

Fault displacement hazard at natural gas storage fields-a future research and regulatory direction: with a discussion of the Santa Susana fault displacement hazard at the Aliso Canyon gas storage field, southern California

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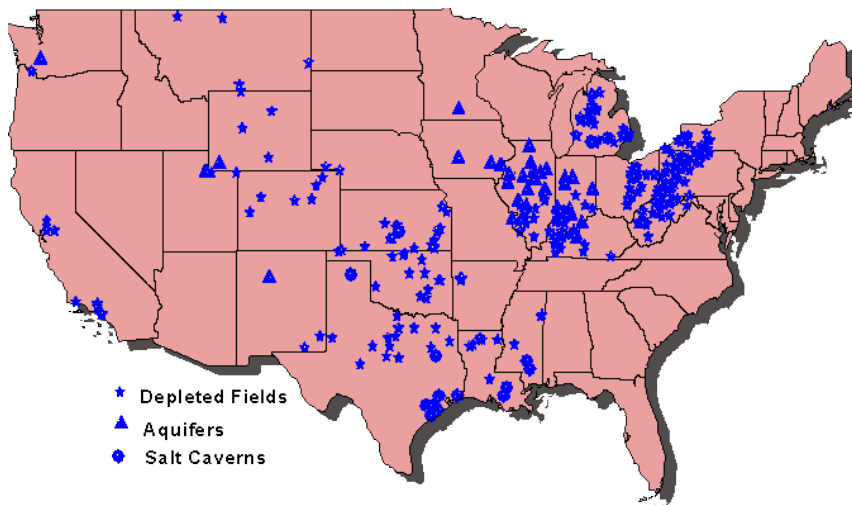
- **Presentation touches on three subjects:**
 - The need for FDHA (and PFDHA) for gas storage wells.
 - Aliso Canyon Gas Storage Field (ACGSF) and Santa Susana fault (SSF) displacement hazard to gas wells.
 - Regulatory changes for gas storage wells and fields in play and need for geologic input.
- **Overview of gas storage fields and wells.**
- **The ACGSF leak and impact: a benchmark.**
- **Coseismic fault displacement across gas wells are a hazard and risk to well integrity.**
- **The SSF is a fault displacement hazard.**
- **Summary-what to get out of this talk.**
- **Mitigation-what are the options?**
- **Recommendations for rulemaking presently being considered.**



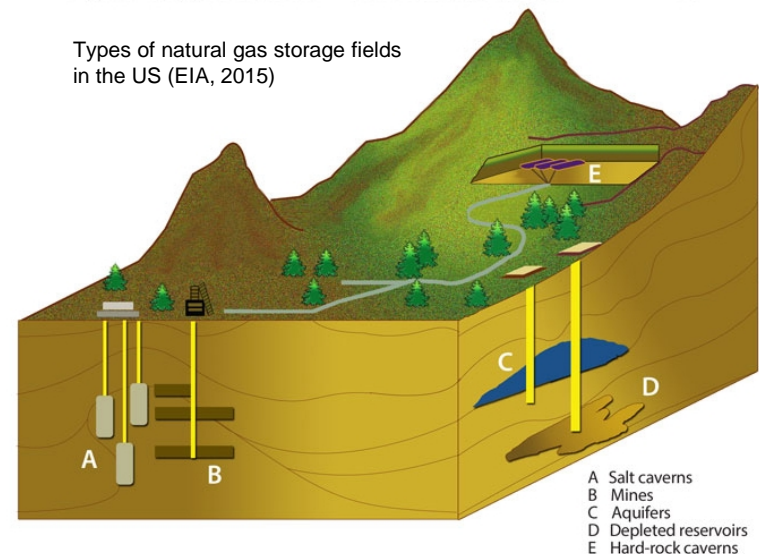
❑ Important to note:

- ✓ The recent massive methane leak at Aliso is probably not due to movement on the SSF: no other wells leaked and there was no nearby earthquake at the initiation of the leak.
- ✓ CA Division of Oil & Gas and Geothermal Resources (DOGGR): "The independent investigations and root cause analysis are still pending."

- **Overview of gas storage fields and wells-key things to consider.**
 - Essential energy supply.
 - US has +400 gas storage fields.
 - Natural gas currently meets nearly 30% of U.S. energy needs (mostly power generation and heating).
 - Natural gas storage fields provide quick access to large volumes of gas during periods of high demand.
 - Low carbon impact; considered a bridge energy source from fossil fuels to renewable sources.
 - However, methane is a much more effective heat-trapping gas than carbon dioxide and has the potential to negate much of the nation's carbon dioxide reduction efforts (IPCC, 2014).
 - **Guiding idea for siting storage fields:** American Petroleum Institute RP 1171 (API, 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.
 - **Importance of well integrity:** there is no way to quickly draw-down a gas storage field because of their high pressure and large volume.



Distribution of natural gas storage fields in the lower 48 states (PNP Petroleum)



