Report on SCEC 2014 funding, project 14118

Using Borehole Data as a Direct Measure of Stress Directions and Variability to help Constrain the Community Stress Model of Southern California

Proposal Category A: Data Gathering and Products
Focus areas: SDOT (Community Stress Model)

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Abstract

Oriented multiple-arm caliper logs from drill holes in the Los Angeles basin were interpreted for principal horizontal stress directions by using borehole breakouts from near-vertical sections of hole. The well logs were obtained from various providers including oil companies, service companies, and oil field operators. The borehole breakouts are identified as elliptical zones seen in the caliper data, where tool rotation stops and the minimum caliper diameter is equal to the drilled diameter, following criteria updated from those of similar studies. We can evaluate variations in the stress field both horizontally and vertically, and compare these to stress directions inferred from earthquake focal mechanisms. For the Inglewood Oil Field, currently our densest data set, we find evidence for variation of the direction of S_H (greatest horizontal principal stress) over horizontal distances less than 1 km at depths from 2-3 km. This variation is over a smaller scale than what is envisioned for the current community stress field models. Yet, the S_H direction appears to be consistent within individual blocks where these are closest to the fault. We relate these variations to stress changes caused by the active Newport-Inglewood fault and possibly other faults active within the fault-cored anticline. These observations in general provide a useful tool for comparison with the larger scale stress field models.

Technical Report

The Community Stress Model (CSM), a project within SCEC's Stress and Deformation over Time (SDOT), is developing spatio-temporal (4D) representations of the stress tensor in southern California lithosphere. This information is needed for seismic hazard estimates, earthquake studies, dynamic earthquake rupture models and earthquake simulation. The CSM currently has two types of models submitted: 1) stress models, often based on focal mechanism inversions, and 2) strain rate models, typically based on geodetically constrained fault system models. CSM still needs observational constraints (e.g. from borehole or anisotropy measurements). Our study provides direct observational constraints from borehole data, in situations where cylindrical boreholes have developed borehole breakouts, and these have been measured with oriented borehole diameter tools (Figures 1 & 2). Such tools are commonly run as part of oil field well logs; the main problem usually is getting access to them.

For vertical drill holes, if one principal stress is assumed to be vertical (S_v), the other two principal stresses (S_h and S_H) lie in the plane perpendicular to the borehole axis. Depending on how the hole is drilled, and the magnitudes of the principal stresses, breakouts may or may not form in a hole. These breakouts represent damage to the borehole wall and make other borehole activities more difficult, so normally drilling operations try to minimize their formation. If breakouts do form, they form at the location of maximum compressive stress around the borehole wall, which corresponds to the direction of S_h in the region around the borehole. Thus, a measurement of the borehole elongation direction corresponds to the S_h direction, and the direction perpendicular to this would be the S_H direction.

Data sets obtained

We contacted the State of California Division of Oil, Gas and Geothermal Resources (DOGGR) to request their borehole data sets that could be used to evaluate the directions of the horizontal principal stresses. In particular we were interested analyzing borehole breakouts from oriented 4-, 6-, and 8-arm caliper logs, or Formation Microimager/Microscanner (FMI or FMS) logs. We concentrated on requesting data from boreholes in the Los Angeles Basin based on the recommendations given when our SCEC proposal was funded. We requested data from segments of wells deeper than 1 km in order to obtain constraints closer to the depths of earthquakes.

The DOGGR digital files are not yet publicly available, due to an ongoing transition from paper to digital archives, and many of the files for the most recent drill holes have not yet been submitted to DOGGR. DOGGR referred us to oil companies, service companies, and well operators to obtain the data from individual wells. Through contact with these operators, and in accordance with confidentiality agreements, we have obtained well logs in digital format, including 4-arm oriented caliper, 6-arm oriented caliper, and equivalent data. The logs are not in consistent formats, even when from the same source, so individual files required different amounts of reformatting before they were suitable for analysis. More data are still coming in. Some of these data are from more highly deviated wells, which will be analyzed using other methods than those used for the vertical wells described below.

