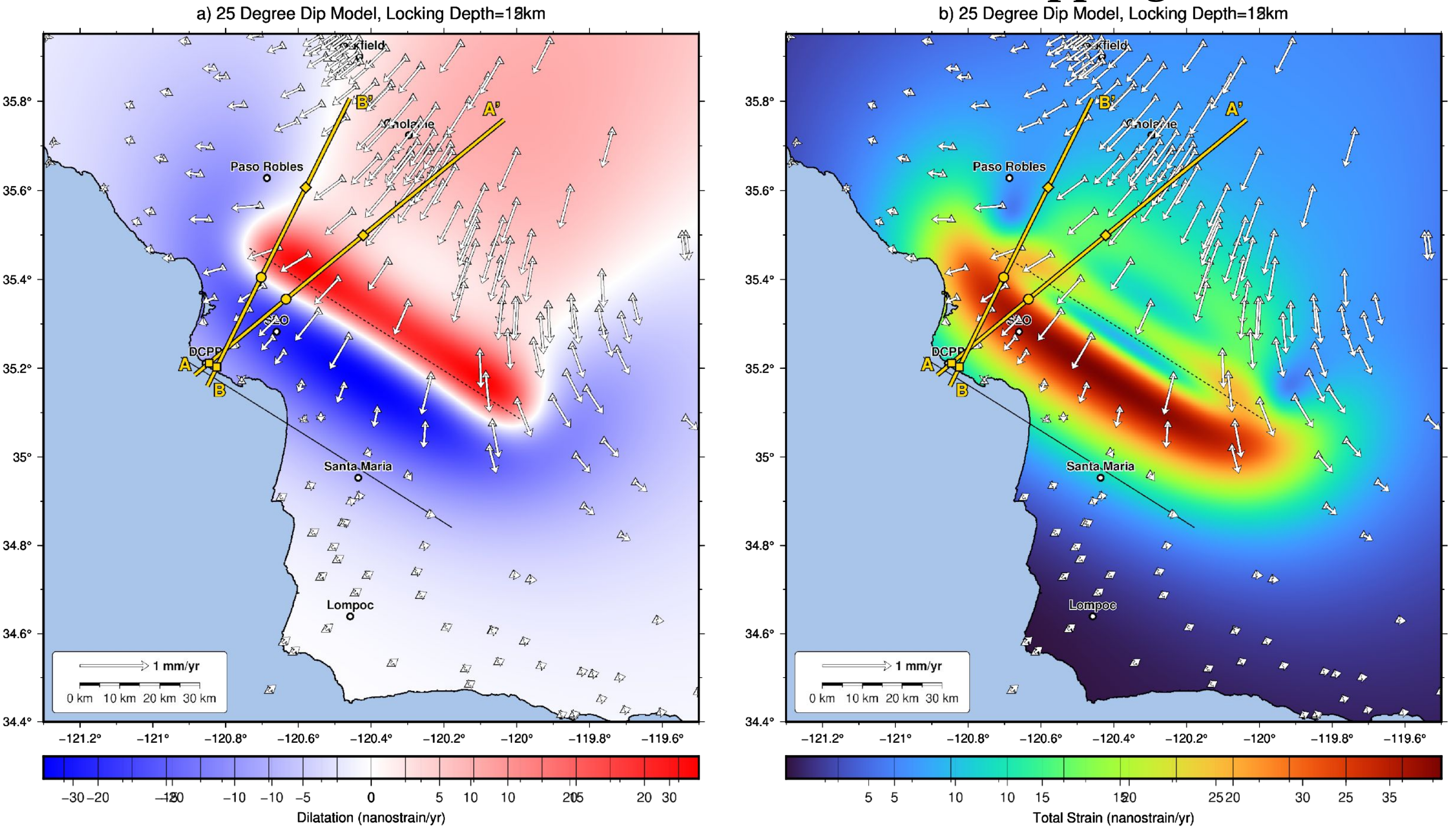
Total strain along the SAF is mostly removed. A few bands of strain appear to follow regional strike-slip faults.

Elastic Dislocation Modeling Methods

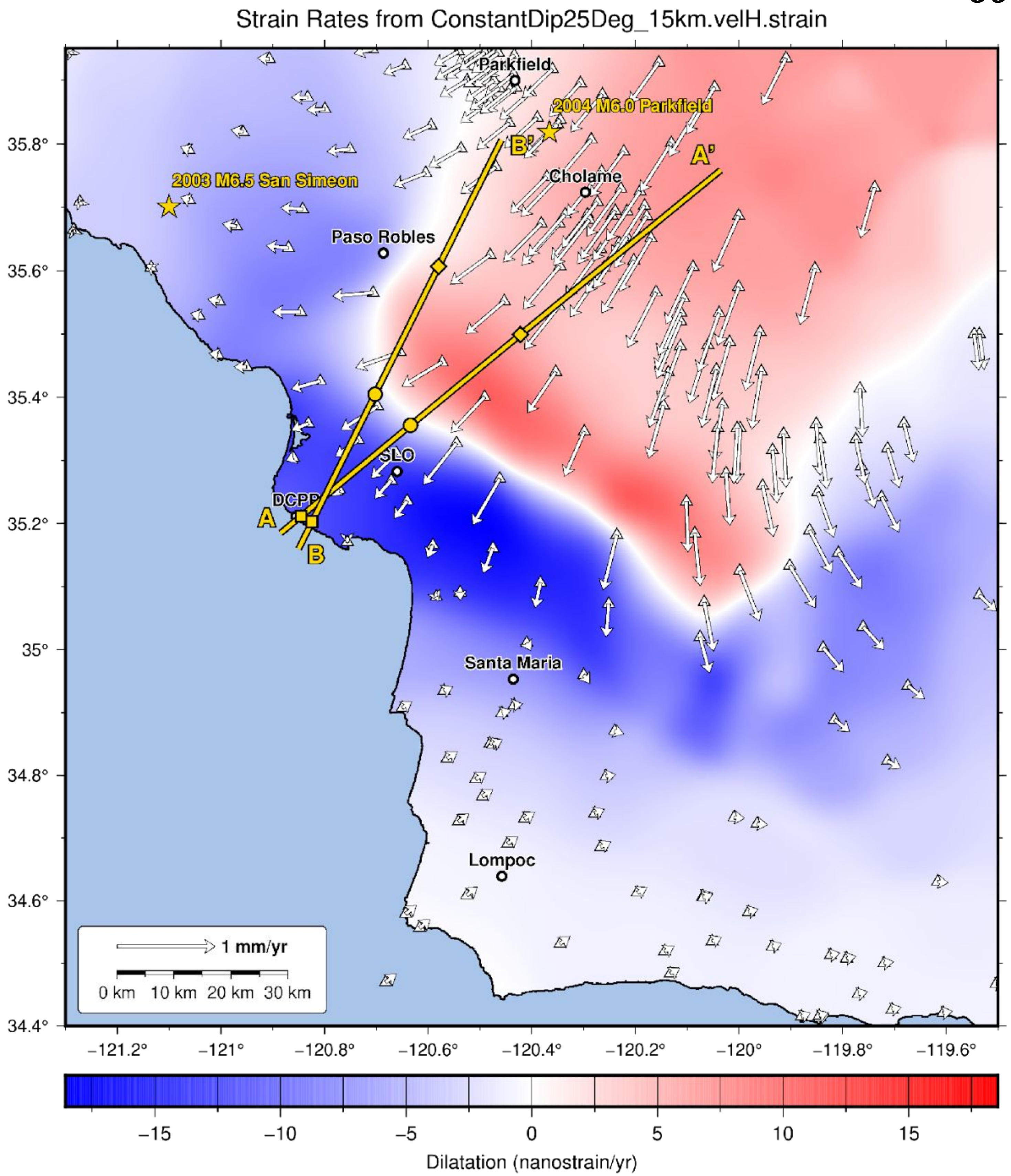
- We next evaluate the predicted deformation due to several potential simplified SWBZ subsurface geometries, all with 2.5 mm/yr of slip
  - 25° dip (Bird assertion)
  - 40° dip
  - Ramp-Flat-Ramp geometry

