Correcting 4 False Assumptions in PG&E's Seismic Source Characterization [2015] and Update [2024] that Caused PG&E to Seriously Underestimate Seismic Hazard at Diablo Canyon Nuclear Power Plant

2024.07.17 presentation to the Petition Review Board of the
U.S. Nuclear Regulatory Commission

by Peter Bird, Professor Emeritus, UCLA
consulting to San Luis Obispo Mothers for Peace,
Friends of the Earth, & Environmental Working Group

4 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.

#1. The Irish Hills are uplifting (at ~0.2 mm/year, stipulated) as a rigid block, with no internal deformation.

Therefore, thrust faulting occurs only at the margins (Los Osos thrust, San Luis Bay thrust, ?Inferred Coastline thrust?) with fault throw (vertical) rates of ~0.2 mm/year.

HOWEVER:

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

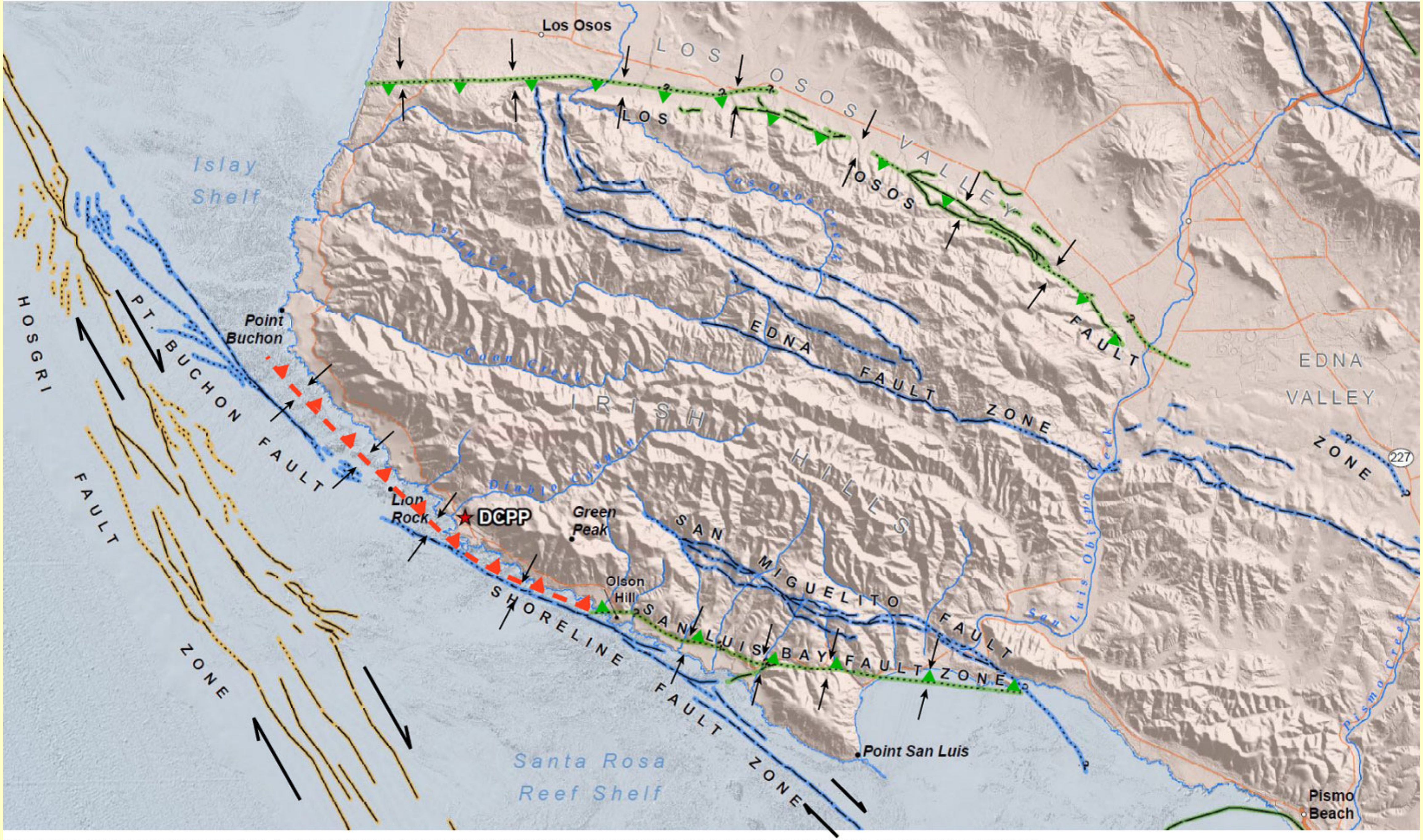
- Rigid-body uplift does not produce crustal thickening. Therefore, if the Irish Hills were a rigid block, they would have a <u>positive</u> isostatic gravity anomaly. However, data shows a <u>negative</u> isostatic gravity anomaly, indicating <u>more</u> than simple Airy compensation by crustal roots (more than the typical Airy ratio of 6:1).

THEREFORE:

A simple isostatic model for the total rate of thrust-fault slip under the Irish Hills is at least:

$$(0.2 \text{ mm/year uplift}) \times 6 / \sin(25° \text{ dips}) = 2.8 \text{ mm/year}$$

This is the 1st of 3 independent analytic estimates developed in this presentation.



Basemap excerpted from Plate 7-1 of Pacific Gas & Electric (2015) Seismic Source Characterization for Diablo Canyon Power Plant;
Inferred Coastline thrust fault trace (in red) added by P. Bird, 2024.06.19. Triangle symbols show direction of dip of thrust faults.

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

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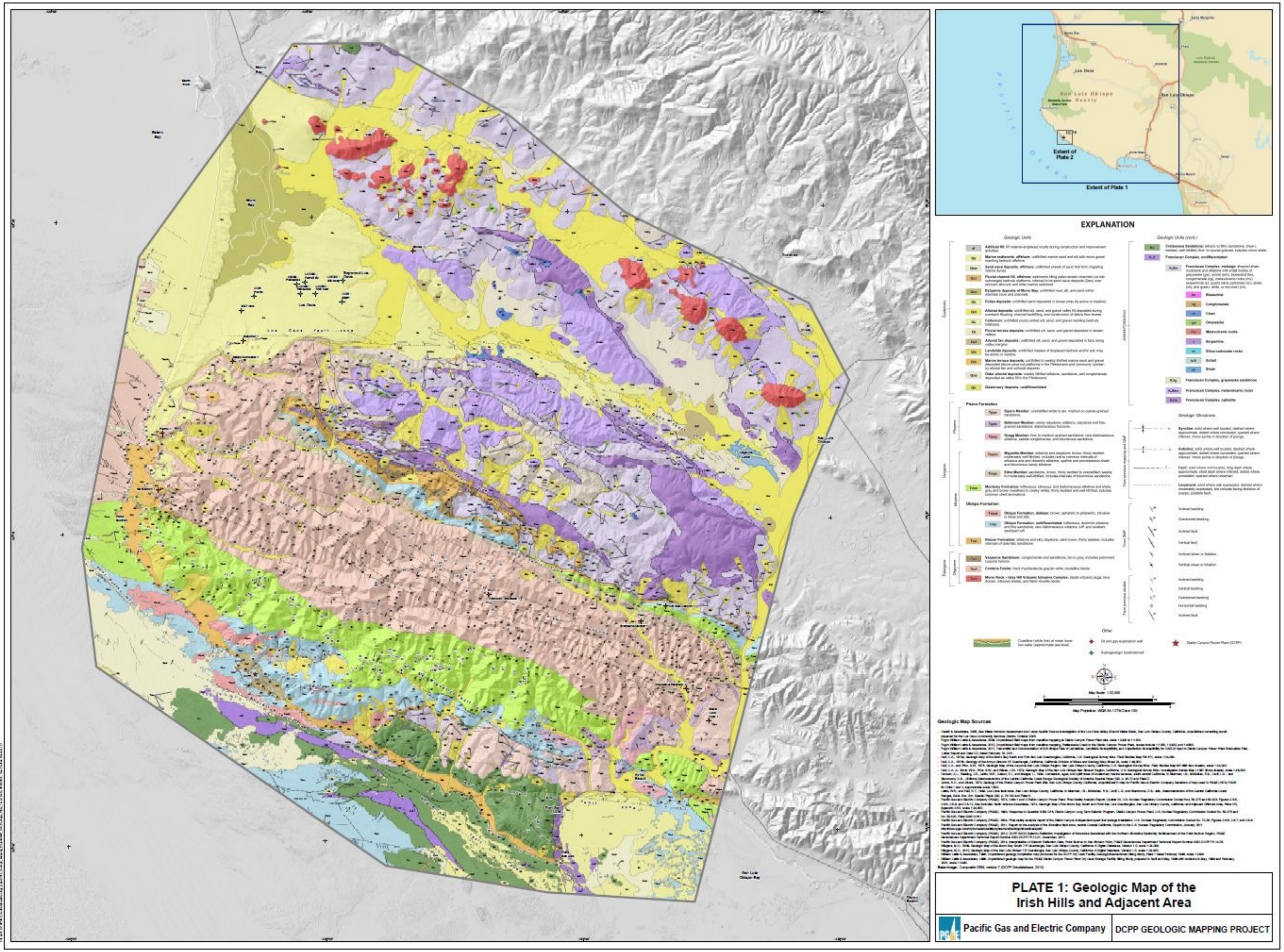