Data analysis.

The multiple-arm oriented caliper logs were processed to identify borehole elongations that might indicate breakouts. To be interpreted directly for maximum principal stress (S_h and S_H) directions, we are currently using the following criteria (e.g., Figure 2 and 3):

1) Tool rotation stops in the zone of elongation

2) At least one of the caliper diameters corresponds to the drilled bit size
3) None of the caliper diameters are smaller than the drilled bit size
4) Minimum caliper difference >= 0.8 cm
5) Maximum caliper difference >= 2.5 cm
6) total sum of the difference in azimuth over 3 m <= 10 degrees
7) borehole deviation from vertical <5 degrees

These criteria were modified from those used by Zajac and Stock (1997) and Reinecker et al (2003) to account for the specific logging tools that had been used, which in some cases had slightly different geometry than the logging tools used in the previous studies. Criteria (4) and (5) were tested with other, slightly different, values that made very little difference in our results. Additionally, because most of the well data we received this year came from vertical drill holes, we have not implemented the full stress tensor inversions that are possible with data from highly deviated drill holes (e.g., Zajac and Stock, 1997; Mastin, 1988).

If the above criteria were met, breakouts were identified, and directions of S_H were calculated. Matlab programs and modules to make these analyses and plot some results were written by Persaud and Smith, and shell scripts for further statistical analysis and plotting were written by Stock.

Major results

In presenting these results we focus on the Newport-Inglewood Oil Field because this is the densest data set we have obtained thus far and the one we have looked at most closely. The other wells obtained are from other oil fields in the LA area but are in smaller data sets that are still being analyzed.

The Newport-Inglewood field lies within an active anticlinal flower structure along the Newport-Inglewood fault in Baldwin Hills (Figure 4). The Newport-Inglewood fault is generally vertical although locally its surface trace may dip slightly E or W in the upper km (Elliott, 2009). The flower structure is complex with branching fault traces intersecting the main fault trace at various depths, some deeper than 3 km. The oil field had more than 1400 wells in it as of 2005 (Figure 5). New wells have been drilled since then, because 3D seismic surveys showed petroleum resources at depths that had not previously been exploited (Lockman, 2005). Drilling is continuing as of 2015 with plans to exploit advanced recovery methods for the petroleum resources. We obtained partial or complete coverage of oriented caliper logs on 24 of these new wells (Figure 6) in a very small region (< 3 km on a side) at depths down to 3000 meters. This provides us an unparalleled opportunity to evaluate how rapidly the stress field may be changing spatially near this active fault system.

Of these 24 wells, seven of them west of the major fault zone did not show any useful breakouts. Other wells on the west side of the major fault zone showed either widely varying breakout directions, or very few breakout directions. However, four of the wells closest to the western active fault trace, on the west side (wells, 4, 5, 6 and 17 on Figure 6) showed numerous breakouts at relatively consistent orientations. These yield S_H directions from 11° to 35° E of North. This is in good agreement with compression directions reported for this general area by

Hauksson (1987) in his study of earthquake focal mechanisms along the Newport-Inglewood fault.

Interestingly enough, for the block just to the east within the flower structure, two drill holes (#1 and #2) suggest that the compression direction is E-W, considerably different from what was generally seen west of the fault. Our preliminary hypothesis is that, in fact, the stress field does change over a very short distance across this active fault system, similar to what has been inferred on a large scale for other active fault systems from seismicity patterns (Yang and Hauksson, 2013) or seen in other data sets of drill holes near active faults. We are still awaiting additional data which we have been promised, but not yet received, for hole #2, which would help to establish whether this E-W compression direction is characteristic of the block E of the fault, or whether the NNE compression direction is locally persistent on either side of the active fault in the region of the other drill holes.