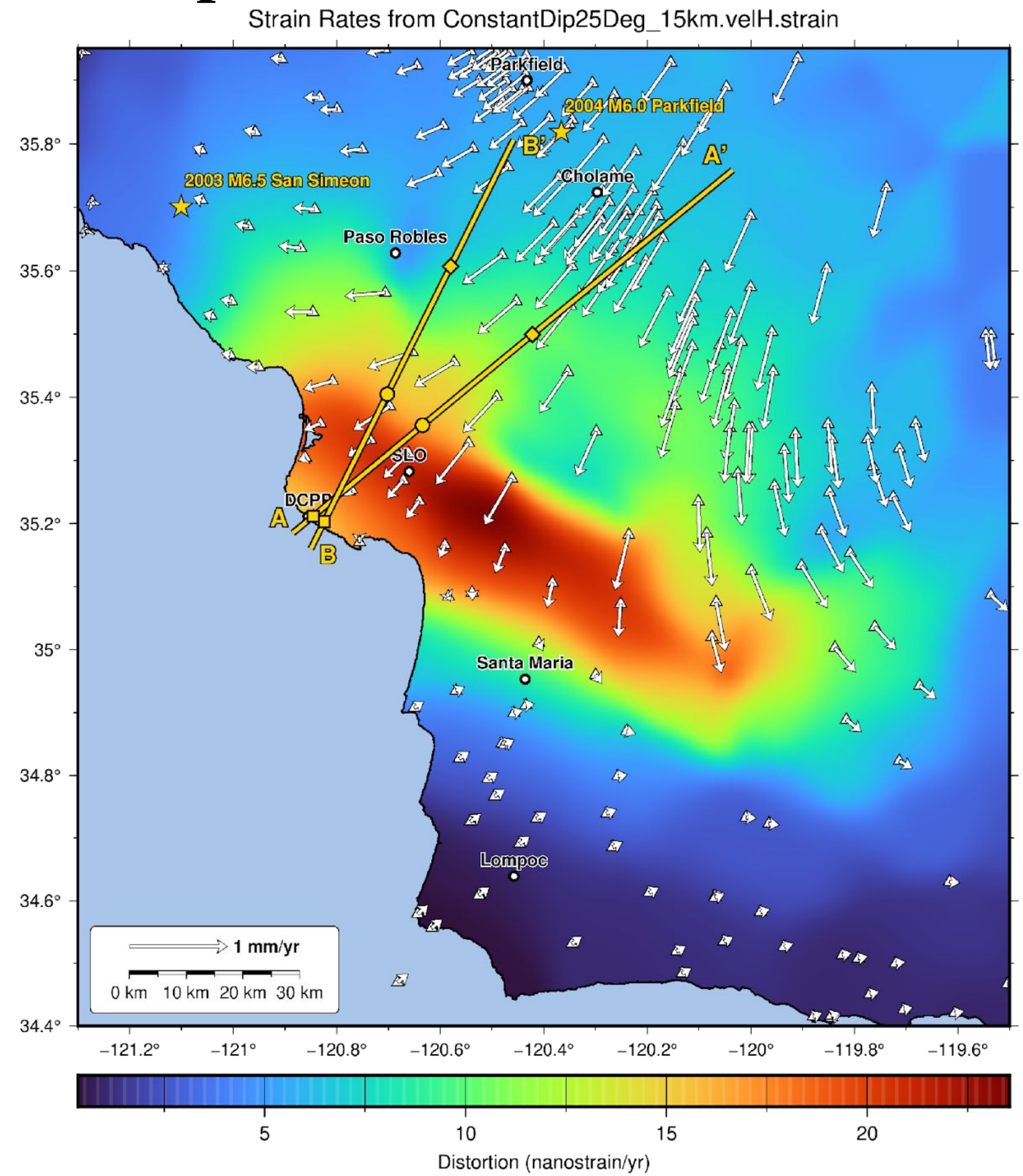
- We use poly3D (Thomas 1993) to predict the velocities and strain rates
  - Linear elastic rheology, triangular fault elements, Poisson’s ratio of 0.25

Elastic Dislocation Model Results: 25º Dipping Fault

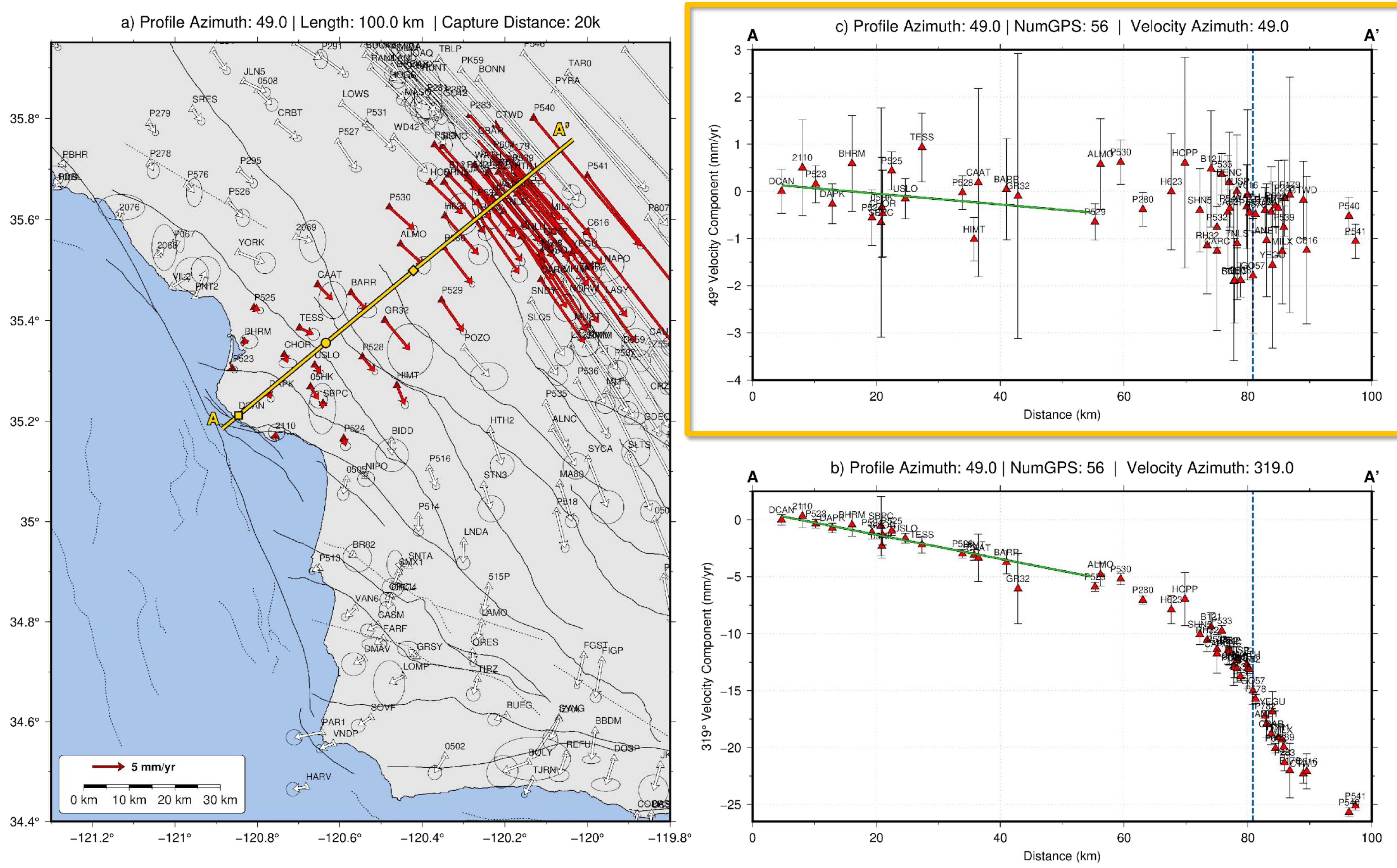


Does the GPS have Sufficient Spatial Resolution?



