Reconciling crustal stress heterogeneity from borehole breakouts and earthquake focal mechanisms

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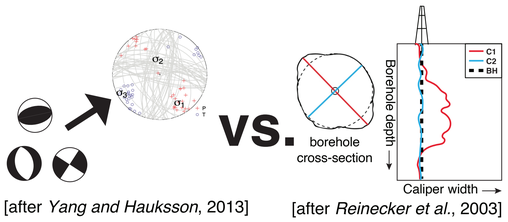
Abstract

Observations of crustal stress orientation from the regional inversion of earthquake focal mechanisms often conflict with those from borehole breakouts, possibly indicating local stress heterogeneity, either laterally or with depth. To investigate this heterogeneity, we compiled SHmax estimates from previous studies for 57 near-vertical boreholes with measured breakout azimuths across the Los Angeles region. We identified subsets of earthquake focal mechanisms from established earthquake catalogs centered around each borehole with various criteria for maximum depth and maximum lateral distance from the borehole. Each subset was independently inverted for 3-D stress orientation and corresponding SHmax probability distributions, then compared with the associated borehole breakout-derived estimate. We find 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 find 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. These results reconcile the apparently conflicting observations of short-length-scale heterogeneity observed in boreholes, which sample primarily the basins, with the relative homogeneity of stress inferred from focal mechanisms, which sample primarily the basement, and imply distinct regimes for the appropriate use of each type of stress indicator.

How heterogeneous is the crustal stress field?

- Observations of stress orientation come from two sources, each representing a different volume of crust:
  - groups of earthquake focal mechanisms (FM), inverted for stress state, generally representing crustal volume of > 5 km laterally and > 5 km depth
  - azimuth of breakouts within drilled boreholes (BH), measured by oriented caliper well logs, generally representing crustal volume of < 1 km laterally and < 3 km depth
- Focal mechanism studies consistently estimate smooth stress fields with little heterogeneity over 10s of km.
- Borehole studies routinely find major stress variations over a few km or less.
- What's going on with the stress state between these two spatial scales? Let's look in Los Angeles and find out.



[after *Yang and Hauksson*, 2013] [after *Reinecker et al.*, 2003]

Figure 1: Types of stress orientation observations being compared in this study: inversions for 3-D stress state from groups of earthquake focal mechanisms (left) versus azimuth of maximum horizontal compressional stress (SHmax) derived from orientation of breakouts observed within well boreholes (right).

Compare Stress Orientation Observations

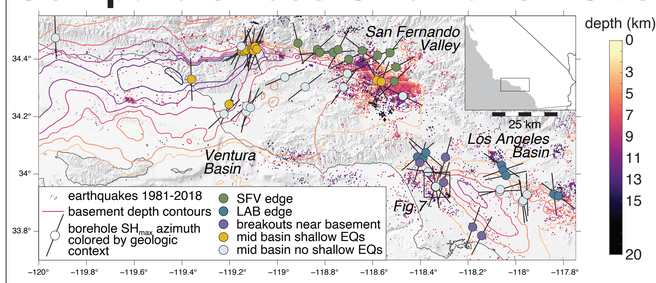


Figure 2: Map of Los Angeles region including earthquakes (dots, colored by depth), contours of sediment-basement interface (lines, colored by depth), and location 57 boreholes with SHmax estimates derived from breakout azimuth (circles, colored by geologic context relative to sediment basins). Black square indicates Newport-Inglewood area discussed in Figure 7.

- Compile previously published SHmax estimates from 57 borehole [*Wilde and Stock*, 1997; *Mount and Suppe*, 1992; *Kerkela and Stock*, 1996]
- Define subsets of FMs from existing catalog [*Yang et al.*, 2012], around each borehole, with a specified maximum depth (z_{max}) and maximum distance from each borehole (d_{max})
- Invert each subset for 3-D stress state, including SHmax azimuth probability density function (PDF).
- Analyze 5 distinct borehole subsets based on geologic context relative to CVM sediment-basement interface [*Shaw et al.*, 2015].