Intellectual Merit

These results provide measurements of the direction of principal horizontal stress S_H in additional areas of Los Angeles basin for which constraints had not yet been directly obtained from boreholes. High density observations in one oil field indicate small scale spatial variations in stress directions similar to those that have been postulated in some theoretical studies. The rapid spatial changes of stress direction across active faults will be important to further quantify for evaluating earthquake ruptures in regions of complicated geological structures such as flower structures and multi-stranded fault zones.

Broader impacts

This project is a collaboration among three female Ph.D.-level researchers, one of whom (Persaud) is a member of a racially underrepresented group. Our interactions with the database managers at the California Division of Oil, Gas and Geothermal Resources have helped them to understand what forms of digital data and metadata are needed in the data base for scientific use. This should have a long-term effect of making the data base eventually more useful not just for us but for other researchers.

Presentations of the results

We have not yet presented these results at any meetings, because most of our data were obtained last fall after the meeting deadlines, and more data are still coming in. We will present results at the 2015 SCEC conference.

References

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Plumb, R., and S. Hickman, "Stress-induced borehole elongation: A comparison between the four-arm dipmeter and the borehole televiewer in the Auburn geothermal well," Journal of Geophysical Research: Solid Earth, vol. 90, pp. 5513-5521, 1985.

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WELL	X (Survey feet)	Y (Survey feet)
1	1450000	548000
2	1452000	550000
3	1456000	548000
4	1449000	550000
5	4247000	4018000
6	4247000	4018000
7	4248000	4015000
8	4240000	4020000
9	4240000	4018000
10	4235000	4021000
11	4236000	4022000
12	4217000	4027000
13	4217000	4028000
14	4223000	4023000
15	4217000	4028000

WELL	Latitude	Longitude
1	34	-118.3

WELL	X (Easting)	Y (Northing)
1	4175000	4117000
2	4175000	4115000
3	4177000	4113000
4	4175000	4115000
5	4175000	4114000
6	4175000	4113000
7	4180000	4111000
8	4173000	4116000
9	4173000	4115000
10	4172000	4116000
11	4172000	4116000
12	4173000	4116000
13	4174000	4115000
14	4175000	4113000
15	4174000	4115000
16	4172000	4114000
17	4174000	4114000
18	4174000	4114000
19	4173000	4115000
20	4173000	4114000
21	4172000	4116000
22	4172000	4115000
23	4172000	4115000
24	4172000	4117000

Table 1. Examples of well locations for which data have been provided. Locations have been rounded by us to the nearest km for the purpose of this report. More data is coming in, not shown here. For example we received data for 4 more wells on 3/14/15.

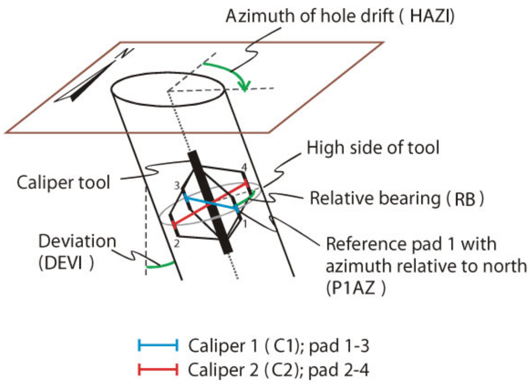


Figure 1.

This figure from Plumb and Hickman [1985] shows the four-arm caliper geometry in the borehole. C1 represents the diameter between pads #1 and #3 and C2 represents the diameter between pads #2 and #4.

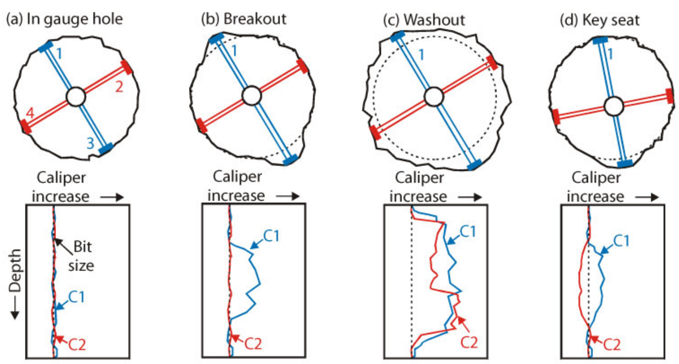


Figure 2.

