TECHNICAL DESCRIPTION

1. INTRODUCTION

One of the SCEC5 priorities is the development of an internally consistent group of Community Models (CXM), including the maturation of the Community Stress Model (CSM) through improved geodynamic models and better incorporation of stress observations. These representations in turn support the development of dynamic rupture models and simulations of predicted ground motion by informing the design of appropriate initial stress conditions. The observations of stress underlying these models are primarily descriptions of orientation, either derived from borehole (BH) breakouts [e.g. *Mount and Suppe*, 1992; *Kerkela and Stock*, 1996; *Wilde and Stock*, 1997], inverted from earthquake focal mechanisms (FM) [e.g., *Yang and Hauksson*, 2013], or inferred from crustal anisotropy described by the azimuth of shear wave splitting (SWS) fast directions [e.g., *Li and Peng*, 2017]. However, these three techniques necessarily sample different locations within the 3-D crust, and it is unclear how these observations should be jointly interpreted and incorporated into ongoing modeling efforts. Are the sets of observations consistent with one another? Should we expect agreement to be scale dependent? If so, over what length and depth scales? Can these disparate observations jointly suggest a unified representation of crustal stress heterogeneity that can inform both regional-scale geodynamic models and fault-scale dynamic rupture simulations?

A recent study comparing maximum horizontal compressive stress azimuth (SHmax) from borehole breakouts and earthquake focal mechanisms in the Los Angeles area examined the vertical and horizontal length scales over which the two datasets were consistent [*Luttrell and Hardebeck*, 2020a]. The investigation found evidence that stress orientation varies with depth within sediment basins, but approaches more homogeneous basement orientations at the bedrock interface. Furthermore, lateral stress orientation heterogeneity was found to be mostly associated with basin margins and proximity to active faults at length scales of 1 – 20 km. However these investigations were necessarily limited to areas where existing boreholes had been drilled for industrial use, heavily biased toward sedimentary basins. We propose to broaden our assessment of crustal stress heterogeneity by incorporating proxy SHmax azimuth derived from SWS fast directions with SHmax indicated by borehole breakouts and earthquake focal mechanisms to further test the model of crustal stress heterogeneity proposed by *Luttrell and Hardebeck* [2020a]. In order to accomplish these objectives, we propose the following tasks:

- *Compile and compare existing indications of BH SHmax and SWS fast direction within southern California.*
- *Compare BH SHmax and SWS fast directions with SHmax from existing FM inversions.*
- *Perform new local FM inversions around seismic stations with SWS fast direction estimates.*
- *Contribute to the development of the SCEC Community Models (CXM).*

This work will directly support the objectives of the Community Models (CXM) and Stress and Deformation over Time (SDOT) interdisciplinary working groups to answer the basic earthquake science question of "How are faults loaded across temporal and spatial scales?" by quantifying the spatial scale of stress heterogeneity (SCEC Research Priority 1d), and synthesizing the available observations used to constrain absolute stress and stressing rate (SCEC Research Priority 1c). This project will also provide training and experience for an Undergraduate Student Research Assistant, who will assist with data analysis activities.

2. Crustal Stress Heterogeneity and the Role of Sediment Basins

The crustal stress field plays an important role in understanding earthquake processes and predicting ground motions from earthquakes [*Harris et al.*, 2018], but direct observation of stress state is difficult [*Zoback et al.*, 2010]. Observations of stress field orientation may be provided either by the inversion of earthquake focal mechanisms [*Michael*, 1984; 1987; *Hardebeck and Hauksson*, 2001; *Hardebeck and Michael*, 2006; *Yang and Hauksson*, 2013] or by the azimuth of borehole breakouts [*Stock and Healy*, 1988; *Mount and Suppe*, 1992; *Shamir and Zoback*, 1992; *Zoback and Healy*, 1992; *Kerkela and Stock*, 1996; *Wilde and Stock*, 1997; *Zajac and Stock*, 1997]. However previous studies of these stress indicators have reached different conclusions about the extent and characteristic length scales of heterogeneity, with studies of predominantly FMs finding smooth variations at regional length scales of 10s to 100s of km [*Yang and Hauksson*, 2013; *Heidbach et al.*, 2018] and studies of BHs finding considerable heterogeneity at local length scales as low as 1 km [*Wilde and Stock*, 1997; *Schoenball and Davatzes*, 2017].