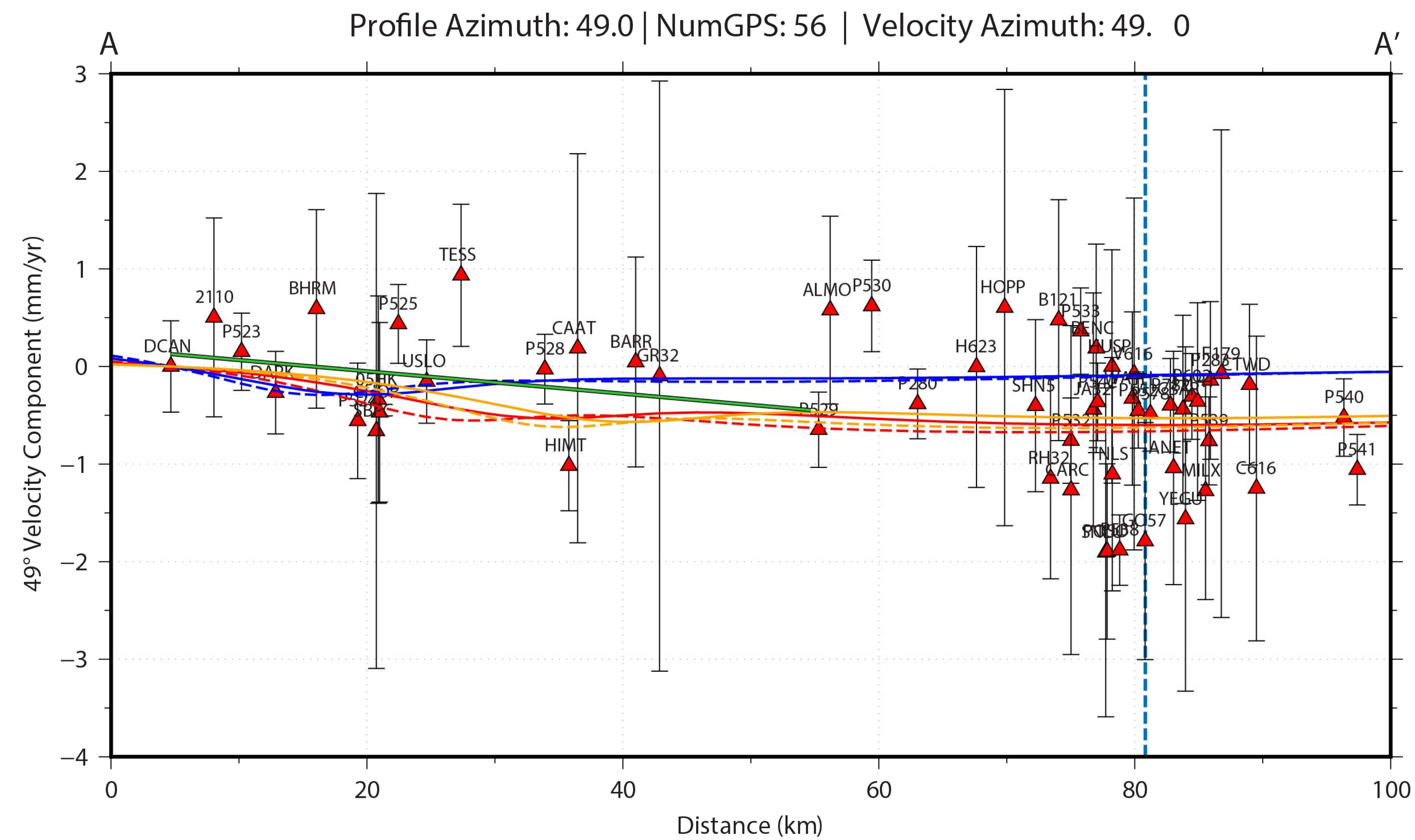


Can the GPS Data Uniquely Resolve the SWBZ Slip Rate?



Can the GPS Data Uniquely Resolve the SWBZ Slip Rate?

- Surface velocities are small compared to the GPS uncertainties
- The GPS, alone, cannot uniquely resolve slip on the SWBZ
- A 3D kinematic and/or mechanical model of all faults is necessary to determine of the SSC slip rates agree with the GPS deformation rates

