Scales of Stress Field Variation Determined from Borehole Observations in Southern California

Joann Stock, Caltech

(See poster #232 at this meeting by Persaud et al.)

Caltech

Motivation

- Lots of potential for looking at more borehole data in California
- It’s not that hard to analyze
- It can yield interesting constraints on the stress field
- Main bottleneck is: getting the appropriate files from state Division of Oil, Gas and Geothermal Resources (DOGGR) or from industry

Borehole observations can constrain:

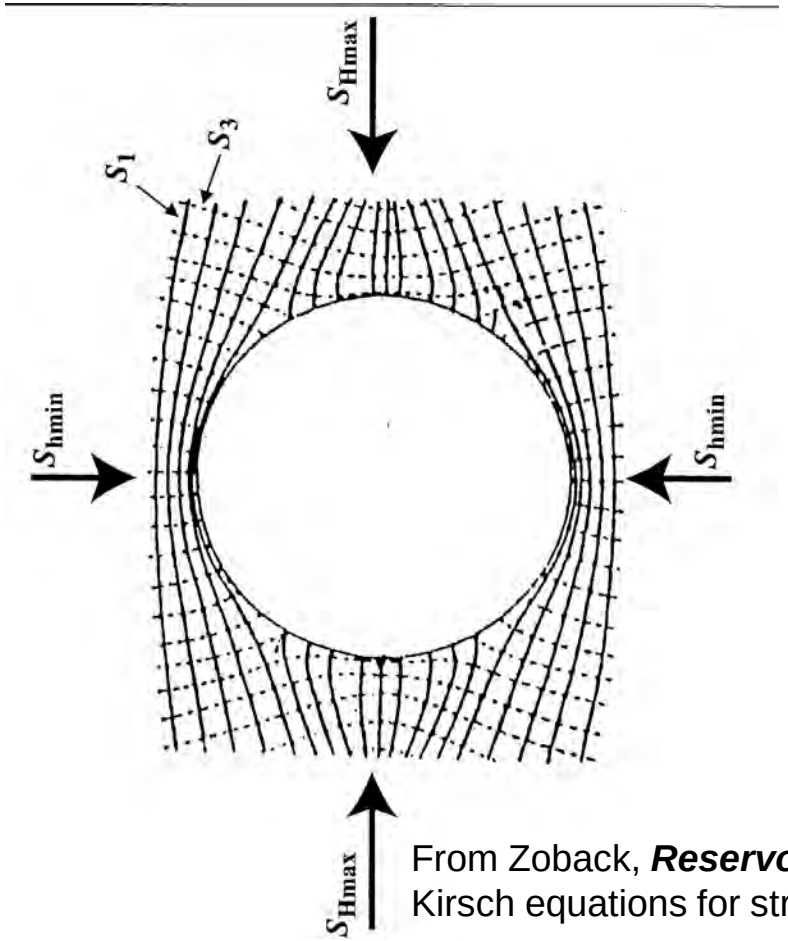
- **Directions** of horizontal principal stress $\boldsymbol{\sigma_h}$ and $\boldsymbol{\sigma_H}$ (from wellbore breakouts or drilling induced tensile fractures in a vertical borehole)

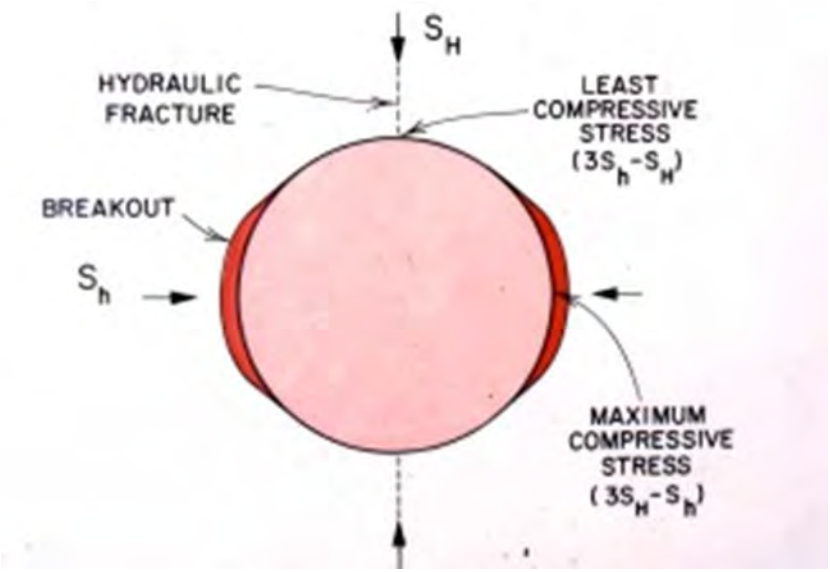
- **Directions** and **relative magnitudes** of all three principal stresses, $\boldsymbol{\sigma_1}$ $\boldsymbol{\sigma_2}$ $\boldsymbol{\sigma_3}$, from multiple deviated wells in a small volume

- **Magnitudes** of one or more of the principal stresses, from hydraulic fracturing stress measurements, leakoff test pressures

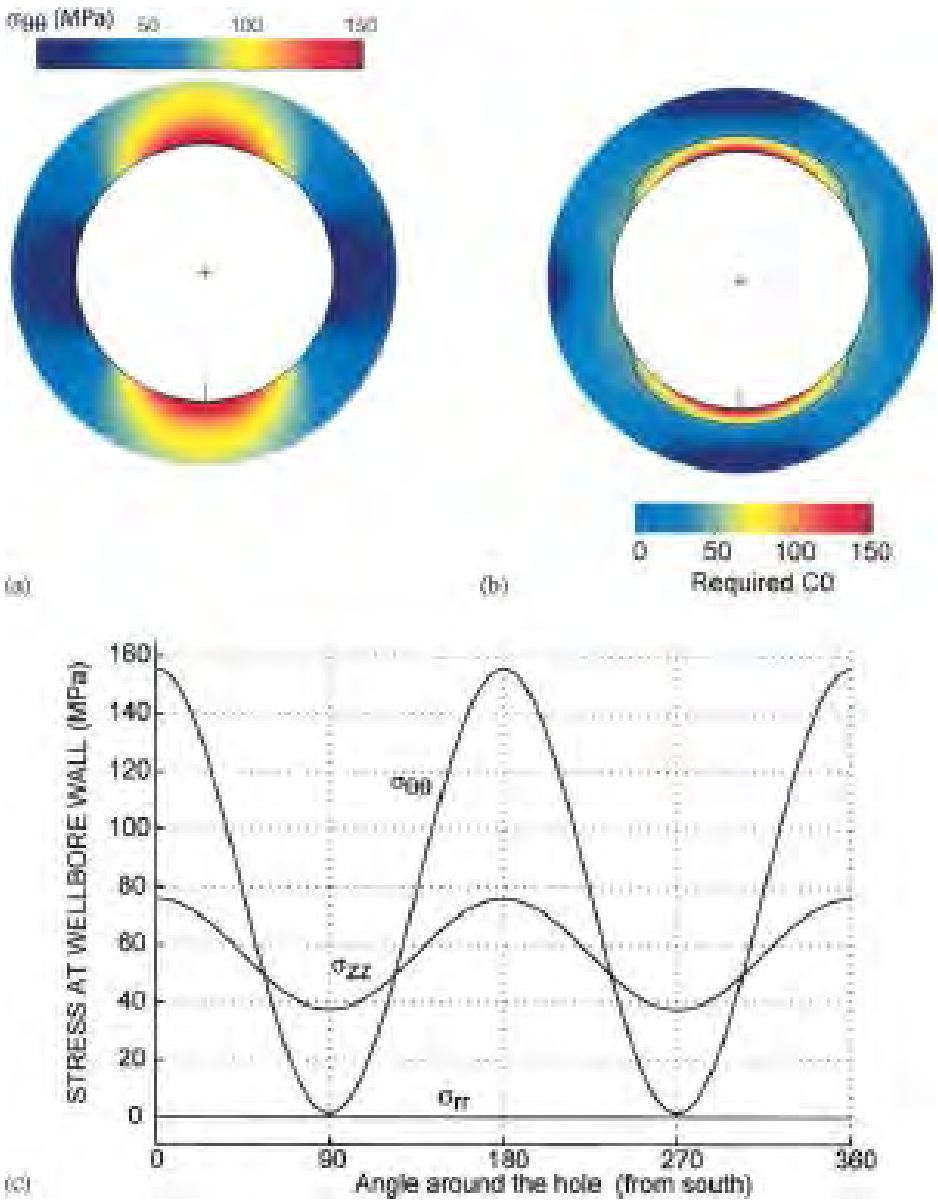
- Other constraints on magnitudes from widths of breakouts