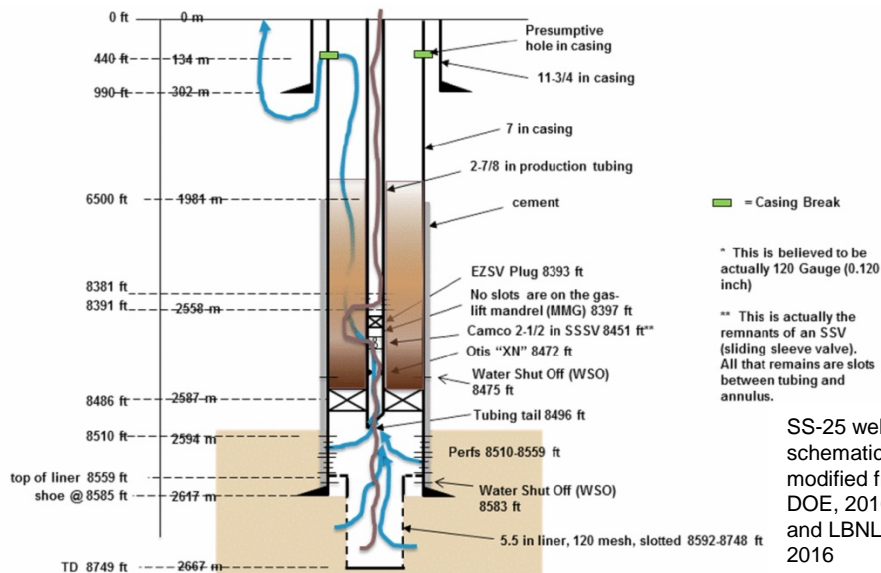
Source: PB-KBB, inc., enhanced by EIA.

- **The ACGSF leak and impacts: a benchmark (modified from DOE, 2016).**

- SS-25 well completed in 1954 as an oil producer and converted to a gas storage well in 1973.
- Gas injected and withdrawn through tubing and casing (single barrier protection).
- Leak was initially ~2 MMcfd (1300 metric tons of methane per day, the blue flows lines) and created a 1x4 ft surface vent.
- Eight surface control attempts failed. These top kills involve pumping heavy drilling muds, fluids, and additional material down the tubing (brown flow lines).
- Top kill attempts caused erosion and expansion of the vent around the wellhead.
- Leak went from 2 to 25-60 MMcfd (DOE, 2016).
- Hill side vents created.



SS-25 site showing 60x40x20 ft deep vent.



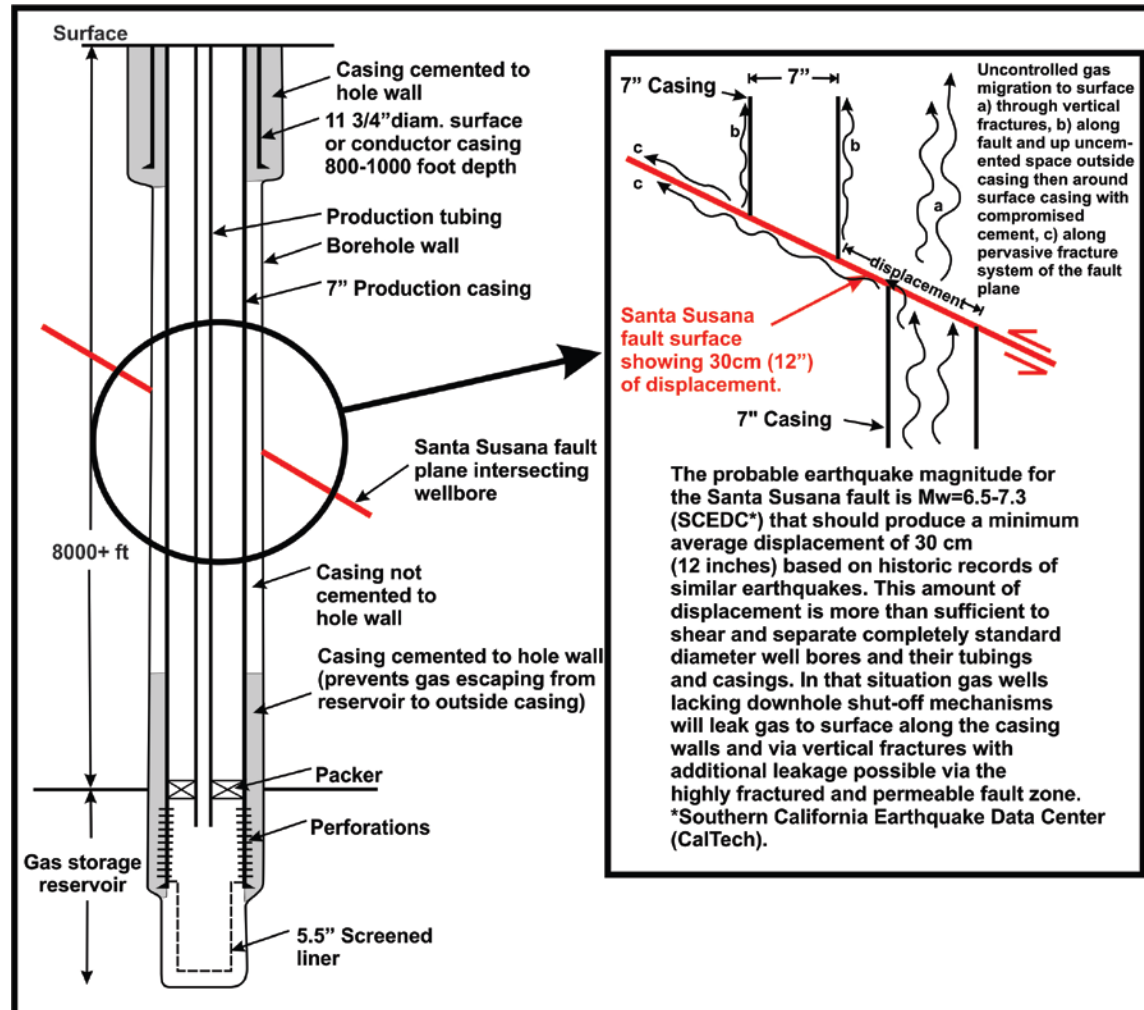
Bridge across vent to secure well head with mist abatement

- **The ACGSF leak and impacts: a benchmark (modified from Harris & Walker, 2016).**
 - ~8,000 residents were relocated and two schools closed.
 - ~ 5 Bcf of methane released to the atmosphere.
 - Operator has spent \$700+ MM dealing with the leak.
 - 25 + class action suits against the operator were active.
 - Substantial cost of the lost commodity (methane).
 - Up to 109,000 metric tons of methane that was responsible for 20% of California's annual methane emission (CARB, 2016).