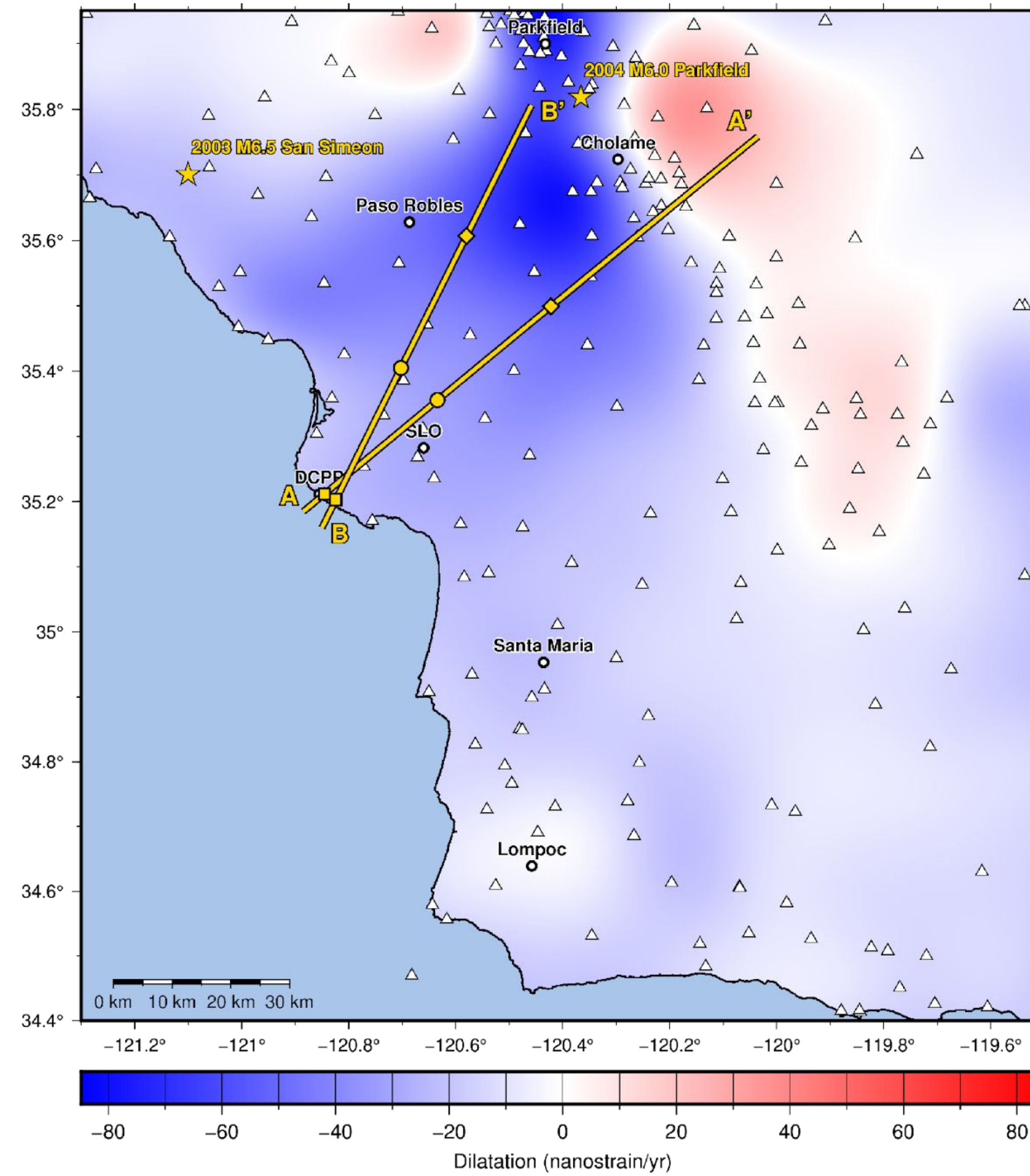


Red: 25˚ dip model
Blue: 40˚ dip model
Orange: ramp-flat-ramp model

Dashed / Solid line:
12 km / 15 km locking depth

Geodetic Findings

1. Geodetic results are dependent on removing the deformation associated with the San Andreas and other regional faults
2. Corrected GPS data show
   - Right-lateral deformation across the Irish Hills
   - Contractional component is ~20-40 nanostrain/yr
3. GPS cannot directly resolve the slip rates of individual faults without a comprehensive 3D model of all regional faults
   - Faults are densely spaced
   - Spatial distribution of stations is sufficient; need less velocity uncertainty



Dilatation rates from inversion of gridded corrected GPS data

Geodetic Recommendations

1. PG&E should follow up the SRT's preliminary work with a more complete study of the available GPS data.
2. The fault slip models that underlie the DCPP SSC should be developed into kinematic and mechanical models that can predict the interseismic deformation and can thus be directly tested against the GPS data.
3. Geologic slip-rate information should be acquired from the Rinconada, Huasna and Los Osos faults to permit better modeling of the shear component evident in the GPS data.

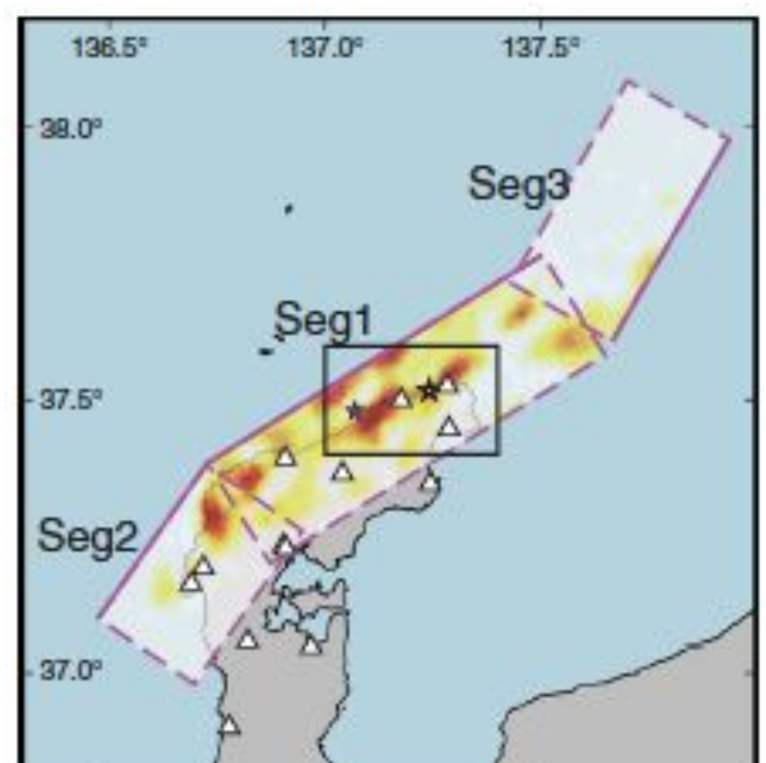
Analysis of the 2024 Noto Peninsula Earthquake

Tom Jordan

Analysis of the 2024 Noto Peninsula Earthquake

Bird's assertions:

- January 1, 2024, Noto Peninsula (Japan) earthquake (**M**7.5) is a good analog for a large thrust event beneath the Irish Hills
- Recurrence interval of a Noto24-type earthquake involving Irish Hills thrust faulting is 715-1000 yr, posing an unacceptable risk to the DCPP



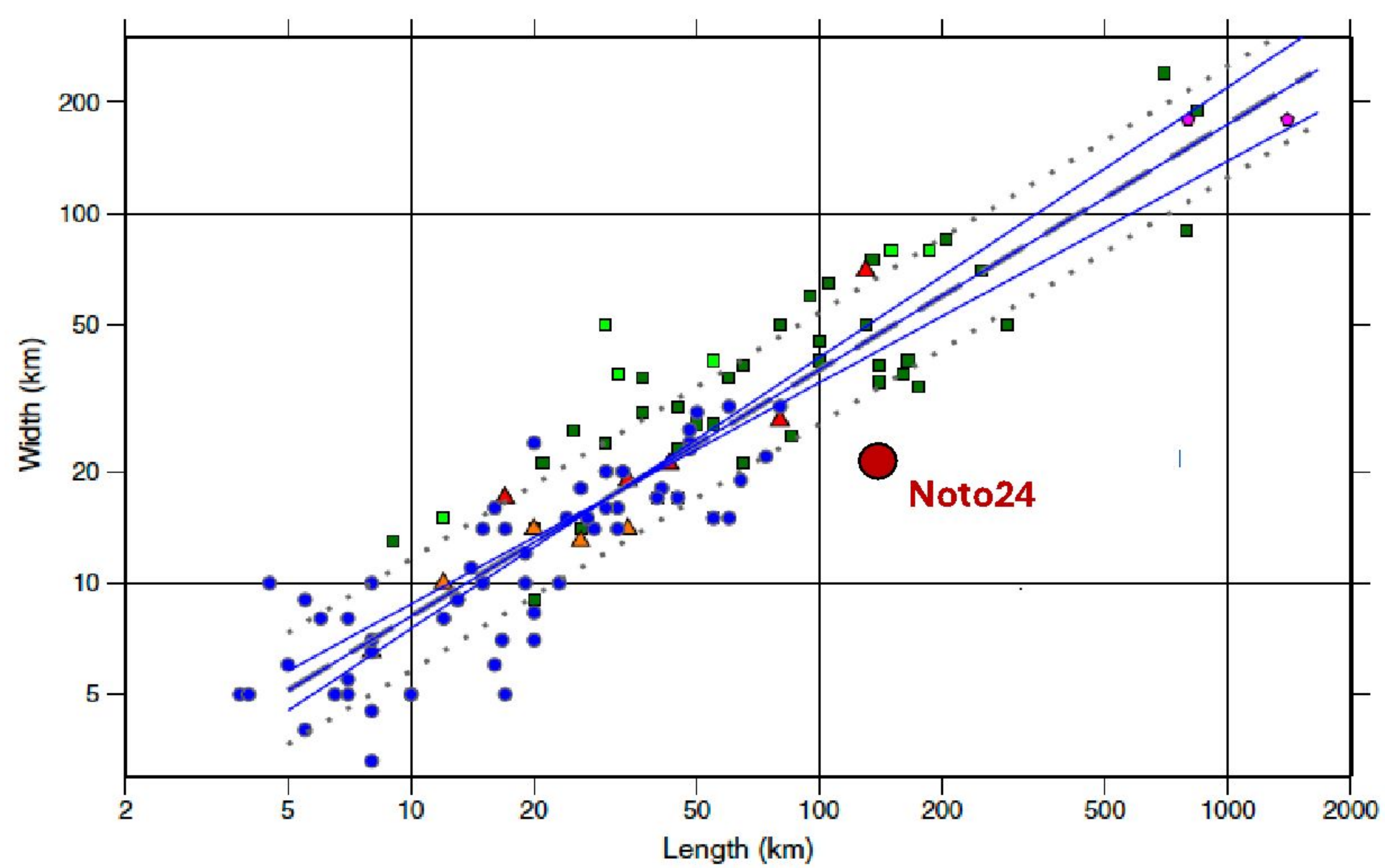
Xu et al. (2024, fig. 4)

