Suitable 3D Geometry for the San Andreas Fault ShakeOut Scenario 2.0 from Seismicity

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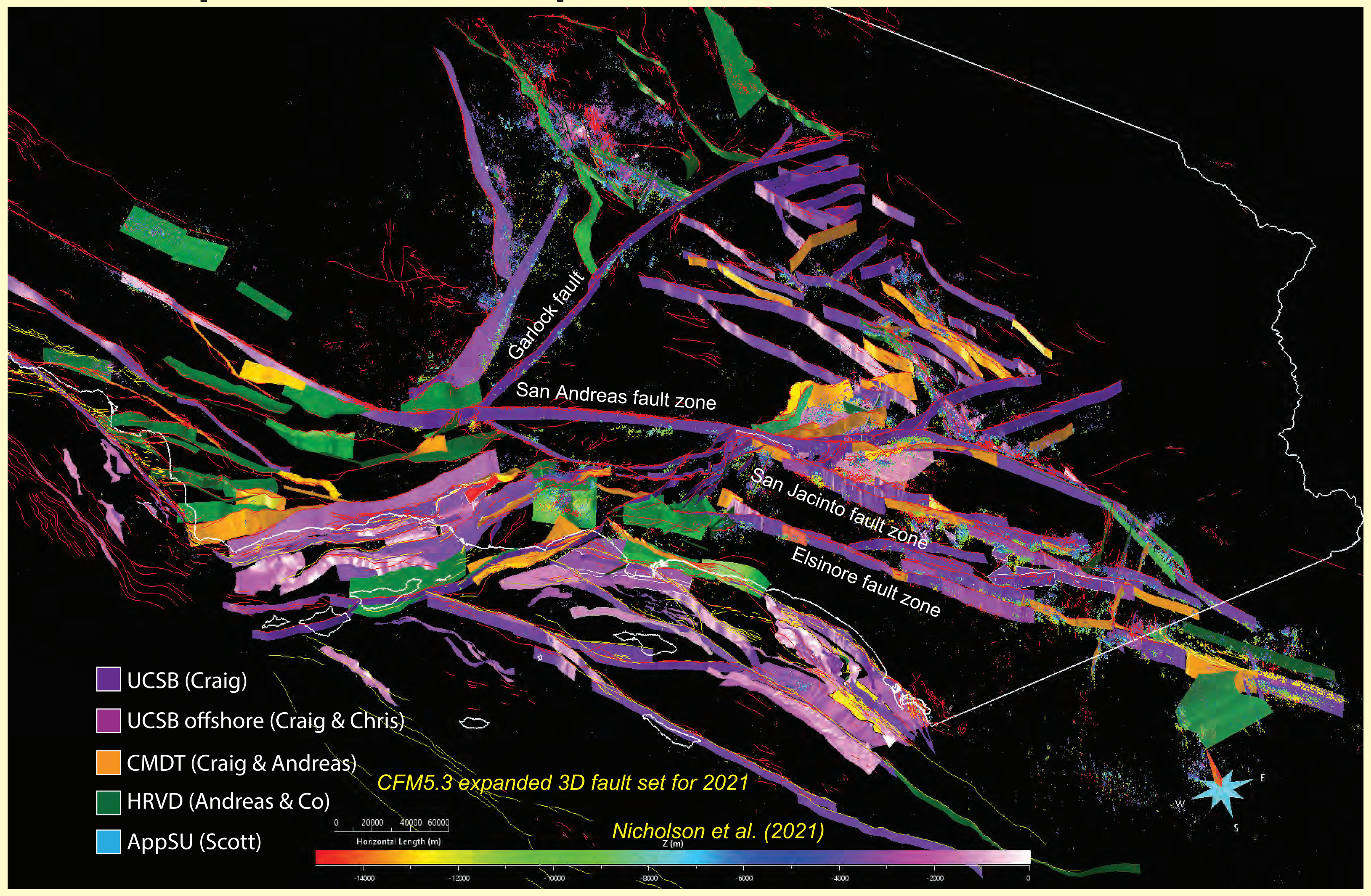
ABSTRACT

