Fault Displacement Hazards at Aliso Canyon (ACGSF) and Honor Rancho (HRGSF) Natural Gas Storage Fields (UGS), Southern California, USA*

Thomas L. Davis[1]

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[1]Geologic Maps Foundation, Inc., Ventura, CA, United States (tldavisgeo@gmail.com)

Abstract

Faults that have a significant potential for future displacement and intersect natural gas storage wells in the subsurface are an underappreciated hazard to well integrity. The American Petroleum Institute's RP 1171 (API, 2015), that is guiding State of California and Federal new rule-making for gas storage fields, states "Depleted hydrocarbon reservoirs are candidates for natural gas storage because the reservoir integrity has been demonstrated over geologic time by hydrocarbon containment at initial pressure conditions." True, but gas wells at storage reservoirs have not existed over geologic time and when wells cross faults capable of future movement there exists a fault displacement hazard to well integrity. If displacement were to occur, then the potential exists for methane leakage to the surface and risks to public safety, the environment, energy supply, and a valuable resource. As with all energy sources, natural gas comes with its own set of challenges: the largest methane leak in US history occurred at the Aliso Canyon Gas Storage Field (ACGSF). Taking almost four months to control, the ACGSF leak demonstrated the difficulty of stopping an underground leak from one well in a pressured gas storage field and showed the need to evaluate all hazards to gas well integrity and to estimate and mitigate the risks. At the ACGSF and Honor Rancho fields, all the storage wells cross the Santa Susana (SSF) and Honor Rancho faults, respectively, to reach their storage reservoirs. Both faults have had significant displacement during the last 2-3 ma, and the SSF may have a slip-rate as high as 7.0-9.8 mm/yr during the last ~700 ka. The Southern California Earthquake Data Center estimates the characteristic earthquake magnitude for the SSF to be from MW 6.6-7.3, and historic records for this range of magnitudes indicate that from 0.3 to 2.8 meters of fault displacement can be expected on the SSF. Small, earthquake-fault movements of up to 0.25 meters severely damaged numerous oil wells in the subsurface at the Wilmington oil field and are significantly smaller than the moderate to large tectonic earthquakes common to

southern California that will generate much larger fault displacements. To insure public safety and awareness, new Federal and State regulations should require independent and transparent evaluations of the hazard and risk of capable faults for planned and existing gas storage fields.

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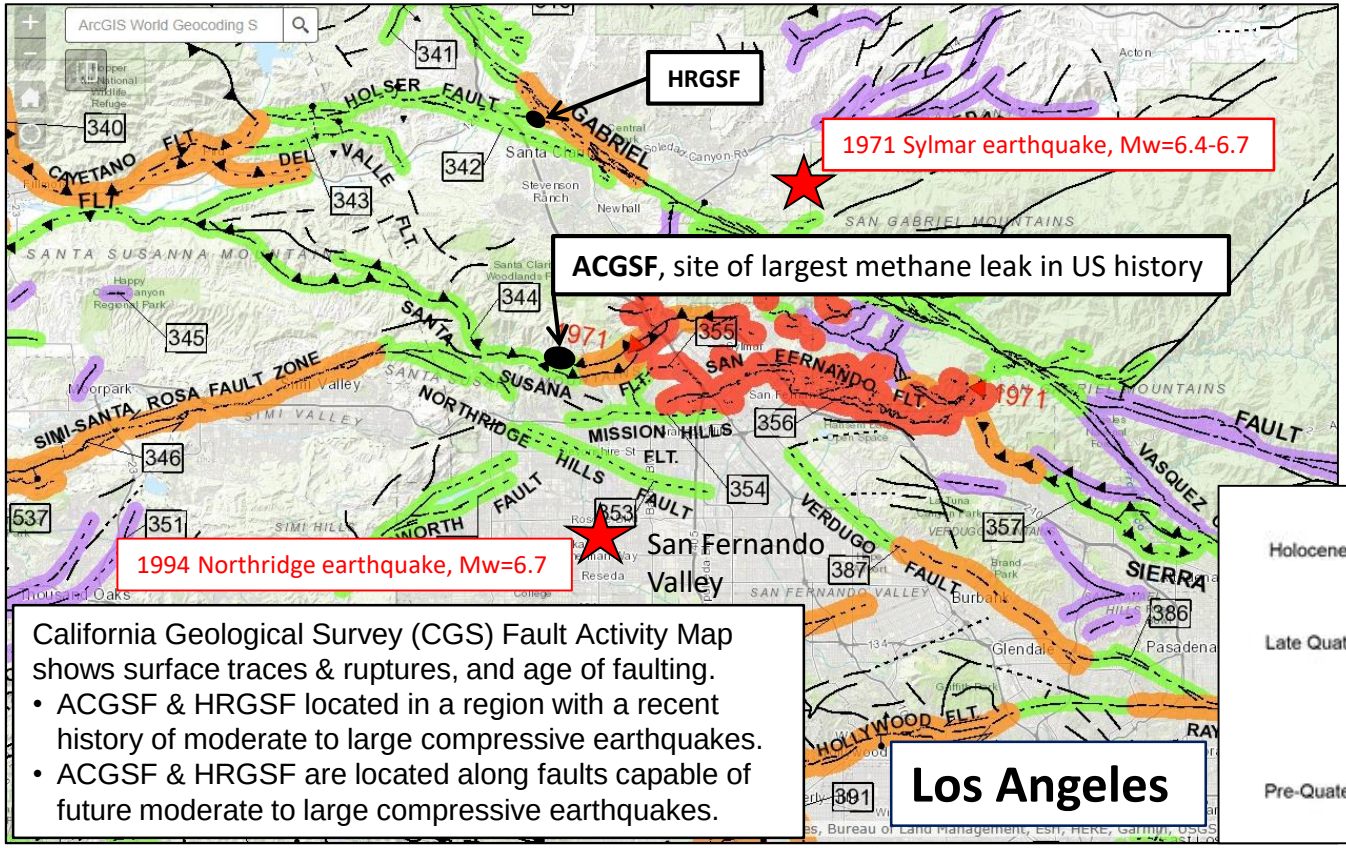
Fault displacement hazards at Aliso Canyon (ACGSF) and Honor Rancho (HRGSF) natural gas storage fields (UGS), southern California, USA

Thomas L. Davis, Geologic Maps Foundation, Inc. (GMF), www.geologicmapsfoundation.org

American Petroleum Institute RP 1171 (2015): “Depleted hydrocarbon reservoirs are candidates for natural gas storage because the reservoir integrity has been demonstrated over geologic time by hydrocarbon containment at initial pressure conditions." True, but gas wells at storage reservoirs have not existed over geologic time and threats to well integrity such as fault movements are hazards and create significant risks-especially near urban areas.

- 2015-16 methane leak at ACGSF, a benchmark event: largest in US history, single point source, impact in an urban setting.
- Should gas storage wells be sited across faults capable of generating moderate to large earthquakes?
- Published responses of the operator SoCalGas and State of CA regulators to the fault displacement hazard are noted here.



California Geological Survey (CGS) Fault Activity Map shows surface traces & ruptures, and age of faulting.

- ACGSF & HRGSF located in a region with a recent history of moderate to large compressive earthquakes.
- ACGSF & HRGSF are located along faults capable of future moderate to large compressive earthquakes.