The Noto24 earthquake was caused by reverse faulting that nucleated near the northern end of the Noto Peninsula and ruptured bilaterally for 150 km across multiple fault segments

Analysis of the 2024 Noto Peninsula Earthquake

Characteristics of the Noto24 earthquake:

- High stress drop with an average slip of 4 m (twice Bird's value)
- High shaking intensities (due to high stress drop)
- Long rupture with high length-to-width aspect ratio (~7)

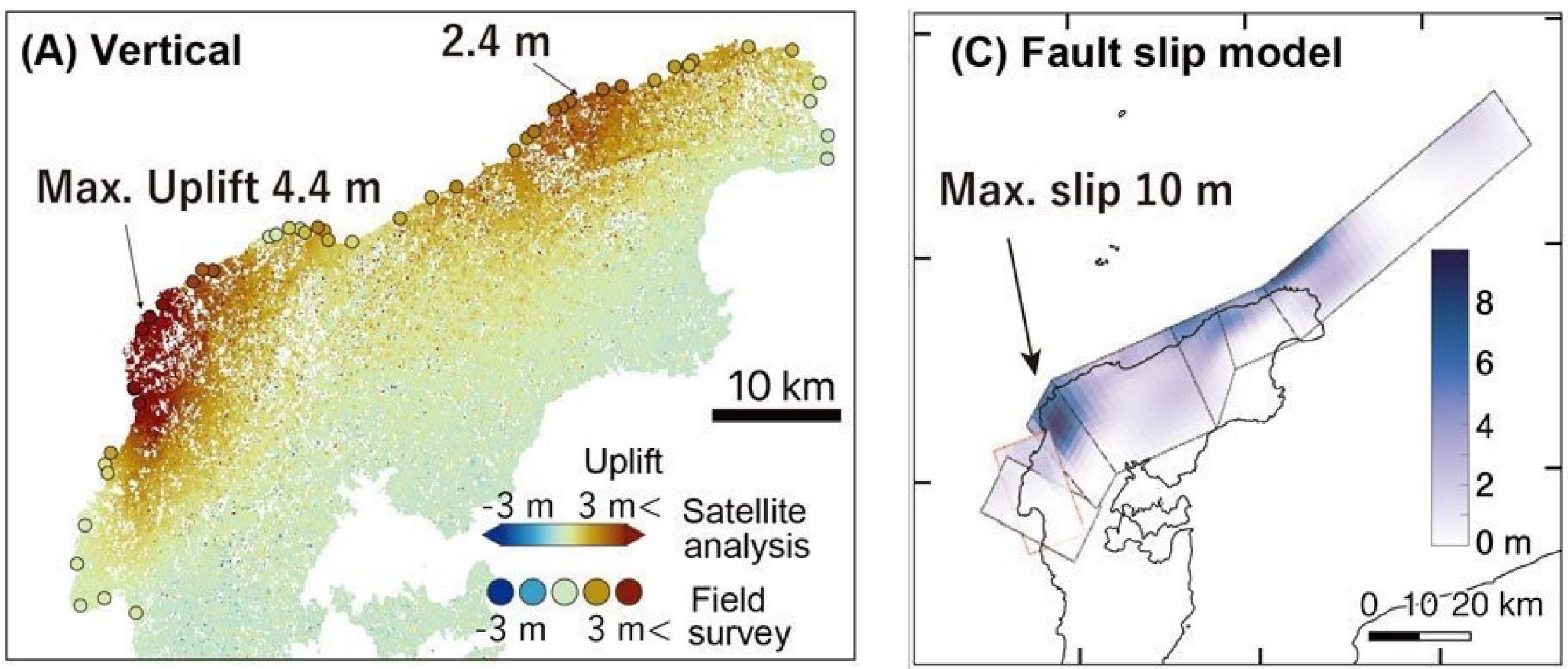


Leonard (2010, fig. 1)

Analysis of the 2024 Noto Peninsula Earthquake

Characteristics of the Noto24 earthquake:

- High stress drop with an average slip of 4 m (twice Bird's value)
- High shaking intensities (due to high stress drop)
- Long rupture with high length-to-width aspect ratio (~7)
- Good correlation between uplift and slip – <u>uplift is proxy for slip</u>

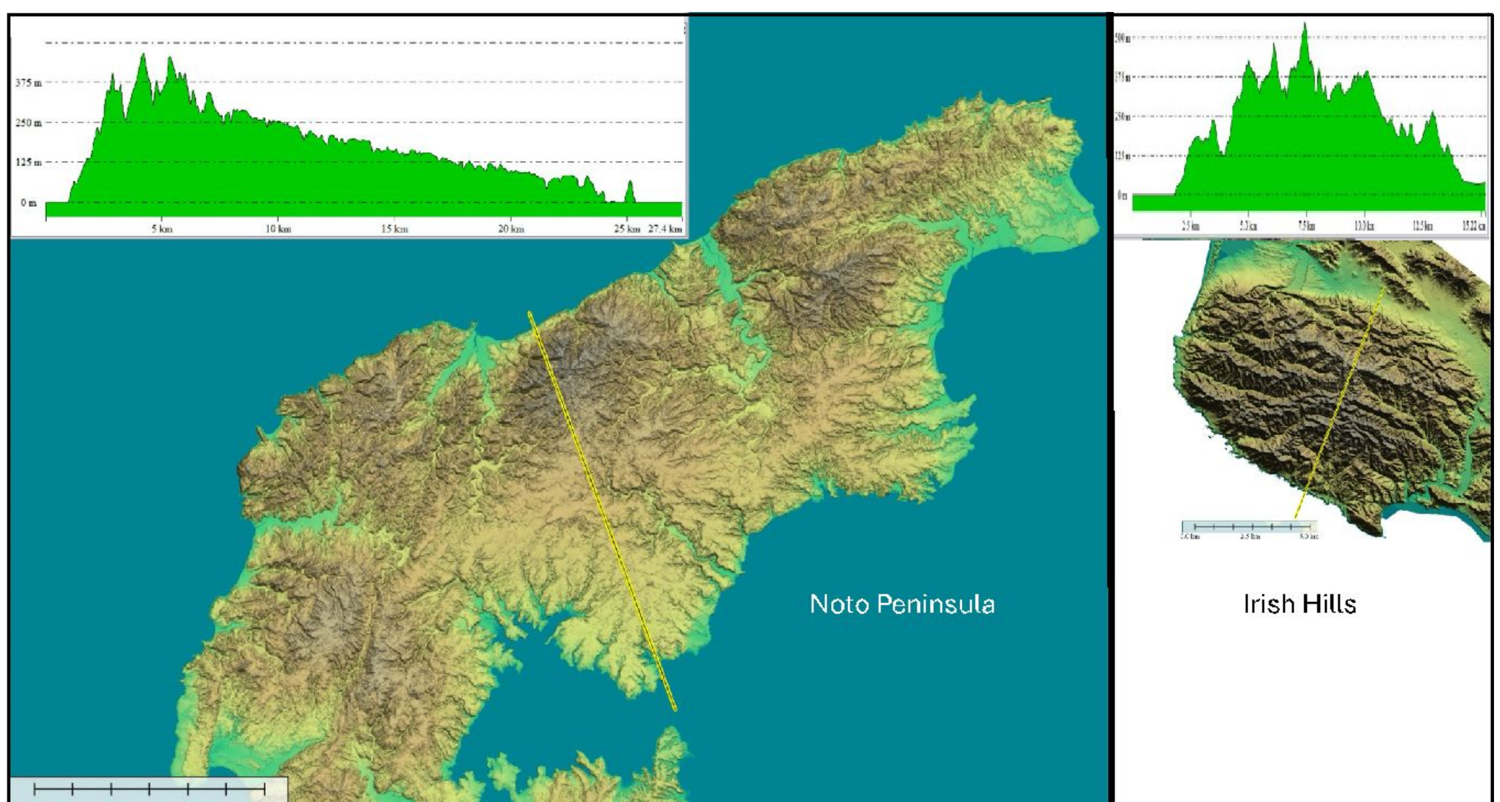


Fukushima et al. (2024, fig. 2)