A critical component of the San Andreas Fault (SAF) ShakeOut Scenario 2.0 rupture model is accurate and reliable 3D fault geometry. This geometry can be provided by the fault models in CFM5.3 that are based on surface mapping, seismicity and multiple data validation methods. Where seismicity is present, relocated hypocenters and aligned focal mechanism nodal planes define a consistent steep-to-near-vertical, largely planar SAF extending from Parkfield to the Salton Sea, including around the Big Bend and a through-going steeply-dipping predominantly strike-slip Banning strand at depth in San Gorgonio Pass [*Nicholson and Hauksson*, 2023]. In the northern Coachella Valley, seismicity indicates that the Garnet Hill and Banning strands are sub-parallel and steeply dipping (≥70°NE) to depths of >15 km, and interact with a stack of low-to-moderately dipping oblique thrust faults. The Mission Creek strand is also steep-to-near vertical (≥80°NE). Farther south, earthquakes define a near-vertical southern SAF and an adjacent sub-parallel Mecca Hills-Hidden Springs fault system that dips ~60°NE. This CFM5.3 3D geometry of complex interacting fault sets and SAF strands is further validated by independent subsurface imaging and other data. CFM5.3 can also provide suitable 3D geometry and proper context for the proposed large LA basin ShakeOut Scenario aftershock on the Hollywood-Raymond fault.

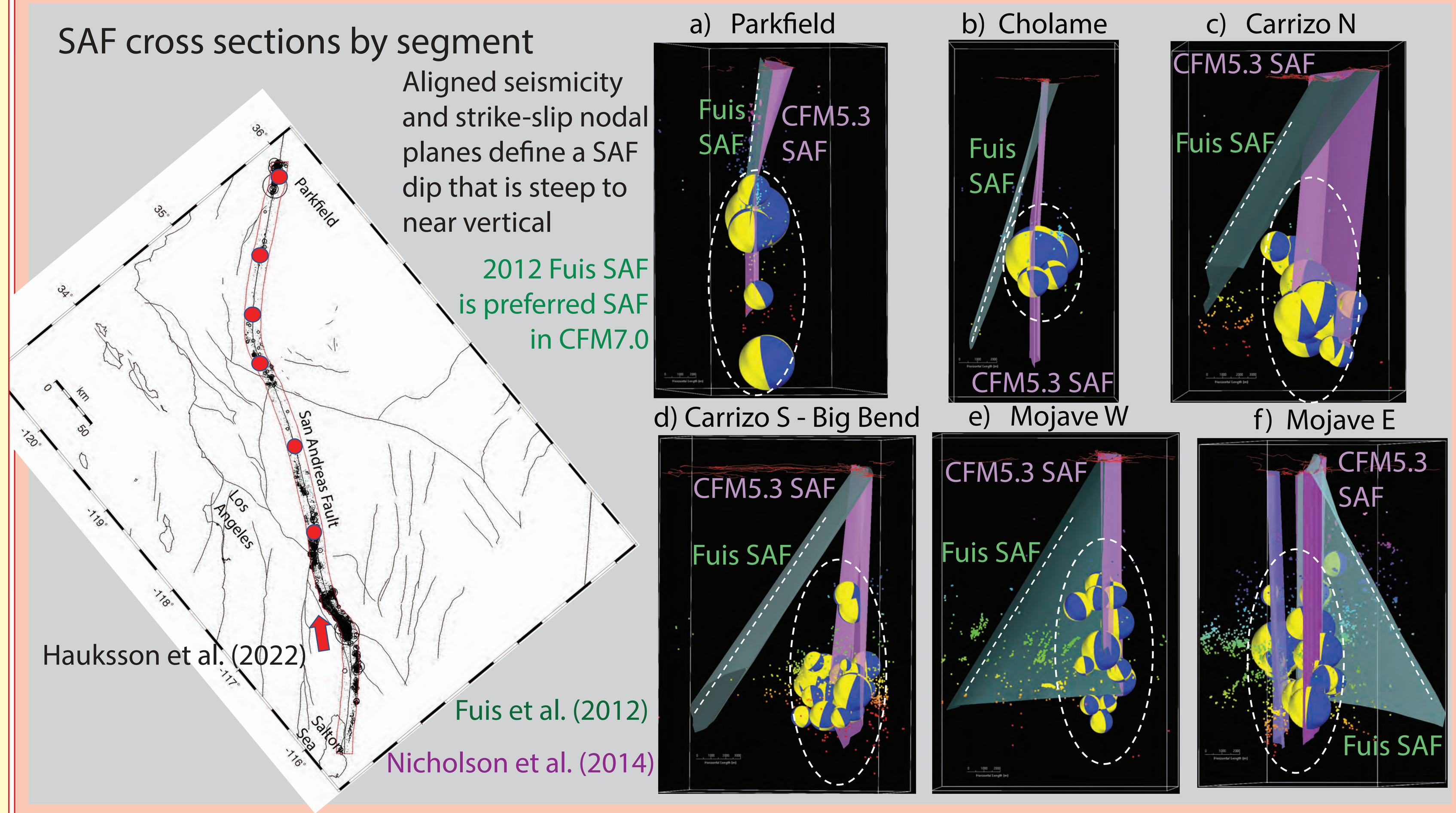
In contrast, several faults adopted in 2022 for CFM6.1/7.0 are actually older outdated alternative models not independently validated with data, or are mutually exclusive and thus incompatible with each other or with adjacent faults. In particular, CFM7.0 SAF models with low-to-moderate dips (37°-60°) from the fault surface trace are inconsistent with and thus invalidated by this persistent steep-to-near-vertical SAF seismicity and nodal plane alignment. These alternative SAF models are based on gravity, or presume the SAF is everywhere single stranded [*Fuis et al.*, 2012]. The net result is that active adjacent secondary faults can be misidentified as the SAF principal slip surface, the CFM7.0 southern SAF is incompatible with the steeply dipping Mission Creek fault with which it merges, exhibits a major fault gap near Bombay Beach, and is not consistent with various subsequent, updated studies since 2012 of seismicity, finite fault displacements, seismic imaging, or gravity modeling, including those by the authors themselves [*e.g., Fuis et al.*, 2017].