Far field stress related to features in a fluid- or gas-filled cylindrical hole; NOTE ***breakouts*** and ***hydraulic fractures*** may not be found together





From Zoback, ***Reservoir Geomechanics***,
Kirsch equations for stress around a borehole

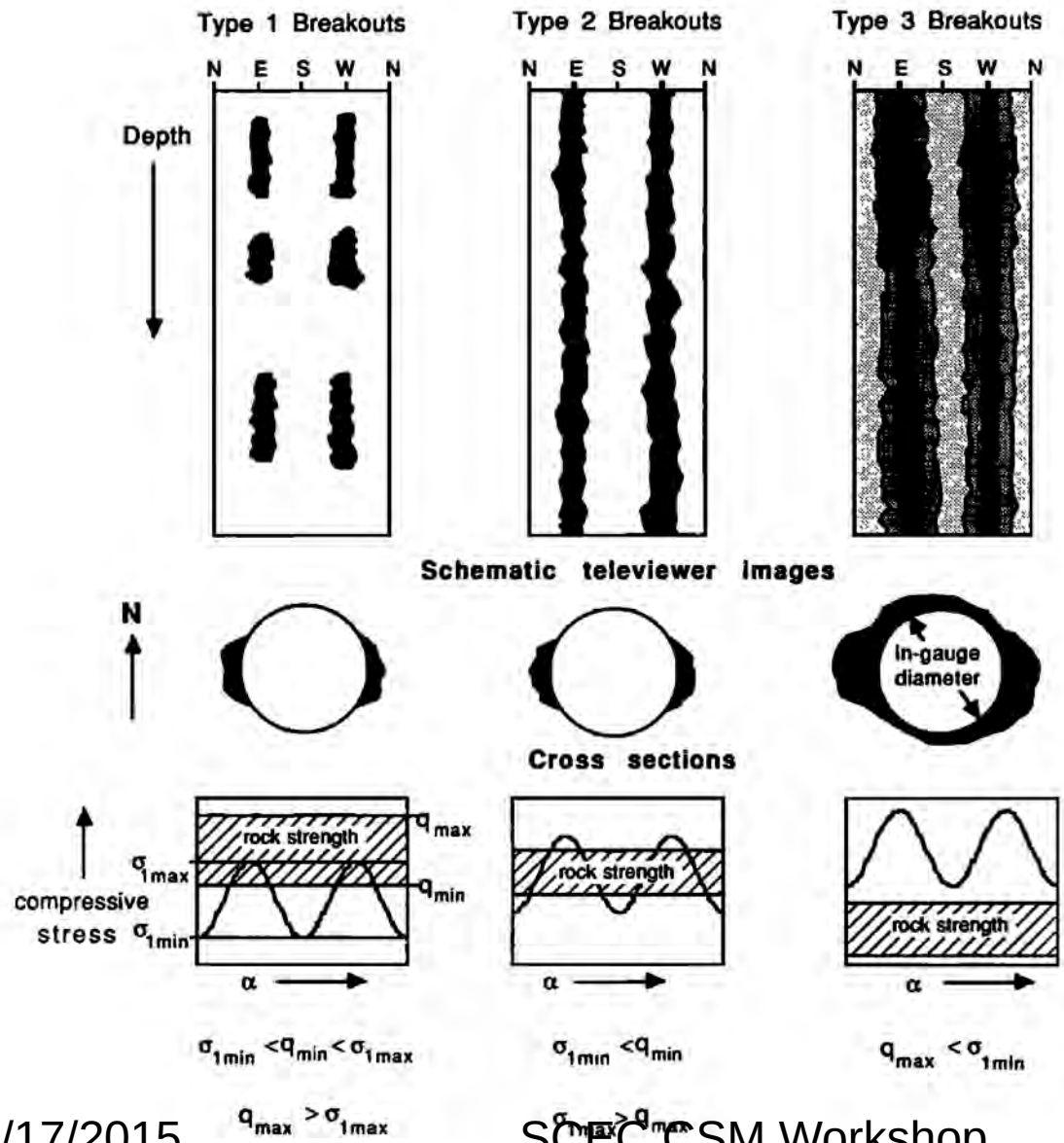


From Zoback et al., International Journal of Rock Mechanics & Mining Sciences 40 (2003) 1049–1076

Circumferential effective stress around a vertical wellbore subjected to east–west compression

Rock strength 45 MPa,

Breakouts depend on stress tensor and rock strength



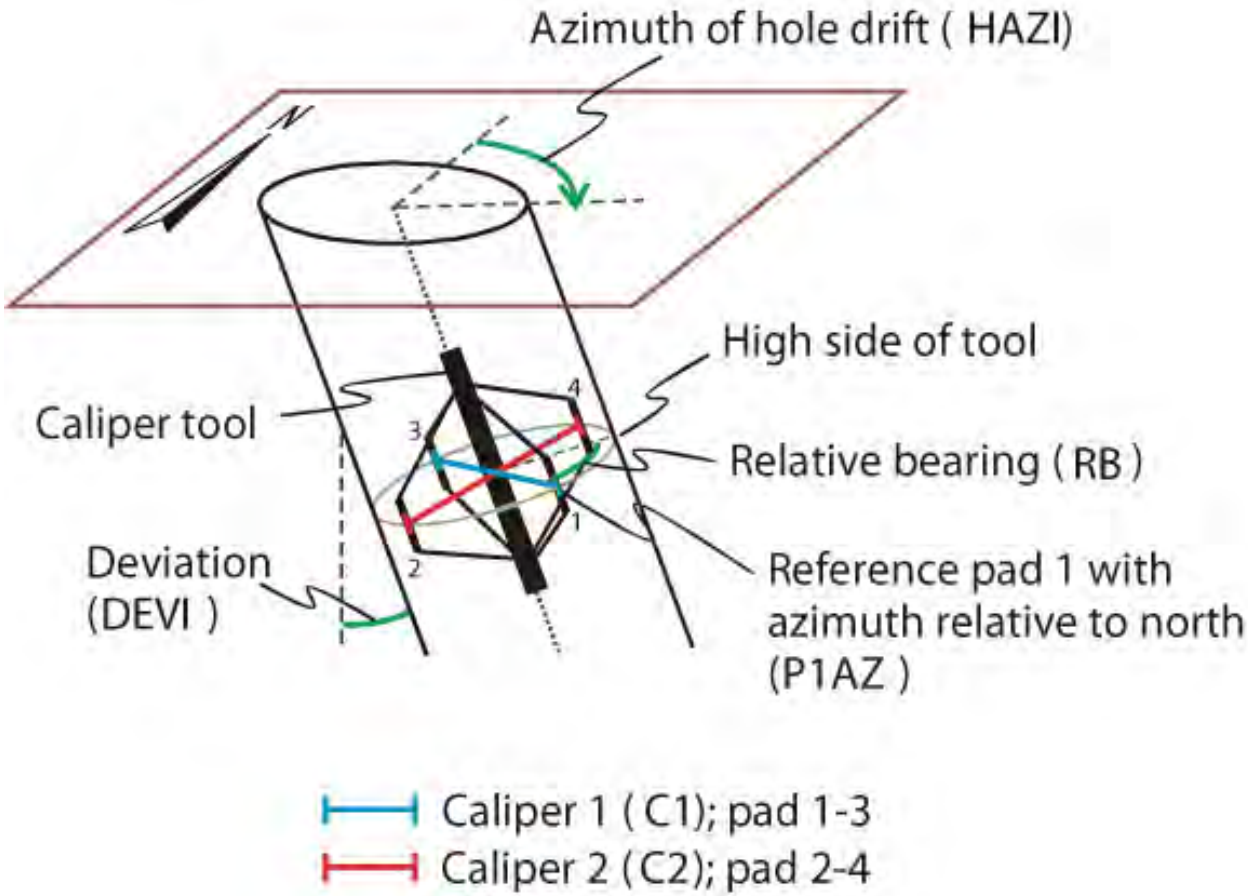
Mastin, JGR, 1988

FIELD OPERATIONS – MEASURING BREAKOUTS

TYPES OF TOOLS:

- Acoustic borehole televiewer (works in water)
- Oriented 4-arm or 6-arm caliper
- 4-arm to 8-arm electrical imaging log