Analysis of the 2024 Noto Peninsula Earthquake

Characteristics of the Noto24 earthquake:

- High stress drop with an average slip of 4 m (twice Bird's value)
- High shaking intensities (due to high stress drop)
- Long rupture with high length-to-width aspect ratio (~7)
- Good correlation between uplift and slip – uplift is proxy for slip
- Good correlation between uplift and 120 ka uplift rate – <u>uplift rate is proxy for slip rate</u>



LCI (2024, fig. 12)

Analysis of the 2024 Noto Peninsula Earthquake

- Estimation of Noto24 recurrence interval T_R from co-seismic uplift and uplift rate:

$$T_R = \left(1 + \frac{\lambda_{GR}}{\lambda_C}\right) \times \text{co-seismic uplift} \div \text{uplift rate}$$

1.0 (maximal)
2.0 (GR)

2 m (Noto24 eqk) ÷ [0.7-1.0] mm/yr (Noto Peninsula)

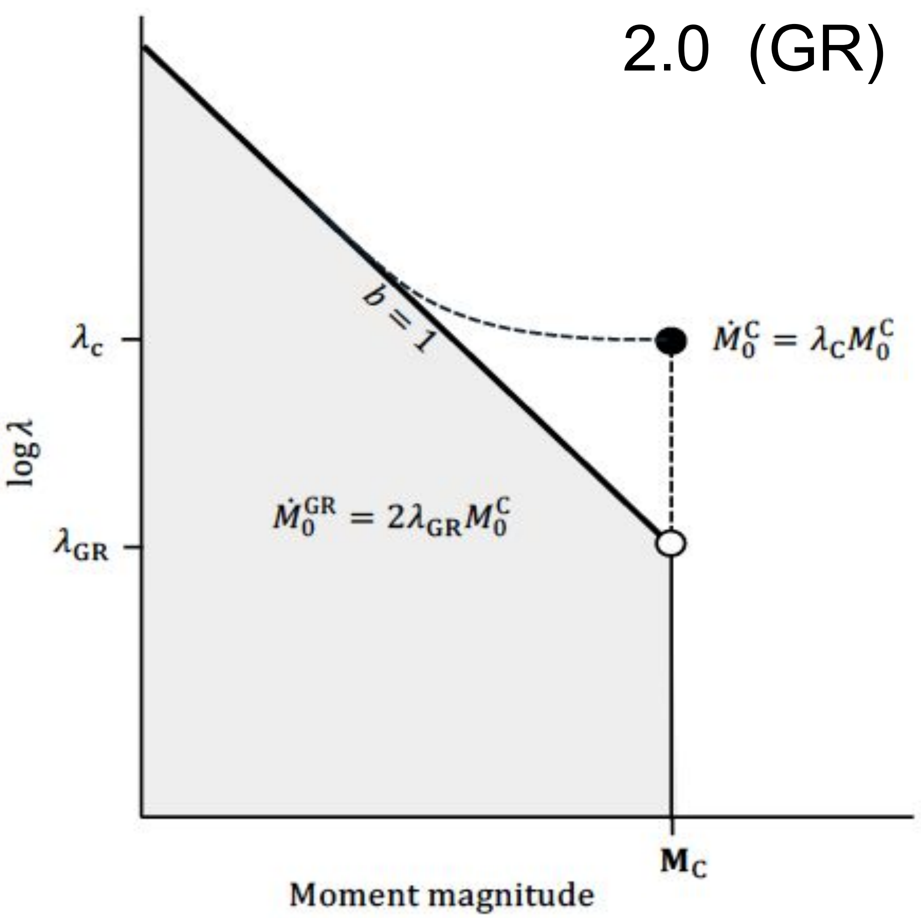


Table 3.5. Estimates of Noto24 recurrence intervals based on uplift data

Recurrence model	λ_{GR}/λ_C	Noto Peninsula (yr)	Irish Hills (yr)
Bird (2024)	0	–	715-1,000
Maximal earthquake	0	2,000-2,900	8,300-16,700**
Characteristic earthquake	0.5	3,000-4,290	12,500-25,000**
Gutenberg-Richter*	1	4,000-5,700	16,700-33,300**

*Preferred model **95% CI

Masuda et al. (2024): “Tectonic geomorphology investigations on uplifted marine terraces along the northern Noto Peninsula suggest that the 2024 earthquake was a rare event occurring once every several thousand years.”

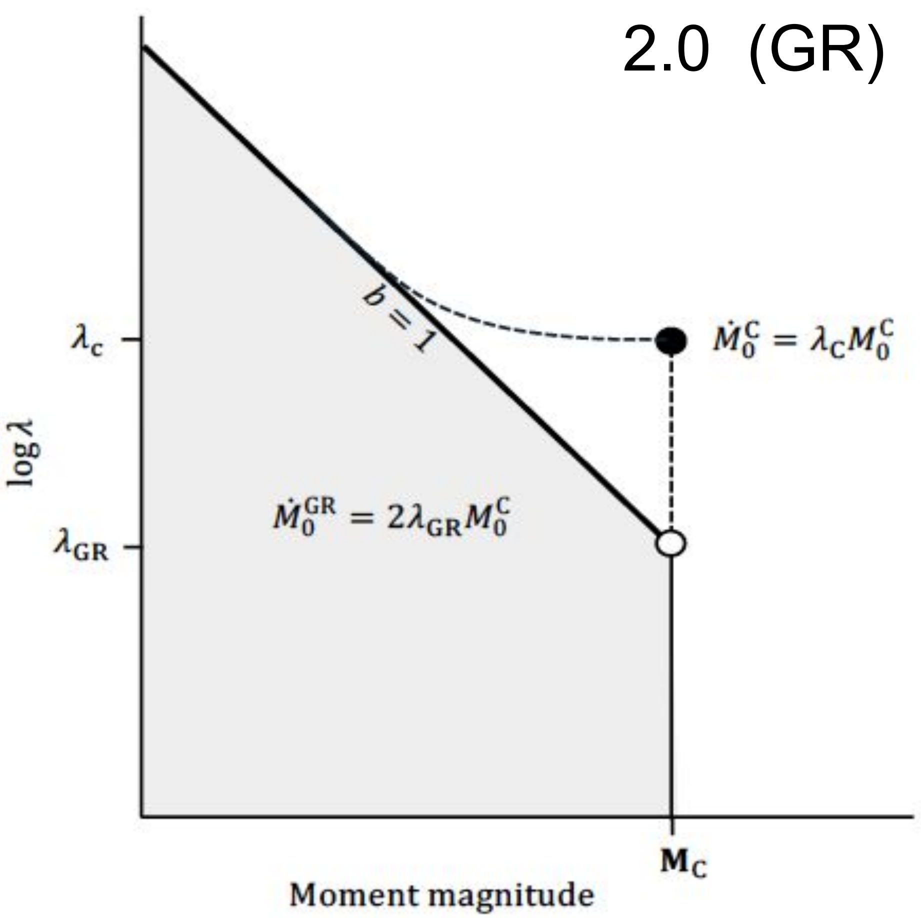
Analysis of the 2024 Noto Peninsula Earthquake