Expanded CFM5.3 preferred 3D fault set for 2021



Oblique 3D view of expanded CFM5.3 preferred 3D fault set [*Nicholson et al.*, 2021] with faults color-coded by developer. Craig developed or co-developed (purple, pink, orange) ~88% of the updated or newly added faults since 2009. This updated CFM5.3 fault set strived to be *internally consistent*, kinematically compatible, and *predictive* of fault geometry and seismicity patterns at depth. Steeply dipping to near vertical 3D models for the San Andreas Fault (SAF) in CFM5.3 and other adjacent secondary faults have been independently data validated; preferred SAF models in CFM7.0 have not.

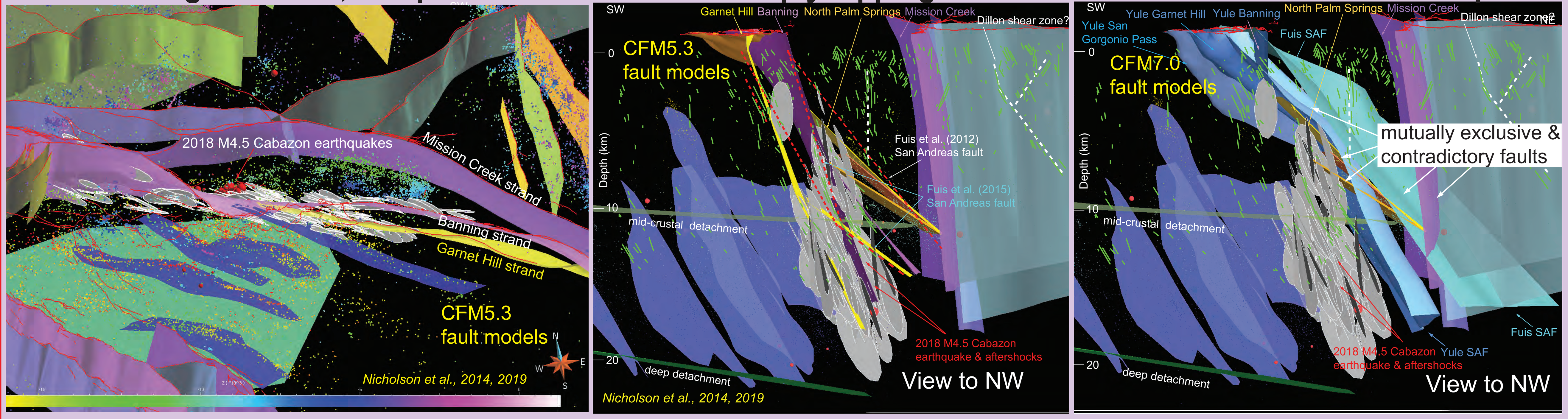
Data show San Andreas fault is steep to near-vertical