Fault activity explanation (CGS)

Fault traces on land are indicated by solid lines where well located, by dashed lines where approximately located or inferred, and by dotted lines where concealed by younger rocks or by lakes or bays. Fault traces are queried where continuation or existence is uncertain. All offshore faults based on seismic reflection profile records are shown as solid lines where well defined, dashed where inferred, queried where uncertain.

FAULT CLASSIFICATION COLOR CODE
(Indicating Recency of Movement)

Fault along which historic (last 200 years) displacement has occurred.

A triangle to the right or left of the date indicates termination point of observed surface displacement. Solid red triangle indicates known location of rupture termination point. Open black triangle indicates uncertain or estimated location of rupture termination point.

Holocene fault displacement (during past 11,700 years) without historic record.

Late Quaternary fault displacement (during past 700,000 years).

Quaternary fault (age undifferentiated).

Pre-Quaternary fault (older that 1.6 million years) or fault without recognized Quaternary displacement.

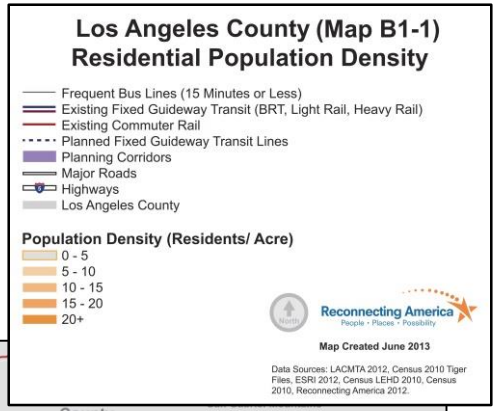
Importance of well integrity:

- ACGSF had a high reservoir pressure (~3,500 psi before 2015-16 leak).
- Gas field and wells must remain a closed system with no loss of integrity (LOI).
- No quick and safe way to draw-down a gas storage field with uncontrolled LOI.

Hazards to well integrity:

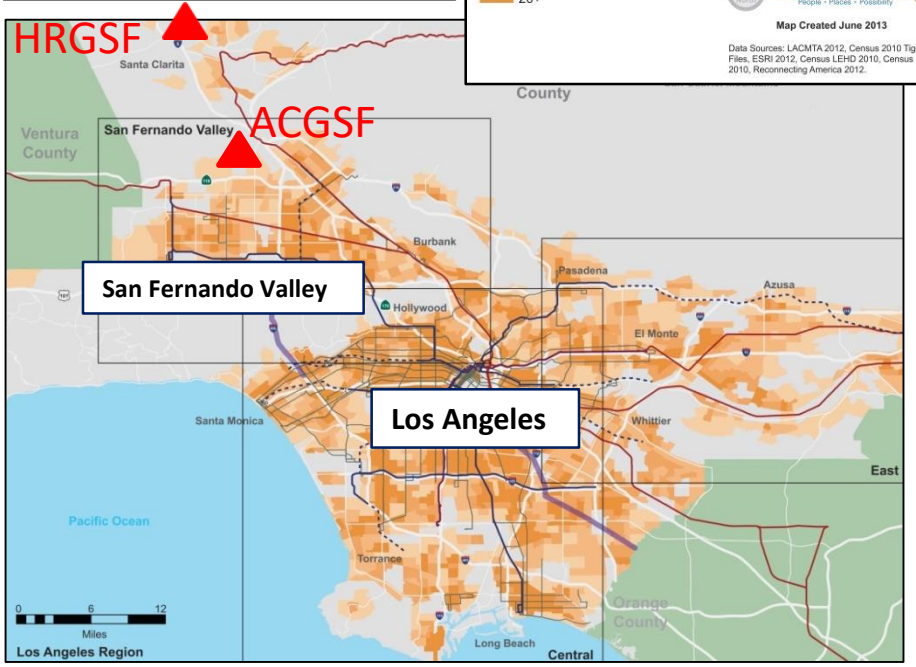
- Well corrosion and erosion (probably the cause of 2015-2016 leak, but public still doesn't know proven cause).
- Landslides, slip surfaces intersecting wells.
- Seismic activity (2 types): a shaking hazard and a fault-displacement hazard (often combined or confused) but are clearly separate hazards with different mitigations.
- Here we focus on the fault-displacement hazard.

In contrast, Moss Bluff, Texas, August 19, 2004: A wellhead fire and two explosions occurred at a gas storage field, releasing 6 BCF methane, mostly combusted to CO_2. Rural setting with little long-term impact.



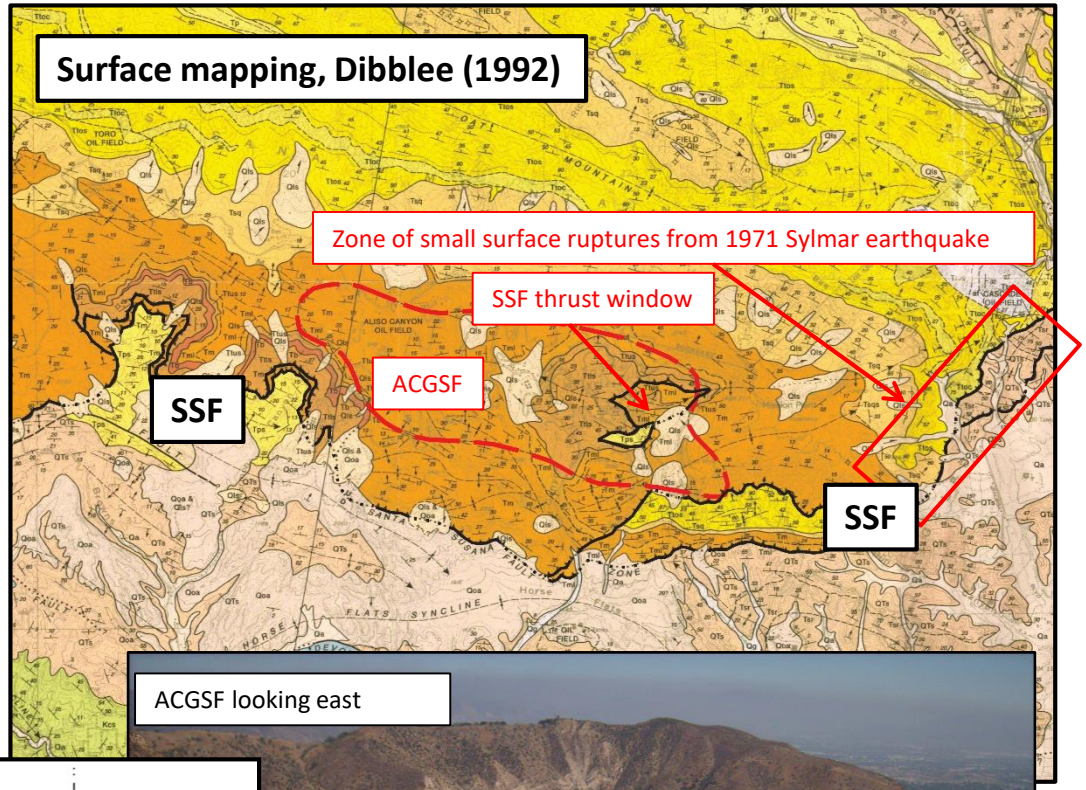
Impact of loss of integrity (LOI) in an urban setting :