The geologic map of the Irish Hills demonstrates large internal deformation since 5 Ma, especially in the Pismo Syncline.

PG&E [2014]

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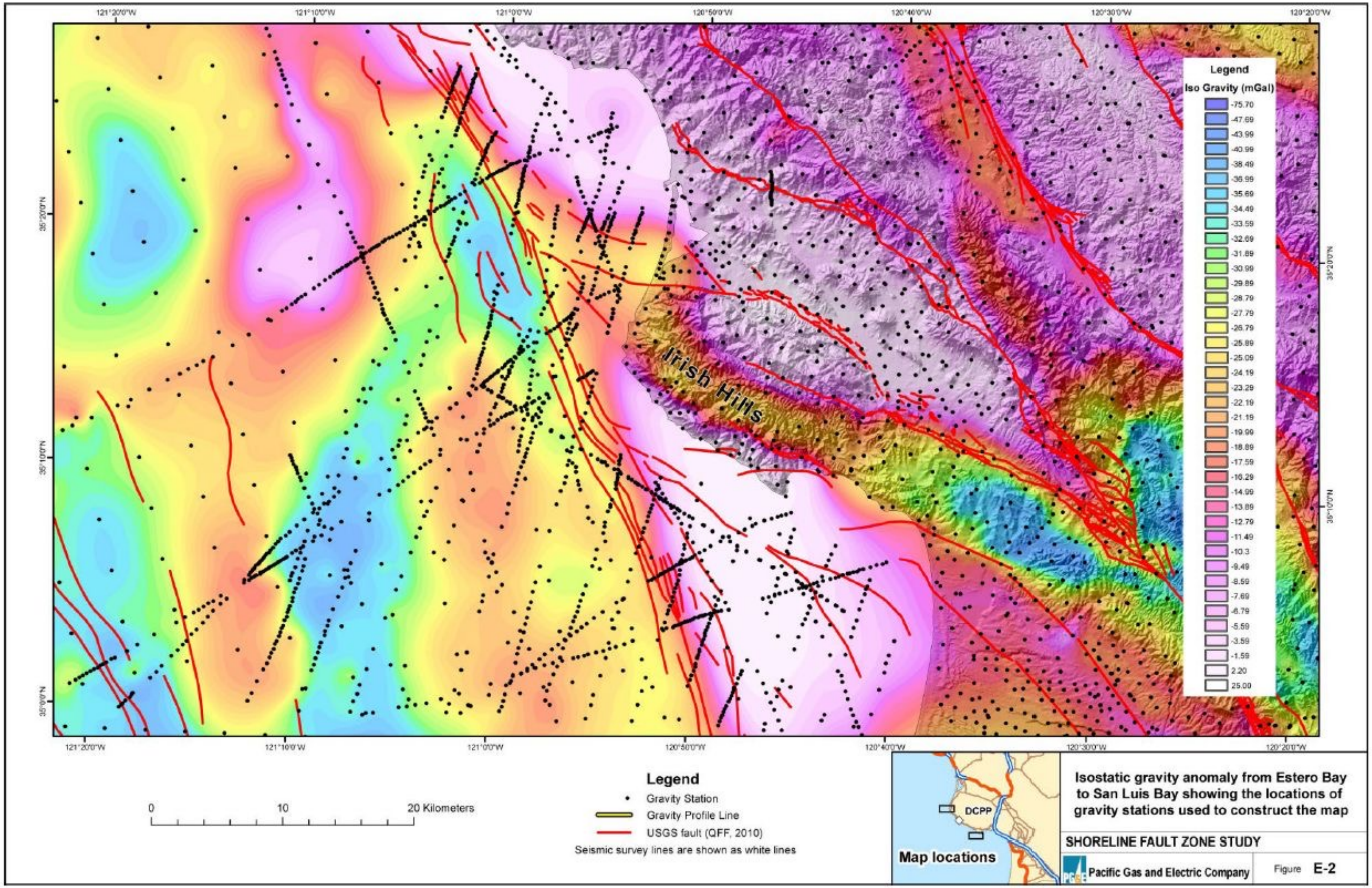

Figure 6-2. Large-Scale Residual Isostatic Gravity Anomaly Map Showing a Negative Gravity Anomaly Coincident with the Irish Hills (modified from Langenheim et al., 2008 and PG&E, 2011, Figure E-2)

The negative isostatic gravity anomaly here means that:

The topography
of the Irish Hills
is not just
isostatically
compensated,
it is OVER-
compensated by
crustal thickening.

PG&E [2024]

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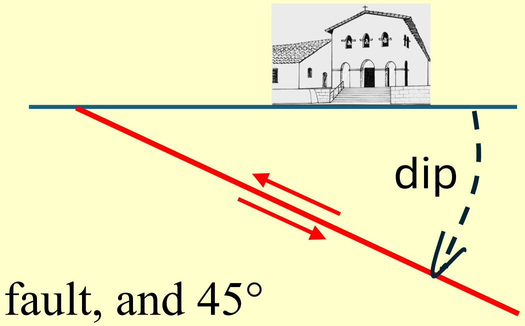


#2. Active thrust faults may dip at any angle (measured from the horizontal).

PG&E assigned alternative model dips of 30°, 50°, and 80° for the Los Osos thrust fault, and 45° to 75° for the San Luis Bay thrust fault.

HOWEVER:

125-year-old Mohr/Coulomb friction theory shows that thrusts never form at dips steeper than 45°, and most commonly dip at ~25° [for rock friction coefficient of 0.85; *Byerlee*, 1978].

THEREFORE:

Seismic potency rate (per m of fault trace) is defined as = (slip rate) × (down-dip width).

This important measure of earthquake generation varies as $1/\sin^2(\mathrm{dip})$ when throw-rate is held constant (as in these 2 SSC studies).

Compared to reasonable estimates (obtained with dip of 25°), an assignment of 50° dip reduces seismic potency rate by a factor of **3.3×**. An assignment of 80° dip reduces seismic potency rate by factor of **5.4×**.

Thus, PG&E underestimated seismic potency of these 2 thrusts (which were the <u>only ones they recognized</u>) by large factors.