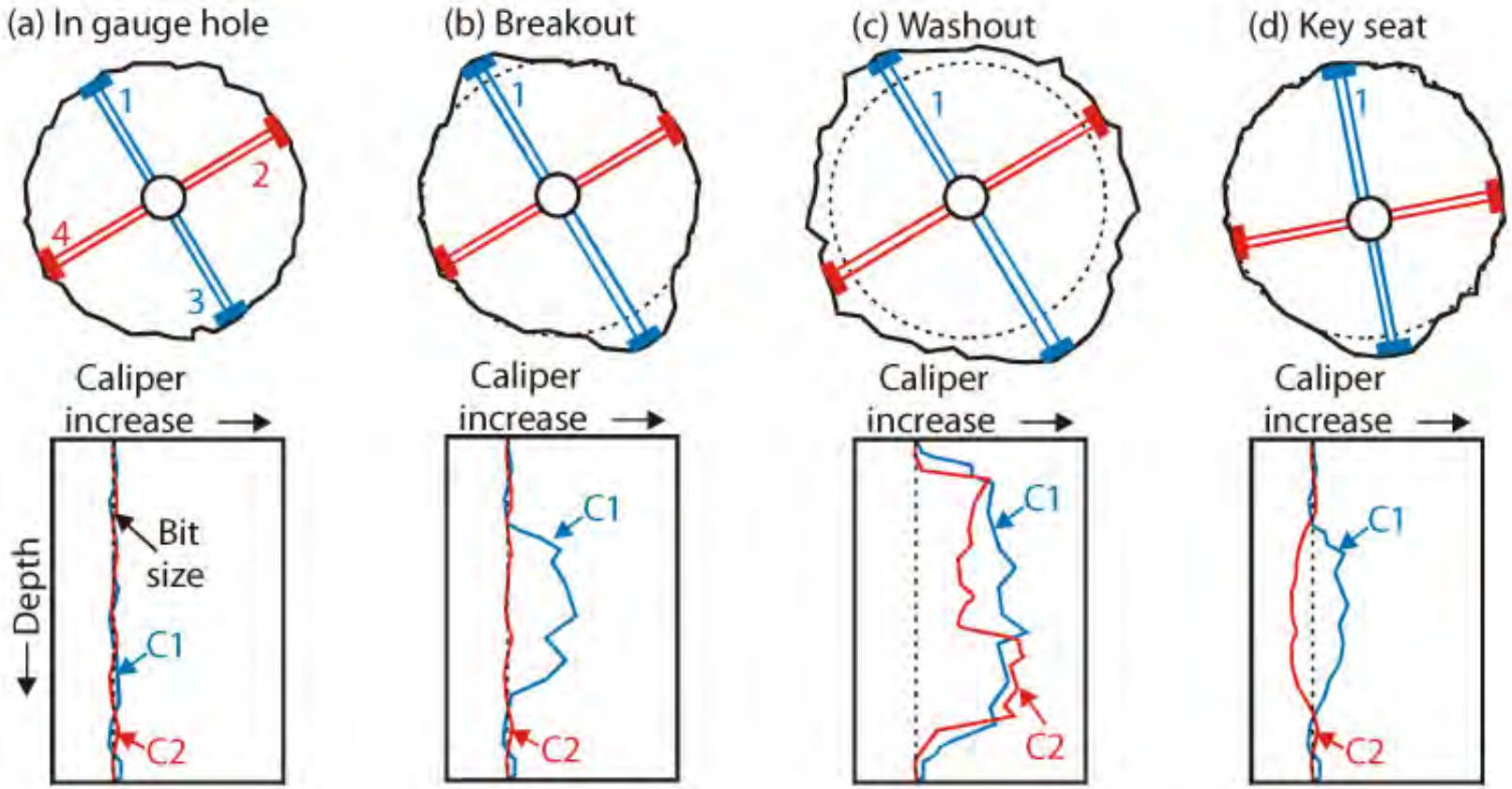
1. Lower tool (with arms closed) into bottom of section of open hole to be logged
2. Open the arms and winch the tool up the hole at a constant speed.
3. If the hole is cylindrical, the tool will rotate.
4. If the hole is not cylindrical, the long diameter of the tool will tend to stay along the longest axis of the borehole



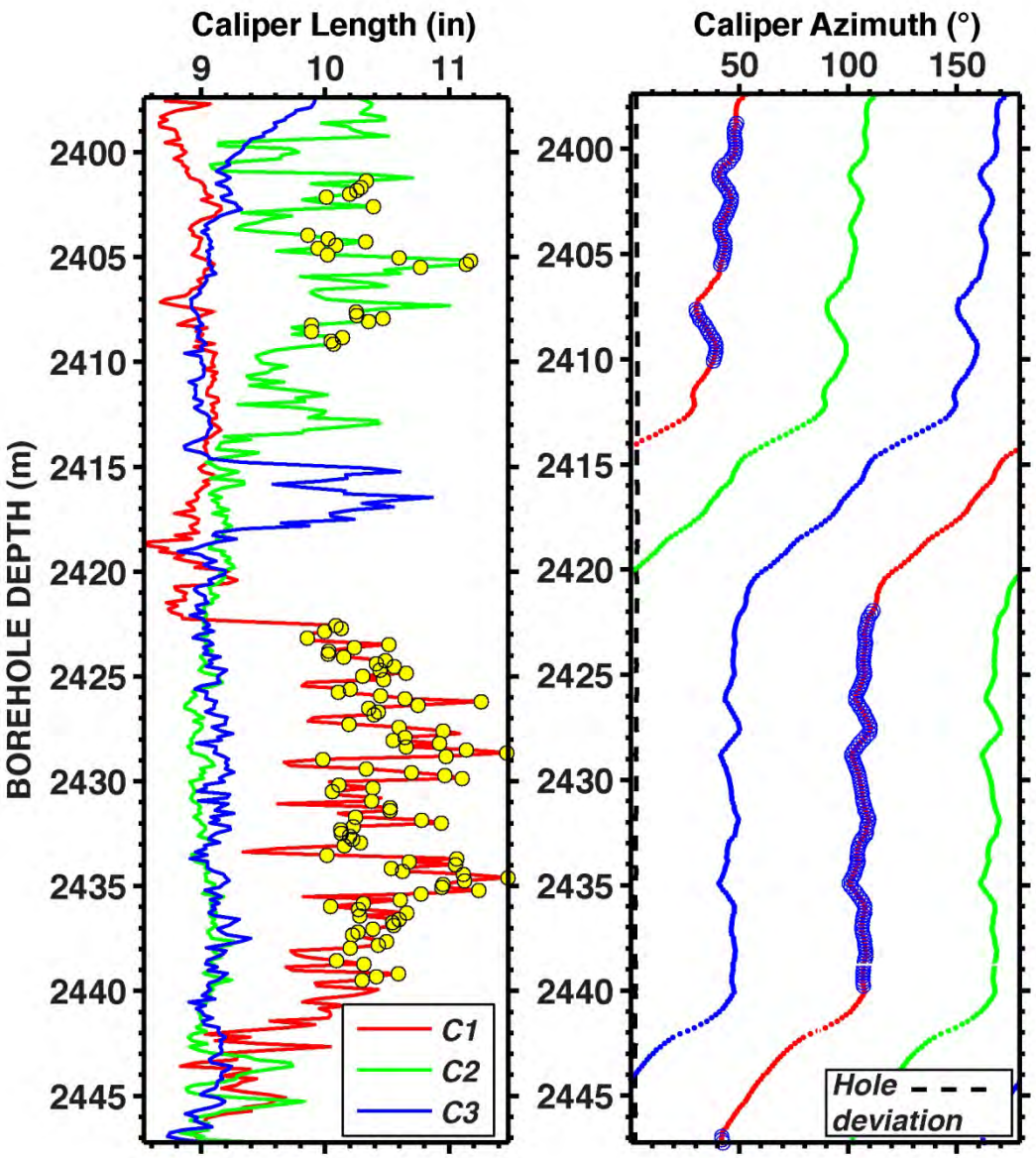
From Reinecker et al., World Stress Map project, after Plumb and Hickman (1985)
4-arm caliper tool

All tools have centralizers above and below (not shown in this diagram)

Identifying breakouts from borehole shape and instrument behavior (tool stops rotating in breakout)



From Reinecker et al., World Stress Map project, after Plumb and Hickman (1985)



Example of breakouts identified from some newly obtained oriented 6-arm caliper data

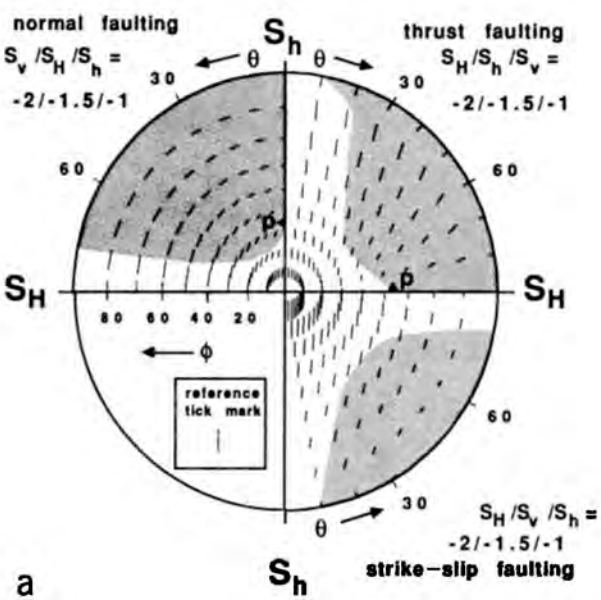
Criteria:
no tool rotation,
C1 ~ C2
C3 – C2 > 2 cm
Length > 3 m