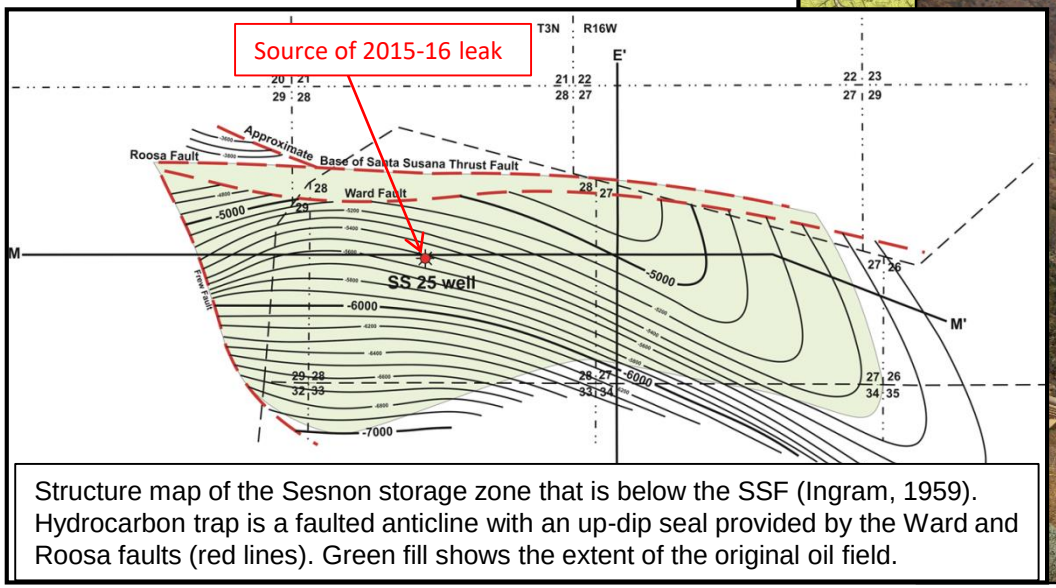
- 2015-16 ACGSF leak demonstrated the impact of LOI from one well in an urban area (a benchmark event due to its proximity to the urbanized San Fernando Valley).
  - 5 to 15 residents/acre within 3 miles of ACGSF.
  - Concentrations of 20+ residents/acre within 6 miles of ACGSF.
  - Four months to control and ~8,000 residents were relocated, two schools closed (Harris & Walker, 2016).
  - SoCalGas announced on 5/07/2018 it had spent $954 million on leak.
  - Numerous legal actions against the operator.
  - Los Angeles County vs DOGGR & SoCalGas legal actions.
  - 4.6 BCF methane released, ~20% of California's annual CH_4 emissions plus ~7,300 tonnes ethane (CARB, 2016).
  - Heat-trapping equiv of 460,000 cars/yr in CO_2 release (CARB, 2016).



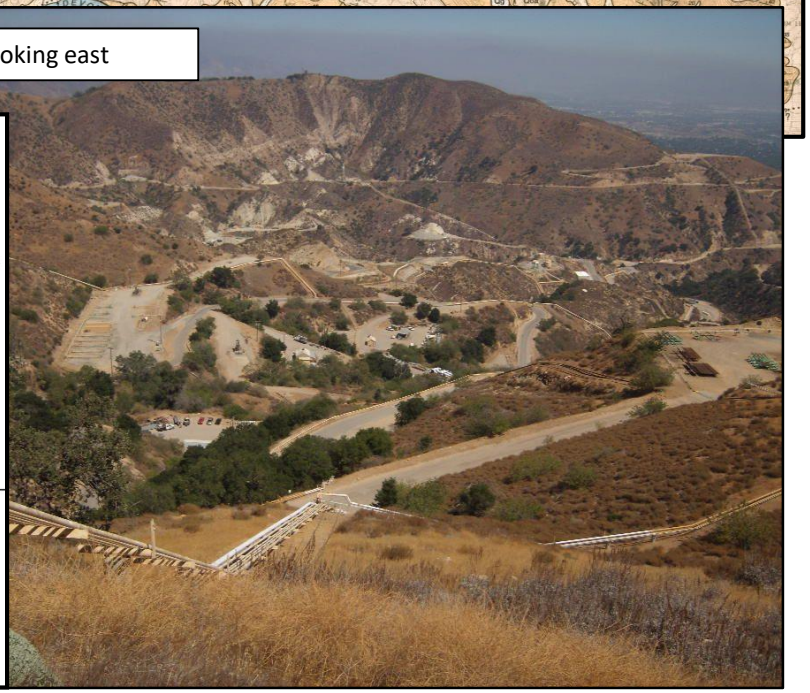
Santa Susana fault (SSF) fault displacment hazard at the Aliso Canyon Gas Storage Field (ACGSF):

- The Santa Susana fault (SSF), a north-dipping thrust fault with late Quaternary displacement.
- Yeats (2001), Oregon State University and ECI (Earth Consultants International) states that the SSF is active.
- All 114 storage field wells intersect the SSF at shallow depths (active wells before the 2015-2016 leak).
- ACGSF is an old oil field acquired for gas storage in 1972. Gas storage reservoirs (Sesnon and Frew zones) are located below the SSF.



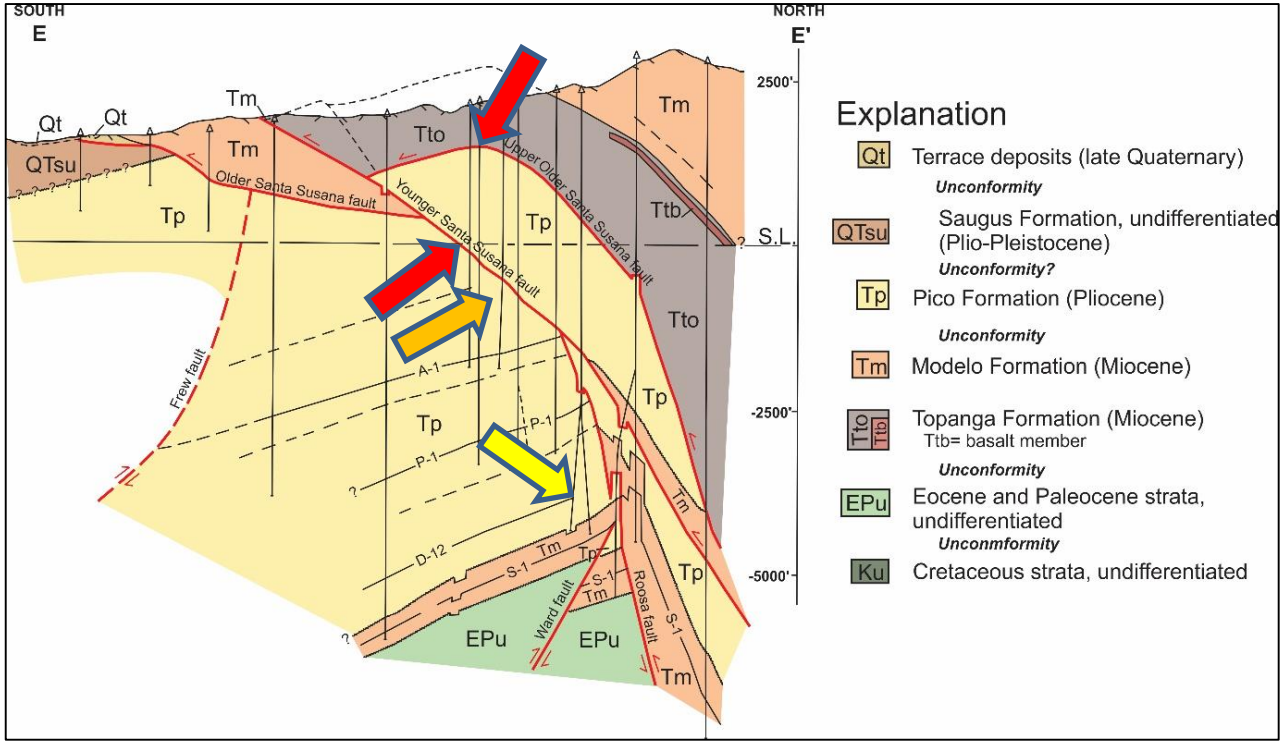


Structure map of the Sesnon storage zone that is below the SSF (Ingram, 1959). Hydrocarbon trap is a faulted anticline with an up-dip seal provided by the Ward and Roosa faults (red lines). Green fill shows the extent of the original oil field.