MAXIMUM FRICTION

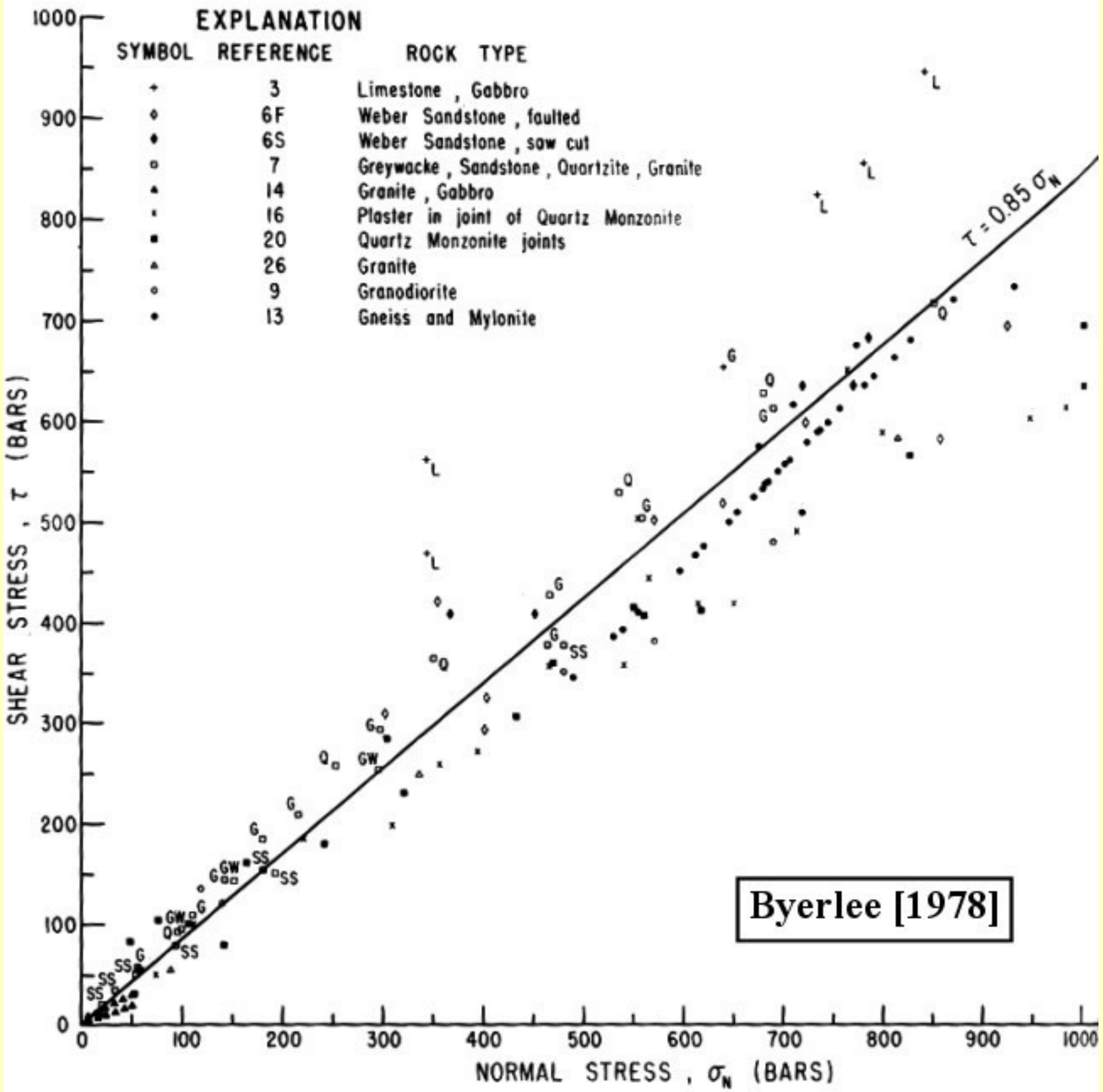
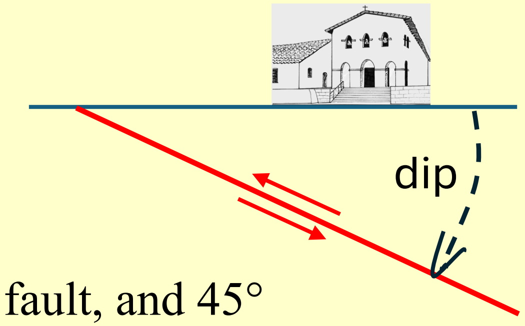


Figure 5

Shear stress plotted as a function of normal stress at the maximum friction for a variety of rock types at normal stresses to 1000 bars.



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#3. Geologic structures older than ~0.33 Ma are irrelevant to seismic hazard estimation.

PG&E based the throw-rates of the San Luis Bay thrust fault and the Los Osos thrust fault on vertical offsets of marine & fluvial terraces with Upper Pleistocene ages, typically ~0.12 Ma.

PG&E never attempted to model the uplift and folding of sedimentary rocks in the Irish Hills which occurred since 5 Ma.

HOWEVER:

A statistical study of all dated fault offsets in California by *Bird* [2007] showed that the risk of "inapplicability to neotectonics" is constant for offset features with ages of to 3 Ma, and then rises only modestly for features of 5 Ma age [his Figure 8].

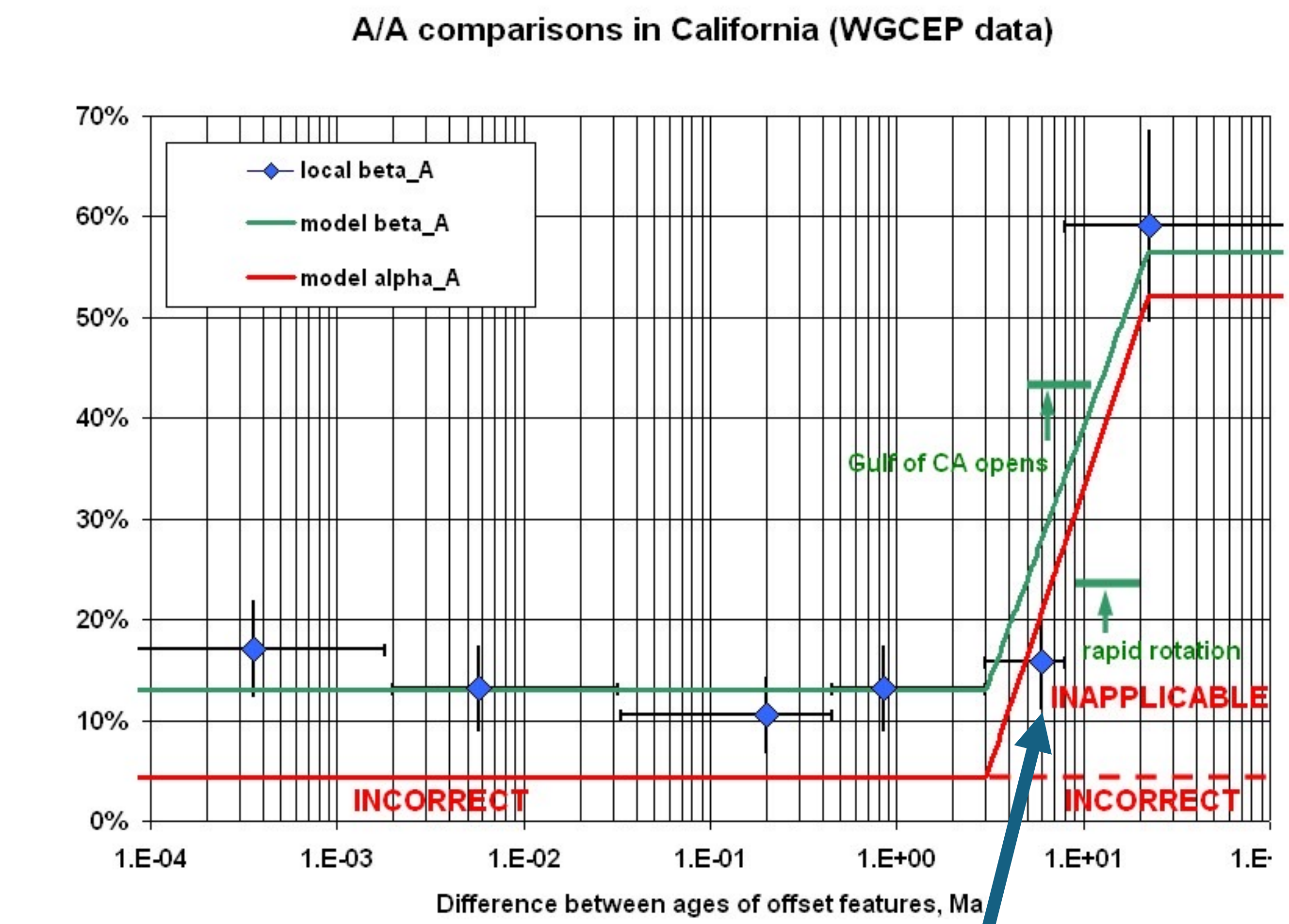
Bird [2007] also showed that a well-constrained fault offset rate requires 4~7 offset features, not just 1 or 2 [his Figure 9].