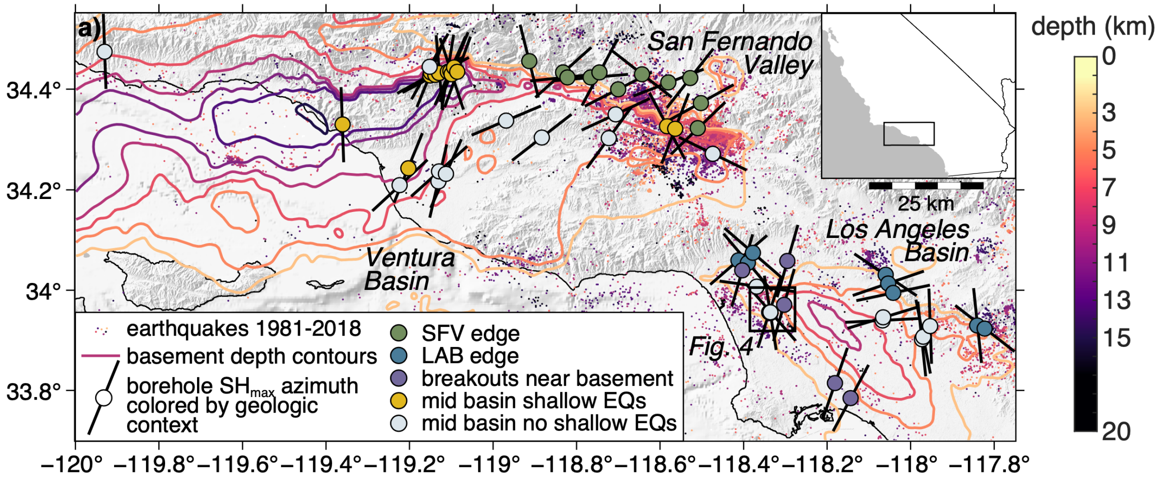

Figure 1: map of boreholes considered in this study, colored by geologic context, with estimates of SHmax azimuth from breakouts indicated by thick black lines. Contours of depth to sediment basement interface [*Shaw et al.*, 2015] for 3 – 15 km depth are shown as thick colored lines. Dots indicate earthquakes with available focal mechanism solutions [*Yang et al.*, 2012], colored by depth. After *Luttrell and Hardebeck* [2020a].

The main difference between these two measurement types is the crustal volume represented by each. Near-vertical boreholes provide a direct observation of maximum horizontal compressional stress (SHmax) azimuth at a discrete location over the depth range of existing breakouts, which are typically within sedimentary basins. FM stress inversion requires a population of FMs derived from earthquake records, and the resulting 3-D stress orientation represents the entire crustal volume sampled by those earthquakes, which are predominantly within bedrock. In a recent study, we compiled published estimates of SHmax from 57 BHs across the Los Angeles area (Figure 1) and compared them to stress orientation indicated by new FM inversions for earthquake populations covering a range of depth and distance criteria [*Luttrell and Hardebeck*, 2020a; 2020b]. By comparing the variations in SHmax agreement over different crustal volumes sampled by FMs, the spatial variability of stress state heterogeneity could be assessed across the region and in different geologic contexts (Figure 1).

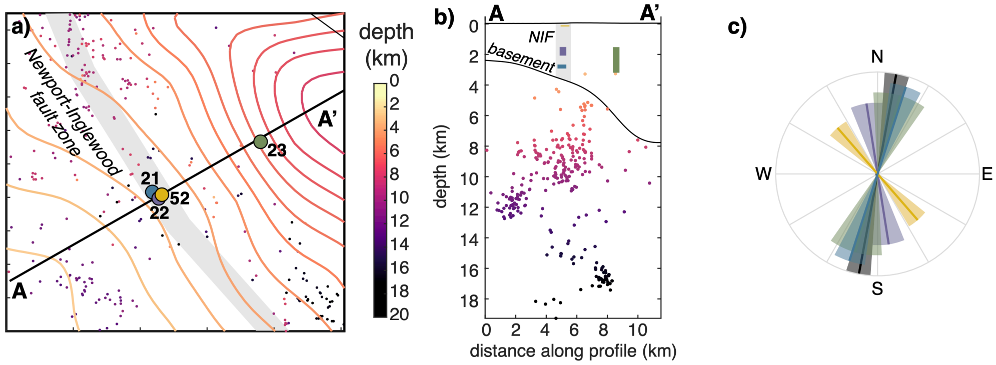

Figure 2: Example of depth dependent rotations in stress near the Newport-Inglewood fault. a) closeup of 4 boreholes (colored circles) along the Newport-Inglewood fault (black box in Figure 1), with contours of sediment basement interface [*Shaw et al*., 2015] and earthquakes with available focal mechanism solutions [*Yang et al*., 2012] colored by depth. b) depth cross section along profile A-A' showing depth range of breakouts in each borehole (colored bars, corresponding to colored circles in (a)). c) SHmax estimates with confidence intervals at 4 boreholes (colored lines and shading, corresponding to colored circles in (a)) and from inversion of local earthquake focal mechanisms shown in (b) (black bar and shading). After *Luttrell and Hardebeck* [2020a]