Dip cross section ACGSF (modified from Lant,1977):

- Gas storage field reservoir located below strands of the Santa Susana Fault (SSF).
- Well intersections with SSF range from very near surface to ~4500 ft (TVD).
- DOGGR now allows a maximum pressure of 2,926 psi at ACGSF which is the hydrostatic pressure at 6650 ft (TVD), assuming a hydrostatic gradient of 0.44 psi/ft (TVD).
- Most, if not all, SSF/well intersections are at hydrostatic pressures less than the maximum storage pressure of 2,926 psi, assuming a hydrostatic gradient of 0.44 psi/ft (TVD).
- Many of the shallower SSF/well intersections are at lithostatic pressures less than the maximum storage pressure of 2,926 psi, assuming 1.0 psi/ft (TVD).



Recognition of SSF in wells:

- Drilling breaks
- Changes in e-log curves & other types of logs
- Paleo
- Dip meter changes
- Core descriptions
- Lithology changes

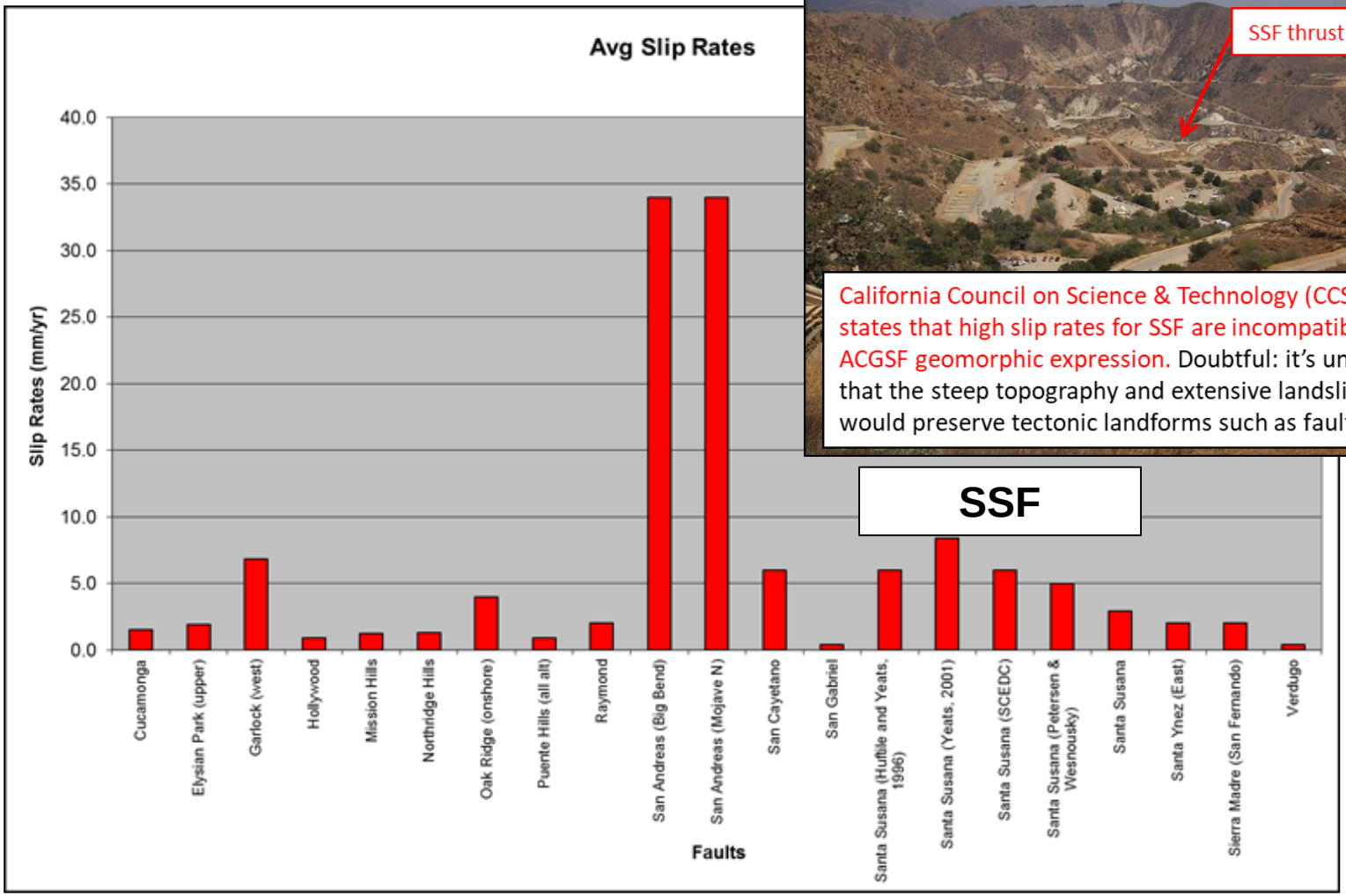
ACGSF parameters before 2015-16 leak (Kunitomi & and Schroeder, 2001):

- Working inventory=70 BCF
- Cushion gas=90 BCF
- Deliverability=2 BCFD
- Original Pressure= 3600 psi
- Gas storage zone= Sesnon & Frew
- Oil band beneath gas cap produces ~495 BOPD

SoCalGas' SRMP2 (2016) states "Just like Aliso Canyon, most oil and gas fields in California are inherently bounded by or otherwise constrained by Holocene faults." **Statement is inconsistent with the known geology and characteristics of other SoCal fields, and detracts from the unique setting at the ACGSF that has a high-slip rate fault intersecting all the high-pressure storage wells at shallow depths and adjacent to a large urban area. Most, if not all, oil fields in SoCal are well below hydrostatic pressures (less potential for leaks to the surface).**

SSF has been very tectonically active during the late Quaternary:

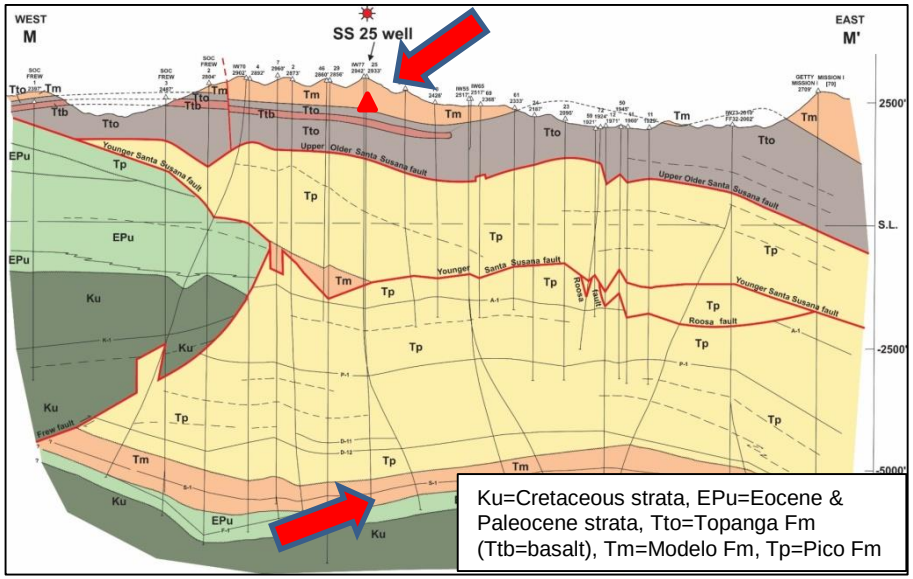
- Estimated fault slip rates for the SSF are high compared to other faults in southern California faults.
- Yeats (2001) concludes 4.9-5.9 km of slip during the last 600-700 ka, or a slip rate of 7.0-9.8 mm/yr.
- Version 3 of UCERF3 (2015) shows the SSF with a slip rate at 6 mm/yr, that is one of the highest slip rates in the western United States (CCST, 2018).
- High slip rates on locked faults such as the SSF are most likely the result of more frequent moderate to large earthquakes over geologic time.



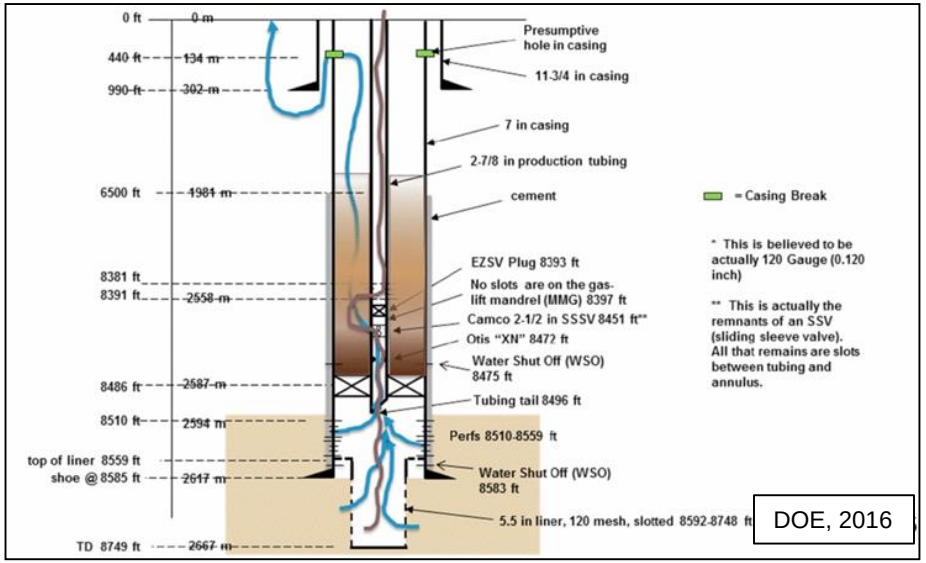
California Council on Science & Technology (CCST, 2018) states that high slip rates for SSF are incompatible with ACGSF geomorphic expression. Doubtful: it's unlikely that the steep topography and extensive landslides would preserve tectonic landforms such as fault scarps.

Strike section showing SS-25 well and methane leak:

- Strike cross section shows geometry of the SSF (modified from Lant,1977, cross section M-M').
- SS-25 leak was discovered 10/23/2015. Leak estimated at 887 ft TVD and possibly due to corrosion of casing (+ 2 years later the exact cause remains unknown to the public).



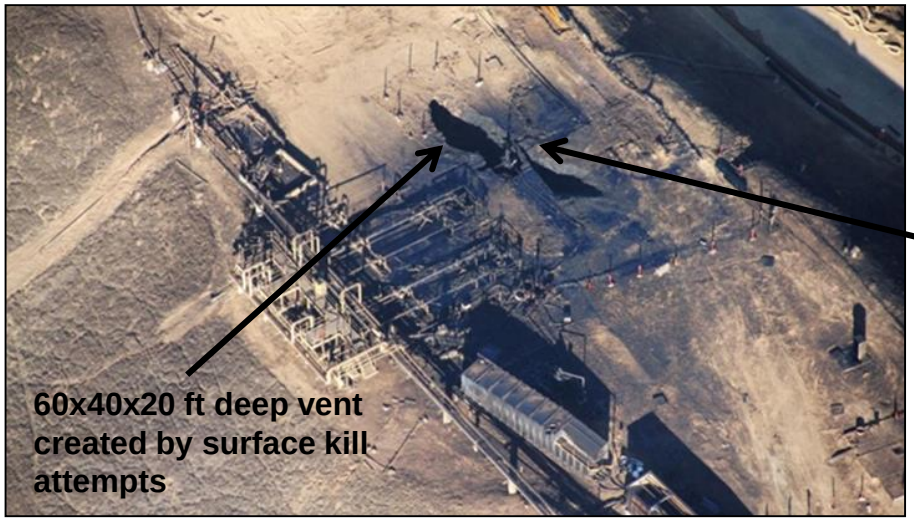
Ku=Cretaceous strata, EPu=Eocene & Paleocene strata, Tto=Topanga Fm (Ttb=basalt), Tm=Modelo Fm, Tp=Pico Fm



DOE, 2016

Details of SS-25 methane leak and kill attempts:

- Leak increased from 2.0 to 25-60 MMCFD (DOE, 2016).
- Eight surface control attempts failed. Top kills involved pumping heavy drilling muds, fluids, and additional material down the tubing (brown flow lines). Note the complicated and narrow pathway for top kills to follow downhole (reduced effectiveness).
- On February 11, 2016 a relief well intercepted the lower part of the SS-25 well and heavy fluids were pumped to control (cease) the flow of gas. Leak was then terminated.
- Event showed the serious impact of an uncontrolled natural gas leak from a single source in a high pressure storage field adjacent to a large urban area.