THEREFORE:

Therefore, all the structures in the Irish Hills, which formed since 5 Ma, should have been studied and modeled to provide geologic constraints on the rates of thrust-faulting.

I provided one example in Figure 1 of my March 2024 Declaration: Throw of the Obispo Formation at the San Luis Bay-Inferred Coastline thrust fault is 1.6~2.2 km since 5 Ma, implying throw-rate of 0.32~0.44 mm/year, and fault slip rate of 0.76~1.04 mm/year.

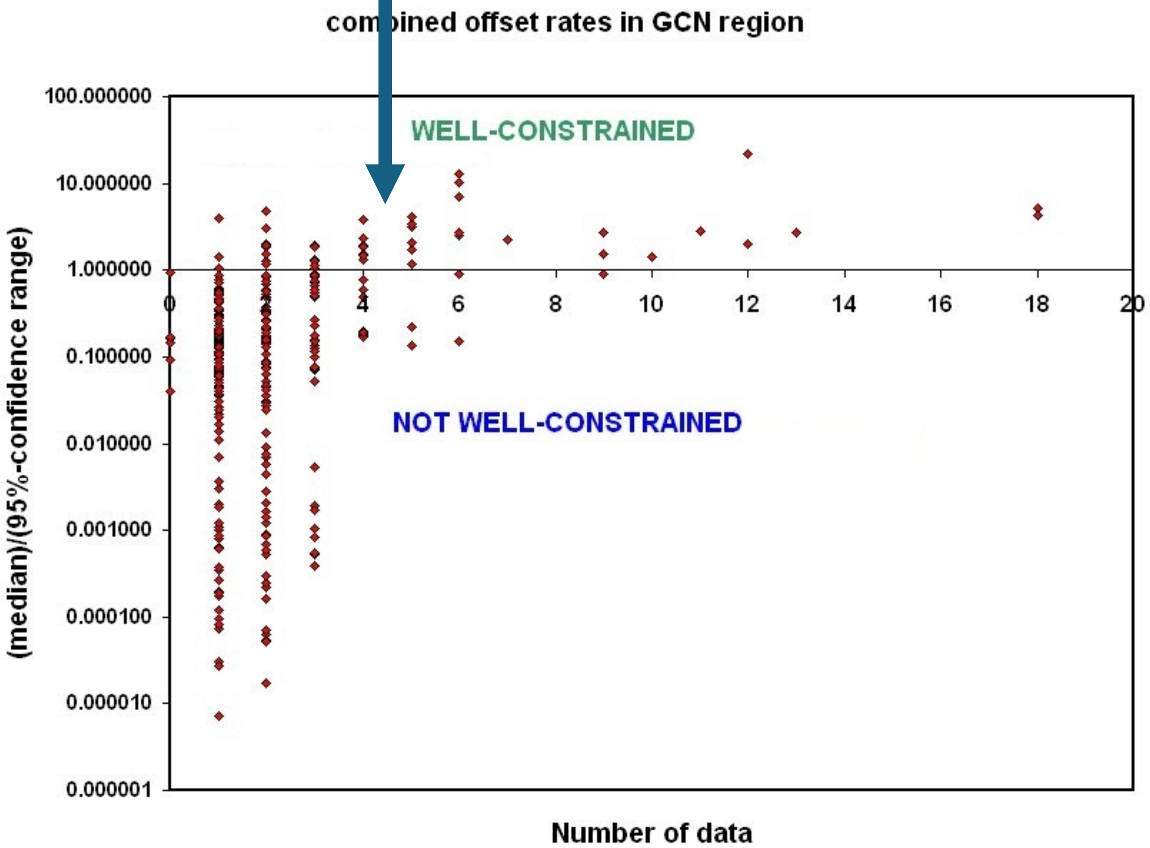
If thrusting in the Irish Hills has been symmetrical(?), then a minimum total thrust slip-rate by this method would be 1.52~2.08 mm/year. (However, this neglects any internal blind thrusts.)



In California, "inapplicability to neotectonics" is only a problem for offset features older than 5 Ma. All younger features are equally relevant.

Bird [2007, *Geosphere*]

It takes more than 1 (or 2) offset features to give a well-constrained fault slip rate; actually it takes more than 4!



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Mark-up (in red) by P. Bird, 2023 of
Figure 13-17 of SSC for DCPP
(PG& E, 2015)