This figure from Reinecker et. al after Plumb and Hickman [1985] shows how the caliper responds to different types of borehole enlargements and how to distinguish a borehole breakout from others.

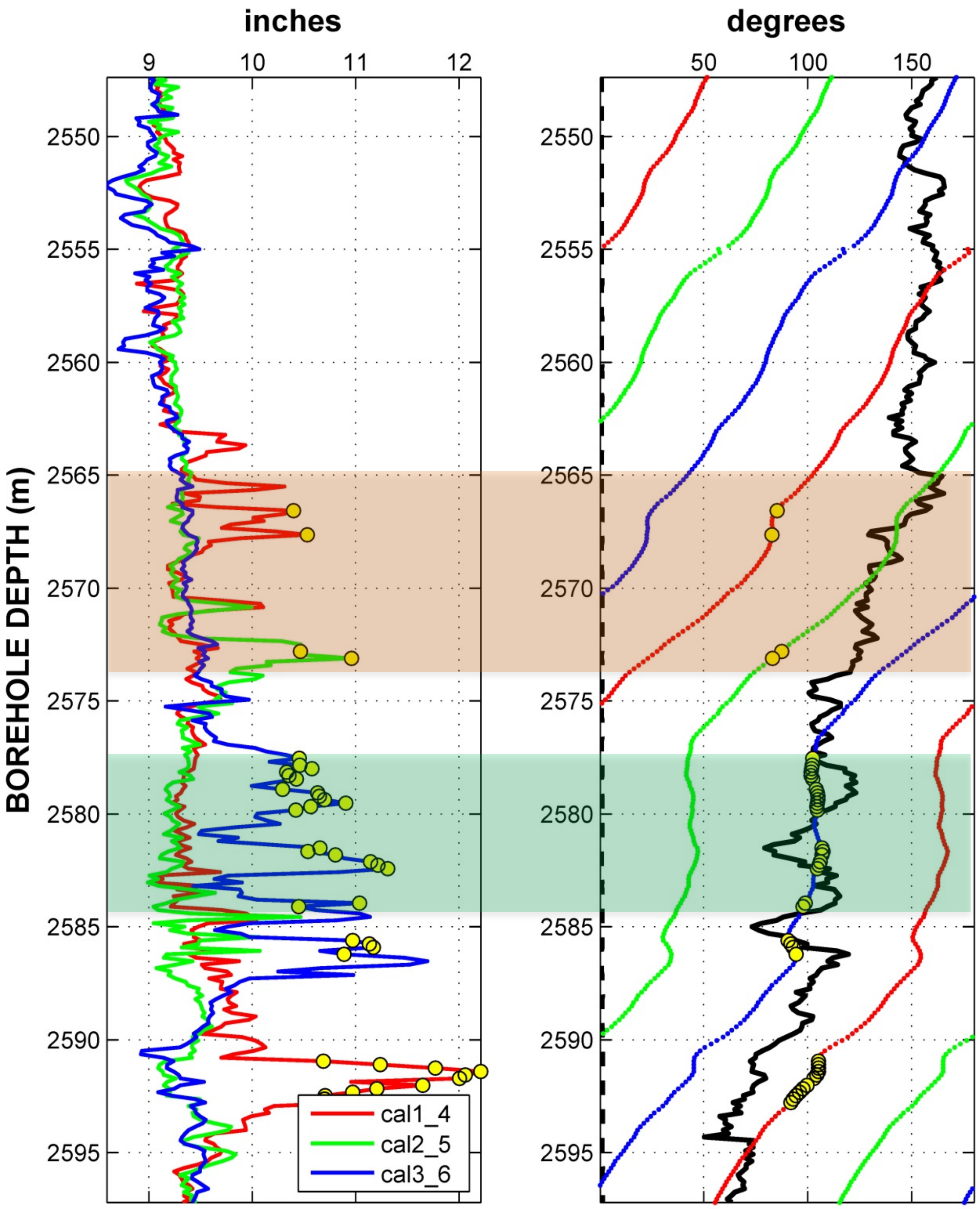


Figure 3. Example of caliper log information, from a section of a drill hole in this study, showing identified breakouts. Left panel: caliper diameters from 3 pairs of arms mounted at 60° spacing (1=red, 2=green, 3=blue). Right