(criteria modified from Zajac & Stock, JGR, 1997)

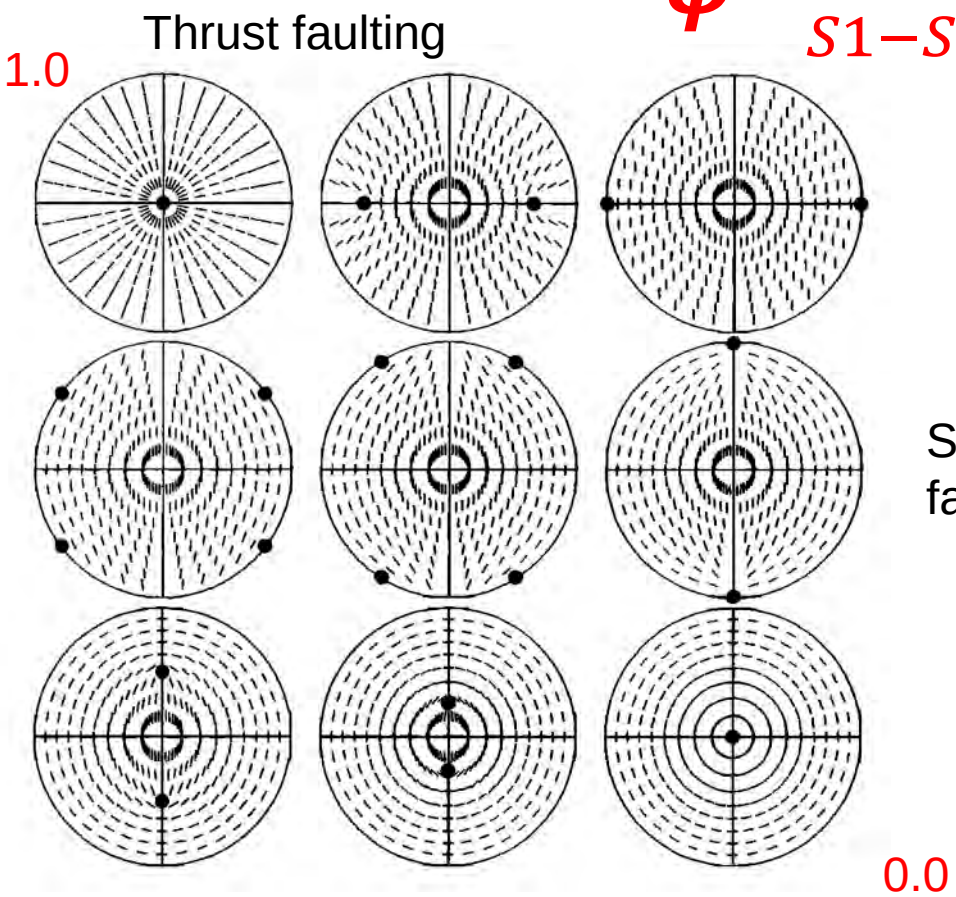
Caltech

Method for multiple wells with different deviations from a central platform

$$\phi = \frac{S2 - S3}{S1 - S3}$$



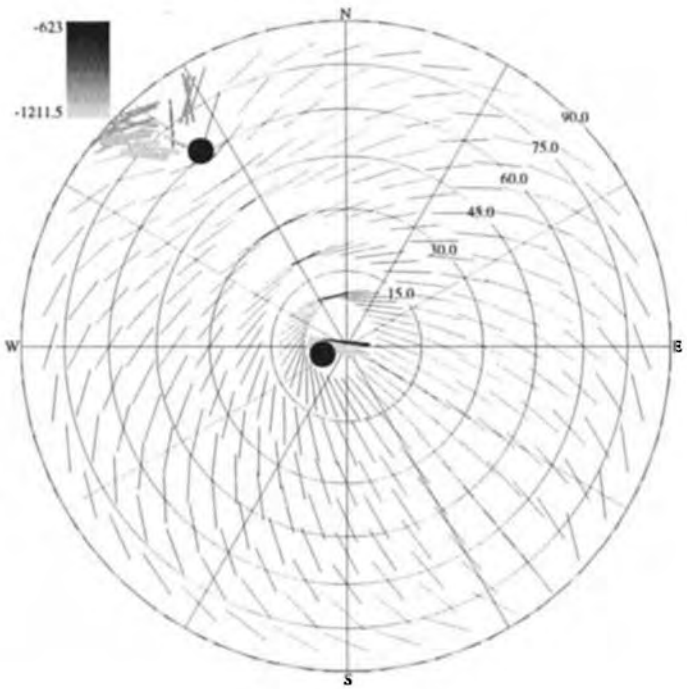
Mastin, JGR, 1988



Zajac & Stock, 1997 JGR

Lower Hemisphere Projections

Breakout observations



Stress Tensor

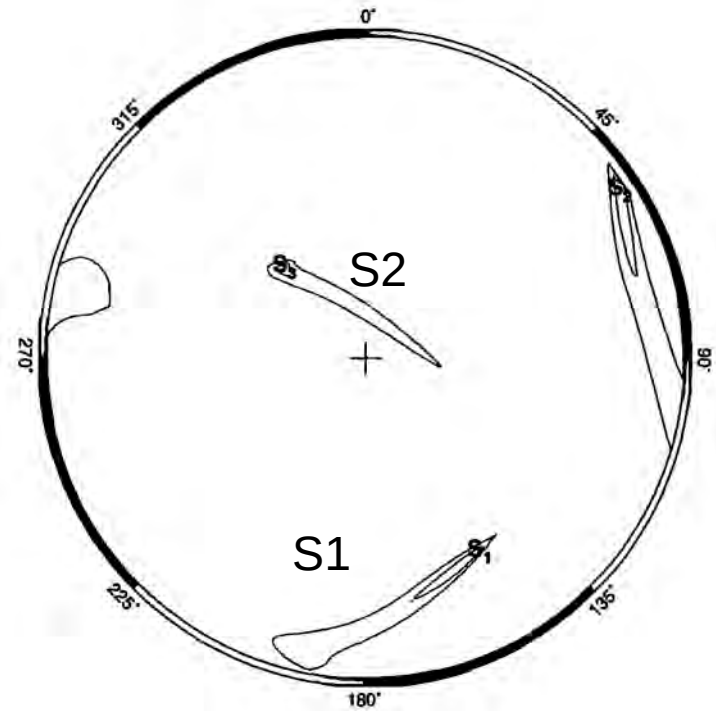


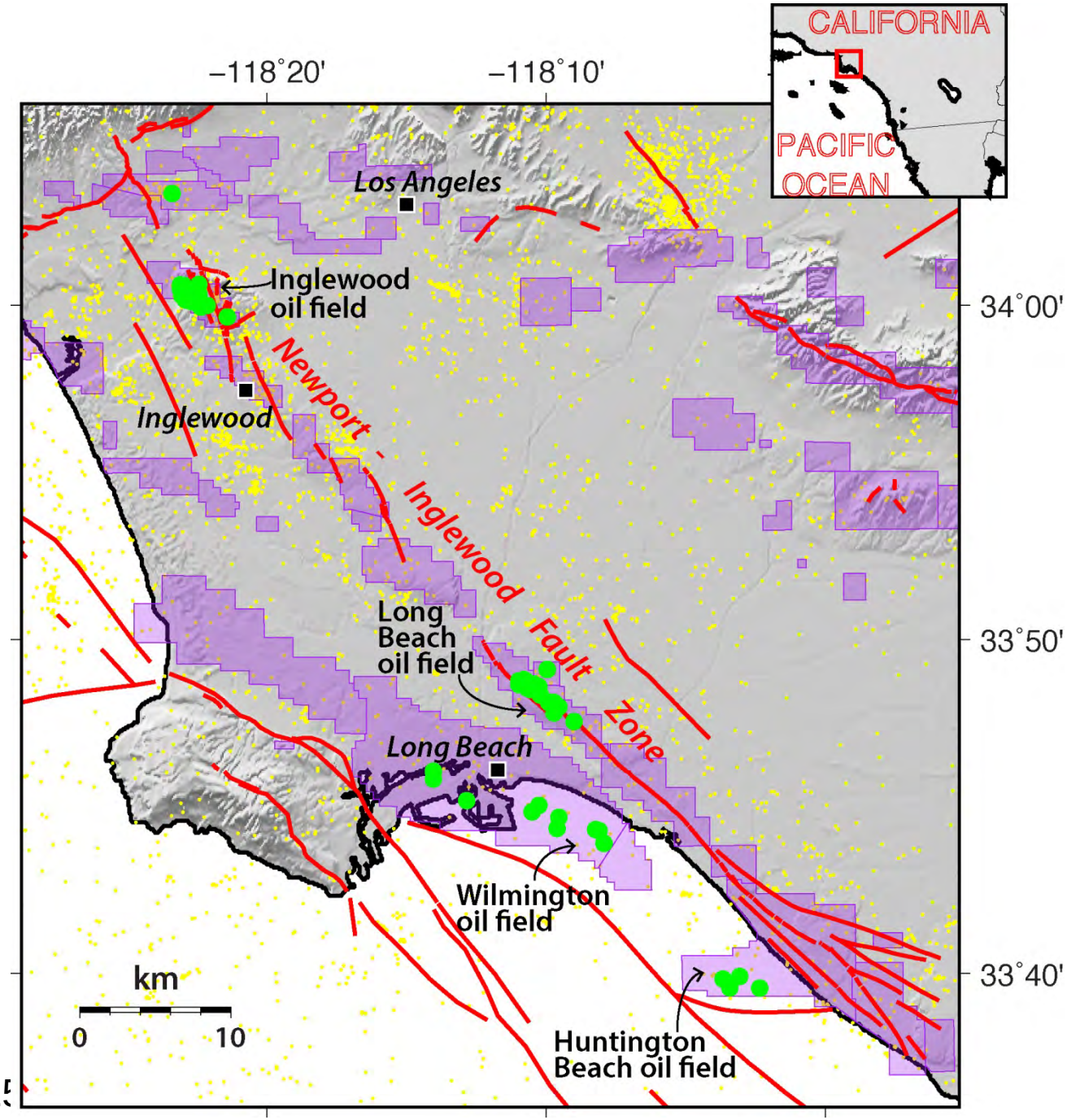
Table 3. Characteristics of the Stress State That Minimized the Weighted One-Norm Misfit of the Point Pedernales Borehole Breakout Data

	S_1	S_2	S_3
Azimuth	N148.5°E	N55.8°E	N318.7°E
Plunge	31.5°	4.4°	58.1°
Value	2	$1.821^{1}_{1.584}$	1

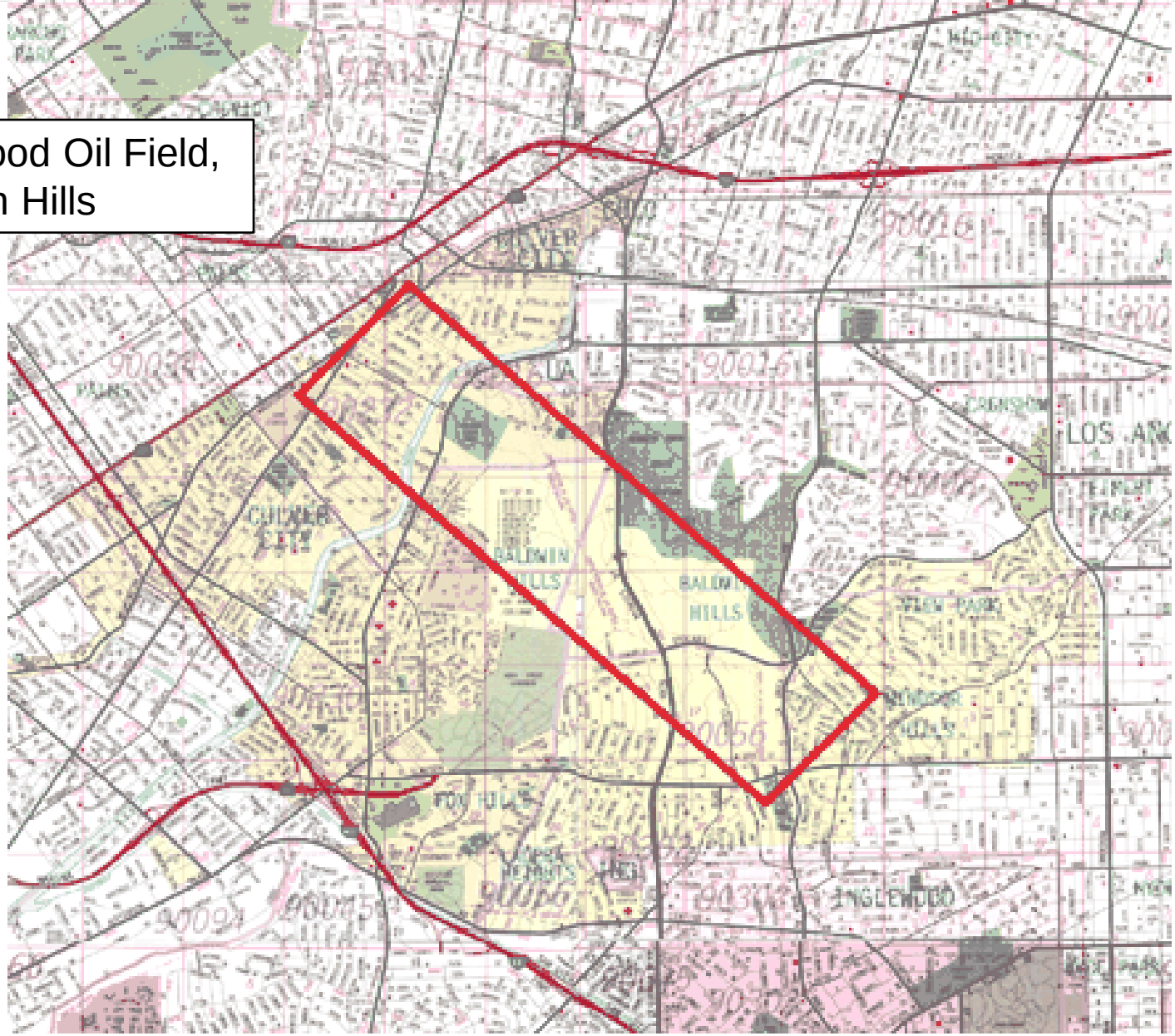