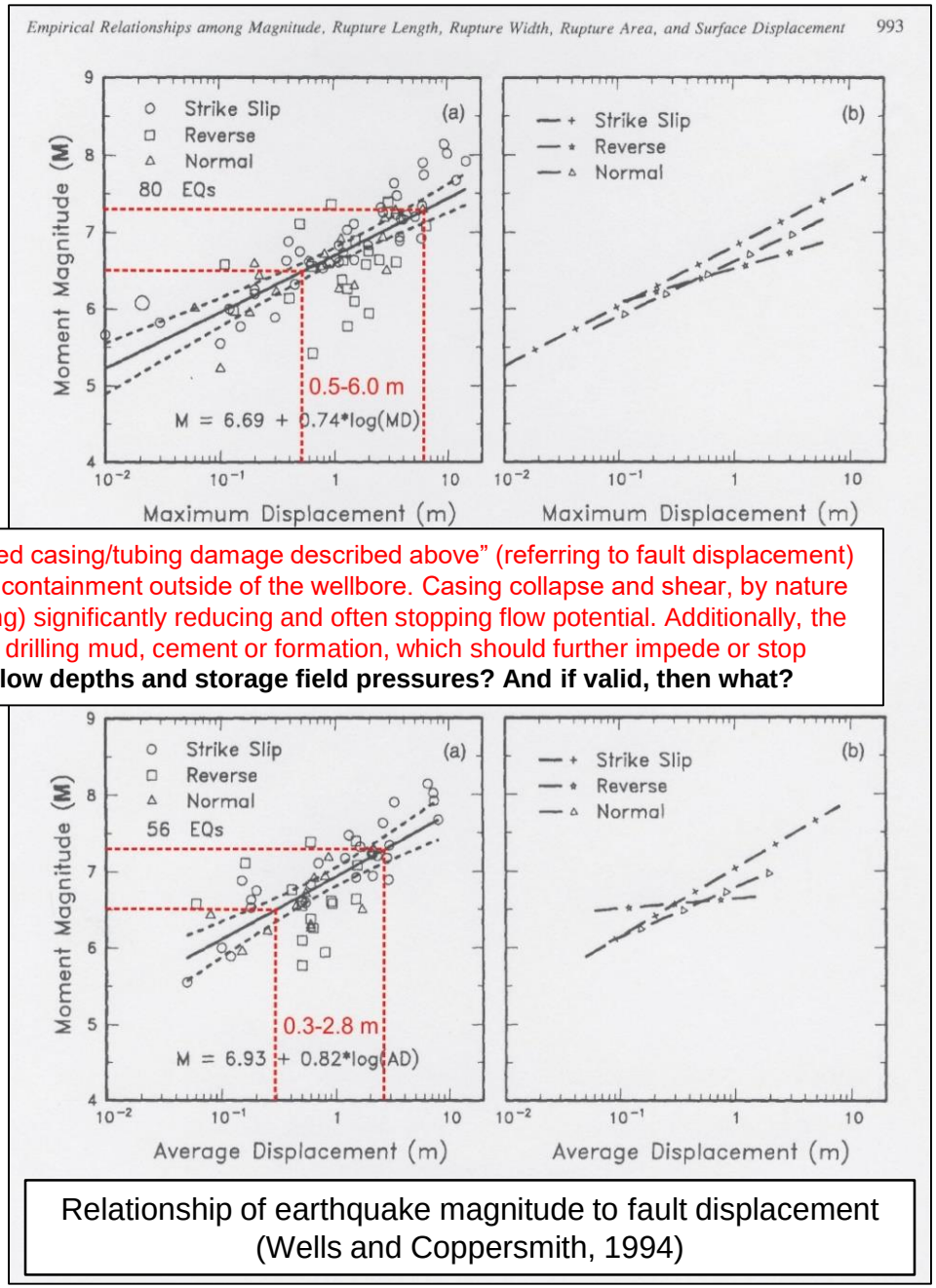
Bridge across vent to secure well head. In addition to the well head crater created by high pressure leakage, hillside vents away from the well head were observed.

The SSF fault displacement hazard at the ACGSF: characteristic earthquake and displacement:

- A Mw 6.6-7.3 earthquake is estimated by the Southern California Earthquake Data Center (SCEDC) to be characteristic of the SSF.
- Average fault displacement from such a seismic event is estimated to be 0.3 to 2.8 meters and maximum displacement up to 6.0 meter-using Wells and Coppersmith (1994).
- At the Wilmington oil field fault displacements of up to **0.25** meter severely damaged numerous wells (Frame, 1952).

Oil field casing damage caused by small fault displacement at the Wilmington oil field (Frame, 1952).

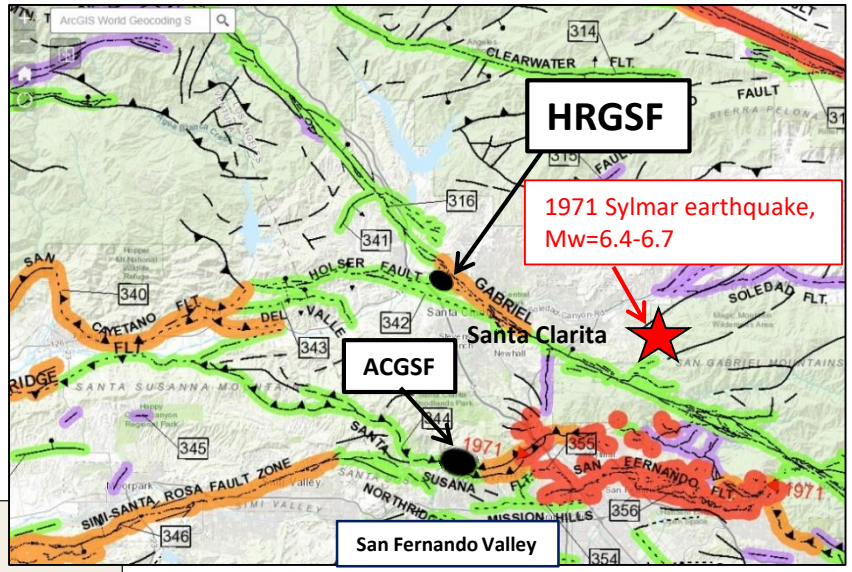
SoCalGas' RMP2 states "The tectonically induced casing/tubing damage described above" (referring to fault displacement) "normally does not result in loss of hydrocarbon containment outside of the wellbore. Casing collapse and shear, by nature of the failure, **pinches off the casing** (and tubing) significantly reducing and often stopping flow potential. Additionally, the area around the collapsed pipe will be filled with drilling mud, cement or formation, which should further impede or stop flow." **Speculation, can this be proven at shallow depths and storage field pressures? And if valid, then what?**



Relationship of earthquake magnitude to fault displacement (Wells and Coppersmith, 1994)

Honor Rancho Gas Storage Field (HRGSF):

- Field is located in a earthquake prone area of active compressive tectonics. 1971 Sylmar earthquake (Mw=6.4-6.7) occurred on a northeast-dipping thrust fault with surface rupture.
- At the surface HRGSF lies between the narrow intersection of the late Quaternary San Gabriel and Holser faults.
- The San Gabriel has had Holocene movement(s) and the Holser fault had movement(s) sometime during the late Quaternary.
- The Holser fault merges westward with San Cayetano fault. Dolan and Rockwell (2001) found evidence along the eastern San Cayetano fault for a M_w>7.5 event with at least 4.3 m of surface slip and occurring since 1660.