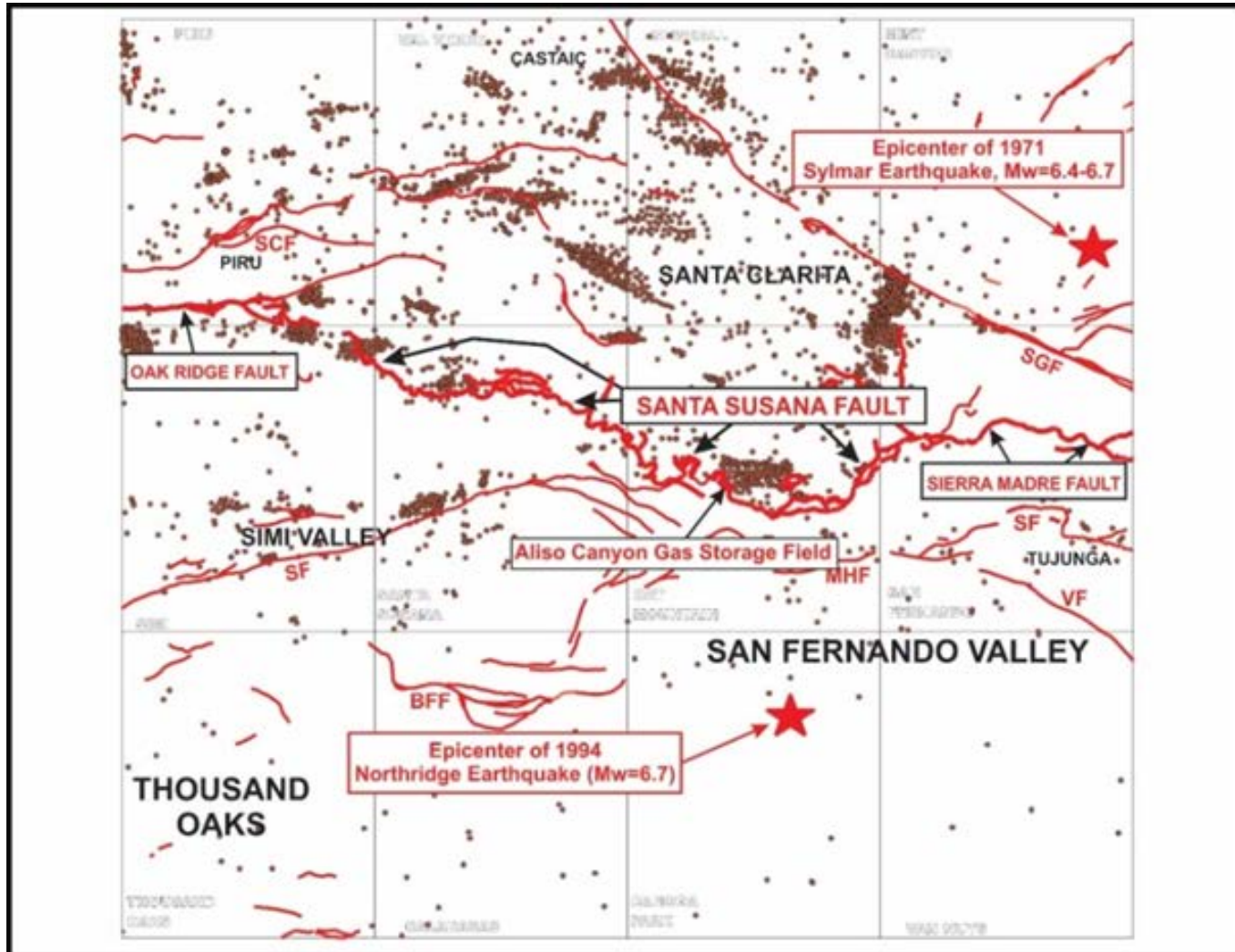
Relief well #1 (background) Relief Well #2 (foreground)



- **Coseismic fault displacement across gas storage wells are a hazard and risk to well integrity- the SSF case.**
 - It's basic geology to conclude that a fault that ruptures at the surface during a seismic event also moves at depth as the displacement derives from a deeper earthquake source.
 - Highly fractured rocks in hanging-wall of the SSF are potential gas migration pathways.
 - Fault zone is a potential gas migration pathway.
 - Shallow intersections of well and SSF make gas migration to the surface more likely.
 - Fault displacement hazard analysis of gas storage wells would be very useful.



- **The SSF is a fault displacement hazard-fault characterization:**
 - SSF merges with active faults along strike.
 - Area is very tectonically active with the 1971 Sylmar and 1994 Northridge EQs.
 - Recent movement history of the SSF is unclear due to poor surface exposures and the various geotechnical reports are conflicting and limited in scope.



- **The SSF is a fault displacement hazard-fault characterization:**

- The State of California recognizes (CGS, 2003), via the Alquist-Priolo Act (AP), that the eastern segment of the SSF is an earthquake and surface rupture hazard based on surface displacement during the 1971 Sylmar earthquake ($M_W=6.4-6.7$).
- Surface developers have been required to do geologic studies of the SSF and mitigate for surface rupture along its entire length since 1974 as there are observations indicating late Quaternary and in places Holocene displacement.



Aliso Canyon Gas Storage Field (ACGSF)

Explanation

SYMBOL EXPLANATION

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).