Optimized ϕ, $0.821^{1.000}_{0.584}$; minimum weighted one-norm misfit, 4.84°; 95% confidence level for weighted one-norm misfit, 5.96°.

Stress tensor derived from sparse breakout data, 5 wells in Point Pedernales oil field (Zajac & Stock, 1997 JGR). Nodal points are constrained by breakouts in highly deviated well.

Caltech


CALIFORNIA
PACIFIC OCEAN
−118˚20'
−118˚10'
34˚00'
33˚50'
33˚40'
Los Angeles
Inglewood oil field
Inglewood
Newport - Inglewood Fault Zone
Long Beach oil field
Long Beach
Wilmington oil field
Huntington Beach oil field
km
0
10

Inglewood Oil Field, Baldwin Hills

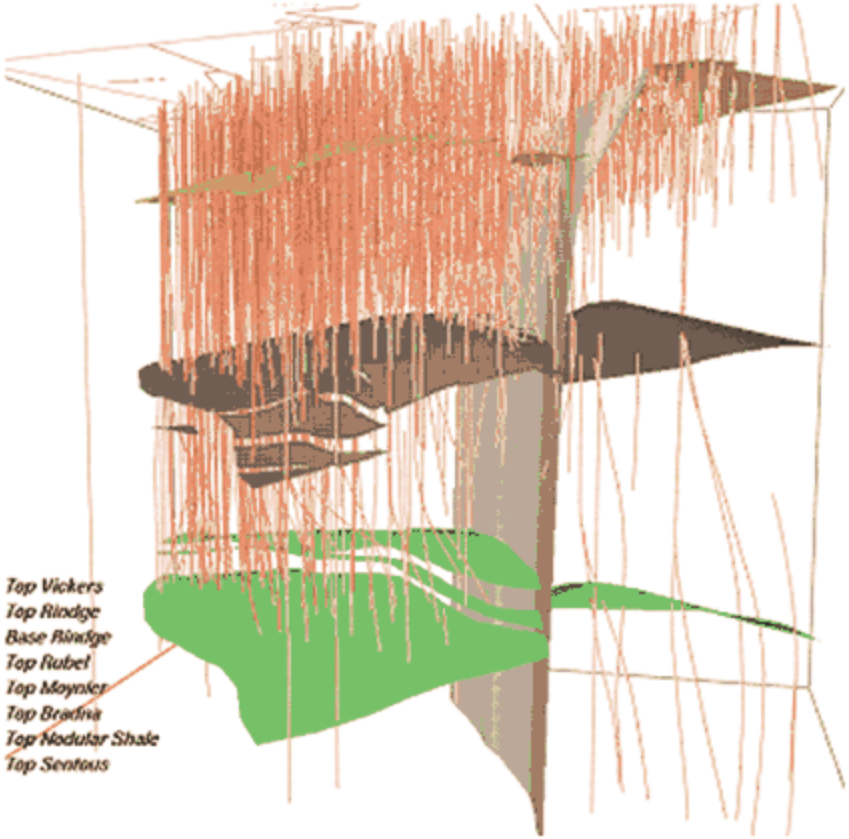


From Lockman, *The Leading Edge October 2005 vol. 24 no. 10 1008-1014*

Caltech

We have data from 24 of the wells here, mostly on the west side of the Newport-Inglewood fault, 2-3 km depth.