- Estimation of Noto24 recurrence interval T_R from co-seismic uplift and uplift rate:

$$T_R = \left(1 + \frac{\lambda_{GR}}{\lambda_C}\right) \times \text{co-seismic uplift} \div \text{uplift rate}$$

1.0 (maximal)
2.0 (GR)

2 m (Noto24 eqk) ÷. [0.12-0.24] mm/yr (Irish Hills)



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Gutenberg-Richter*	1	4,000-5,700	16,700-33,300**

*Preferred model **95% CI

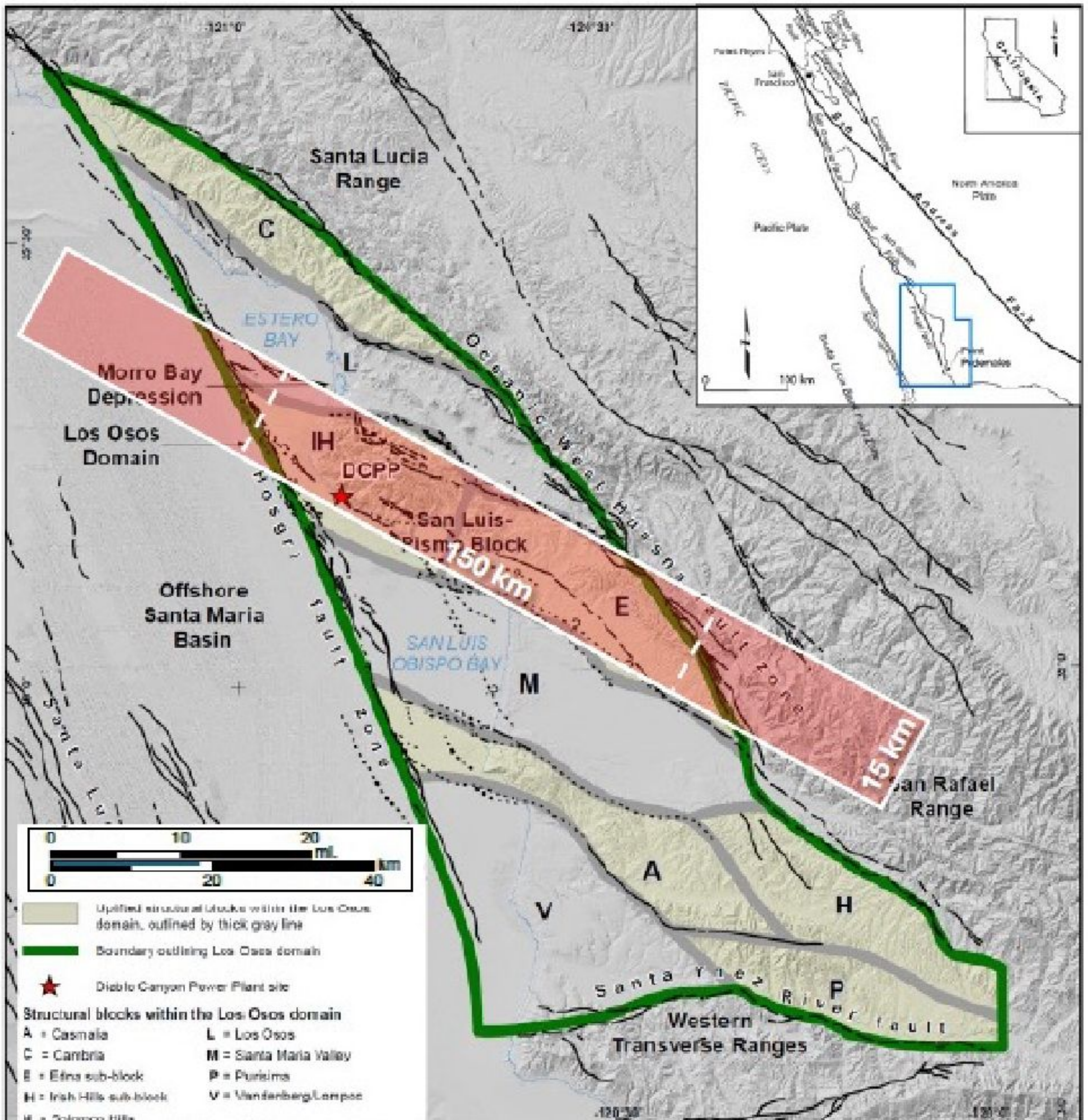
Analysis of the 2024 Noto Peninsula Earthquake

- **Tectonic differences between the Noto Peninsula and the Irish Hills/San Luis-Pismo block (SLPB)**

1. Uplift rate of Noto Peninsula is five times faster than uplift rate of Irish Hills
2. Historical rate of large earthquakes (**M** ≥ 6) is much greater in the Noto region than in the SLPB region
3. Tectonic deformation of the Noto Peninsula is compressional with little shear, whereas SLPB deformation is transpressional with a significant component of shear
4. Length of Noto Peninsula faulting is about twice the length of the SWBZ
5. Large, prominent fault scarps mapped offshore Noto Peninsula; no prominent scarps offshore Irish Hills
6. Rapid tilting of Noto Peninsula is on a larger scale than the block-like uplift of Irish Hills

   ⟹ indicates different fault configurations: single ramp or listric fault beneath Noto Peninsula vs. fault ramp bending to flat fault at intermediate seismogenic depths (7-8 km) beneath Irish Hills

Analysis of the 2024 Noto Peninsula Earthquake



<u>SRT Finding</u>: *Based on the anomalous characteristics of Noto24, including its*

- *extreme length,*
- *high stress drop, and*
- *large block tilting,*

a Noto24-type earthquake is not suitable as a characteristic earthquake for thrust faulting beneath the Irish Hills

Four Main Assertions of the Bird Critique

a. PG&E (2015, 2024) underestimated the hazard to DCPP from thrust faulting under the Irish Hills because it made four false assumptions. Removing these assumptions increases the thrust-faulting potency rate by a large factor.

b. Three independent analytic methods give values for the total slip rate on shallow-dipping thrust faults under the Irish Hills in the range of 2.0-2.8 mm/yr.

c. The January 1, 2024, Noto Peninsula (Japan) earthquake (**M**7.5) is a good analog for a large thrust event beneath the Irish Hills.

d. The recurrence interval of Noto24-type earthquakes involving Irish Hills thrust faulting is 715-1000 yr, which poses an unacceptable risk to DCPP.

Bird's Critique of PG&E Modeling Assumptions

a. PG&E (2015, 2024) underestimated the hazard to DCPP from thrust faulting under the Irish Hills because it made four false assumptions. Removing these assumptions increases the thrust-faulting potency rate by a large factor.

Table 4.1. Evaluation of Bird's False Assumptions

Assumption	Truth value	Assumed by PG&E?	Impactful?
1. The Irish Hills are uplifting as a rigid block, with no internal deformation	false	no	no
2. Active thrust faults may dip at any angle	false	no	no
3. Geologic structures older than ~0.33 Ma are irrelevant to seismic hazard estimation	false	no	no
4. GPS geodetic velocities are not useful for site-specific seismic hazard estimation	false	yes	no

* Bird deems this assumption to be false; evidence that it is true is given in §3.2

Bird's Critique of PG&E Modeling Assumptions

a. PG&E (2015, 2024) underestimated the hazard to DCPP from thrust faulting under the Irish Hills because it made four false assumptions. Removing these assumptions increases the thrust-faulting potency rate by a large factor.

