# Borehole-derived Constraints on the SCEC Community Stress Model

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## A. Background:

Borehole observations can provide direct measurements of stress directions in the crust. If differential stress conditions and drilling mud pressures are suitable, there may be two types of induced structures directly related to the stress tensor: drilling induced tensile fractures (DITFs) and borehole breakouts. Borehole breakouts are caused by compressive failure processes at the borehole wall if the hoop stress exceeds the compressive strength of the rock (Bell and Gough, 1979). If the hole is near vertical and one of the principal stresses is vertical, the DITFs form at the azimuth of the maximum horizontal stress, $S_H$ (or $S_{Hmax}$) and the borehole breakouts form at the azimuth of the minimum horizontal principal stress, $S_h$ (or $S_{hmin}$), elongating the hole diameter in that direction. If the borehole is deviated, and/or if no principal stress is vertical, the interpretation of stress orientations relative to the borehole elongations becomes more complicated, but can still be determined if enough data exist (e.g., Mastin, 1988; Zajac & Stock, 1997). Off-center petal-centerline cracks may also form parallel to the $S_H$ direction. Other borehole features such as key seats or tool drag marks are unrelated to the stress field.

We use oriented 4-arm, 6-arm, or 8-arm caliper data or dipmeter data, which measures the borehole diameter in 2, 3, or 4 directions, and Formation Micro Scanner (FMS) logs/Formation Micro Imager logs/acoustic image logs that measure the shape of the borehole. The caliper data can detect borehole breakouts, whereas the FMS logs and image logs can detect additional modes of failure including sometimes DITFs.

## B. Previous Studies and SCEC projects (14118, 15012, 16062)

Seismicity provides key constraints for the principal stress directions and relative magnitudes in southern California (e.g., Yang and Hauksson, 2013). These results are by necessity averaged over some seismogenic volume but can be complemented at shallower depth and finer spatial resolution with drill hole data. Stress orientations from well log data in Southern California include the compilation in the World Stress Map 2008 (Heidbach, et al., 2010), as well as newer data (Blake and Davatzes, 2011, 2012; Blake, 2013; Day-Lewis et al., 2010), or data that were not included, or for which only summaries were given, in the World Stress Map (e.g., Zajac & Stock, 1997; Wilde & Stock, 1997). Our 1997 project, funded by SCEC and NEHRP, used elongation directions in all logs available in the Division of Oil and Gas (DOG) public data base (71 wells) to constrain directions of $S_H$ for areas including Santa Barbara, Ojai, Central/East Ventura Basin, and West/East Los Angeles Basin. Observations in both vertical and deviated boreholes constrained the relative magnitudes of the principal stresses. Stress orientations were broadly consistent with focal mechanism studies available at the time, but also showed strong heterogeneity (*http://www.data.scec.org/stress*). In 2014-16 we received SCEC funding to obtain additional constraints on SH directions using borehole data from the past 15 years. We have concentrated on L. A. and Ventura counties, including the Newport-Inglewood fault and offshore Santa Barbara Channel. We get well logs directly from logging companies, well operators, or energy companies, subject to their requests for confidentiality. We have analyzed a total of 88 wells (36 from the Long Beach oil field, 24 from Inglewood, 24 from Wilmington, and 4 from Huntington Beach). We also obtained well data from 10 wells at the Gail platform (Fig. 5), and 11 wells at the Holly platform. Bureau of Safety and Environmental Enforcement (BSEE) also provided us with 232 digital well log files from the Santa Ynez Unit (Fig. 5) and the expired Gato Canyon lease block. The California Division of Oil, Gas and Geothermal Resources (DOGGR) provided us with thousands of digital well files from the Cymric, McKittrick and Midway-Sunset oil fields in Kern County.

Our results highlight the possibility of stress variations at length-scales less than 1 km (Persaud et al., 2015a, 2015b). The short-length-scale variations in SH directions are attributed to the proximity to faults or fault segmentation, and indicate the likely complexity that is expected in stress fields near active faults.

### 1. Inglewood

In the Inglewood oil field, we have a dense dataset of 24 wells with 6-arm caliper logs, located in a ~2 $km^2$ area, in the western flank of a NW-trending anticline (Fig. 1). The wellbores cover a depth range of 1-3 km with large sections deviated less than 5° from the vertical. The overall $S_H$ direction is N25°E (Fig. 1) with notable lateral variations found in the dataset. $S_H$ varies from N9°E (Well 5) to N32°E (Well 4) within 400 m of the fault in the western fault block, with more variability occurring in wells father away. In contrast, $S_H$ is oriented E-W in the eastern fault block based on constraints from two wells (Wells 1 and 3 in Fig. 1).