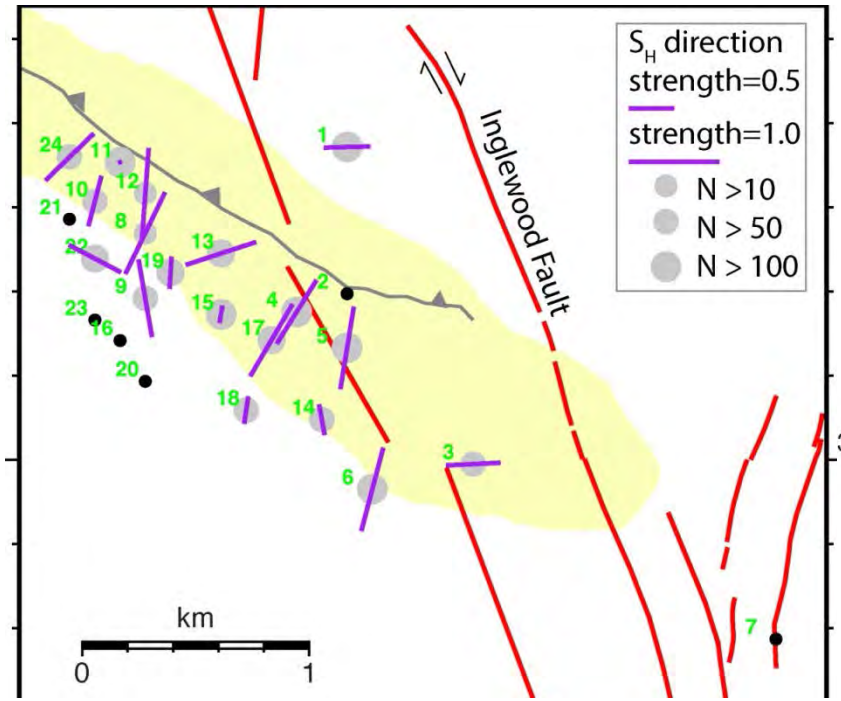
The wells were drilled 8 to 10 years ago.

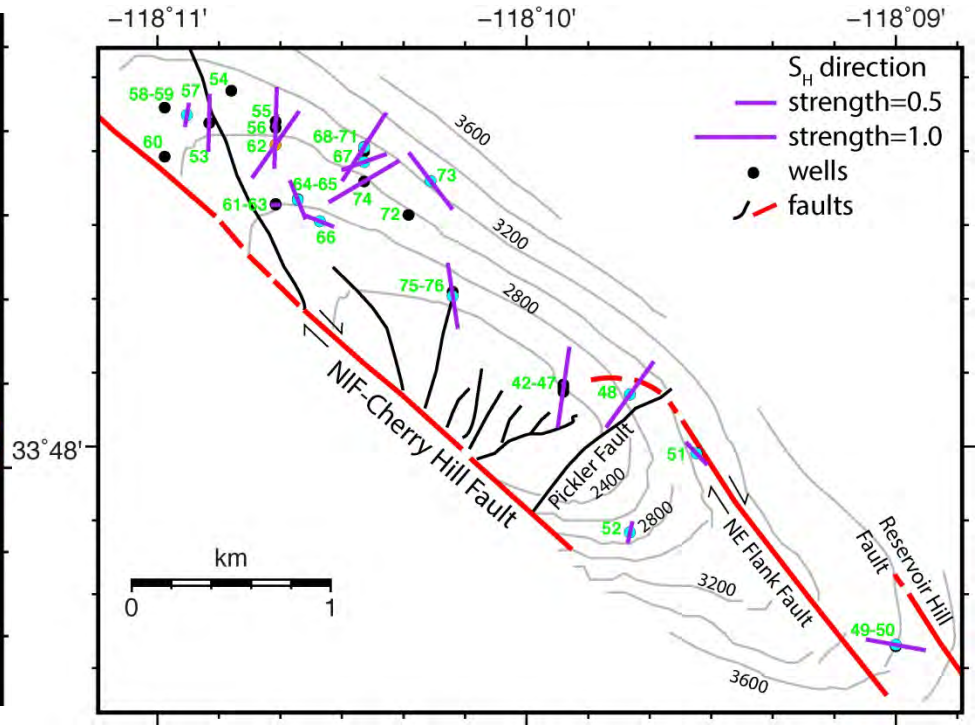


Our previous study (Wilde & Stock, JGR, 1997) had data from only 1 older well in this field

Well Bores, Inglewood Field, Baldwin Hills

From Lockman, *The Leading Edge October 2005 vol. 24 no. 10 1008-1014*





Inglewood Oil field

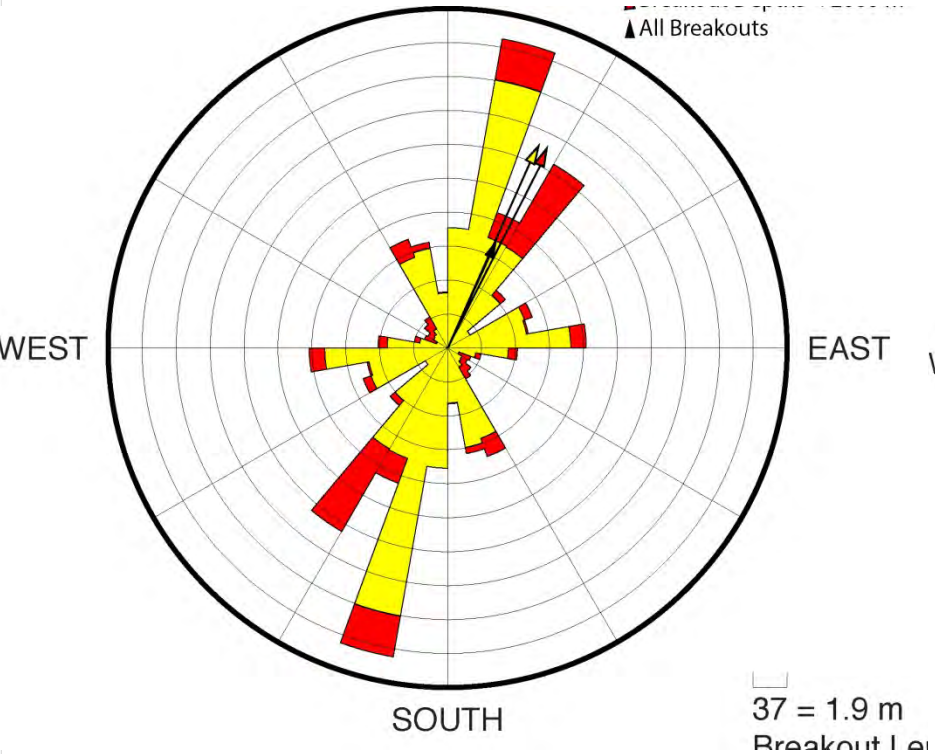
Maximum horizontal compression, vertical wells, 2-3 km depth