Nicholson and Hauksson (2023)

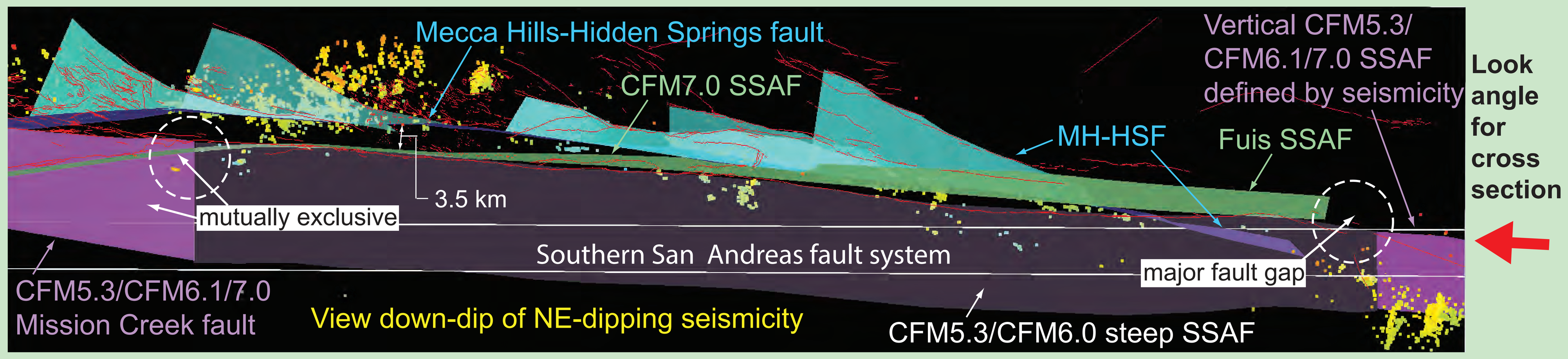
Vertical cross sections by segment (red circles on map) looking NW along the San Andreas fault (SAF) extending from Parkfield to Cajon Pass showing relocated seismicity and focal mechanisms compared with CFM5.3 (purple) and Fuis (green) 3D SAF models [*Nicholson and Hauksson*, 2023]. Outdated 2012 Fuis SAF model was adopted as the preferred SAF geometry in CFM7.0 even though its low-to-moderate dips (dashed lines) are inconsistent with (and ***thus invalidated by***) the abundant aligned relocated hypocenters and focal mechanism nodal planes that exhibit steep-to-near-vertical dips directly beneath its mapped surface trace (dashed ovals), including around the Big Bend (d). Unlike the CFM5.3 SAF, the alternating, oppositely dipping fault geometry along strike of the Mojave section of the pure strike-slip CFM7.0 Fuis SAF ***is not mechanically feasible***.

In San Gorgonio Pass, independent data confirm steeply dipping San Andreas fault strands to 18 km depth