We found good agreement when both methods sample the basement stress (breakouts are close to the sediment-basement interface), or when both methods sample the mid-basin stress (sufficient earthquakes are present within a sedimentary basin). Along sedimentary basin margins, in contrast, we found acceptable agreement only when focal mechanisms are limited to shallow and close earthquakes, implying short-length-scale heterogeneity of < 20 km. While the region as a whole shows evidence of both lateral and vertical stress orientation heterogeneity, we find a more homogeneous stress state within basement rock, over length scales of 1 – 35 km. Figure 2 shows a specific example of clockwise stress rotation with depth within sediments near the Newport-Inglewood fault, converging near the sediment-basement interface with the SHmax direction inverted from nearby basement earthquakes. Figure 3 shows a schematic summary of the results for the region as a whole, with vertical heterogeneity prominent within sedimentary basins, but short-length-scale lateral heterogeneity primarily near sediment basin margins. While we are confident in the analysis leading to this description, it is necessarily limited by the spatial availability of boreholes directly sampling the crust. These observations, therefore, serve as a testable hypothesis for a study using a more widely distributed set of crustal observations.

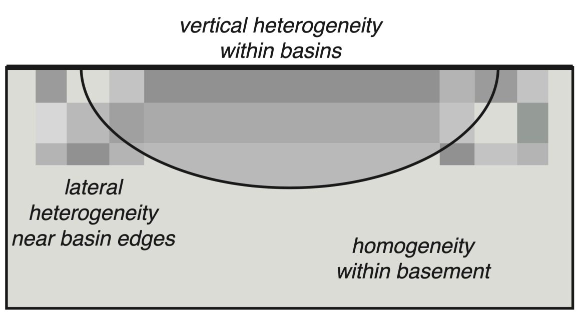

Figure 3: Schematic summary of spatial variations in stress orientation (represented by variations in gray shading) within the shallow crust suggested by analysis of borehole breakouts and earthquake focal mechanism inversion in the Los Angeles area. Solid black line represents sediment-basement interface. This serves as the testable hypothesis we propose to investigate in this study. After *Luttrell and Hardebeck* [2020a].

3. Incorporating Anisotropy to Testing Stress Heterogeneity Hypotheses

Seismic anisotropy in the upper crust can be observed by comparing the arrival time of differently-polarized shear waves from nearby earthquakes within the upper crust. This shear wave splitting (SWS) can be assessed for individual raypaths between an event-seismic station pair, or can be averaged over multiple local raypaths from earthquakes nearby a single seismic station. The resulting anisotropy is characterized by a horizontal azimuth of the "fast" direction and the delay time between the polarized shear wave phases. *Li and Peng* [2017] analyzed 330,000 relocated local earthquakes within southern California from 1995 to 2014 [*Hauksson et al.*, 2012] resulting in 90,000 high-quality estimates of fast directions and delay times associated with 407 seismic stations (Figure 4). Seismic anisotropy of this sort may be indicative of SHmax azimuths, either associated with preferential mineral alignment from recent deformation or the present-day preferential opening of fluid filled cracks [e.g., *Nur & Simmons*, 1969; *Leary et al.*, 1990].

As part of their analysis, *Li and Peng* [2017] compared averaged fast directions associated with each seismic station with SHmax azimuths at those locations from the regional inversion of earthquake focal mechanisms [*Yang and Hauksson*, 2013] and found systematic discrepancies between the two. However, by comparing SWS observations that necessarily represent local variations (~10 km) with a regional inversion specifying the smoothest possible stress field, these apparent discrepancies may instead be indicative of finer-scale variations in stress orientation, similar to those observed in borehole breakouts. Comparison of BH SHmax and SWS fast direction versus regional FM SHmax reveals that the apparent misfit is primarily a function of greater heterogeneity from these local observations (Figure 4).