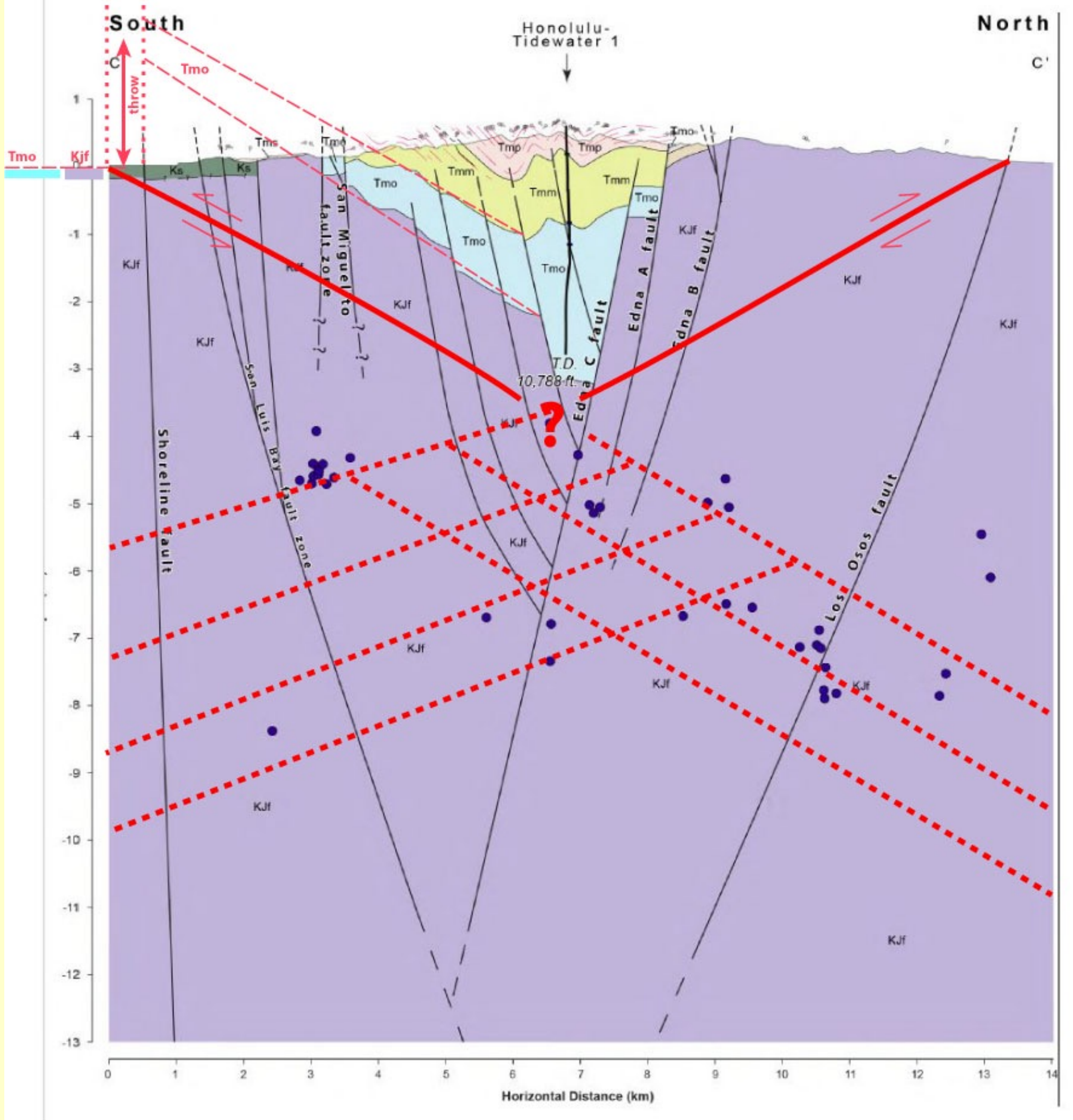

Figure 1. Revised geologic section through the Irish Hills near DCPP. The base for this figure is Figure 13-17 of the Seismic Source Characterization for DCPP (*PG&E*, 2015). Note that the fault dips suggested by black lines in their figure were not based on data, but were constrained by *PG&E*'s (2015) *a priori* assumption that only strike-slip tectonics is active in the area. In red, I have suggested more plausible 25° dips for the Los Osos thrust (at right/North) and the Inferred Coastline thrust (at left/South). The upper- left portion of this figure is also edited to show the throw (vertical offset) of map unit Tmo across the Inferred Coastline thrust, discussed in my text paragraph IV.B.25(b).

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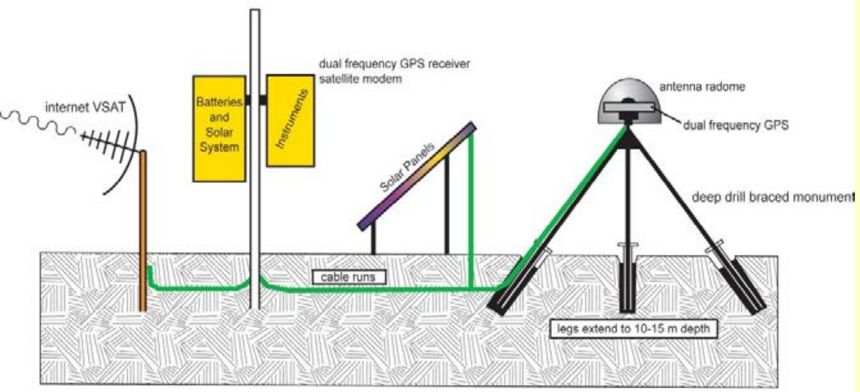
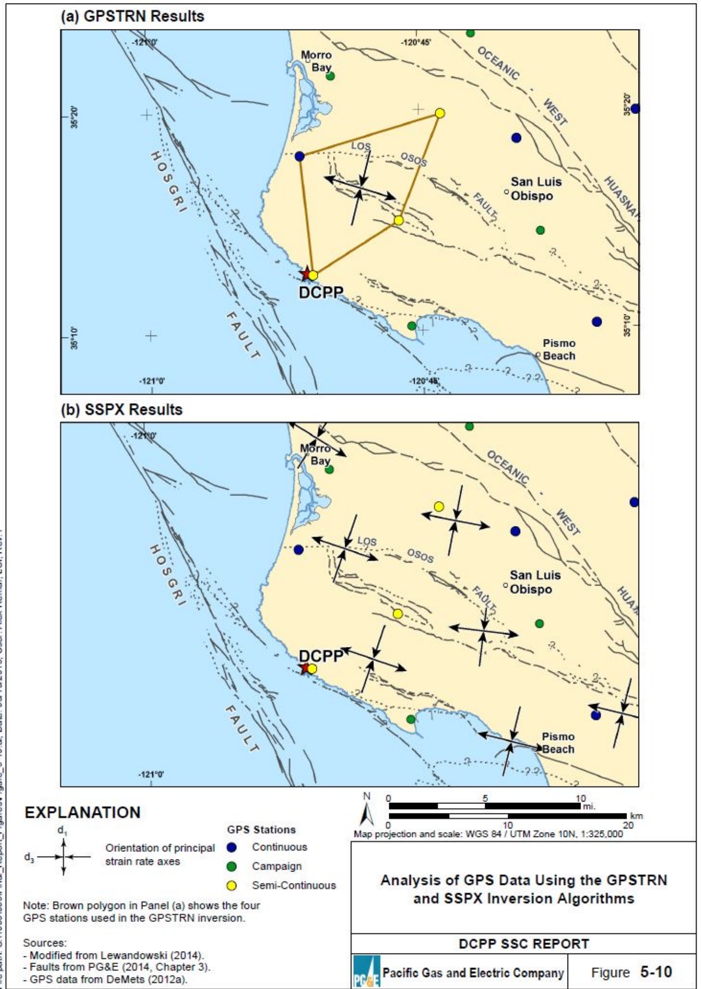


An EarthScope continuous GPS station, ~2004



#4. GPS geodetic velocities are not useful for site-specific seismic hazard estimation.

PG&E operated a GPS receiver at DCPP, and *PG&E* [2015] reported the shortening direction across the Irish Hills (~N15°E), but <u>not</u> the rate. The *PG&E* [2024] update adds <u>no new geodetic information</u>!

HOWEVER:

Seismicity has been successfully forecast using <u>only</u> GPS data, both in southern California [*Shen et al.*, 2007] and globally [*Bird et al.*, 2010; *Bird & Kreemer*, 2015]. Therefore, GPS data are useful. Any deformation model used in SSC should fit GPS strain-rate constraints (within their uncertainties).

THEREFORE:

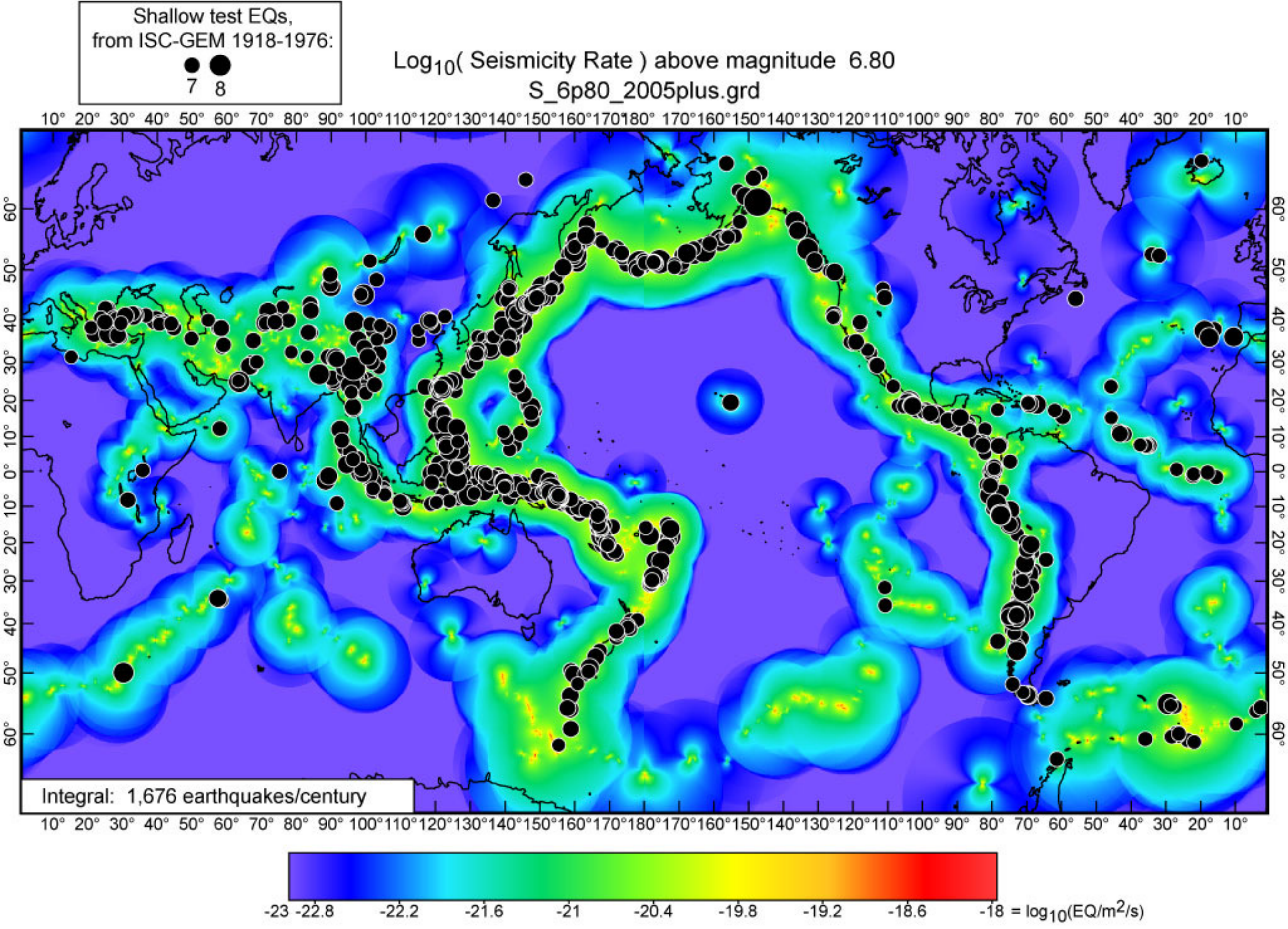
Our two NeoKinema models of neotectonics in the western US [*Field et al.*, 2013; *Shen & Bird*, 2022] had low-resolution F-E grids in the Irish Hills region, but:

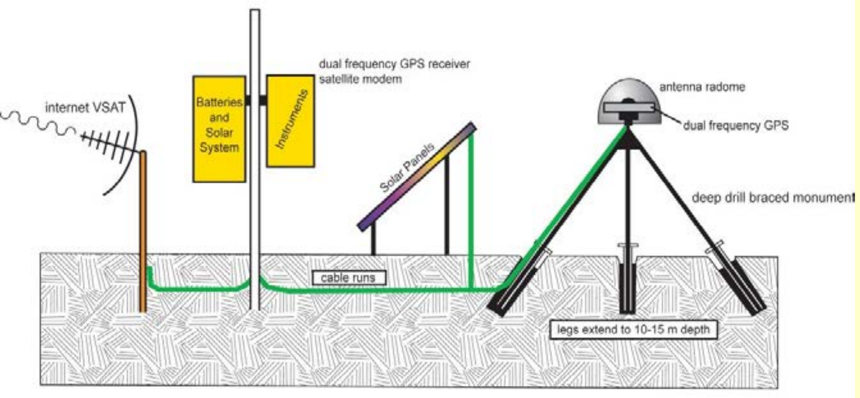
Both showed ~2 mm/year shortening across the Irish Hills, implying total thrust fault slip rate of (~2 mm/year) / cos(25°) = ~2.2 mm/year.

This is the 3rd of 3 independent analytic estimates developed here.

Bird & Kreemer [2015, *BSSA*] global forecast based on strain-rates measured by GPS geodesy.

Historic earthquakes (black dots) <u>were not used</u> in creating this forecast.