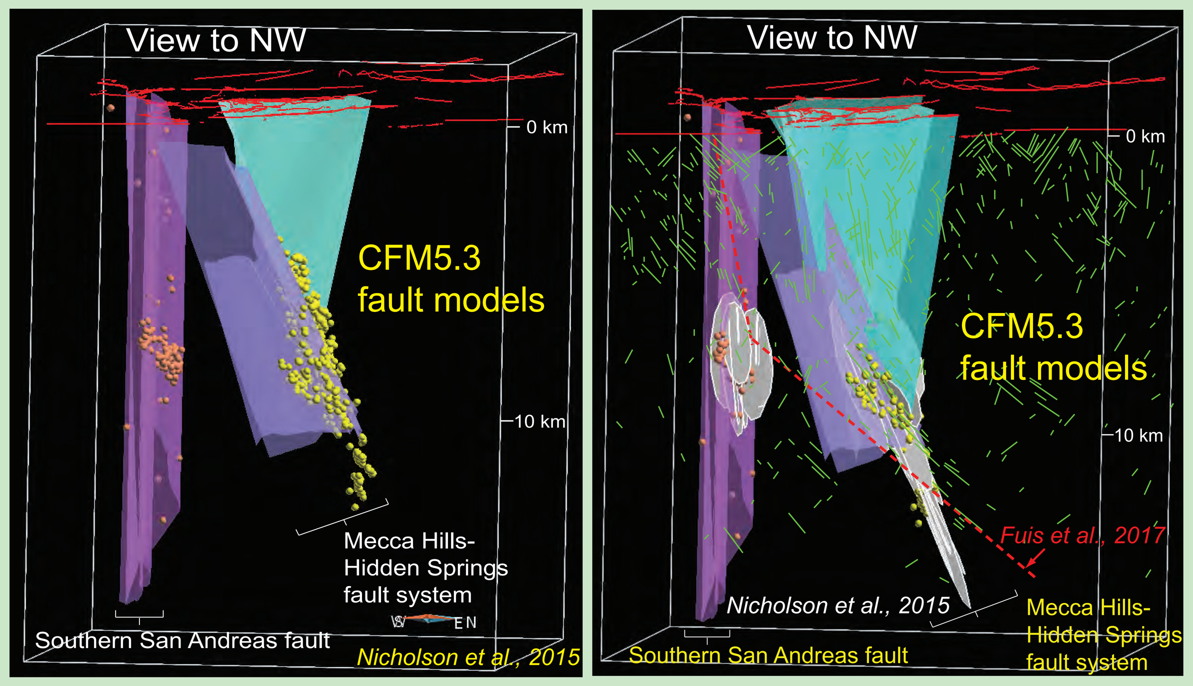


(*left*) Oblique 3D view looking down-dip of Banning strand through San Gorgonio Pass of CFM5.3 3D faults, relocated hypocenters (dots) and 2018 M4.5 Cabazon hypocenters (red spheres) [*Nicholson et al.*, 2019]. Circular gray disks are nodal planes that align along and validate active, through-going, steeply dipping Banning (purple) and Garnet Hill (yellow) faults to depths of 18 km. (*middle*) Oblique cross-section view looking NW of steeply dipping CFM5.3 Banning and Garnet Hill faults that interact with various moderately dipping oblique-slip faults and down-dip splays. Note consistency with strong reflectors imaged by SSIP Line 6 (green lines)[*Fuis et al.*, 2015], strike-slip nodal planes (gray disks) and 2018 Cabazon events. (*right*) Outdated alternative 2003 Yule (light blue) and 2012 Fuis (light blue-green) SAF models [*Yule and Sieh*, 2003; *Fuis et al.*, 2012] adopted by CFM7.0. ***These models contradict each other*** and other adjacent faults, and are inconsistent with the alignment of steeply dipping, strike-slip nodal planes, reflectors imaged by SSIP Line 6, and relocated hypocenters, like the 2018 Cabazon sequence [*Nicholson and Hauksson*, 2023]. Outdated 2003 Yule SAF represents combined Banning, Garnet Hill and San Gorgonio Pass thrust geometry in CFM6.1/7.0, and as such ***is not mechanically feasible*** given the disparity in dip and slip orientation between these three faults.

Seismicity and other independent data validate the Southern San Andreas fault in CFM5.3 is steep to near-vertical (80°-90°) and NOT moderately dipping (55°-65°) as it is in CFM7.0