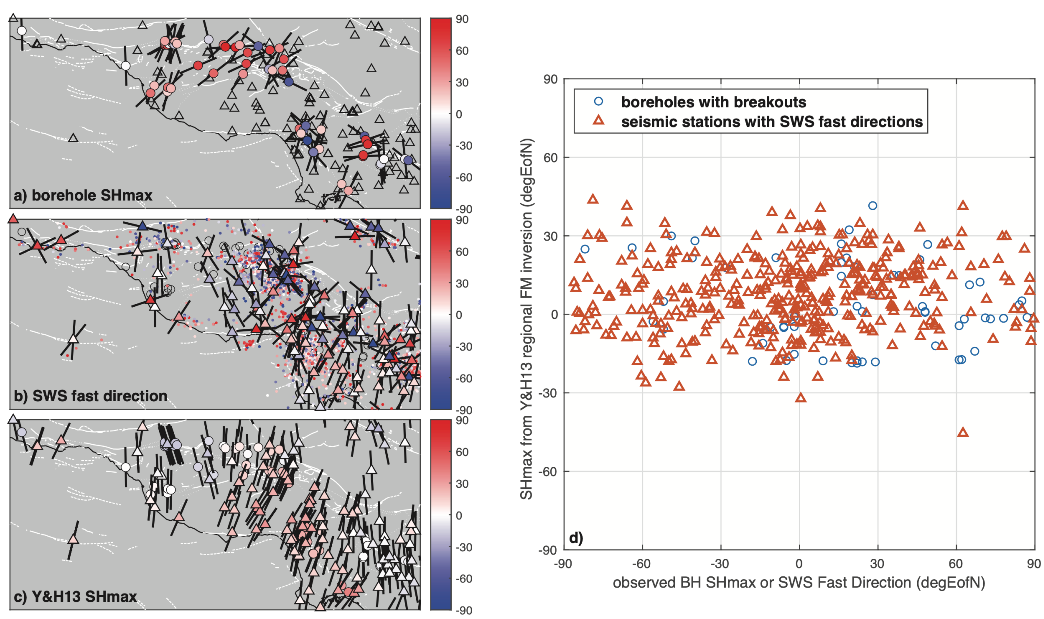

Figure 4: a) SHmax directions from borehole breakouts (circles and bars) [*Luttrell and Hardebeck*, 2020a], b) average SWS fast directions per event (dots) and per seismic station (triangles and bars) [*Li and Peng*, 2017]. c) SHmax orientation from smoothest possible regional inversion of earthquake focal mechanisms [*Yang and Hauksson*, 2013], sampled at locations of boreholes (circles) and seismic stations (triangles). d) comparison of SHmax directions indicated by borehole breakouts (blue circles, horizontal axis) or SWS fast directions (red triangles, horizontal axis) with SHmax directions from smoothest possible regional inversion of earthquake focal mechanisms (vertical axis).

We propose to extend the analyses of *Luttrell and Hardebeck* [2020a] to include a systematic comparison of crustal stress orientations indicated by all three available observation types: borehole breakouts, SWS fast directions, and inversion of earthquake focal mechanisms. We will perform new local FM inversions over a range of depth and lateral distance scales around each of the seismic stations with SWS fast direction estimates and compare with nearby observations to quantify spatial patterns of stress orientation heterogeneity across the study area. This will allow us both to directly test the hypothesized stress distributions from *Luttrell and Hardebeck* [2020a] (Figure 3) and to further investigate the nature of the SHmax discrepancies observed by *Li and Peng* [2017] (Figure 4). The results will be of immediate relevance to the SCEC community as they directly support the objectives of both the CXM and SDOT interdisciplinary working groups.

4. Proposed Research Plan

In summary, the goal of this research will be to assess heterogeneity in crustal stress orientation and test the hypothesis that heterogeneity is more pronounced within and around sedimentary basins relative to either surrounding areas or underlying basement rock. To this end we propose the following tasks:

- *Task 1: Compile and Compare existing indications of BH SHmax and SWS fast direction within southern California*. We will compare SWS fast directions from both individual earthquake-station pairs and station averages [*Li and Peng*, 2017] with SHmax directions from available borehole breakouts [*Luttrell and Hardebeck*, 2020a], to assess the nature, degree, and spatial extent of heterogeneity indicated.
- *Task 2: Compare BH SHmax and SWS fast directions with SHmax from existing FM inversions*. We will compare both regional scale [*Yang and Hauksson*, 2013] and local scale [*Luttrell and Hardebeck*, 2020a] FM inversions for SHmax, particularly testing the role of sediment basins on lateral and vertical stress heterogeneity indicated by *Luttrell and Hardebeck* [2020a].
- *Task 3: Perform new local FM inversions about the seismic stations with SWS fast direction estimates*. We will compare the new local SHmax estimates with those compiled in Tasks 2 and 3, which will allow us to further test the hypotheses about stress heterogeneity in and around sedimentary basins at greater spatial resolution that has been available from studies of BH and FM alone.
- *Task 4: Contribute to the development of the SCEC Community Models (CXM)*. Our results will be directly relevant to the CSM, and to the multi-model integration efforts of the CXM. We will participate in CXM workshops, dialog with CXM model contributors and users, and contribute new and revised models and analysis code to the suite of CSM models made available to the SCEC community.

The above tasks will leverage current support from the USGS, as Hardebeck will be a no-cost participant in this study. We expect to present the findings at scientific meetings throughout the year, including the SCEC Annual Meeting, and to develop these investigations sufficiently to be suitable for publication in a peer reviewed journal.