Using Borehole Data as a Direct Measure of Stress Directions and Variability to Help Constrain the SCEC Crustal Stress Model for Southern California

Report for SCEC Award #15012
Submitted March 14, 2016

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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

We determined principal stress directions (S_H and S_h) in the LA basin, using borehole breakouts obtained from well logs in the onshore Long Beach, and Inglewood, and the offshore Wilmington and Huntington Beach oil fields down to depths of 3 km. In Inglewood, NE S_H orientations occur in most wells south of a NW-striking thrust fault, which are oriented sub-perpendicular to the thrust fault rather than at a consistent angle to the Newport-Inglewood Fault (NIF) zone. An E-W S_H direction in two wells likely reflects the stress state of the flower structure in the graben just west of the Inglewood fault. In Long Beach, substantial lateral variation of S_H at depths less than 900 m indicates a more variable shallow structure influenced by overthrusting across the Pickler Fault, and merging of the NE Flank Fault and Cherry Hill faults in the topmost 1 km. The large variations in S_H in the northern flank of the anticline appear to be related to the N-NW-striking faults that merge with the NIF-Cherry Hill Fault near the anticlinal crest. Relative changes in the principal stress magnitudes are observed in Huntington Beach. The observed short-length-scale variations in S_H direction are attributed to the proximity to faults, fault segmentation, or fault overlap. They indicate the likely complexity that may be found in stress fields near other active faults.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Stress and Deformation Through Time (SDOT)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 1.
Caption: Left: *Map with Inglewood well locations. Purple lines representing mean S_H 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 S_H orientations for all Inglewood wells. Breakouts at depths greater than 2000 m, and less than 2000 m are shaded yellow and red respectively.*
Credits*: Figure produced by Patricia Persaud.*

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

2d. Development of a Community Stress Model (CSM) for Southern California

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

As far as we know, we are the only group working with borehole breakout data to constrain the SCEC Community Stress Model. This provides a useful complement to the various scales of models being derived from seismicity and geodynamics. We are working with new types of well logs and have updated the methods needed to analyze these.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

As a result of this study we have made contact with other researchers who have access to offshore Santa Barbara data sets. These data sets will be analyzed in our future work. We have established partnerships with more oil field operators and service providers who are learning about what SCEC does, and the importance of their data to the SCEC CSM efforts. We are broadening the participation of underrepresented groups with the involvement of Dr. Patricia Persaud, who is an ethnic minority female scientist.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

See SCEC publications data base #6066 and #6218.

II. Technical Report

Using Borehole Data as a Direct Measure of Stress Directions and Variability to Help Constrain the SCEC Crustal Stress Model for Southern California

Report for SCEC Award #15012
March 15, 2016

Investigators: Joann Stock[1], Patricia Persaud[1,2] and Deborah E. Smith[3]

1 – California Institute of Technology, Pasadena CA
2 – California Polytechnic University, Pomona CA
3 – United States Geological Survey, Menlo Park CA

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 have been using 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 measure borehole breakouts, whereas the FMS logs and image logs can detect a greater variety of failure including sometimes DITFs.

B. Previous Studies and SCEC projects (14118 and 15012)

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 and 2015 we received SCEC funding to obtain additional constraints on the stress directions using borehole data from drilling in the past 15 years. We get well logs directly from logging companies, well operators, or energy companies, subject to their requests for confidentiality. We have focused on requesting the deepest data available, at depths below 2 km, concentrating on Los Angeles and Ventura counties. Short spatial scale variations in S_H are apparent with this high density of observations, as well as changes along strike of faults at a larger scale (e.g., Persaud et al., 2015a, 2015b).

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).

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. 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 and 15012.

