Understanding Crustal Stress Heterogeneity in the Los Angeles Region using Focal Mechanism Inversions and Shear Wave Splitting Fast Velocities

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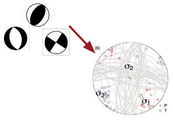
Abstract

The Los Angeles region of southern California is structurally complex with demonstrated heterogeneity in crustal stress orientation. Maximum horizontal compression azimuth (SHmax) can be calculated from focal mechanism inversion, inferred from shear wave splitting fast directions (presumably corresponding to stress-induced crustal fabric), or sometimes directly measured from borehole breakouts. These different techniques are sensitive to stress over different depth ranges and crustal volumes, making it unclear how these observations should be jointly interpreted and incorporated into ongoing stress modeling efforts. In this study, we use published catalogs of earthquake focal mechanisms and individual earthquake-to-station raypath shear wave splitting fast direction measurements from across southern California. We perform new focal mechanism stress inversions over an assortment of crustal volumes and compare the indicated SHmax direction with the shear wave fast directions indicated by ray paths through the same crustal volumes. In particular, we investigate the degree to which these two indicators of crustal stress orientation are consistent, and over what spatial scales they are consistent, both vertically and laterally. These comparisons can help us both illuminate the present crustal stress heterogeneity and potentially understand the linkages between the development of crustal fabric and the modern stress state. Preliminary results suggest clear differences between stress orientations indicated by shear wave splitting and focal mechanisms, with subregions of disagreement largely correlating with major structural and fault features of the area. These discrepancies may be reconciled by more detailed analysis of particular crustal volumes, but further research is needed. If the discrepancies persist, this may record changes in southern California crustal stress during basin development, or could indicate low stress magnitudes such that crustal fabric is sensitive to factors other than stress orientation. These results have implications for the broader understanding of the interplay between the evolution of crustal stress and sediment basin structures.

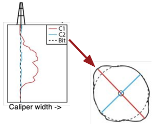
Big Question: What is the crustal stress field?

We can estimate crustal stress orientation from 3 different types of observations:

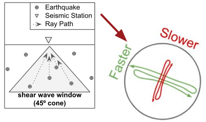
Earthquake Focal Mechanism Inversion (3D orientation)



Borehole Breakouts (SHmax direction)



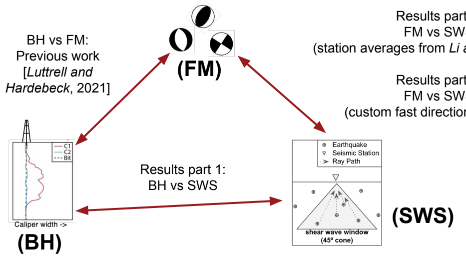
Shear Wave Splitting Anisotropy (Fast direction ≈ SHmax?)



But do they agree? Over what length scales? Are they measuring the same thing?

Methods

- Use existing catalog of Borehole Breakout SHmax [*Luttrell and Hardebeck*, 2021] and existing catalog of shear wave fast direction [*Li and Peng*, 2017].
- Use existing catalog of focal mechanisms [*Yang et al.*, 2012] and create new stress inversions from earthquakes nearby seismic stations or boreholes.
- Compare all 3 types of SHmax estimate, carefully considering the length scales, depth ranges, and overall crustal volume represented by each measurement



Results part 1: BH vs SWS using seismic station averages

- Figure 1a shows the average SWS fast direction determined for earthquakes with near-vertical ray-paths through the shallow crust to 127 seismic stations across the Los Angeles area [*Li and Peng*, 2017, Table S1].
- Figure 1b shows the SHmax direction determined from breakouts within 57 boreholes, compiled by *Luttrell and Hardebeck* [2021, Table 1] from previously published sources.
- Both datasets show considerable heterogeneity, but with some consistency in the vicinity of sedimentary basins.
- Contrary to expectation, the consistent fast directions from the Ventura basin area are nearly orthogonal to the consistent SHmax directions from approximately the same area.
- SHmax and fast direction values are more consistent in the Los Angeles basin area, but still with noteworthy discrepancies, particularly near the Whittier fault zone.
- Are these discrepancies due to differences in the crustal volumes being sampled by each technique?

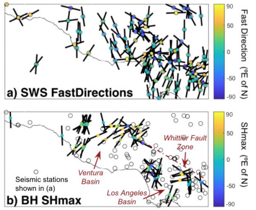
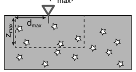


Figure 1: a) SWS station-averaged Fast Directions at 127 seismic stations. b) BH SHmax directions at 57 boreholes. Empty circles indicate locations of seismic stations from (a). Major sedimentary basins labeled.

Results part 2: FM vs SWS using seismic station averages

- We performed 1615 new stress inversions of focal mechanisms around 127 seismic stations in the Los Angeles area, with varying criteria for maximum earthquake depth (z_{max}) and maximum lateral distance (d_{max}).