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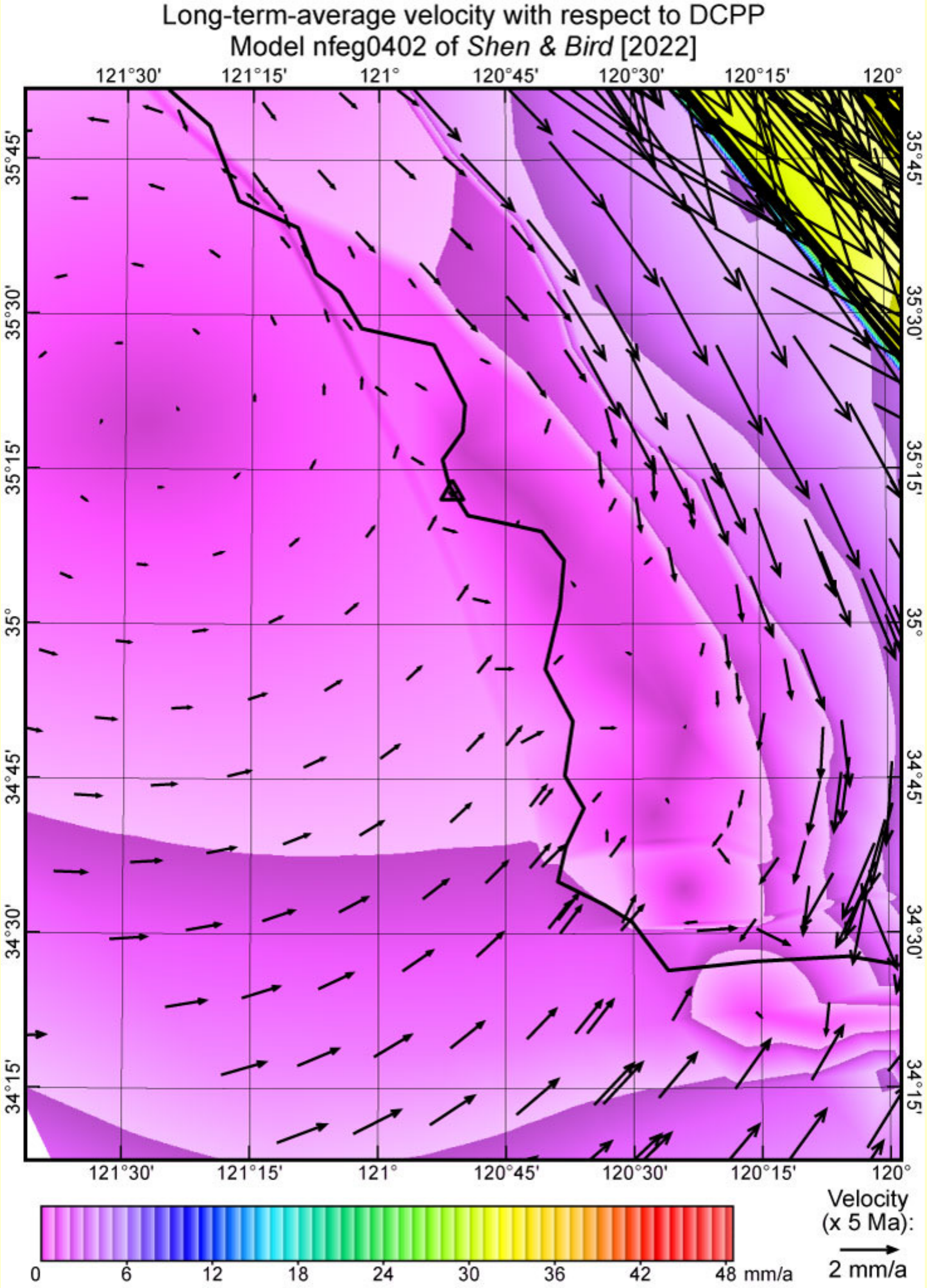
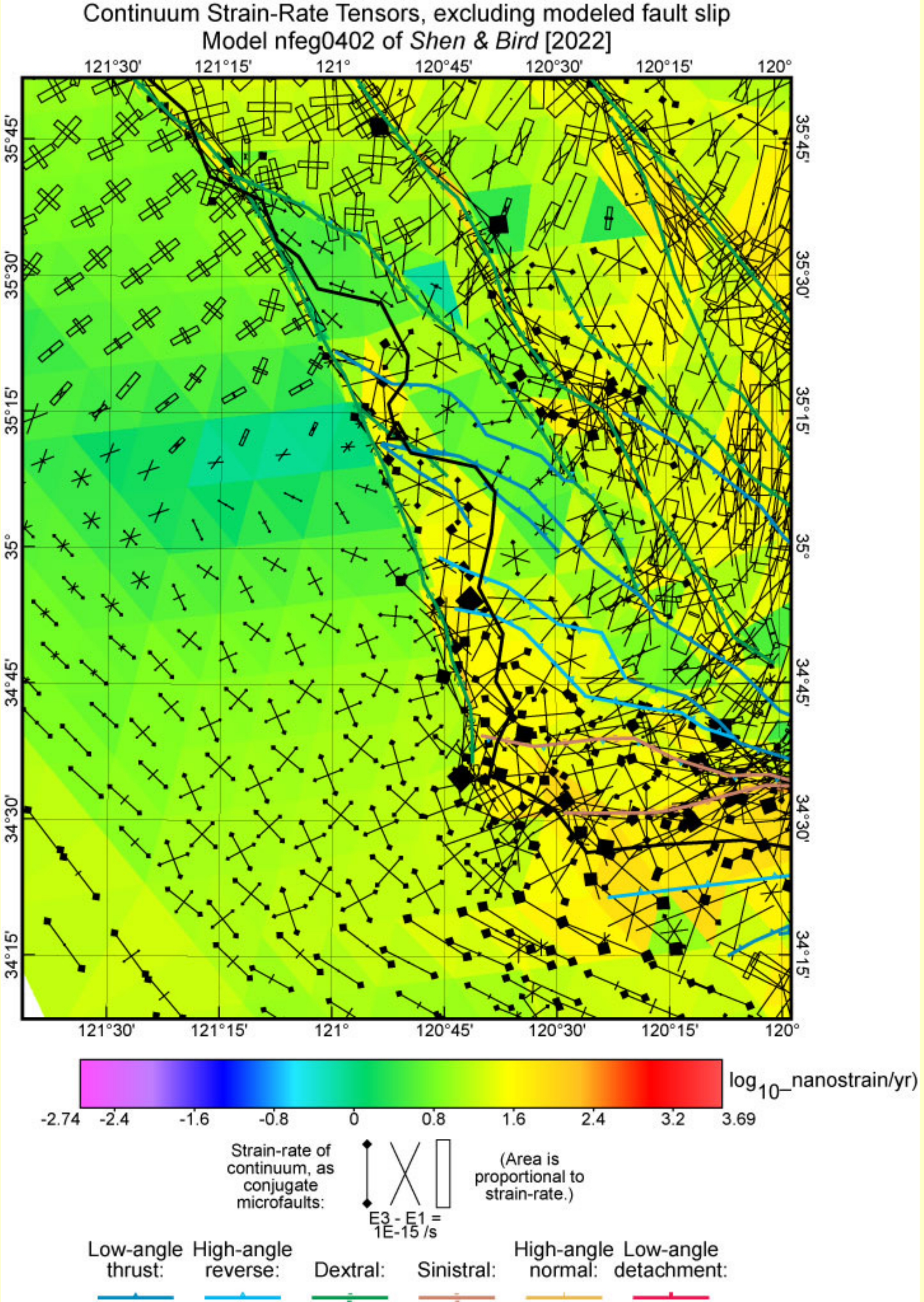
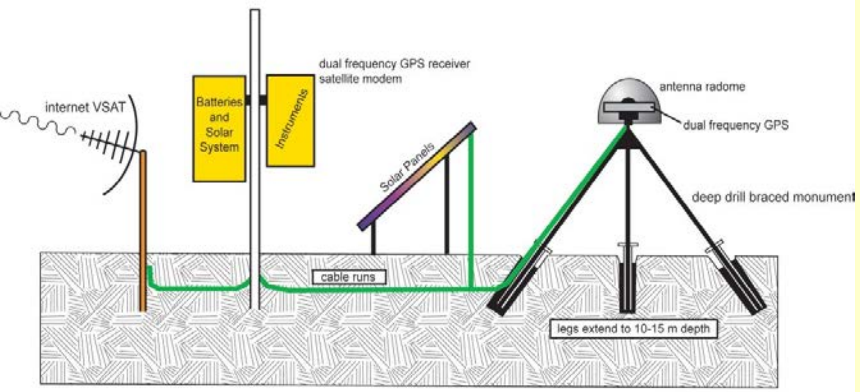


Long-term-average velocity with respect to DCPP
Model nfeg0402 of *Shen & Bird* [2022]
121°30'
121°15'
121°
120°45'
120°30'
120°15'
120°
35°45'
35°30'
35°15'
35°
34°45'
34°30'
34°15'
0
6
12
18
24
30
36
42
48 mm/a
Velocity (x 5 Ma):
2 mm/a



Continuum Strain-Rate Tensors, excluding modeled fault slip
Model nfeg0402 of *Shen & Bird* [2022]
121°30'
121°15'
121°
120°45'
120°30'
120°15'
120°
35°45'
35°30'
35°15'
35°
34°45'
34°30'
34°15'
log10-nanostrain/yr)
-2.74
-2.4
-1.6
-0.8
0
0.8
1.6
2.4
3.2
3.69
Strain-rate of continuum, as conjugate microfaults:
E3 - E1 = 1E-15 /s
(Area is proportional to strain-rate.)
Low-angle thrust:
High-angle reverse:
Dextral:
Sinistral:
High-angle normal:
Low-angle detachment:



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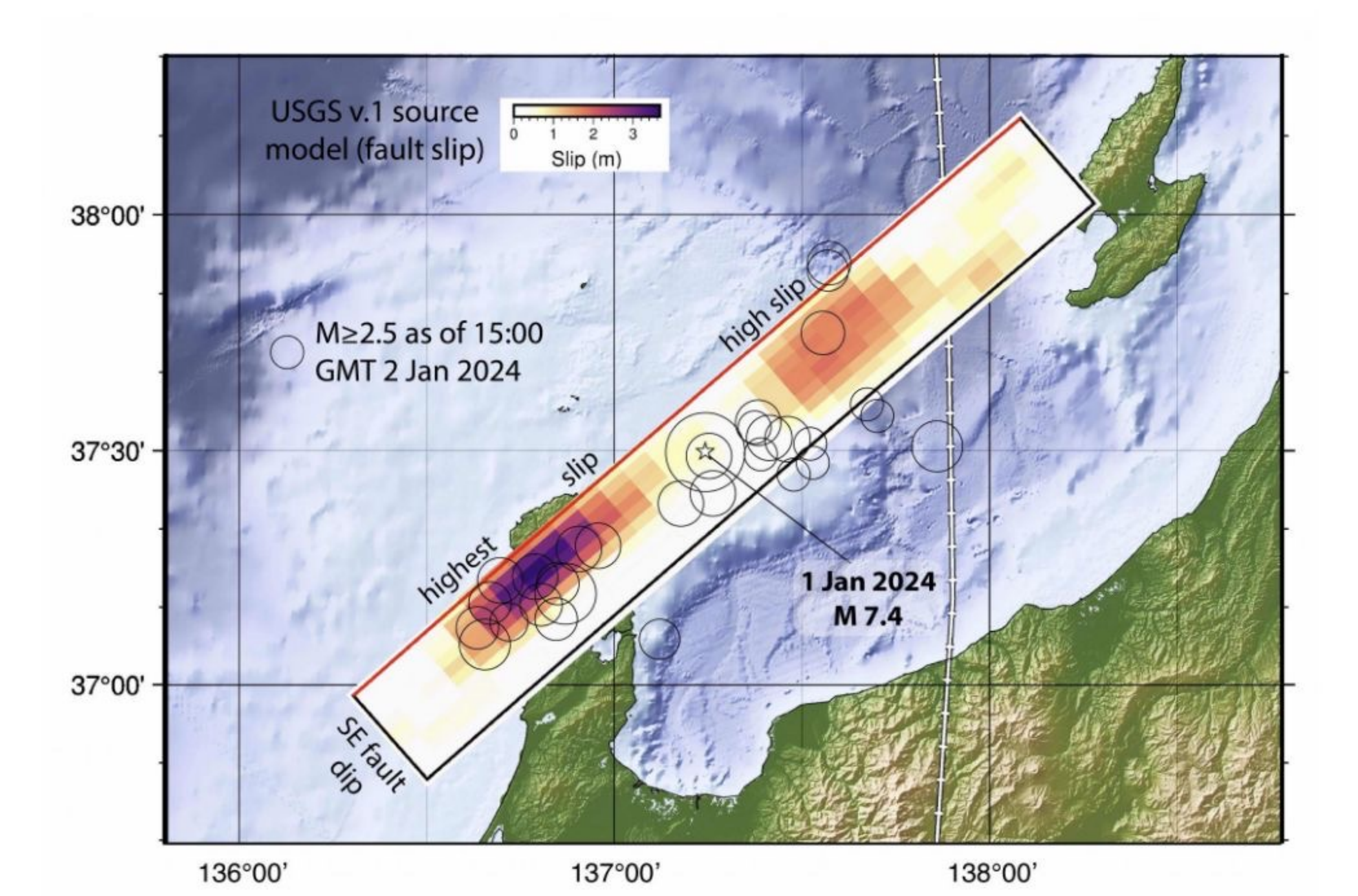
- Each time a false assumption was removed, thrust-faulting activity (seismic potency rate) in the Irish Hills went up by a large factor.
- It is important to estimate how these factors combine, and how much seismic hazard (and SCDF) is increased at DCPP.
- This could be done with a new SSC study and a new SPRA study, except that we cannot afford years of time and millions of $.
- Instead, we will use a much simpler method to show that the lower limit on seismic hazard (and SCDF) due to thrust-faulting ***alone*** is much higher than the total hazard claimed by PG&E.
- We will do this by adopting a characteristic great thrust earthquake for this tectonic setting, and then estimating its frequency in the Irish Hills.

A CHARACTERISTIC GREAT THRUST EARTHQUAKE?

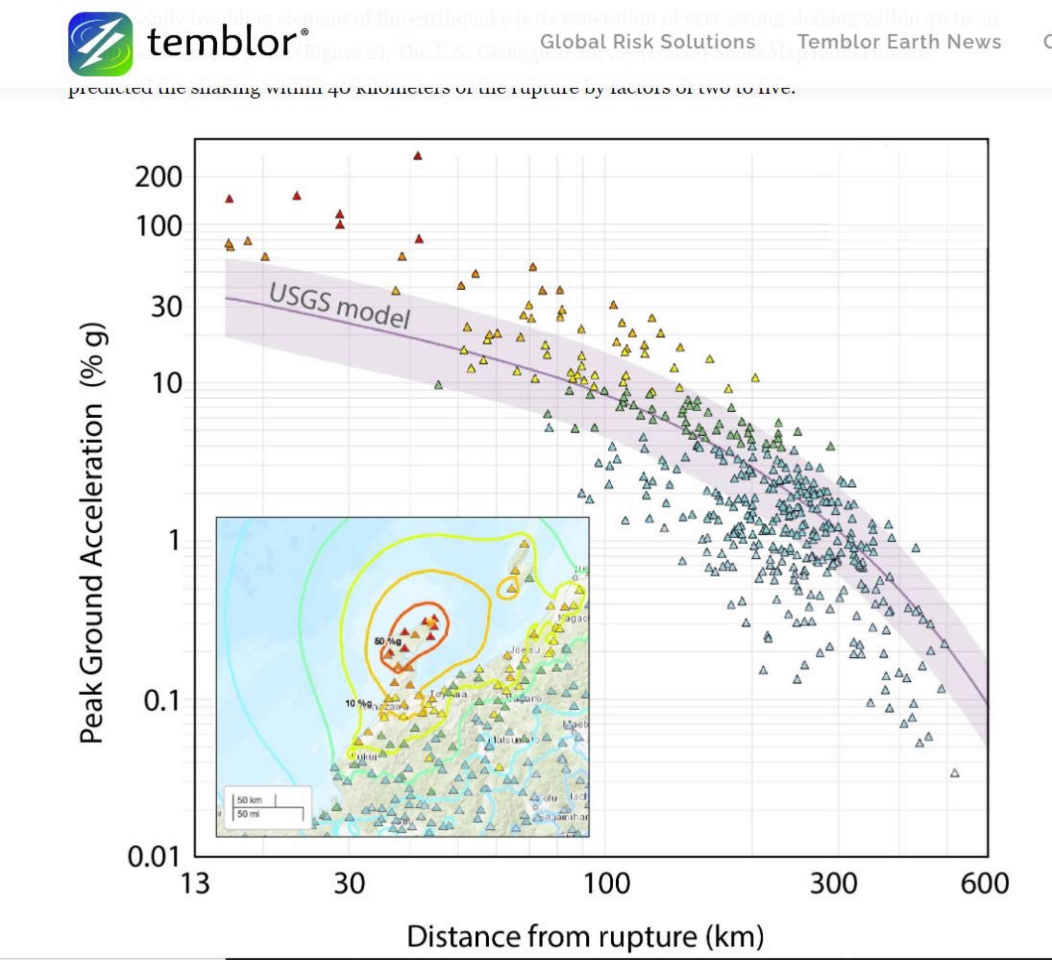
The Noto Peninsula on the northwest coast of Japan is tectonically analogous to the Irish Hills: a block of crust now being uplifted between two conjugate intraplate thrust faults.

We learned 2 essential facts from the 2024.01.01 m7.5 earthquake there:

- Mean slip on the seismogenic part of the thrust was 2 m [*USGS finite-fault solution*].
- Peak ground accelerations (PGA) at 5 strong-motion seismometers were 1.0~2.3 g.



Toda & Stein [2024]



CONCLUSIONS:

- The two SSC studies by *PG&E* [2015; 2024] seriously underestimated the seismic hazard from thrust-faulting under the Irish Hills because they relied on 4 demonstrably false assumptions.

- Three independent analytic methods give values for the total slip-rate on all shallow-dipping thrust faults under the Irish Hills:
  2.8 mm/year, ~2.0 mm/year, or 2.2 mm/year.

- Using the 2024.01.01 Noto Peninsula earthquake as a characteristic great thrust earthquake (with its 2 m of mean slip) yields recurrence times for great thrust earthquakes under the Irish Hills of 715 years, 1000 years, or 910 years, respectively.

- Because such a great thrusting earthquake <u>would</u> cause seismic core damage at DCPP, its seismic core damage frequency (SCDF) is <u>at least</u>

$$1.4\times10^{-3}\text{ /year, or }1.0\times10^{-3}\text{ /year, or }1.1\times10^{-3}\text{ /year, respectively.}$$

[This is before the hazard contribution from strike-slip faults like the Hosgri is added.]

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