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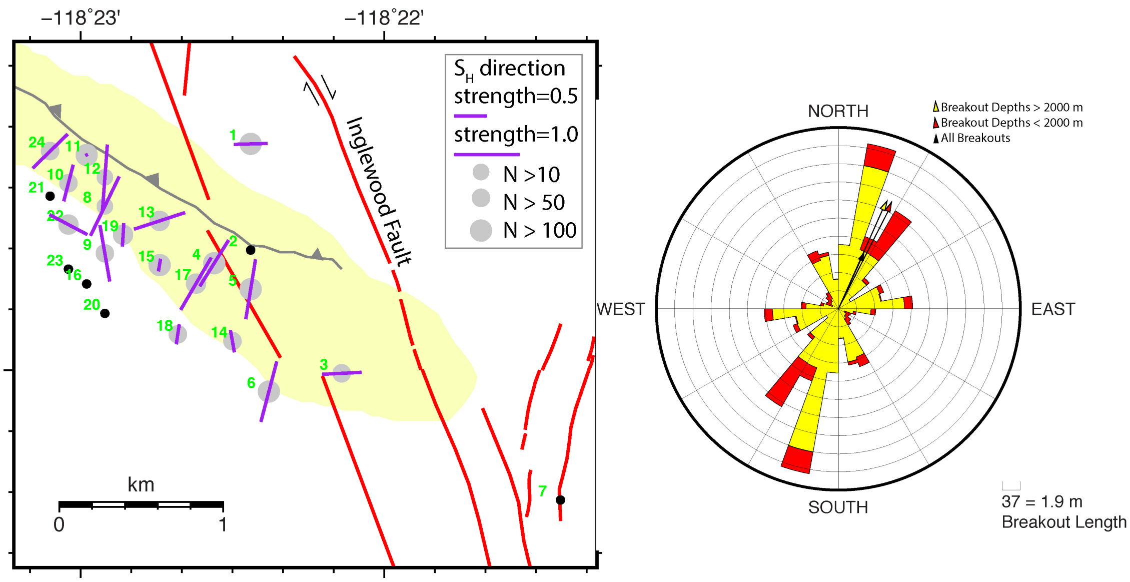


Figure 1. Left: *Map with Inglewood well locations. Purple lines representing mean SH orientations are scaled with the strength of the breakout (mean resultant length) based on the method of Mardia and Jupp (2000). The yellow-shaded area represents the outline of the anticline based on depths to the 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.*

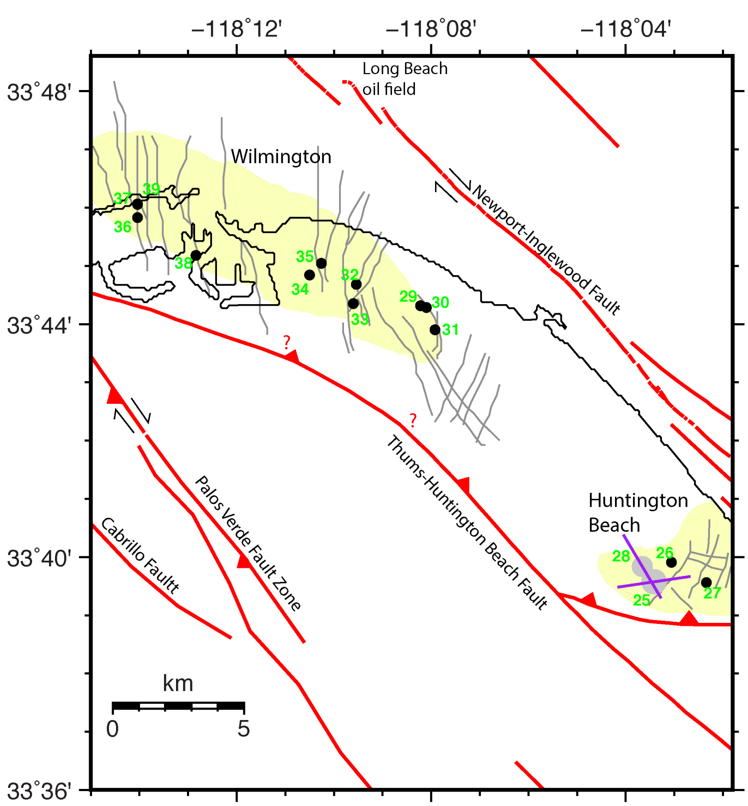
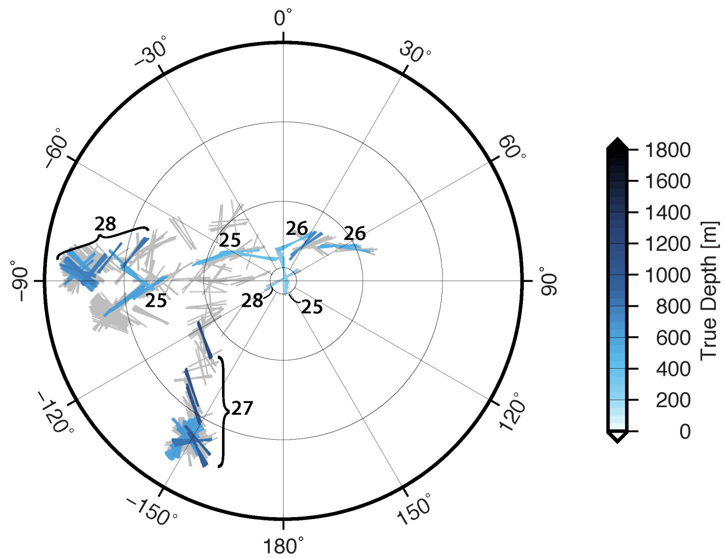


Figure 2.