- For each set of d_{max} and z_{max} criteria, we compared the SHmax value and Fast Direction indicated at each seismic station (Figure 2).
- For large crustal volumes (high d_{max} or z_{max} value), the FM SHmax values are much more homogenous over the region, indicating an overly smooth representation of stress state.
- For smaller crustal volumes, FM SHmax values are more heterogeneous, but still not as heterogeneous as the SWS fast directions.
- Is the absence of strong correlation between SHmax and Fast Direction an artifact of the differences in crustal volume compared? What if we were more careful about this? (see next section)

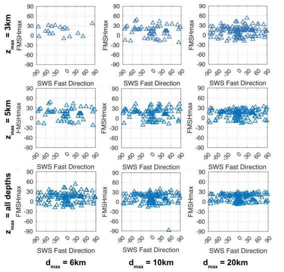
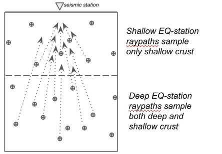


Figure 2: Correlation plots comparing station-averaged SWS fast directions with SHmax orientation from FM inversion, for different maximum earthquake depth (zmax) and maximum earthquake distance from seismic station (dmax)

Try something else: Making new fast direction averages

- Maybe the reason for the discrepancies between SWS fast directions and BH or FM SHmax is due to differences in the crustal volume sampled.
- Individual SWS fast directions represent average anisotropy over the raypath, smoothing out differences with depth.
- What if we calculate SWS fast-direction averages using only shallow or only deep earthquakes, and compare them to FM SHmax from inversion of only focal mechanisms from the same crustal volume?



Results part 3: Comparing new fast direction averages

- Figure 3 shows histograms of fast directions from individual EQ-station ray paths around station OLI. At this station, fast directions from shallow-only EQs better match the SHmax direction from FM inversion.
- Figure 4 shows histograms of fast directions from individual EQ-station ray paths around station LFP. At this station, fast directions from shallow-only EQs are similar to those from deep-only EQs, and neither match the SHmax direction from FM inversion.
- Several stations exhibit bimodal or even uniform distributions in individual fast direction estimates, indicating these EQ-station ray paths are sampling different crustal stress regimes, even if they're all near the seismic station.
- Figure 5 shows the summary of FM SHmax and SWS mean fast directions calculated around all 127 seismic stations. (Empty circles indicate stations with too few earthquakes within the associated volume to perform FM inversion)
- Similar to the two example stations shown in Figure 3 and Figure 4, some stations show improvement in SWS fast direction vs FM SHmax agreement when using comparable crustal volumes, but at most stations the discrepancies remain.
- The patterns of match vs mismatch seem to follow structural lines, with more heterogeneity along active faults at the edge of sedimentary basins.

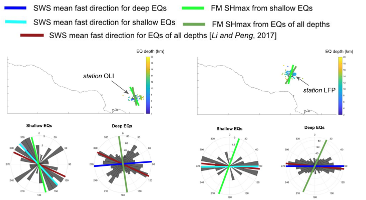


Figure 3: Histogram of fast directions at seismic station OLI (gray), with FM SHmax estimates (green lines), SWS fast direction estimates (blue and red lines), and map of earthquakes used (dots).

Figure 4: Histogram of fast directions at seismic station LFP (gray), with FM SHmax estimates (green lines), SWS fast direction estimates (blue and red lines), and map of earthquakes used (dots).

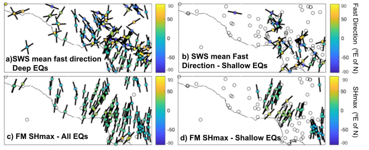


Figure 5: a) SWS mean fast directions from only deep EQs. b) SWS mean fast directions from only deep EQs. c) FM SHmax directions from EQs of all depths. d) FM SHmax directions from only shallow EQs.

Discussion, Conclusions, and Next Steps

- What's going on? If we have 3 different measurement types, and we control for making sure they're sampling the same volume of crust, shouldn't they agree about the SHmax direction?
- From the BH and SWS measurements themselves, clearly there is small scale stress heterogeneity present in some areas, but there are also regions that are broadly consistent within each dataset.
- A previous study compared BH SHmax with FM SHmax and found agreement depending strongly on length scale and geologic context (Figure 6). We also see stress heterogeneity patterns aligning with major structural features, e.g. the Los Angeles and Ventura basins and the Whittier fault zone.
- Next Steps: Maybe we need to stop looking at concentric cylinders of crust centered around seismic stations. Maybe some of the fast direction anisotropy we see is due to having crossed structures (i.e., not SHmax), rather than anisotropy within a block of crust due to past stress-induced deformation (i.e., ≈ SHmax).
- If we redo the analysis, comparing FM inversions and SWS ray paths from only within the same crustal blocks (i.e., not crossing faults), will that reconcile the discrepancies? Would it help to narrow the shear wave window, to avoid averaging over larger crustal volumes? Would it help to redefine "shallow vs deep" as "above vs below sediment-basement interface"?

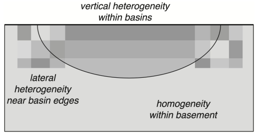


Figure 6: Schematic summary of crustal stress heterogeneity previously predicted from FM SHmax vs BH SHmax comparisons. Solid black line represents sediment basement interface. [*Luttrell and Hardebeck*, 2021]

References

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