### 2. Wilmington and Huntington Beach

The Wilmington and Huntington Beach fields are both located between the Newport-Inglewood Fault and the Thums-Huntington Beach Fault in anticlinal structures (Fig. 2). The Wilmington dataset is comprised of 11 wells with deviated 4-arm caliper logs, and the Huntington Beach dataset consists of 4 wells with 8-arm logs. Comparison of elongation directions (breakout heights ≥3 m) for Wilmington with theoretical breakout patterns shows a reverse faulting stress regime (Fig. 3) although the radial pattern should be interpreted with caution. Interestingly, the Huntington Beach wells located ~12 km to the southeast indicate a transitional strike-slip/reverse stress regime (Fig. 2), with $S_H > S_v = S_h$ for Wells 25 & 26, and $S_H = S_v > S_h$ for Wells 27 and 28.

### 3. Long Beach

The Long Beach oil field is located in a narrow faulted anticline that trends parallel to the NIF-Cherry Hill Fault (Fig. 4). Extensional faults (black lines in Fig. 4) mark the crest of the anticline, which is overthrusted from the southeast along the compressional Pickler Fault (Wright, 1991). The NIF-Cherry Hill Fault is near-vertical down to 1.1-1.5 km, and at deeper depths may dip as much as 60° (Wright, 1991). Our dataset of 36 wells with mainly 4-arm caliper logs reaches maximum borehole depths of 4.2 km. $S_H$ directions show a dominant N-S orientation for all wells in the dataset. This is in part due to the large number of breakouts present for Well 75, which has a consistent near northerly orientation at all depths even in the shallow sections of the well. However, significant spatial variations in $S_H$ orientation are noted in the dataset at sub-kilometer length-scales, e.g., $S_H$ varies from N9°W (Well 75) to N22°W (Well 65) in two wells that are located at roughly the same distance from the Newport-Inglewood Fault, but in different areas of the anticline. Both of these wells have over 525 breakout samples (equivalent to 20 m of breakout length).

## 4. Offshore Ventura (Santa Barbara Basin).

The Santa Barbara petroleum Basin (SBB) is the westward continuation of the largely onshore Ventura petroleum basin. The oil fields in the SBB are related to a series of E-W striking active thrust faults and associated folds (Fig. 5). Because of the offshore location of the SBB drilling platforms, recent exploration involves numerous directionally drilled wells which, jointly evaluated, provide excellent constraints on the complete stress tensor (e.g., Zajac and Stock, 1997). Analyses of these data sets is in progress by Dr. Patricia Persaud's master's student at LSU.

## C. Conclusions

We observe considerable variations in $S_H$ directions possibly related to variations of the stress field with depth, fault segmentation, and changes in fault geometry with depth. This is consistent with previous studies. Wilde & Stock (1997) reported a range of N0°E – N59°W, and Chavez (2015) reported N40°W to N40°E for Long Beach. In Inglewood, a NNW-striking thrust fault dominates the structure at depth (Elliot et al., 2009). This is confirmed by our NE $S_H$ orientations for most wells south of the thrust fault, which are oriented sub-perpendicular to the thrust fault. In Long Beach, substantial $S_H$ variation indicates a more variable shallow structure influenced by overthrusting at the Pickler Fault, and merging of faults in the top 1 km. Large $S_H$ variations in the northern flank of the anticline appear to be related to the N-NW-striking faults that merge with the Newport-Inglewood fault. Such variations will need to be taken into account in assessments of the conditions needed for rupture propagation from segment to segment along this fault zone (e.g., Sahakian et al., 2017). A relative increase in $S_H$ is observed for Wells 25 & 26 compared to 27 & 28 in Huntington Beach.

## D. Acknowledgments

We thank the oil companies and oil field operators including Signal Hill Petroleum, Inc., for generously providing the well data needed to complete this research, and for sharing information on the specific logging tools. We thank the State of California Division of Oil, Gas & Geothermal Resources for their efforts to identify wells with oriented caliper logs. This research was supported by SCEC awards 14118, 15012 and 16062.