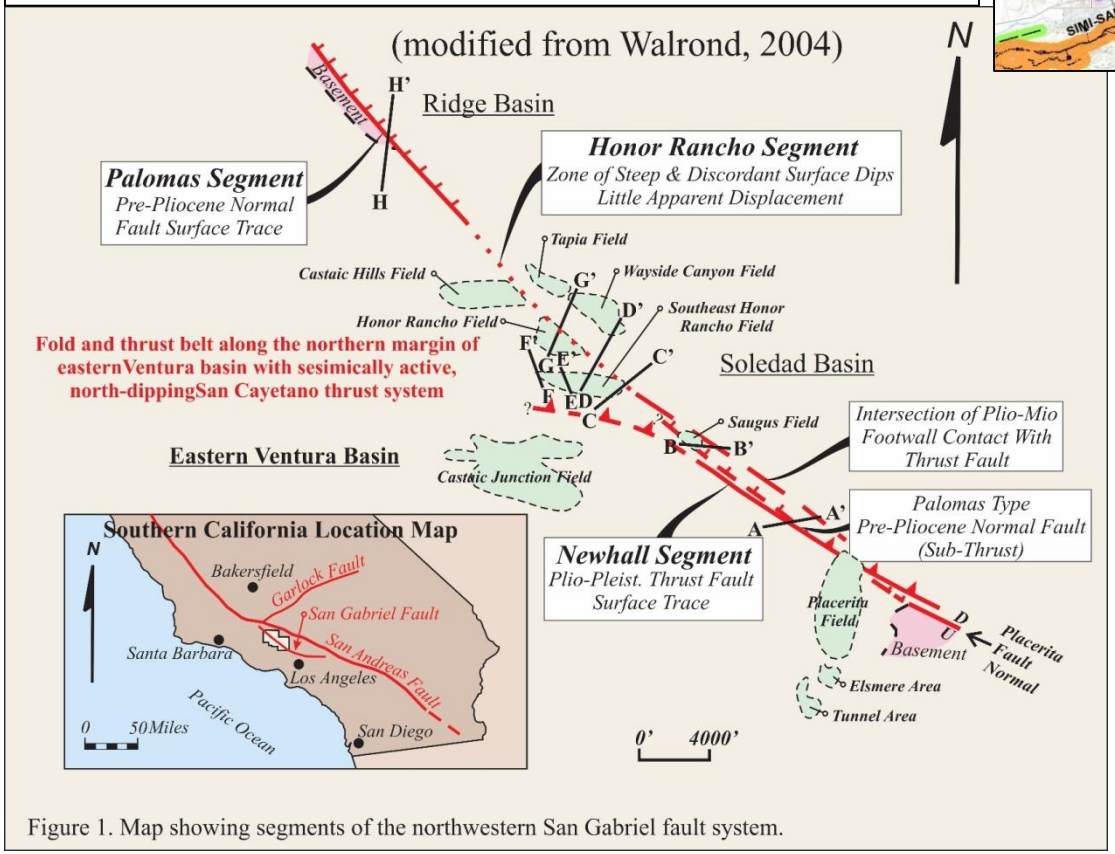


Figure 1. Map showing segments of the northwestern San Gabriel fault system.

Subsurface geology of the HRGSF:

- Walrond (2004) published 7 cross sections across and near the HRGSF.
- Walrond's cross sections show a large Quaternary thrust fault crossing through the subsurface of the HRGSF.
- Walrond mapped the thrust westward towards the San Cayetano thrust system that is known to have had Holocene displacement (Dolan and Rockwell, 2001).
- Walrond concluded that the thrust was a segment of the San Gabriel fault that has had Holocene movement.
- California Council on Science & Technology (CCST, 2018) reviewed the HRGSF and its seismic hazards. Oddly, the CCST report contains no subsurface geology (maps & cross sections) despite its attempt to address a subsurface fault hazard, plus the CCST seems unware of Walrond's published work.

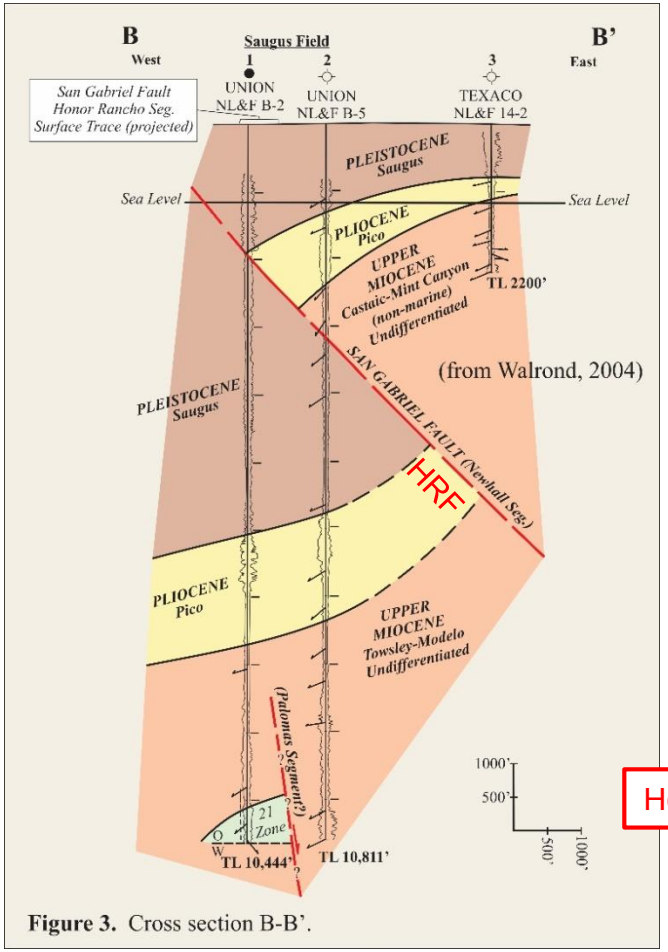


Figure 3. Cross section B-B'.

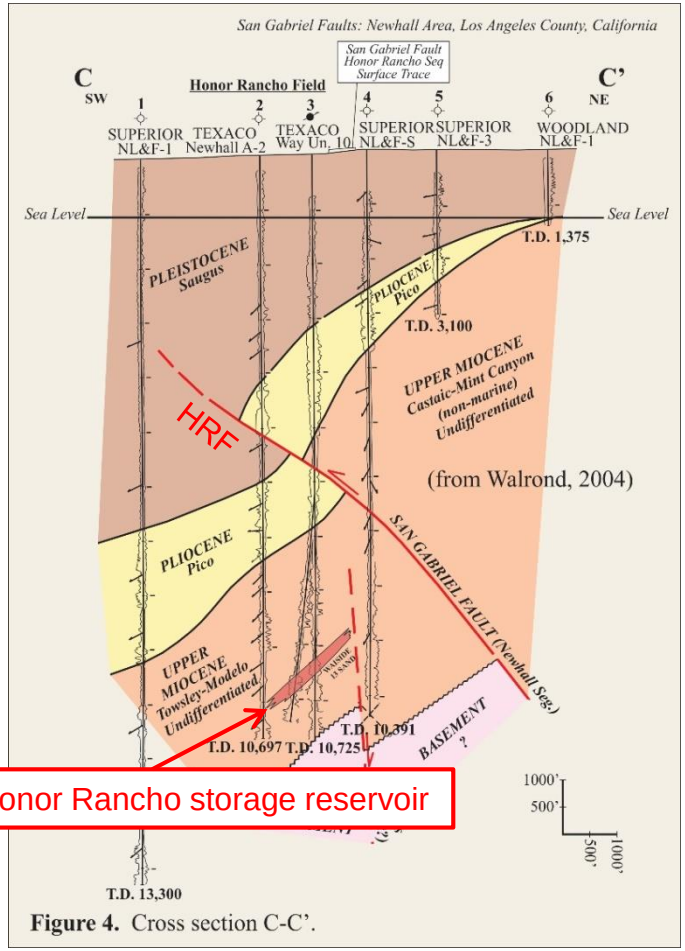
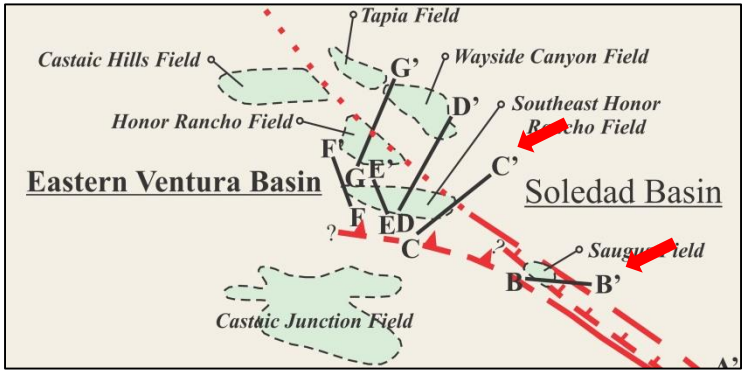


Figure 4. Cross section C-C'.