panel: azimuth of Pads 1, 2 and 3 using same color scheme. Yellow dots indicate possible breakouts. Identifications in orange zone (2565-2574 m) are not considered to be breakouts because difference in pad azimuth over 5 m is > 10°. Identifications in green zone are considered to be breakouts because tool rotation stopped and pad azimuth is constant over a longer interval.

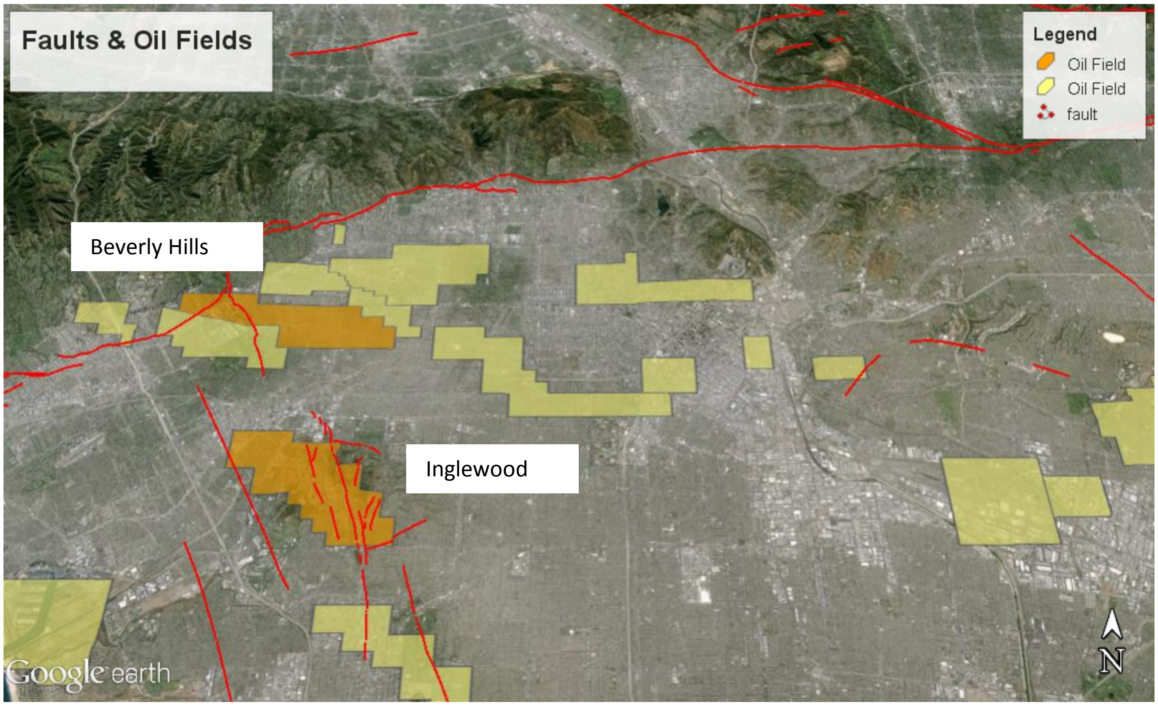
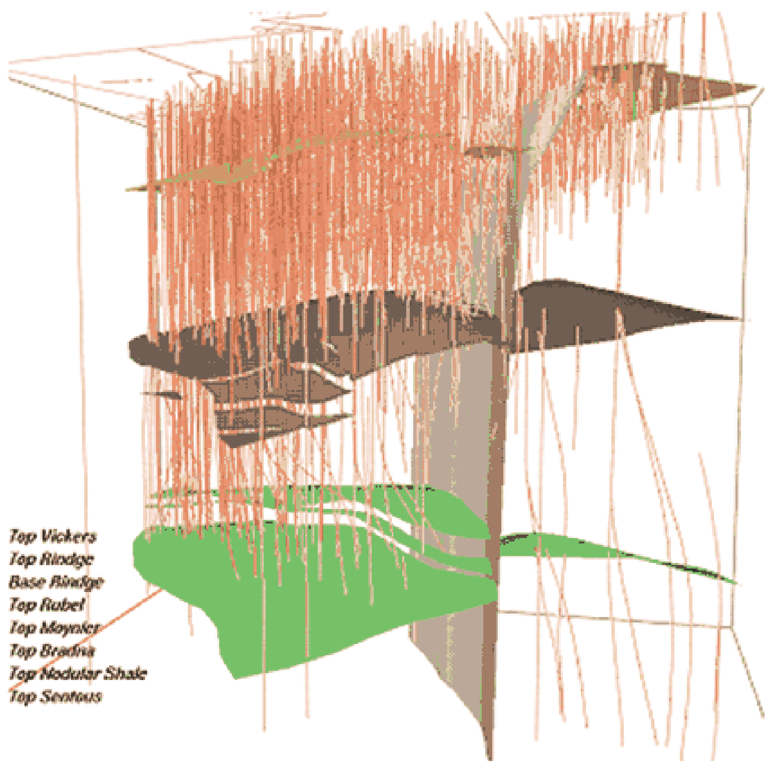