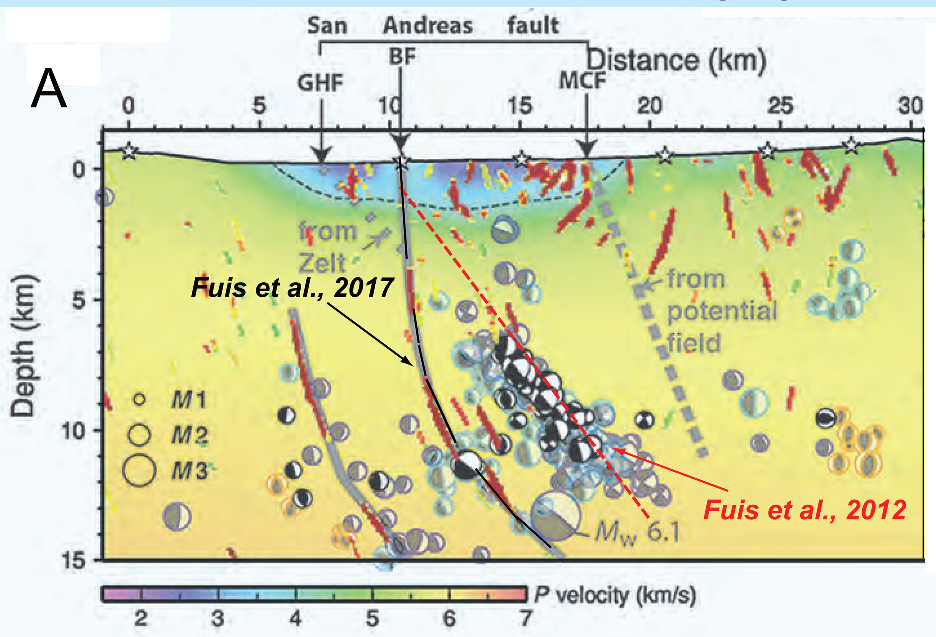


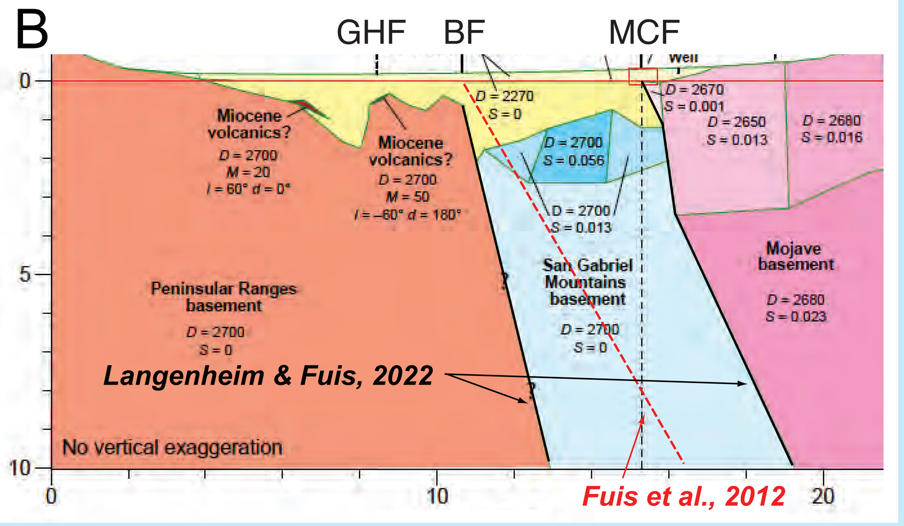
Oblique 3D view looking down-dip of NE-dipping seismicity adjacent to CFM5.3 SSAF. Fuis 2012 SSAF (green) adopted as preferred for CFM6.1/7.0 (but not for CFM6.0) does not align with this seismicity as well as the mapped CFM Mecca Hills-Hidden Springs fault (light blue) with which it is mutually exclusive. It also contradicts independent data, observations and modeling that define steep Mission Creek (purple) and Banning faults at Indio [*Nicholson et al.*, 2014; *Langenheim and Fuis*, 2022; *Vavra et al.*, 2023], a steep SSAF at Mecca Hills [*Fuis et al.*, 2015, 2017] and vertical CFM5.3/CFM6.1/7.0 SSAF at Bombay Beach (purple)[*Nicholson et al*, 2015].