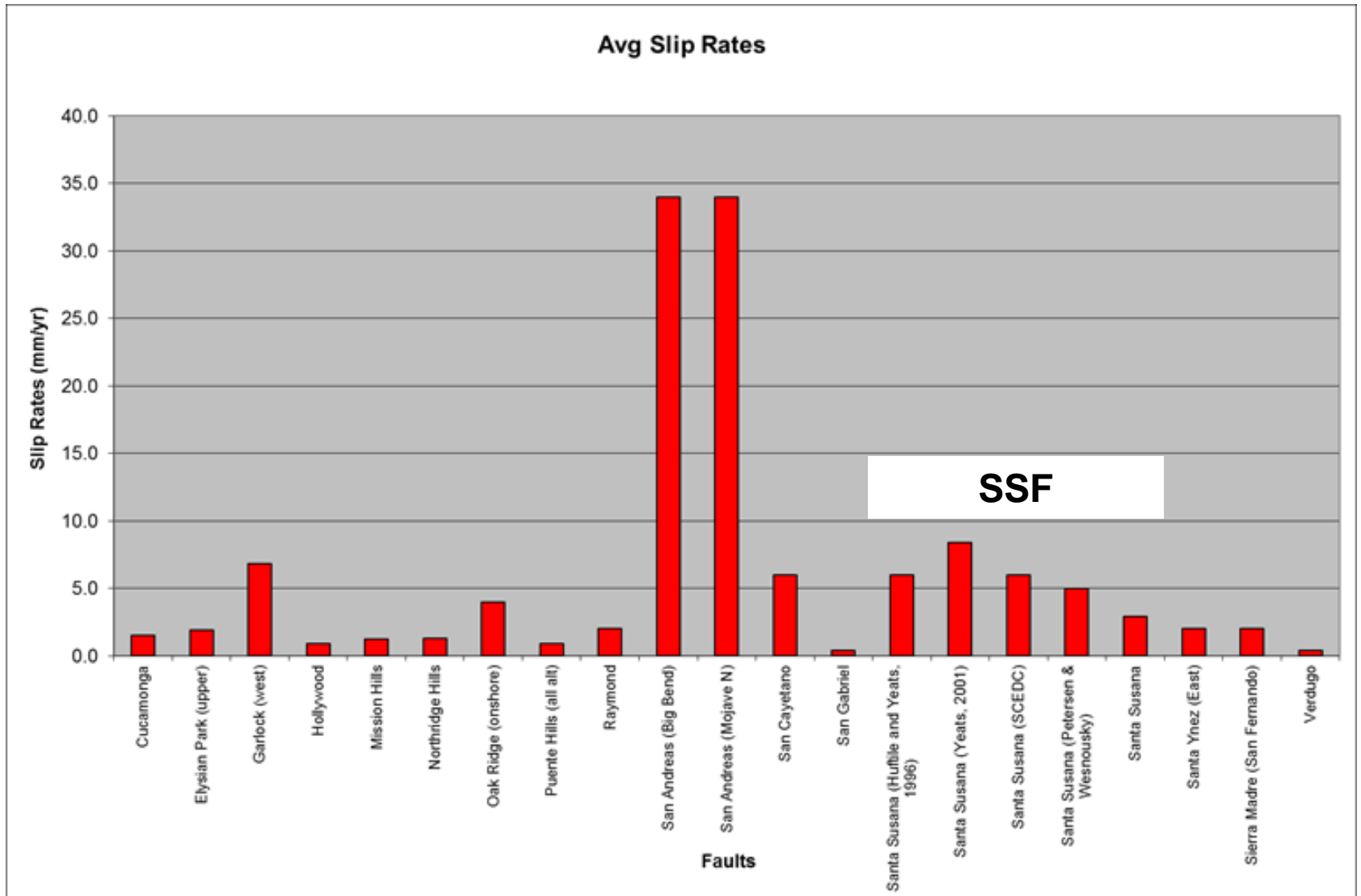


Quaternary fault (age undifferentiated).



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

- The SSF is a fault displacement hazard-slip rates:

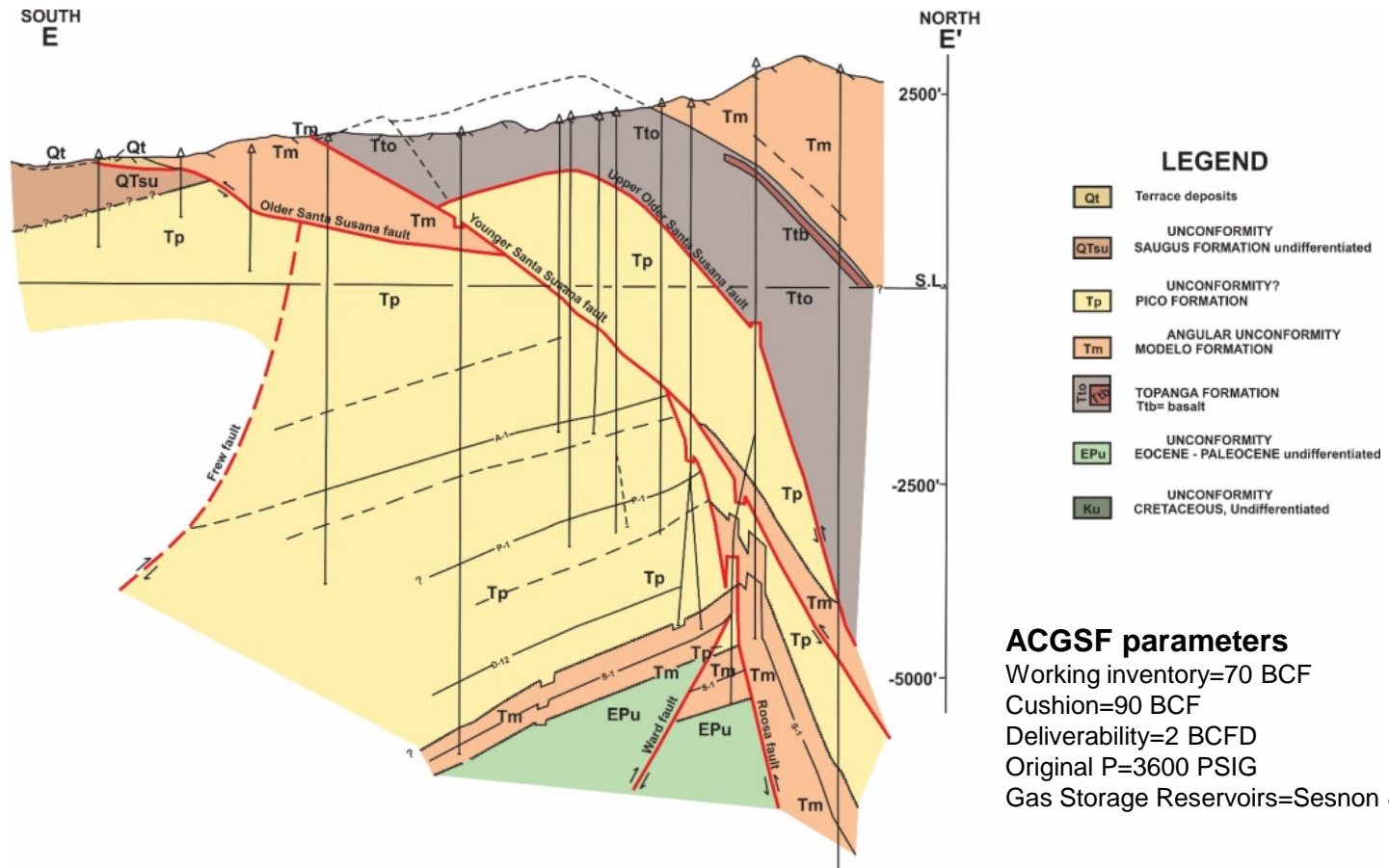


- **The SSF is a fault displacement hazard-slip rates:**
 - Various slip rate estimates for the SSF (all of these are very high rates).
 - 7.0-9.8 mm/yr, Yeats (2001). This is nearly a plate boundary rate and roughly 1/3 to 1/2 the convergence rate of the entire western Transverse Ranges (17.6-26.5mm/yr, Namson and Davis, 1988).
 - 2015 Third Uniform California Earthquake Rupture Forecast, or “UCERF3” is 2.9 mm/yr.

FAULTS	SLIP RATE	SOURCE
Cucamonga	1.5	UCERF3
Elysian Park (upper)	1.9	UCERF3
Garlock (west)	6.8	UCERF3
Hollywood	0.9	UCERF3
Mission Hills	1.3	UCERF3
Northridge Hills	1.3	UCERF3
Oak Ridge (onshore)	4.0	UCERF3
Puente Hills (all alt)	0.9	UCERF3
Raymond	2.0	UCERF3
San Andreas (Big Bend)	34.0	UCERF3
San Andreas (Mojave N)	34.0	UCERF3
San Cayetano	6.0	UCERF3
San Gabriel	0.4	UCERF3
Santa Susana (Huftile and Yeats, 1996)	6.0	Huftile and Yeats (1996)
Santa Susana (Yeats, 2001)	8.4	Yeats (2001)
Santa Susana (SCEDC)	6.0	SCEC (2016)
Santa Susana (Petersen & Wesnousky)	5.0	Petersen & Wesnousky (1994)
Santa Susana	2.9	UCERF3
Santa Ynez (East)	2.0	UCERF3
Sierra Madre (San Fernando)	2.0	UCERF3
Verdugo	0.4	UCERF3

- **Geology of the ACGSF.**

- Dip cross section shows shallow thrust fault geometry of the SSF (modified from Lant ,1977, cross section E-E').
- Section shows the SSF steepening with depth and its large amount of reverse displacement during the Quaternary.
- Shallowest well intersections are along the southern margin of the storage field and nearby the SSF reaches the surface as two major fault splays separated by a block of highly-fractured Modelo Formation.
- Upper Saugus locally derived and age estimates based on magnetic stratigraphy (Levi and Yeats, 1993).
- SSF acquired 4.9-5.9 km of slip during the past 600,000-700,000 yrs (Yeats, 2001).