Figure 4 (above). Oil fields in the western Los Angeles Basin. Red lines = Quaternary faults from the State of California 2010 fault map. Beverly Hills and Inglewood oil fields shown in orange. Inglewood field lies along the Newport-Inglewood fault zone.

Figure 5 (right). Three-dimensional model, looking NNW, with orange lines showing the trajectories of many of the > 1400 wells that exist in the Inglewood field (Lockman, 2005) with newer ones reaching down to ~3 km depth. Vertical Newport-Inglewood fault zone (light gray) cuts black horizon (top Lower Pliocene, depth < 1500 m), and green horizon (top middle Miocene, depth ~ 3 km). Gaps indicate where these horizons are interrupted by other thrust faults.



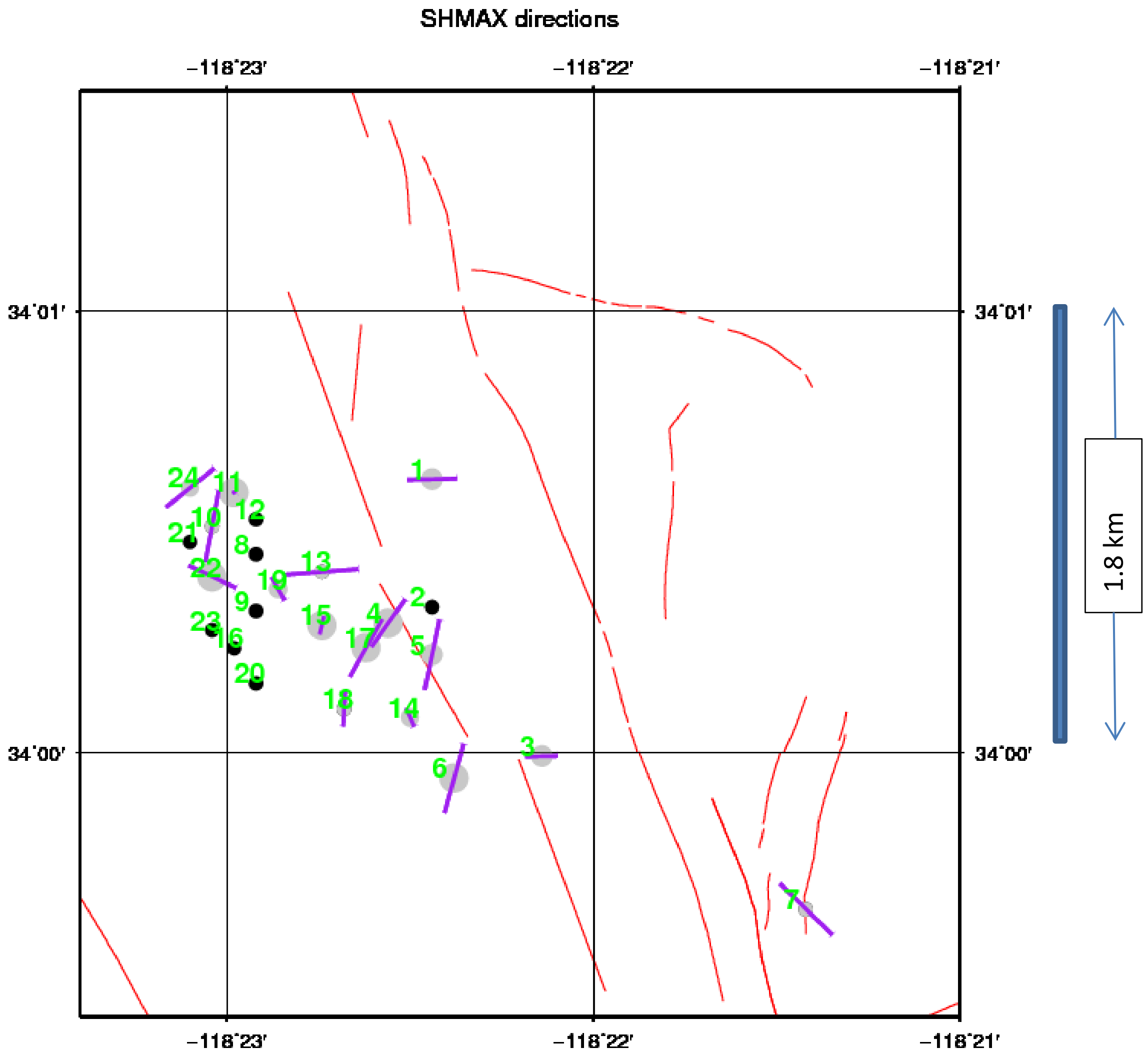


Figure 6. Stress variability in the Inglewood Oil Field (see Figure 4 for location). Map shows the Newport-Inglewood fault system (red lines from California State Fault Map, 2010), with locations of 24 drill holes (green numbers) with data provided by one operator. S_H (maximum horizontal stress) directions (purple) were determined from breakouts measured between 2000 and 3000 meters depth in drill holes. Black dots: drill holes with few or no breakouts. Gray dots: drill holes with breakouts. Dots are sized according to total length of breakouts seen in the drill hole. Largest to smallest gray dots: > 17 meters of breakouts, 8-16 m of breakouts, 2-7 m of breakouts, or less than 2 m of breakouts. Length of purple line reflects the consistency of the breakout azimuth in the drill hole, with longer purple lines representing tightly clustered breakout azimuths and shorter purple lines reflecting more scattered breakout azimuths in the drill hole. Wells 4, 17, 6, and 5 show S_H azimuths of 35°, 29°, 15°, and 11°, respectively, suggesting that the stress field close to the active fault has a NNE direction of S_H but with some degrees of variation over a small scale. The narrow block within the flower structure appears to be characterized by E-W compression in holes 1 and 3. We are still awaiting additional data from hole 2 to determine if its SH direction is NNE like the other holes nearby, or E-W like holes 1 and 3 within the central block of the flower structure.