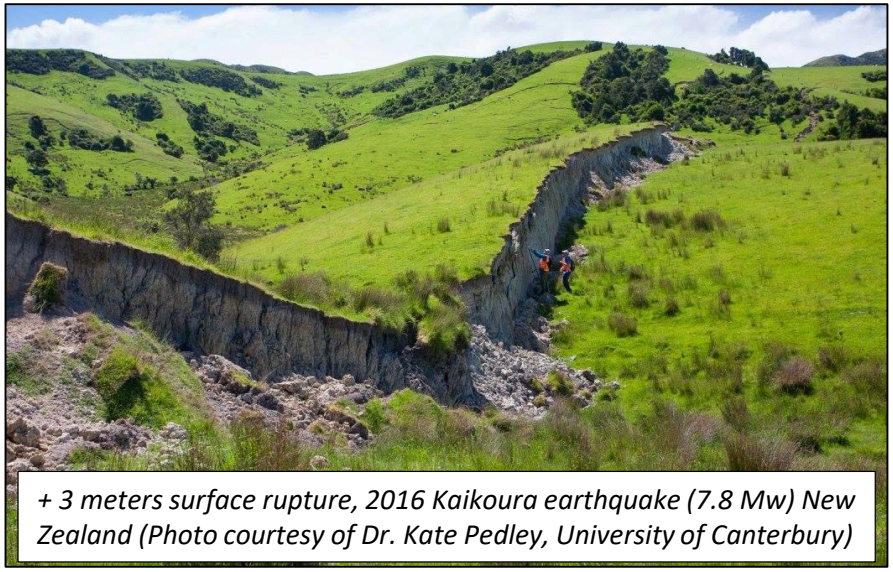
California Council on Science & Technology (CCST, 2018) states when referring to the San Gabriel fault and the HRGSF, "Therefore, it is unlikely that the portion of the fault within the EFZ (Earthquake Fault Zone) intersects any active wells in the subsurface." This is in direct contrast to Walrond's work! Who is correct, Walrond or CCST? No subsurface work provided in the CCST report!

Warlrond's cross sections at HRGSF:

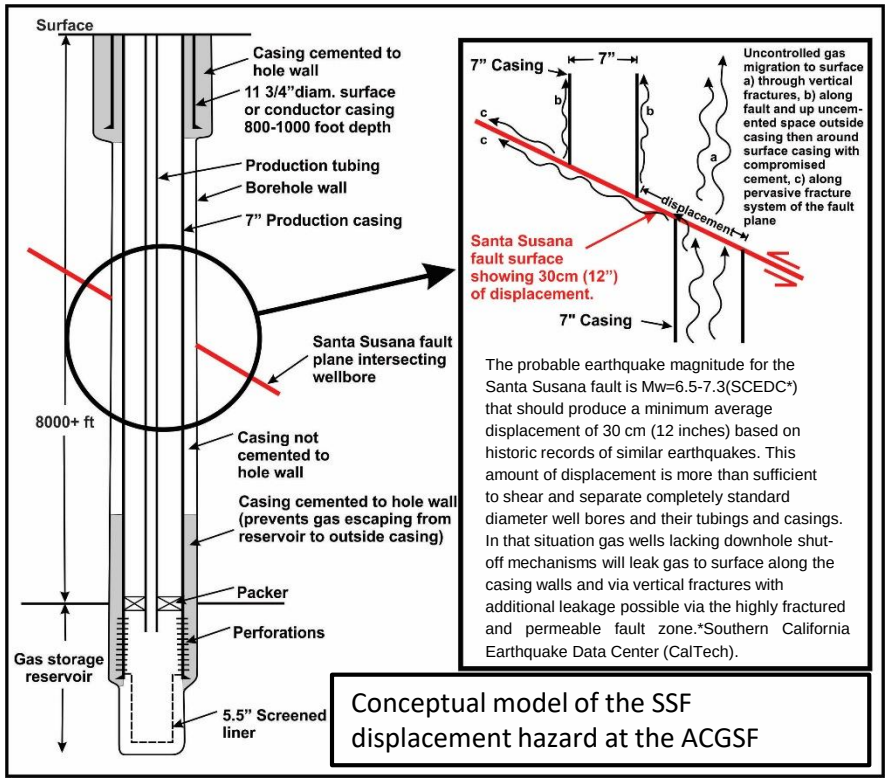
- B-B' is south of the HRGSF and cross section C-C' is through the HRGSF.
- Walrond's San Gabriel fault (his Newhall segment) is referred to here as the Honor Rancho fault (HRF) and documented by stratigraphic repeats in numerous wells (upper Miocene faulted over Pleistocene strata).
- HRF is a late Quaternary thrust fault dipping to the northeast with up to 4,000 ft of dip separation in the subsurface. Fault may be the Holser or may not reach the surface (blind thrust).
- <u>At HRGSF it is likely that all gas storage wells cross the low-angle HRF before reaching the storage reservoir.</u>
- Using Yeat's (2001) conclusion that most of the convergent tectonics in the Saugus sub-basin portion of the eastern Ventura basin occurred during the last 600-700 ka then the average slip rate on the HRF is 1.74-2.03 mm/yr.

Conclusions & recommendations:

- Operators, regulators, and geotechnical community should recognize that a fault rupture hazard at the surface is also a hazard in the subsurface (oil & gas industry subsurface data must be utilized to evaluate the hazard).
- Avoid siting gas storage wells across late Quaternary faults.
- Fault displacement across storage field wells are low probability occurrences but can be very high impact events if near an urban area.
- California's Alquist-Priolo (AP) Act should be extended to subsurface fault displacement hazards.
- In highly urbanized southern California the depleted offshore oil fields are probably the safest locations for gas storage fields.
- American Petroleum Institute (API), Recommended Practices 1171: RP should be revised to include more about fault displacement hazards.
- Pipeline and Hazardous Materials Safety Administration (PHMSA-DOT) now regulates surface pipelines crossing "active" faults so why not extend this role to the subsurface where leaks can be much harder to control?
- 30 months since the discovery of ACGSF leak and the public is still in the dark about the operator's and regulator's evaluation of the fault displacement hazard and risk from the SSF. SoCalGas' and State of CA regulator's responses to the hazard (SRMP2, 2016; CCST, 2018) are poor quality studies (lack available data and highly speculative). **And where is SoCalGas' Aliso Canyon Gas Storage Field Geologic, Seismologic, and Geomechanical Studies (Harris, et al, 2017)?**
- Producing timely, independent and well-documented fault studies would address the public's growing concern about storage fields. In CA such reports must be prepared by a registered CA professional geologist according to the CA Board for Professional Engineers, Land Surveyors, and Geologists. **There's no indication in SRMP2 (2016) or in CCST (2018) that this requirement is being followed.**
- New CA state regulations for storage fields recently **removed** active faults from the list of hazards to gas storage wells despite the obvious hazard and significant risk to SoCal (outlined in **Science** [Davis, 2017]).



+ 3 meters surface rupture, 2016 Kaikoura earthquake (7.8 Mw) New Zealand (Photo courtesy of Dr. Kate Pedley, University of Canterbury)



Conceptual model of the SSF displacement hazard at the ACGSF

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