ACGSF parameters

Working inventory=70 BCF

Cushion=90 BCF

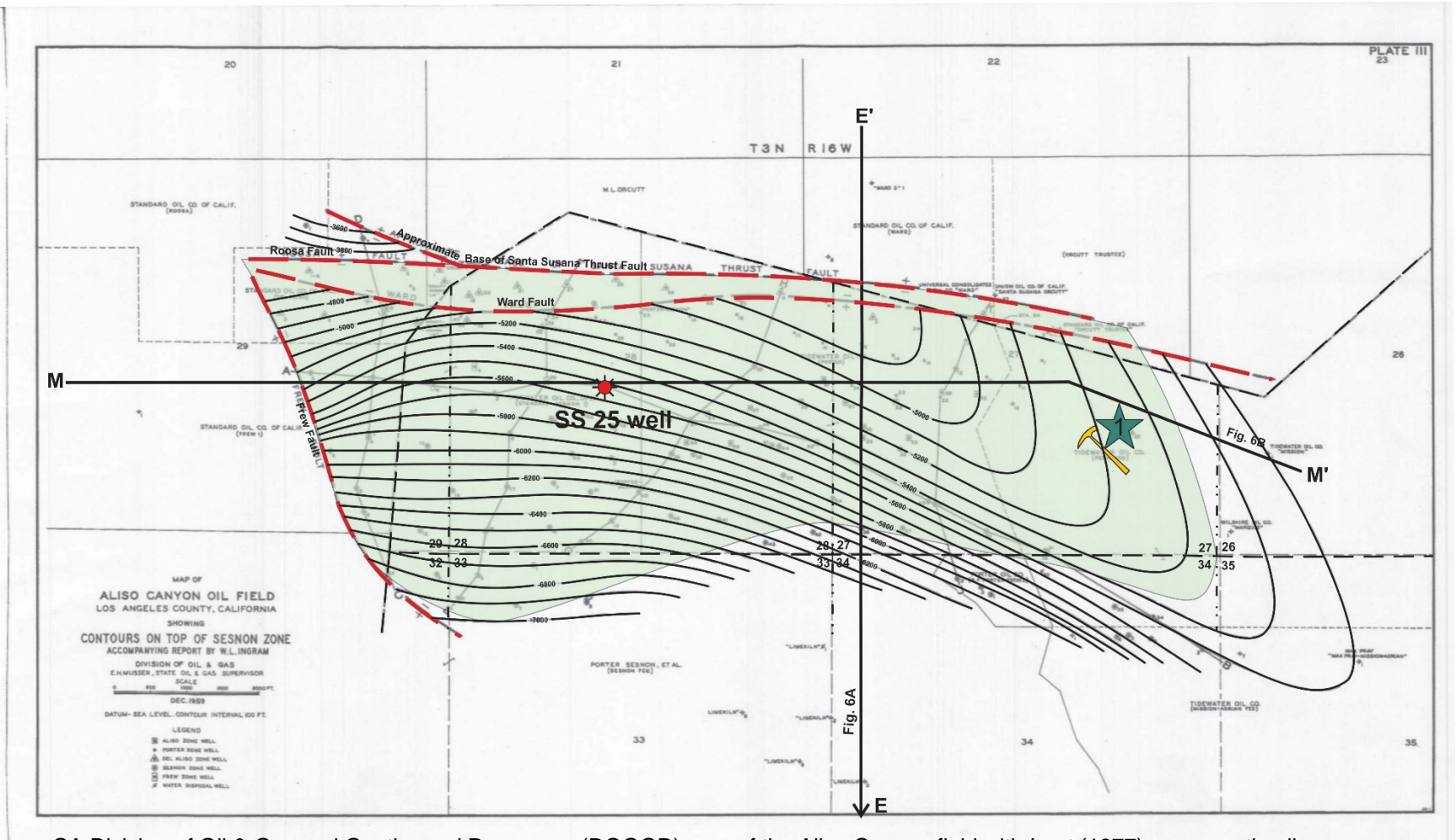
Deliverability=2 BCFD

Original P=3600 PSIG

Gas Storage Reservoirs=Sesnon & Frew

Geology of the ACGSF.

- ACGSF is an old oil field acquired for gas storage in 1972 (Davis, et al. 2015). Green fill shows the extent of the original oil field.
- Hydrocarbon trap is a faulted anticline with an up-dip seal provided by the Ward and Roosa faults (red lines).
- Gas storage reservoir (old oil reservoir) is located below the SSF and all 114 gas storage wells cross the fault to reach the reservoir.



CA Division of Oil & Gas and Geothermal Resources (DOGGR) map of the Aliso Canyon field with Lant (1977) cross section lines. Contours on top of Sesnon storage zone.

- **Fault displacement hazard parameters for the SSF:**
 - A Mw 6.6-7.3 seismic event is estimated by the Southern California Earthquake Data Center (SCEDC).
 - Average fault displacement from such a seismic event is estimated to be 0.3 to 2.8 meters-using Wells and Coppersmith (1994).
 - UCERF3 average slip rate is 2.9mm/yr with a range of offsets from 0.3 m every 103 years to 2.8 m every 967 years.
 - Probabilistic fault displacement hazard analysis (PFDHA) needed (Wells and Kulkarni, 2014). An analysis of the fault rupture hazard for a site/structure. Provides sensitivities for the various model components like the size and rate of earthquake, extent of rupture, expected fault displacement, etc. at a site.

CALIFORNIA INSTITUTE OF TECHNOLOGY Search site. >

SCEDC
Southern California
Earthquake Data Center

ABOUT : RECENT EARTHQUAKES : EARTHQUAKE INFO : SIGNIFICANT EARTHQUAKES AND FAULTS : EQ CATALOGS : DOWNLOAD DATA : STATION INFO

Significant Earthquakes and Faults

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

Fault Name Index

Santa Susana Fault Zone

TYPE OF FAULTING: thrust

LENGTH: 38 km

NEARBY COMMUNITIES: Piru, Sylmar, San Fernando

MOST RECENT SURFACE RUPTURE: Late Quaternary, except for a short segment which ruptured slightly during the 1971 San Fernando earthquake

SLIP RATE: between 5 and 7 mm/yr

INTERVAL BETWEEN MAJOR RUPTURES: uncertain

PROBABLE MAGNITUDES: $M_w 6.5 - 7.3$

OTHER NOTES: The faults in this complex zone primarily dip to the north.