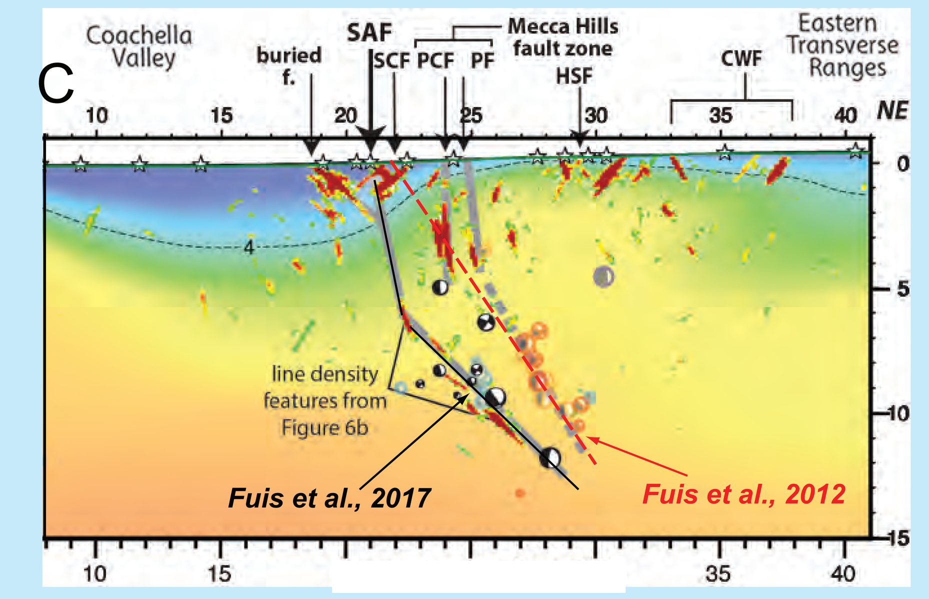


Oblique cross section views looking NW along CFM5.3 southern San Andreas fault (SSAF) and CFM Mecca Hills-Hidden Springs fault system (MH-HSF). (*left*) Aligned relocated hypocenters define a steep-to-near-vertical SSAF (orange spheres) and a separate moderately NE-dipping MH-HSF at depth (yellow spheres) [*Nicholson et al.*, 2015]. (*right*) Aligned focal mechanism nodal planes (gray disks), together with strong reflectors from SSIP Line 4 (green lines), independently validate these distinctly separate faults. Inferred non-planar SSAF geometry (red-dashed lines) from *Fuis et al.* [2015, 2017] is inconsistent with previous Fuis 2012 SSAF and the fault geometry defined by aligned seismicity and nodal planes at depth. However, it does infer a steeply dipping (>80° dip) SSAF in the upper 7-8 km, which matches the CFM5.3 steep-to-near vertical dip.

Later studies based on SSIP imaging, seismicity and gravity no longer support earlier Fuis 2012 southern SAF model adopted by CFM7.0





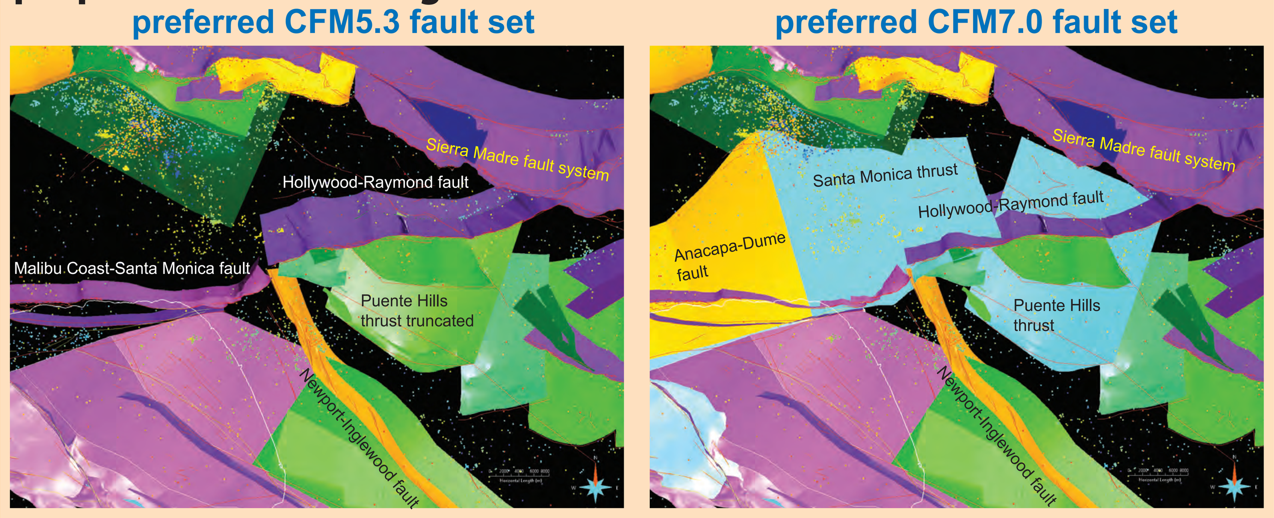


Vertical cross sections showing major reflectors from subsurface imaging (red lines) along (A) SSIP Line 6 in San Gorgonio Pass and (C) Line 4 at the Mecca Hills, p-wave velocity (shaded colors), focal mechanisms and inferred southern San Andreas fault (SSAF) geometry (black/gray lines)[*Fuis et al.*, 2015, 2017], and (B) gravity model at the Indio Hills [*Langenheim and Fuis*, 2022]. These later studies contradict the earlier moderately dipping, single-stranded, planar SSAF geometry (red dashed lines) from *Fuis et al.* [2012] adopted by CFM6.1/7.0 in 2022, and basically reaffirm the active strands of the SSAF (including the BF - Banning fault, MCF - Mission Creek fault, GHF - Garnet Hill fault) are steep-to-near vertical in the upper 7-10 km, as previously modeled in CFM5.3 since 2012-2014 [*Nicholson et al.*, 2012, 2014].