Interpret results for stress heterogeneity

- If stress orientation is homogeneous
  - FM and BH SHmax should match well, regardless of z_{max} or d_{max}
- If stress has vertical heterogeneity
  - shallower FM subsets should fit better
- If stress has horizontal heterogeneity
  - closer FM subsets should fit better
- If stress has both vertical and horizontal heterogeneity
  - closer AND shallower should fit better
- If nothing fits well, regardless of z_{max} or d_{max}
  - stress is heterogeneous at scales smaller than what we're able to resolve with the available distribution of FMs.

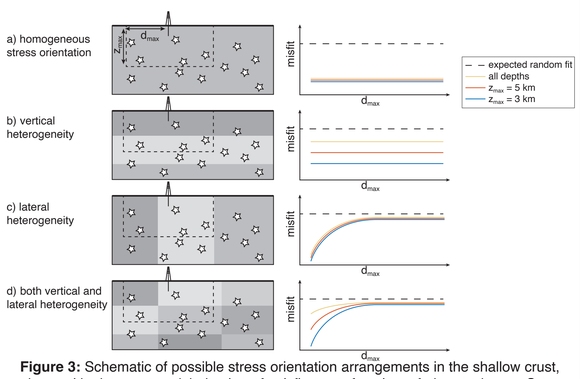


Figure 3: Schematic of possible stress orientation arrangements in the shallow crust, along with the expected behavior of misfit as a function of d_{max} and z_{max}. Stars represent earthquakes in the vicinity of the borehole.

Results: region wide

- Far away (d_{max} ≥ ~15 km), depth and distance don't matter
  - Fits are slightly better than random, indicating sensitivity to broad regional stress state
- For d_{max} ≤ 10 km,
  - fit improves significantly for FM depth < 3 km (probability distributions don't overlap)
  - fit improves somewhat for FM depth < 5 km
  - fit for all FM depths does not improve
- Across the region as a whole, FMs fit boreholes about as well as boreholes fit one another.

Region-wide Vertical and Lateral Stress Heterogeneity at lengthscales < 10 km

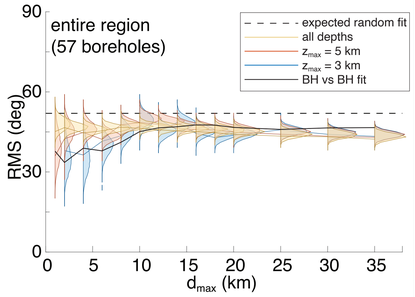


Figure 4: PDFs of SHmax misfit stacked over all 57 boreholes considered in this study, considering different FM subset distance criteria. Dashed line is expected random fit. Solid black line represents misfit between pairs of boreholes.

Results: within sediment basins

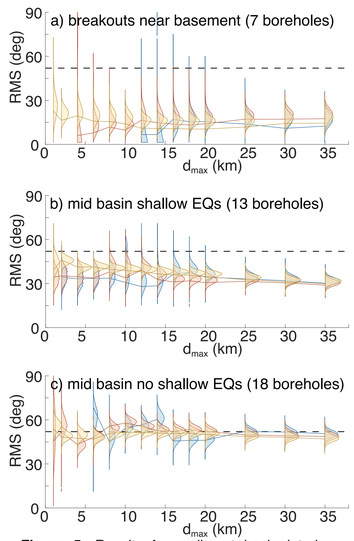


Figure 5: Results for sediment basin interiors: SHmax misfit curves for FM subsets of shallowest < 3 km (blue), shallow < 5 km (red), and all depths (yellow). Dashed line is expected random fit.

- When breakouts are close to the sediment-basement interface, misfits are low regardless of z_{max} or d_{max} (Fig. 5a).
  - Suggests both methods are sampling the same stress field
- When breakouts are mid basin and FMs are present within the sediments, misfits are moderate (Fig. 5b).
- When breakouts are mid basin and FMs are NOT present within sediments, misfits are no better than random (Fig. 5c).
  - Demonstrates that stress state varies between the sediments and basement, but that the SHmax values converge toward the sediment basement interface.
- There is no indication of systematic lateral heterogeneity within basins from these results.