Table 4.1. Evaluation of Bird's False Assumptions

Assumption	Truth value	Assumed by PG&E?	Impactful?
1. The Irish Hills are uplifting as a rigid block, with no internal deformation	false	no	no
2. Active thrust faults may dip at any angle	false	no	no
2a. Active reverse faults may dip more steeply than 45°	true*	yes	yes
3. Geologic structures older than ~0.33 Ma are irrelevant to seismic hazard estimation	false	no	no
4. GPS geodetic velocities are not useful for site-specific seismic hazard estimation	false	yes	no

* Bird deems this assumption to be false; evidence that it is true is given in §3.2

SRT finding: *Removing the four false assumptions in the development of a revised SSC would have little to no impact on the hazard estimates.*

Bird's Estimates of Slip Rates

- Method #1: SWBZ slip rate based on a 120-ka uplift rate of 0.18 ± 0.03 mm/yr and dip of 38º ± 3º is 0.29 ± 0.07 mm/yr
  - 10 times smaller than Bird's value of 2.8 mm/yr

Method	Bird (mm/yr)	SRT (mm/yr)
1. Isostatic	2.8	0.29 ± 0.07
2. Thrust fault heave rate	~2	0.50 ± 0.10
3. GPS geodetic horizontal shortening rate	2.2*	0.95 ± 0.32*
*Upper bound assuming all strain is elastic and released by slip only on SWBZ.		
Bird assumptions: dip: 25º; uplift rate: 0.2 mm/yr.		
SRT assumptions: dip: 38º ± 3º; uplift rate: 0.18 ± 0.03 mm/yr.		

Bird's Estimates of Slip Rates

- Method #2: SRT's kinematically constrained fault-related fold model yields a thrust fault slip rate of 0.5 ± 0.1 mm/yr averaged since 5.1 ± 0.4 Ma
  - about 4 times less than Bird's estimate of 2 mm/yr.
  - marginally higher than 120-ka rate, suggesting some slowing of compressive deformation

Method	Bird (mm/yr)	SRT (mm/yr)
1. Isostatic	2.8	0.29 ± 0.07
2. Thrust fault heave rate	~2	0.50 ± 0.10
3. GPS geodetic horizontal shortening rate	2.2*	0.95 ± 0.32*
*Upper bound assuming all strain is elastic and released by slip only on SWBZ.		
Bird assumptions: dip: 25º; uplift rate: 0.2 mm/yr.		
SRT assumptions: dip: 38º ± 3º; uplift rate: 0.18 ± 0.03 mm/yr.		

Bird's Estimates of Slip Rates

- Method #3: SAF-normal contractional strain rate from Zeng GPS velocities averaged over the Irish Hills is –20 to –40 nanostrain/yr
  - 2-5 times smaller than Bird's estimate of –80 to –100 nanostrain/yr
  - Thrust-fault slip rates assume all strain is elastic and released by slip only on SWBZ

Method	Bird (mm/yr)	SRT (mm/yr)
1. Isostatic	2.8	0.29 ± 0.07
2. Thrust fault heave rate	~2	0.50 ± 0.10
3. GPS geodetic horizontal shortening rate	2.2*	0.95 ± 0.32*
*Upper bound assuming all strain is elastic and released by slip only on SWBZ.		
Bird assumptions: dip: 25º; uplift rate: 0.2 mm/yr.		
SRT assumptions: dip: 38º ± 3º; uplift rate: 0.18 ± 0.03 mm/yr.		

Overall Assessment of the Bird Critique

a. PG&E (2015, 2024) underestimated the hazard to DCPP from thrust faulting under the Irish Hills because it made four false assumptions. Removing these assumptions increases the thrust-faulting potency rate by a large factor.

<u>SRT finding</u>: *Removing the four false assumptions in the development of a revised SSC would have little to no impact on the hazard estimates*.

b. Three independent analytic methods give values for the total slip rate on shallow-dipping thrust faults under the Irish Hills in the range of 2.0-2.8 mm/yr.

<u>SRT finding</u>: *Slip rate of the SWBZ thrust faults under the Irish Hills is estimated to be 0.29 ± 0.07 mm/yr, an order of magnitude smaller than Bird's estimates.*

Overall Assessment of the Bird Critique

c. The January 1, 2024, Noto Peninsula (Japan) earthquake (**M**7.5) is a good analog for a large thrust event beneath the Irish Hills.

<u>SRT finding</u>: *A Noto24-type earthquake is not suitable as a characteristic earthquake for thrust faulting beneath the Irish Hills.*

d. The recurrence interval of Noto24-type earthquakes involving Irish Hills thrust faulting is 715-1000 yr, which poses an unacceptable risk to DCPP.

<u>SRT finding</u>: *If Noto24 were adopted as the characteristic event for the Irish Hills, the estimated recurrence interval would be ten to twenty times longer than Bird's estimates.*

Overall Assessment of the Bird Critique

SRT finding: *The best available science does not support the four main assertions of the Bird critique.*

Findings Regarding the SSC Model

- Existing SSC FMGs, with modifications to include a lower range of dip for the SWBZ, can adequately represent the hazard of thrust faulting beneath the Irish Hills.
- Fault system analysis favors the SW-Vergent FGM over the NE-Vergent and Outward-Vergent FGMs in representing what is known about the style of faulting in the SLPB system.
- Though the Los Osos trend displays evidence for neotectonic activity, this evidence does not require reverse slip on a Los Osos reverse fault.
- Observed dip of SWBZ faulting ranges between 25° and 56° with a mean dip of $38^{o} \pm 3^{o}$, which is below the dip range allowed by the SW-Vergent FGM (45^{o}-50^{o})
- SRT's preferred rate estimate for the SWBZ (0.29 ± 0.07 mm/yr) is marginally higher than the estimate from the SW-Vergent FGM (0.17 ± 0.05 mm/yr) partially because the assumed fault dip is lower

Summary of Recommendations

The SRT recommends:

1. Development of a set of kinematically constrained structural models for reverse faults underlying the Irish Hills that can explain the folding observed since 5 Ma.

2. Dating of low-stand abrasion platforms offshore, south of the Irish Hills, to further constrain the rate of footwall subsidence and its contribution to the SWBZ slip rate.

3. Monitoring of IRSL-dating efforts and reassessment, if necessary, of the MIS 5 age assignments for the Q1 and Q2 terraces surrounding the Irish Hills.

4. Further investigation of potential strike-slip faulting along the Los Osos trend and its impacts on the pattern of marine-terrace uplift.

Summary of Recommendations

5. PG&E should follow up the SRT's preliminary work with a more complete study of the available GPS data.
6. The fault slip models that underlie the DCPP SSC should be developed into kinematic and mechanical models that can predict the interseismic deformation and can thus be directly tested against the GPS data.
7. PG&E should compute the transpressional ratios for the SSC24 slip models and compare the values with the geodetic constraints.
8. Geologic slip-rate information should be acquired from the Rinconada and Huasna faults to permit better modeling of the shear component evident in the GPS data.

Summary of Recommendations

9. PG&E should conduct modeling experiments to ascertain the sensitivity of DCPP hazard to the SSC modifications recommended by the SRT

- Decrease the mean dip of the SWBZ faulting to agree with the observed average ($38^{o} \pm 3^{o}$)
- Reweight FMGs to favor the SW-Vergent model over the NE-Vergent and Outward-Vergent models
- Down-weight the hazard of the Los Osos reverse trend

End