Conclusions

- Aligned relocated hypocenters and focal mecahanism nodal planes define a persistent steep-to-near vertical SAF extending from Parkfield to the Salton Sea. This includes around the Big Bend and through San Gorgonio Pass.
- Other independent studies confirm the SAF is steep-to-near vertical in the upper 7-10 km.
- These data contradict and invalidate the preferred moderately dipping Fuis 2012 SAF in CFM7.0.

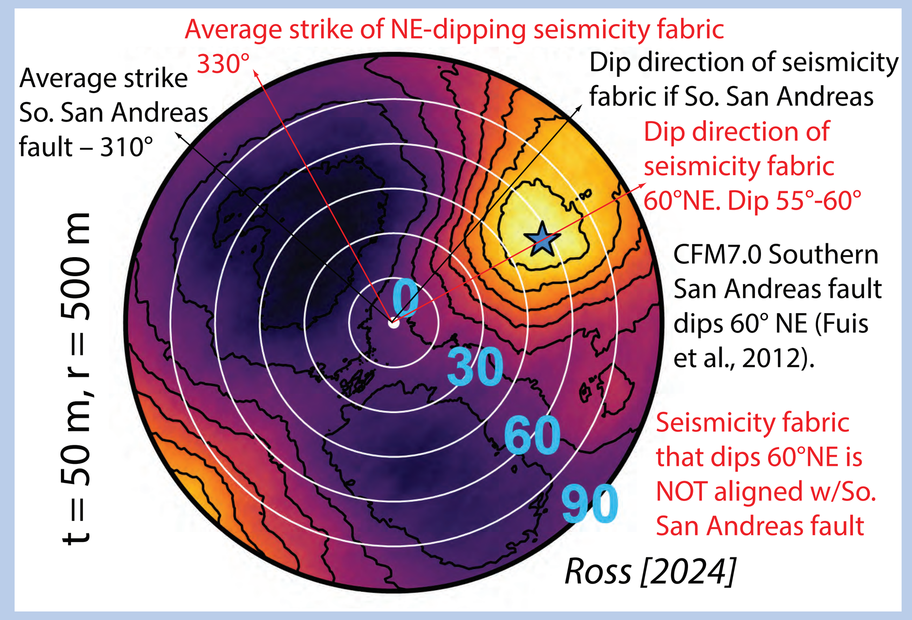
Hollywood-Raymond fault geometry in CFM5.3 & CFM7.0 for the proposed source of large LA Basin ShakeOut Scenario 2.0 aftershock



Map views of preferred CFM5.3 (*left*) and CFM7.0 (*right*) 3D fault sets for the LA Basin area centered on the Hollywood-Raymond fault (HRF, dark purple) adopted as the source for the large ShakeOut Scenario 2.0 aftershock. In CFM5.3, the HRF is steeply dipping to >15 km depth and truncates the Puente Hills thrust (PHT). In CFM7.0, PHT truncates the Raymond at mid-depth, while low-angle Anacapa-Dume (yellow) and Santa Monica (light blue) thrust faults intersect and potentially truncate Hollywood and Malibu Coast-Santa Monica (light purple) faults at shallow depth.

Adjacent NE-dipping seismicity is NOT aligned with the Southern San Andreas fault (SSAF)

Moderately NE-dipping seismicity adjacent to SSAF defines a seismicity fabric with strike (and dip direction) that does NOT match the SSAF. It is rotated 15°-20° CW (330°) from the strike of SSAF (310°) [*Ross*, 2024], and more closely aligns with the mapped Mecca Hills-Hidden Springs fault system [*Nicholson et al.*, 2015]. The implication is that because this moderately NE-dipping seismicity is NOT aligned with the SSAF, it is not the SSAF, but rather strikes oblique to it and converges to the south at the northern end of the Brawley Seismic Zone.



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