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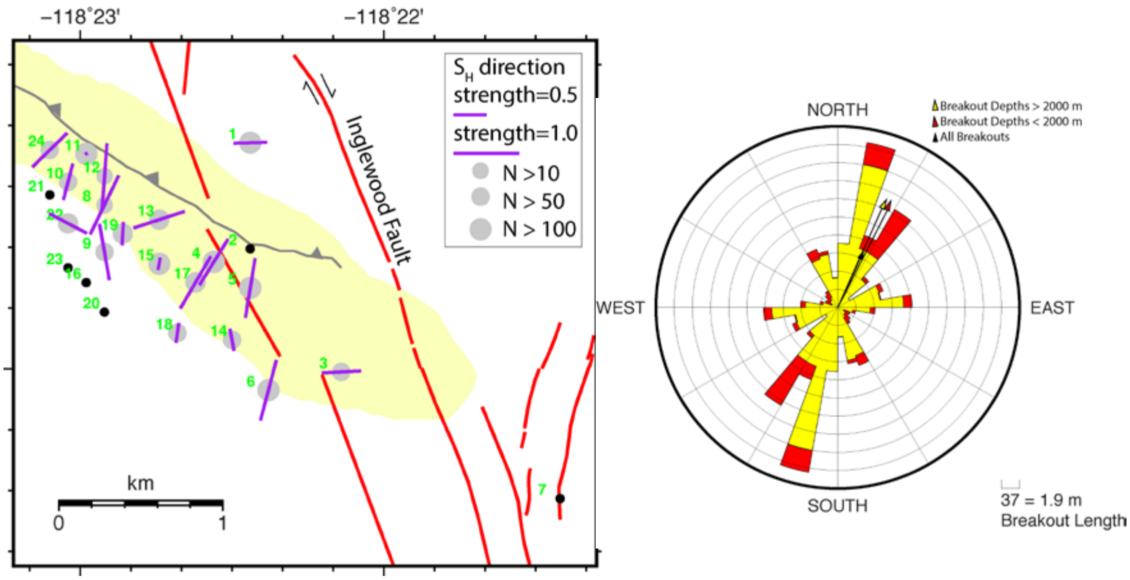



**Figure 1.** Left: *Map with Inglewood well locations. Purple lines representing mean SH orientations are scaled with the strength of the breakout (mean resultant length) based on the method of Mardia and Jupp (2000). The yellow-shaded area represents the outline of the anticline based on depths to the top of the Middle Miocene Sentous formation that are shallower than 8000 ft (2438 m) from Elliott et al. (2009). The gray thrust fault after Elliott et al. (2009) appears to be a deeper structure. Sizes of the gray circles indicate the number of breakout samples for each well (20 = 3 m). Right: Polar histogram showing SH orientations for all Inglewood wells. Breakouts at depths greater than 2000 m, and less than 2000 m are shaded yellow and red respectively.*

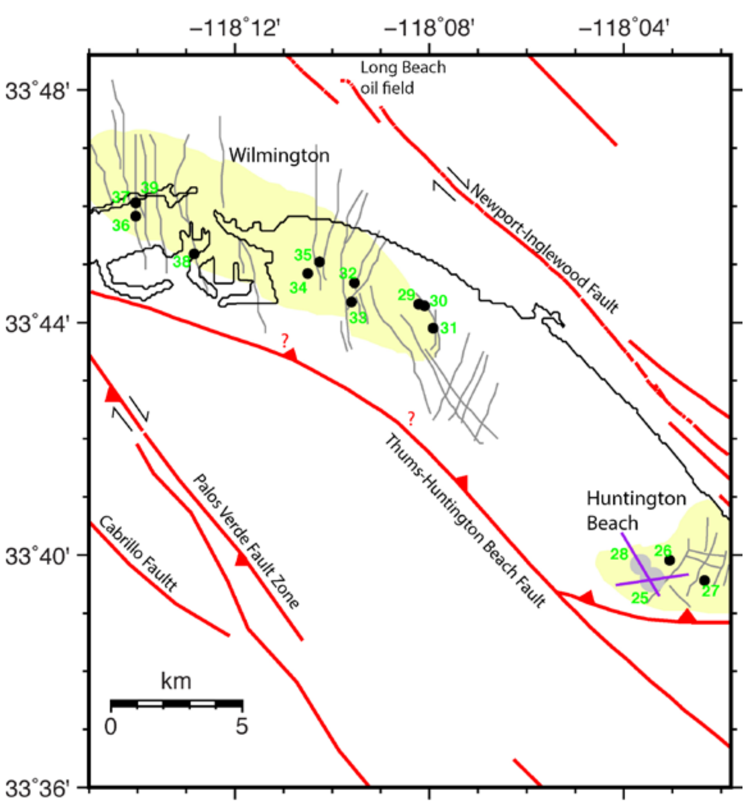
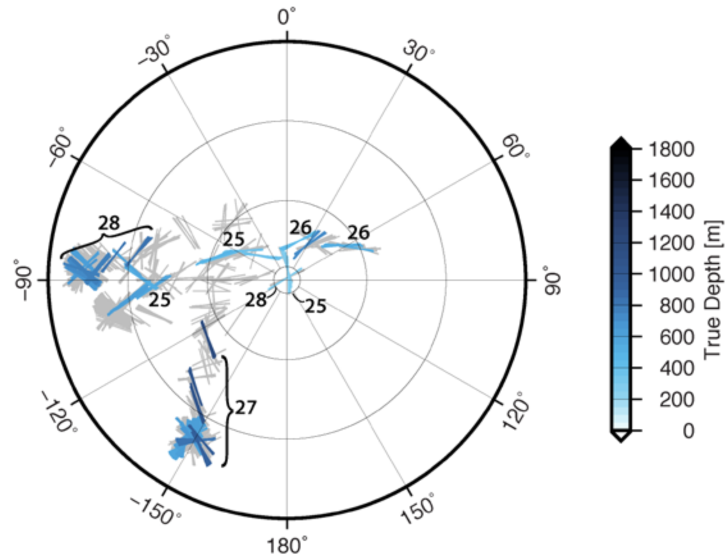