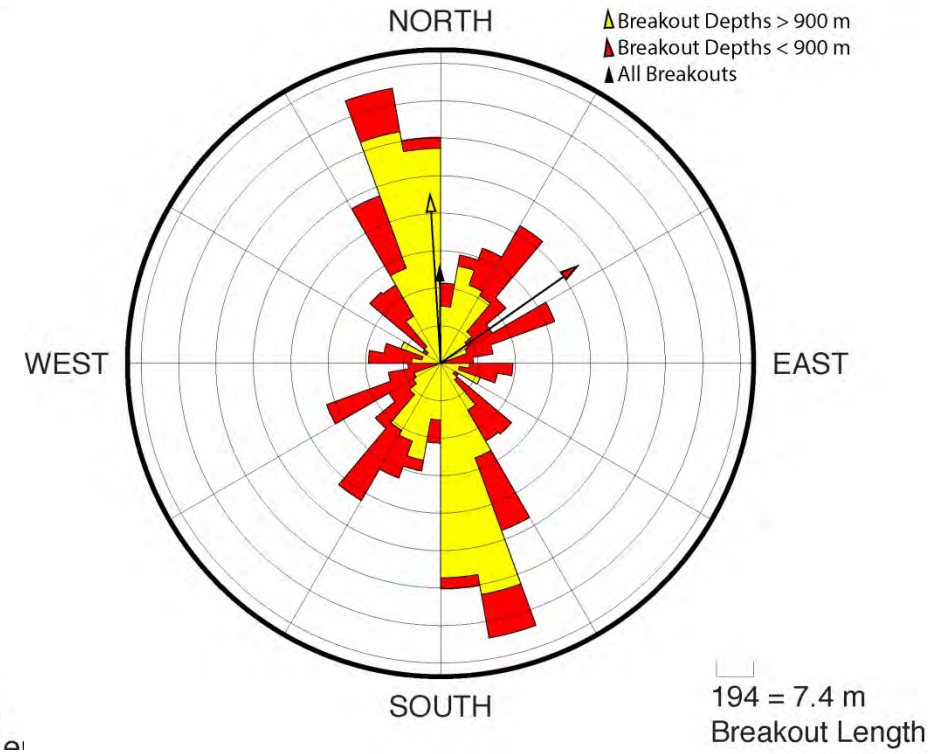
Red lines = fauts (California Geological Survey, 2010)

Long Beach Oil field

Maximum horizontal compression, vertical wells, < 4.2 km depth

Black lines = fauts (Chavez 2015 and Wright 1991))





Inglewood Oil field
yellow > 2000 m depth

Long Beach Oil field
Yellow > 900 m depth

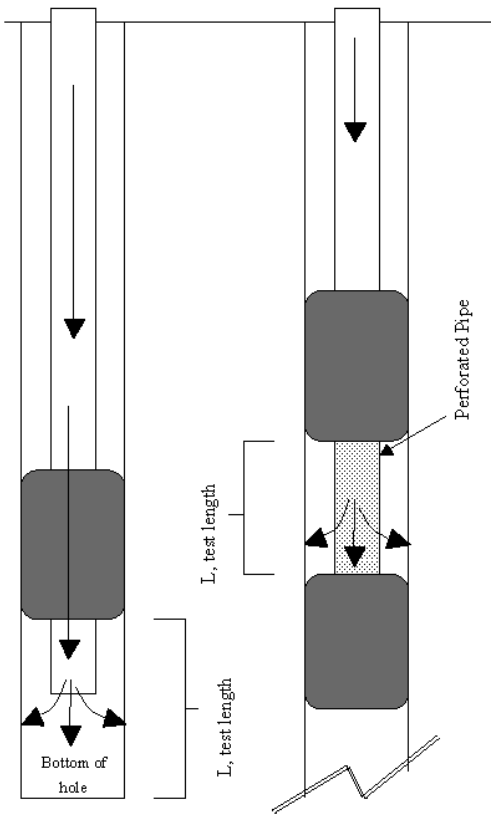
The Hydraulic Fracturing Method (officially in use since 1957)

USGS Drill Rig

Black Butte, Mojave Desert, CA 1987

Caltech

FIGURE 1: Packer Test Assemblies

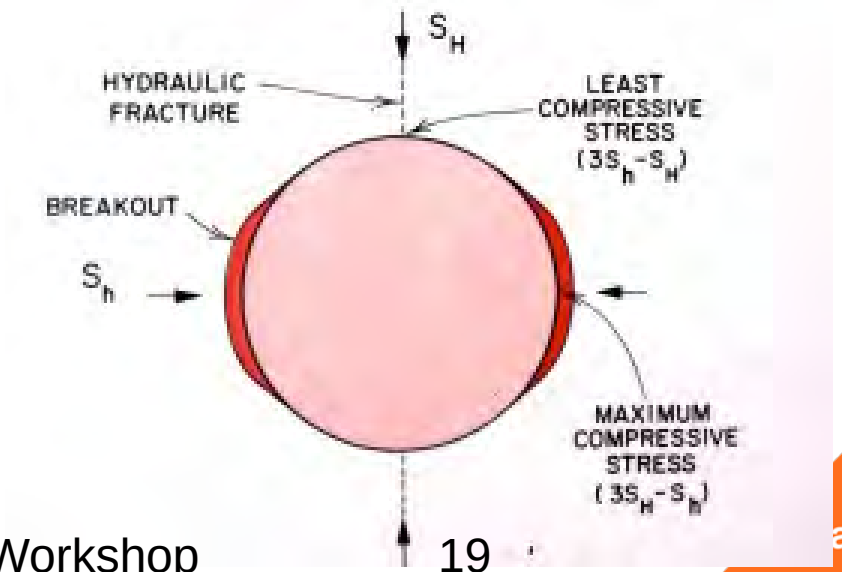


FIELD OPERATIONS – HYDRAULIC FRACTURING

1. Isolate a cylindrical, smooth section of the borehole using a “straddle packer” (two inflatable packers)

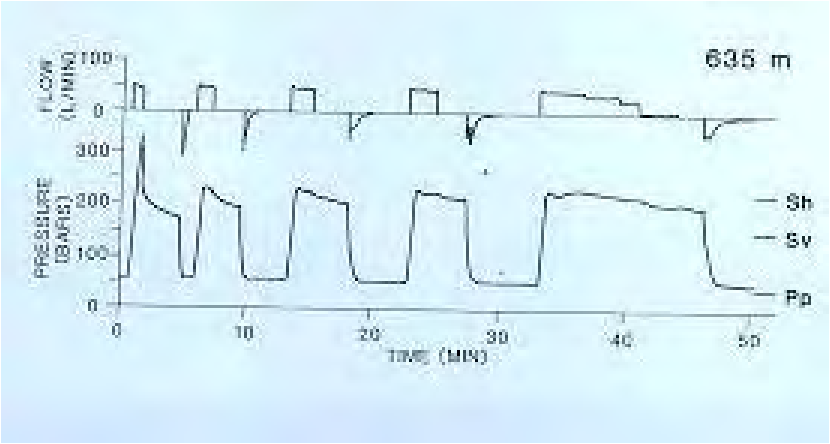
2. Inject fluid under high pressure into this section of the borehole

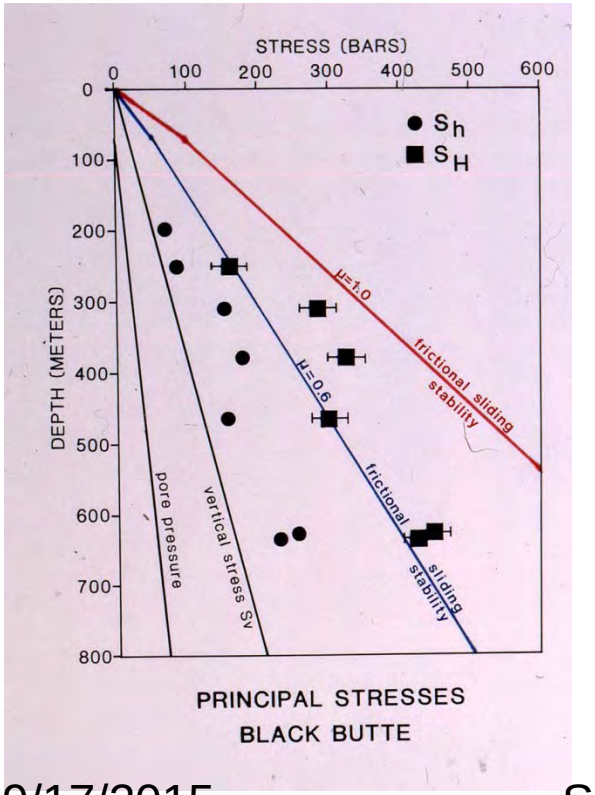
3. When pressure is high enough it will fracture the borehole wall and a fracture will extend out away from the borehole



Packers in borehole

Cross section of borehole





FLOW TESTS

- Measure fluid flow (top curve, left)
- Measure fluid pressure in interval between the packers (bottom curve)

Curves show when fluid is going into fracture and coming out of fracture

Pressure values of curves show the magnitudes of the principal stresses

Stress vs. depth plot (left) shows whether faults are close to slipping

Figures from Stock & Healy, 1988, J. Geophys. Res.