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).



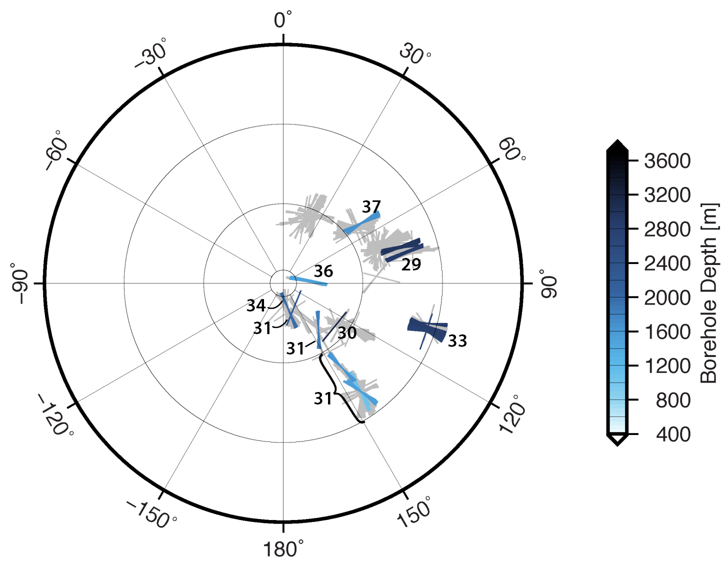


Figure 3 *Top: Huntington Beach breakouts larger than 3 m, color-coded by true depth. The breakout position corresponds to the borehole trend and plunge. B Wilmington breakouts larger than 3 m, color-coded by borehole depth. All breakouts are colored gray. Well locations are shown in Fig. 2.*

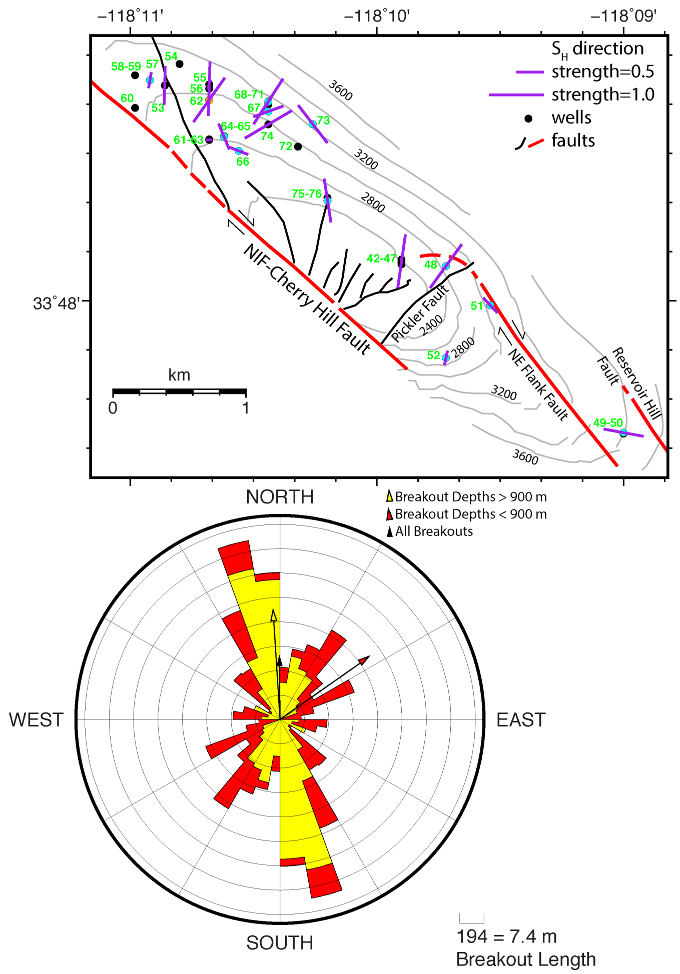


Figure 4. *Top: S_H orientations in the Long Beach oil field. Data for some wells are not shown to avoid overlap. Orange and blue circles mark wells with greater than 3 m and 5 m total breakout length respectively. Gray contours at 200-ft interval are modified from Chavez (2015) and represent the top 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.*