**Figure 2.**

*Bottom hole well locations and SH orientations for the sections of the wellbore deviated by less than 5° are shown. Other elongations are shown in Fig. 3. Wilming ton had no undeviated sections. The yellow shaded re gions are depths to the top of the middle Mohnian shale lower than 4000 ft, and to the top of the lower Pliocene horizon shallower than 3000 ft for Huntington Beach and Wilming-ton respectively based on Wright (1991). Gray faults are mainly normal faults after Wright (1991).*



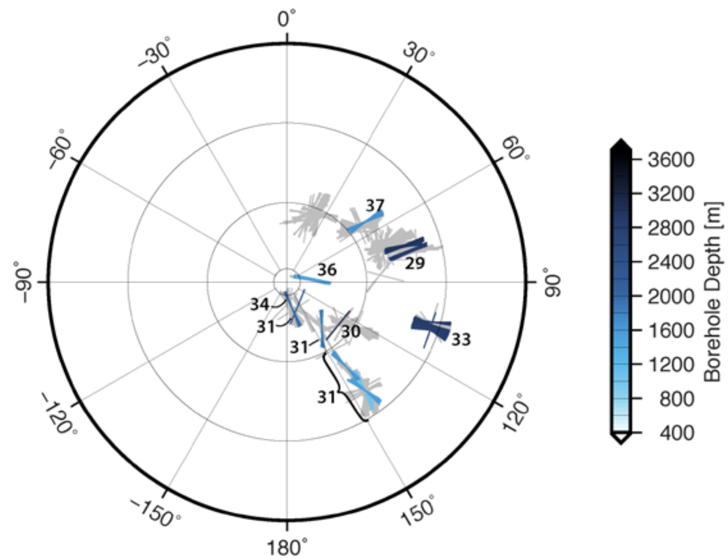




**Figure 3** *Top: Huntington Beach breakouts larger than 3 m, color-coded by true depth. The breakout position corresponds to the borehole trend and plunge. B Wilmington breakouts larger than 3 m, color-coded by borehole depth. All breakouts are colored gray. Well locations are shown in Fig. 2.*