[References](#)

This fault is featured on the following maps:
[Northwest Fault Map](#)
[Los Angeles Fault Map](#)

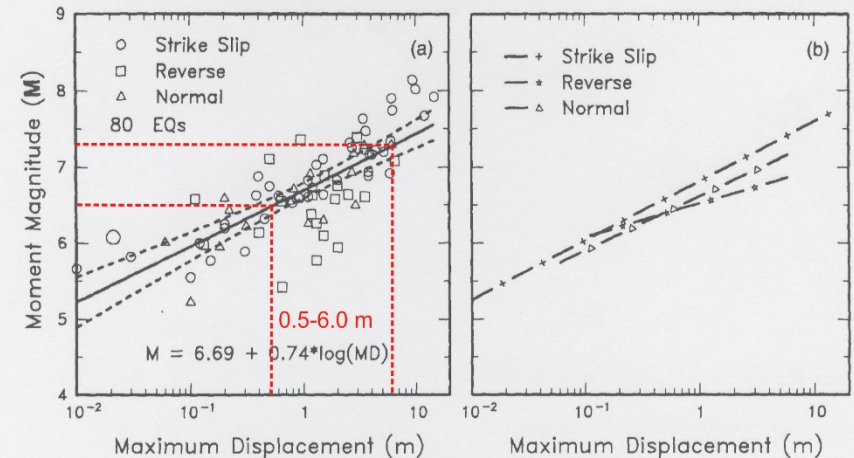


Figure 10. (a) Regression of maximum surface displacement on magnitude (M). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Wells and Coppersmith (1994)

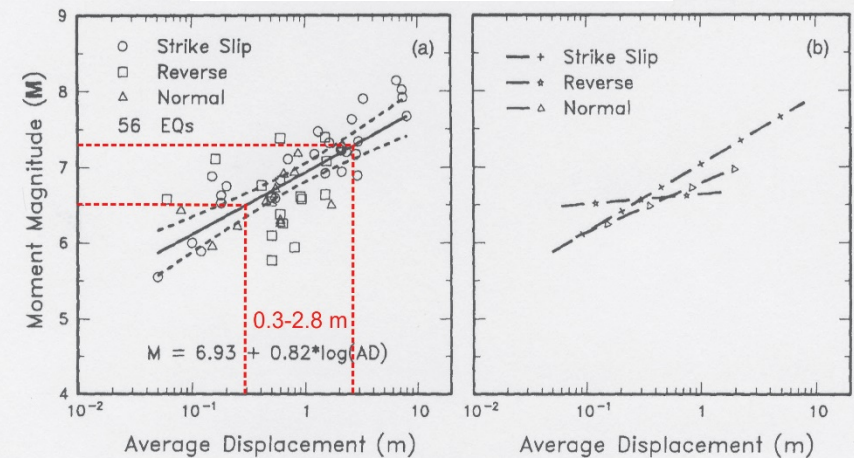


Figure 11. (a) Regression of average surface displacement on magnitude (M). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

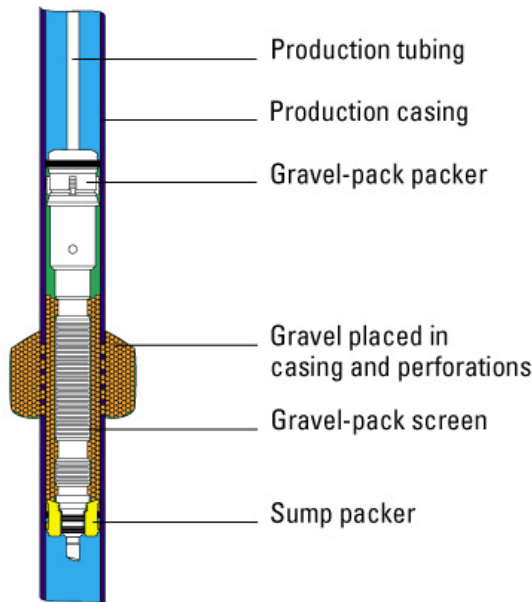
- **Summary-what to get out of this presentation:**

- A fault rupture hazard at the surface is a rupture hazard in the subsurface.
- There is **no** quick way to draw-down a gas storage field . Most gas storage fields have large volumes of methane at high pressures.
- The shallower the well and fault intersections the more likely well casing leaks will migrate to the surface.
- The SSF is a recognized and regulated fault rupture hazard at the surface with a high slip rate. All 114 gas storage wells cross SSF at shallow depths.
- There are significant global, regional, and local impacts from the release of massive amounts of methane to the atmosphere:
 - ✓ Globally: Methane is a much more effective heat-trapping gas than carbon dioxide and has the potential to negate much of the nation's carbon dioxide reduction efforts (IPCC, 2014).
 - ✓ Regionally: The ACGSF leak accounted for 20% of California's annual methane emission (CARB, 2016).
 - ✓ Locally: Storage fields such as the ACGSF that are located near large urban areas have significant safety, health, environment, legal, and financial risks.

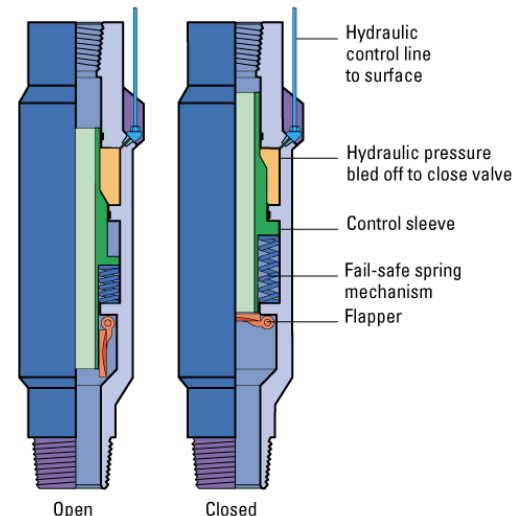
- **Mitigation:**

- Why are gas storage fields located near urban areas? Gas moves slowly through pipelines and storage fields located near the customers are favored to meet customer demand.
- However, storage fields near urban areas have the potential for significant impacts and risks.
- Avoid siting of gas storage wells and fields across active faults.
- In southern California the depleted offshore oil fields are probably the safest locations for gas storage fields.
- Well design:
 - ✓ Gravel packs across fault zones.
 - ✓ Install downhole safety valves above storage zones and below intersecting faults.
 - ✓ Entire length of production casing cemented to hole wall-no open annulus avenues for gas migration.
 - ✓ Cork-screw coiled tubing across fault zone?
 - ✓ Is there a favorable orientation for boreholes crossing fault zone?