Vertical (not lateral) Stress Heterogeneity within sediment basins, and deep basins match basement

Results: at sediment basin margins

- For FMs from all depths, fit is no better than random, regardless of distance.
- For shallow (depth < 5 km) and shallowest (depth < 3km) FMs, closer subsets fit better
  - d_{max} ≤ 10 km (SFV)
  - d_{max} ≤ 15 km (LAB)
- Along basin margins, there is both vertical and horizontal heterogeneity in stress orientation.
- Lateral heterogeneity is present at edges of both basins, suggesting this is a general characteristic.

both Vertical and Lateral Stress Heterogeneity at basin margins

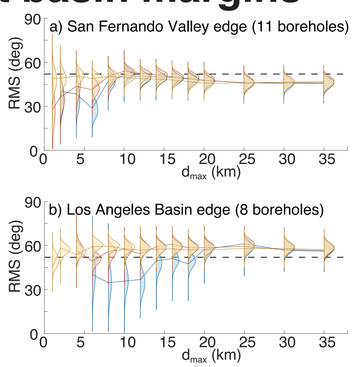


Figure 6: Results for sediment basin margins: SHmax misfit curves for FM subsets of shallowest < 3 km (blue), shallow < 5 km (red), and all depths (yellow). Dashed line is expected random fit.

Newport-Inglewood Example

- Within the Newport-Inglewood fault zone, there are 3 nearly-coincident boreholes with breakouts at 3 different depths, plus a 4th borehole nearby (Fig. 7).
- These show clear evidence for steady clockwise rotation of SHmax with depth:
  - 41° ± 10° WofN near the surface
  - 9° ± 13° WofN at intermediate depths
  - 18° ± 10° EofN near the basement
  - consistent with 18.2° ± 4.5° EofN from FMs
- Nearest borehole 3.5 km to the NE (toward deeper sediments) has SHmax values consistent with neighbors at similar depths.
- Consistent with the broader findings about stress orientation depth heterogeneity within sediment basins.

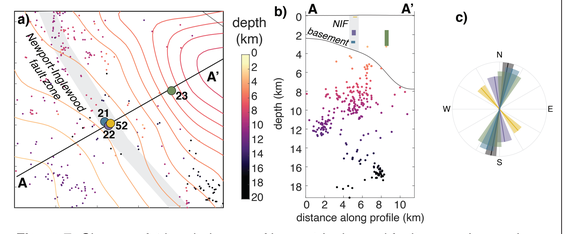


Figure 7: Closeup of 4 boreholes near Newport-Inglewood fault zone. a) map view, with earthquakes and sediment basement contours (as in Fig. 2). b) cross section view. c) SHmax azimuth (with uncertainties) for each borehole (colored) and focal mechanism inversion (black).

Summary and Synthesis

Our analysis shows evidence for:

- broad homogeneity within basement
- vertical heterogeneity within basins
- lateral and vertical heterogeneity near basin edges

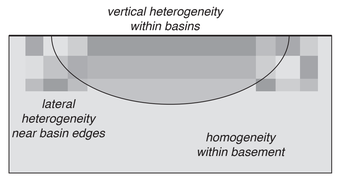


Figure 8: Schematic summary of results for stress orientation arrangements in the shallow crust. Solid black line represents sediment-basement interface.

Conclusions

- By careful compilation of individual borehole SHmax estimates and inversion of nearby earthquake focal mechanism subsets for stress state, we have performed a systematic analysis of the context, extent, and lengthscales of stress orientation heterogeneity across the Los Angeles region.
- Broadly, we find clear evidence for substantial regional heterogeneity at lengthscales of < 10 km.
- Geologic context is particularly important, with broad homogeneity within basement rock contrasted with clear vertical heterogeneity within sediment basins, and both lateral and vertical heterogeneity along basin margins.
- **TAKE HOME POINT FOR THE SCEC CXM:** Studies that rely on stress data (as model inputs or observational constraints) should carefully consider the context and lengthscales of their problem before deciding which stress orientation indicators to adopt.