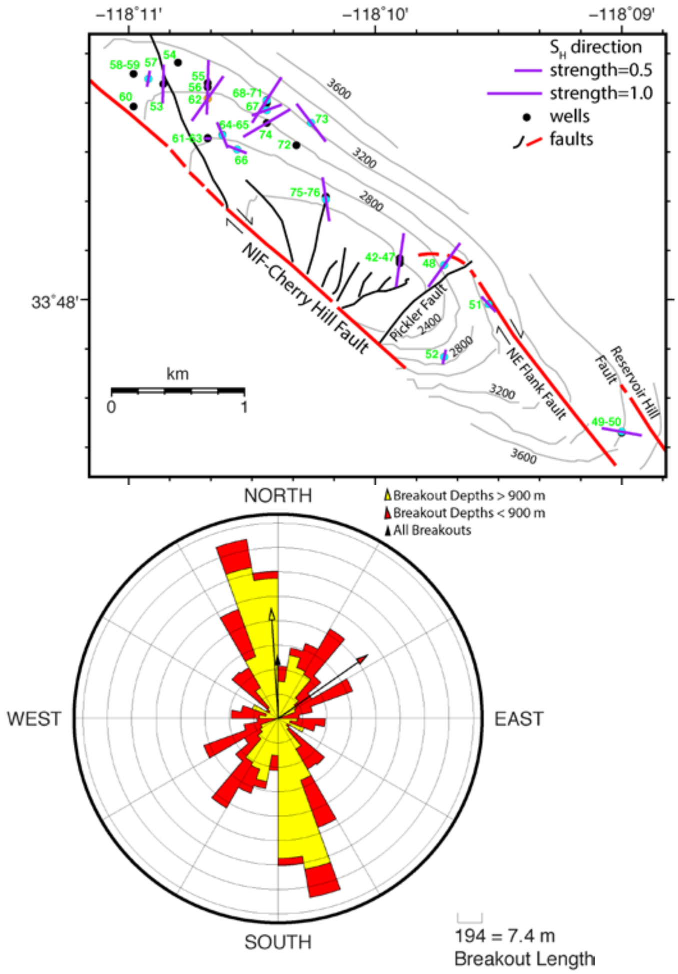



**Figure 4**. *Top: $S_H$ orientations in the Long Beach oil field. Data for some wells are not shown to avoid overlap. Orange and blue circles mark wells with greater than 3 m and 5 m total breakout length respectively. Gray contours at 200-ft interval are modified from Chavez (2015) and represent the top of the Alamitos zone. Black faults are modified from Chavez (2015) and Wright (1991). Map symbols as in Figure 1 except well symbols are not keyed to number of observations; black lines are other faults known from more detailed studies (see Persaud et al., 2015a, 2015b). Gray lines: structure contours. Bottom: Rose diagram of $S_H$ directions. Red = all measurements. Yellow = measurements from depths > 900 m.*

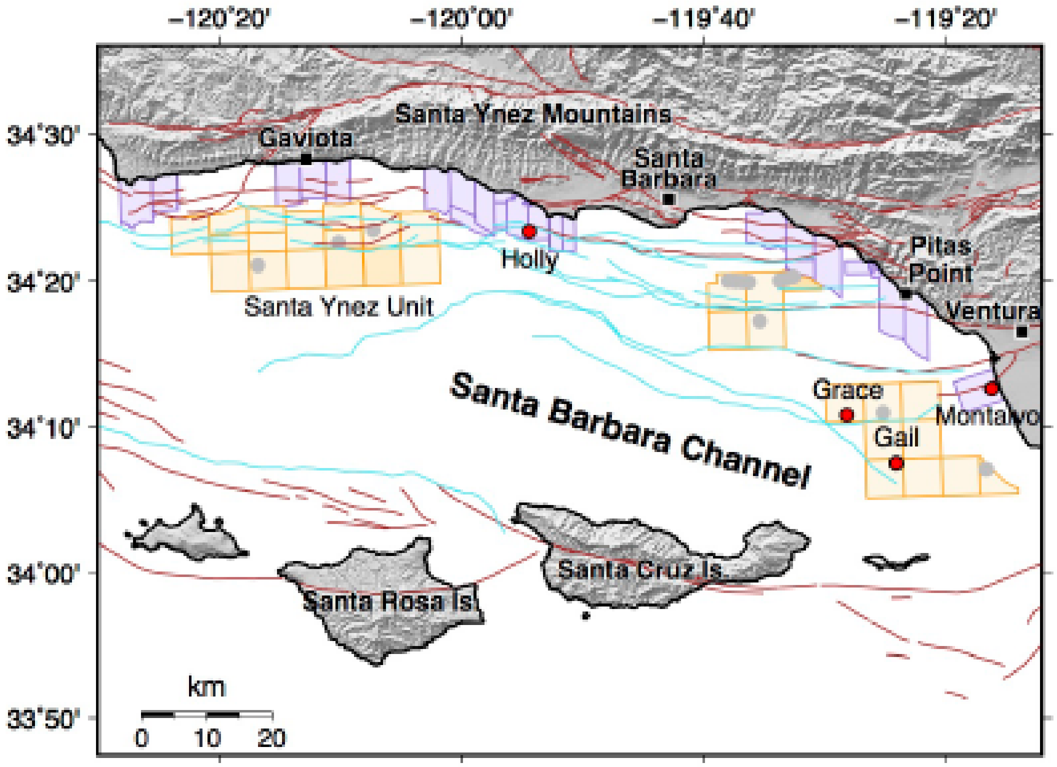



Figure 5. Map of the Santa Barbara Channel region showing oil platforms (red dots) included in our study. Faults are from Sorlien & Nicholson (2015) and Sorlien et al. (2016) (blue) and the 2010 CA Fault Activity Map (brown). Colored blocks are oil fields overseen by DOGGR (purple) and BSEE (yellow).