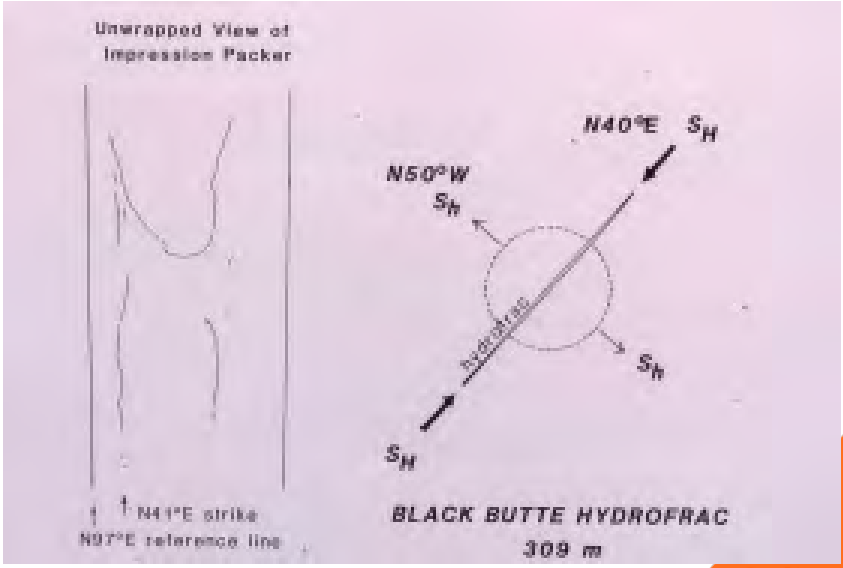
ADDITIONAL TESTS TO GET ORIENTATIONS OF FRACTURES

Impression Packer

Run impression packer to get impression and orientation of fracture that formed, or try to see it with borehole imaging

Get fracture orientation from microseismicity during fracture propagation (need very sensitive nearby array)

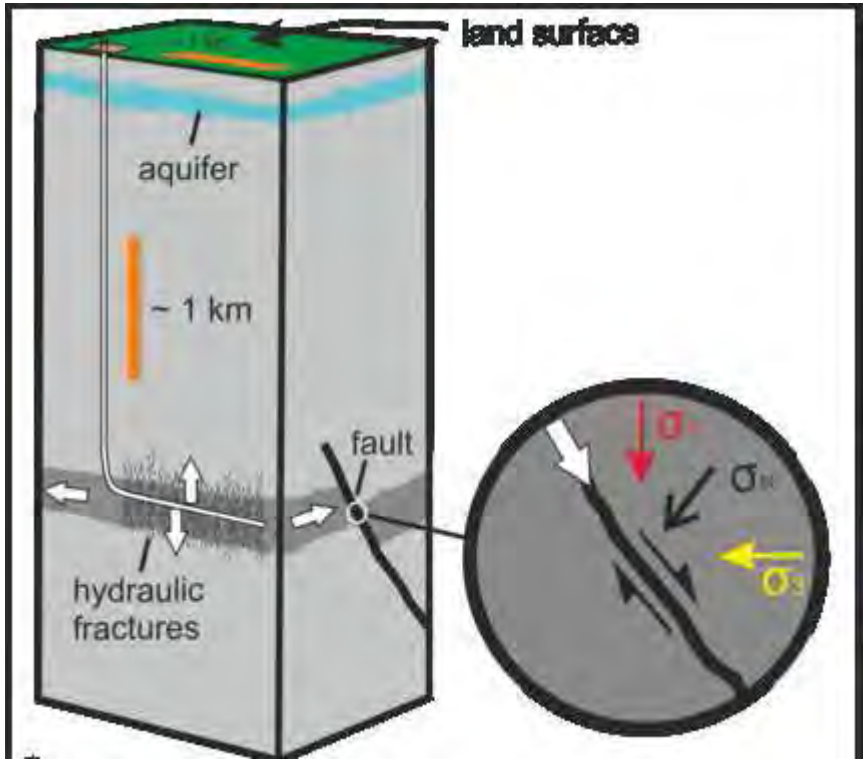
For this location, SH direction cannot be explained by topography!



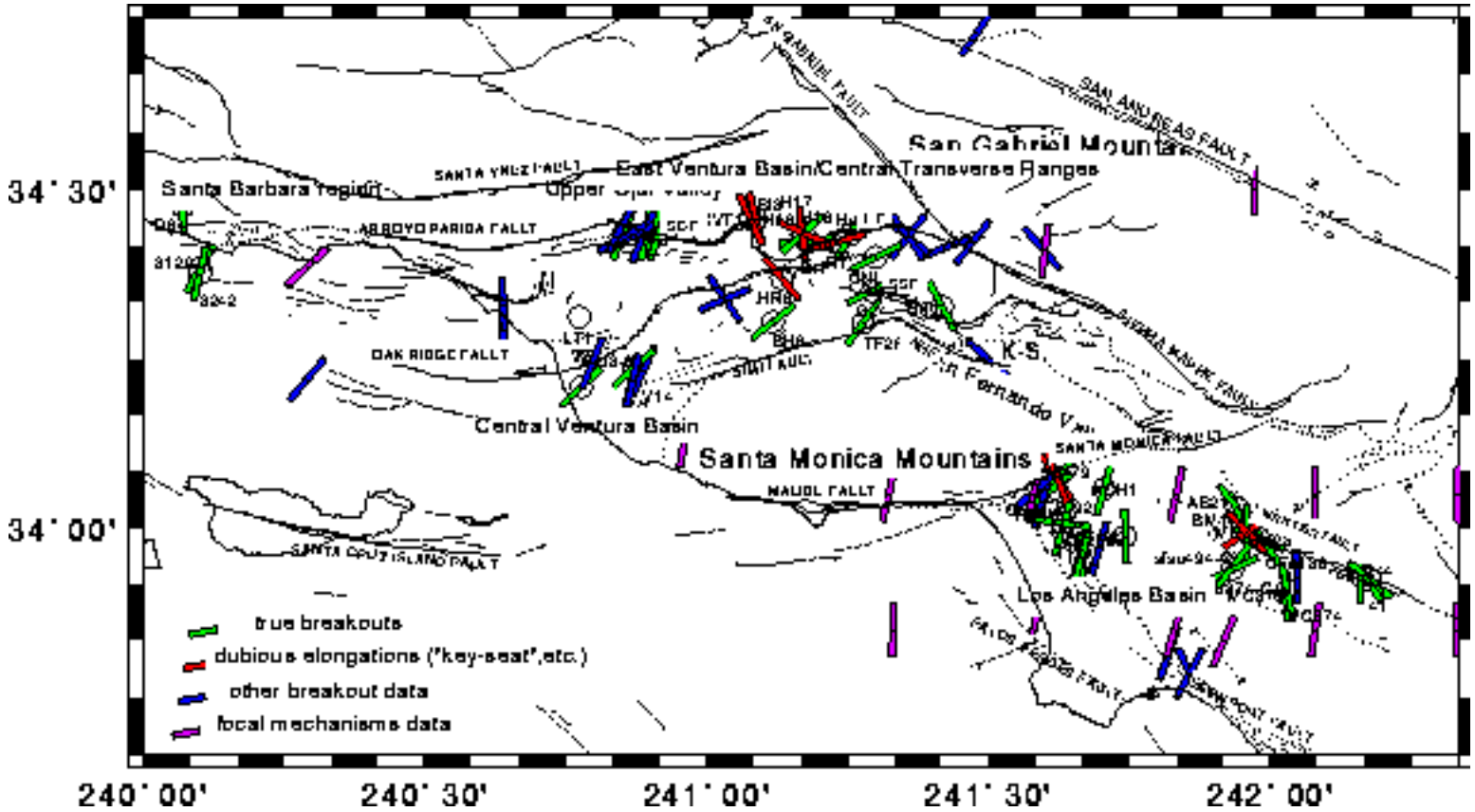
Horizontal drilling and hydraulic fracturing are "unconventional" extraction technologies

- Small volume hydraulic fractures confined to a known stratigraphic layer
- Typically cannot be done in zones of breakouts
- Oil companies usually want to drill horizontal holes in the direction of Sh, and base mud weights on stress tensor for hole stability

Figure from Davies et al., 2013



We expect to provide a lot of new constraints in the regions of the oil fields, compared to this map from Wilde & Stock 1997



Summary & Things to Think About

Small length scale variations are real and may be due to various active structures or faults. Results from regions away from the active faults tend to be much more uniform.

Overall results show smaller scale variation than the earthquake-derived stress results; SH directions are broadly similar but show more variation. How do things change with depth? Or with time? (poster #229 mentioned previously this afternoon)

Models for other regions (sedimentary rocks, e g. Barnett Shale, Texas) include stress relaxation and creep

Web site for previous work (1997):
http://www.data.scec.org/stress/stress.html