Gravel packs have been used across aseismic faults in oil fields (Ershagi, 2016, oral communication).



Installation of downhole shut-off valves (DHSVs) on wells have been proposed at the ACGSF and other fields but the reliability of these valves is unclear especially during a nearby earthquake. DOE and DOT have recommended doing a cost and benefit analysis of DHSVs (DOE, 2016).

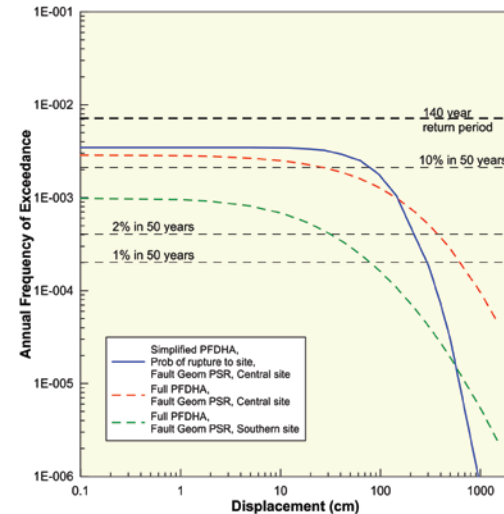


- **Recommendations:**

- **Need more geologic input.**
- **New state and federal regulations for gas storage wells crossing potentially active faults should require FDHA (or PFDHA).**
- **Alquist-Priolo (AP) Act: Statutory and regulatory role of Act should be extended to subsurface fault rupture hazards.**
- **DOGGR Discussion Draft for gas storage fields in CA: includes identification of active faults as a hazard and require a risk management plan.**
- **California Public Utilities Commission CPUC: There will be new requirements for underground gas storage projects and performing FDHA (or PFDHS) on storage fields with active faults should be included.**
- **American Petroleum Institute (API), Recommended Practices 1171: RP should be revised to include more about the hazard, risk, and mitigation of active faults.**
- **Pipeline and Hazardous Materials Safety Administration (PHMSA-DOT). PHMSA already regulates surface pipelines crossing active faults so why not extend this role to the subsurface? PIPES Act of requires PHMSA to issue, within two years, minimum safety standards for underground natural gas storage facilities.**

Sensitivity for Site Location (Wells & Kulkarni, 2014)

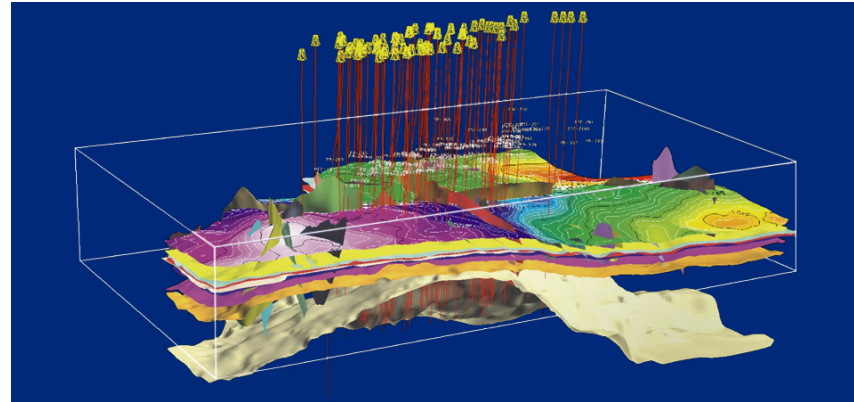
A comparison of simplified PFDHA results and full PFDHA results for the Hayward fault that includes the effect of site location in a model for distribution of slip along the rupture.



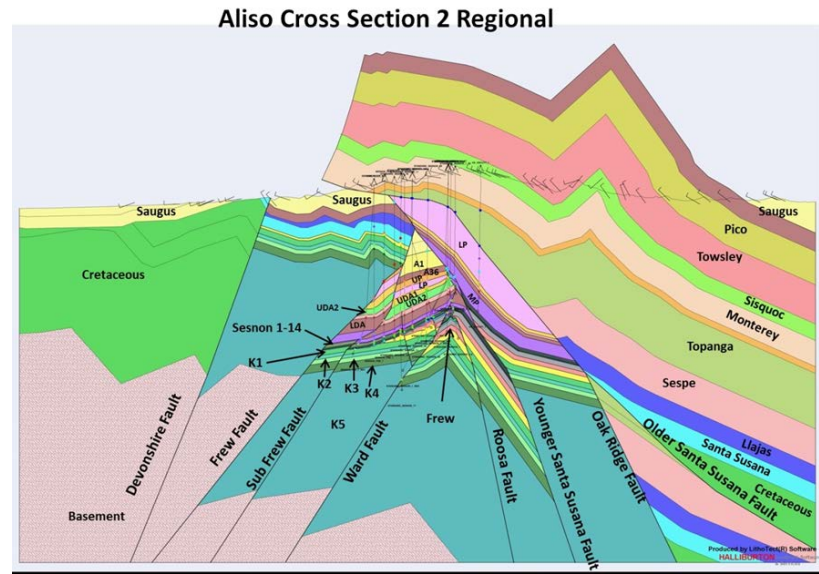
Trans-Alaska Pipeline at the Denali Fault showing major design features. Fault movement and intense ground shaking were accommodated by zigzagging the pipeline and leaving it free to slide.

There is an important role for petroleum geologists and the oil and gas industry to play in earthquake hazards evaluations by virtue of their unique subsurface expertise and familiarity with deeper data sets and modern mapping and structural techniques.

3D surface map of an oil field showing wells, geologic units, and faults (Wintershall, 2016).



Lithotect cross section of the ACGSF showing well and surface data.



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