Technical Report for SCEC Award #22076
Using Local Earthquake Shear Wave Anisotropy to Quantify Stress Changes Over Time

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I. Project Overview and Objectives

A comprehensive understanding of earthquake rupture processes requires the capability to characterize the evolving stress state around the faults before, during, and after large earthquakes. The stress field is distributed heterogeneously around a fault, with regions of higher or lower stress magnitudes than the background. Areas of higher stress concentrations are more likely to experience future seismicity and may also be linked to variations in rupture properties or characteristics in seismicity. This project aims to use shear wave splitting as a tool to examine variations in stress and seismicity in active fault systems.

Seismic anisotropy can arise from a number of physical factors, from structural origins (e.g., development of fabrics, fractures or damaged material) to stress perturbations (which interact with fracture networks). On the time scales relevant to this proposal, we do not expect structure-related anisotropy to change, but changes in stress may cause preferential opening or closing of microcracks, which in turn may be quantified by changes in seismic anisotropy.

For this study, we focus on the San Jacinto Fault Zone. Within the study region, there are over 8,000 recent, documented events of magnitude 1 and greater and 70 seismic stations with continuous data. This region is uniquely well-suited for this analysis because it is well-instrumented and there is a robust catalog with precise locations informed by 3D velocity models for events from 2008 to 2016 (White et al., 2019).

The primary objectives for this project were:

1. Develop user-friendly, Python-based codes for earthquake shear-wave splitting analysis.
2. Perform quality control of S-wave data for earthquakes in San Jacinto Fault Zone.
3. Cluster seismicity into localized clusters for individual analysis.
4. Calculate shear-wave-splitting for each cluster.
5. Interpret seismicity for each cluster-station pair over space and time.

The funding for this project was used primarily for first-year graduate student funding for Annie Patton at the University of Nevada in Reno. We are currently on the final two stages of the project, and anticipate completion in the Fall of 2023, at which time the research will be prepared for submission to a journal. The preliminary results were also presented at the GSA 2023 Cordilleran Section Meeting in Reno, Nevada. Following SCEC's commitment to open science, the codes will be made publicly available on PI Daniel Trugman's GitHub (https://github.com/dttrugman) and we look forward to future research collaborations through such efforts.

II. Summary of Technical Approach

The technical approach follows Silver and Chan (1991) where the windowed S-wave waveforms are shifted and rotated in order to minimize the S-wave on the transverse component. The shift corresponds to the delay time, which represents the strength of the anisotropy, whereas the rotation angle between the incident wave and the fast shear-wave component describes the orientation of anisotropy. This calculation can be carried out at each station and for each individual event.

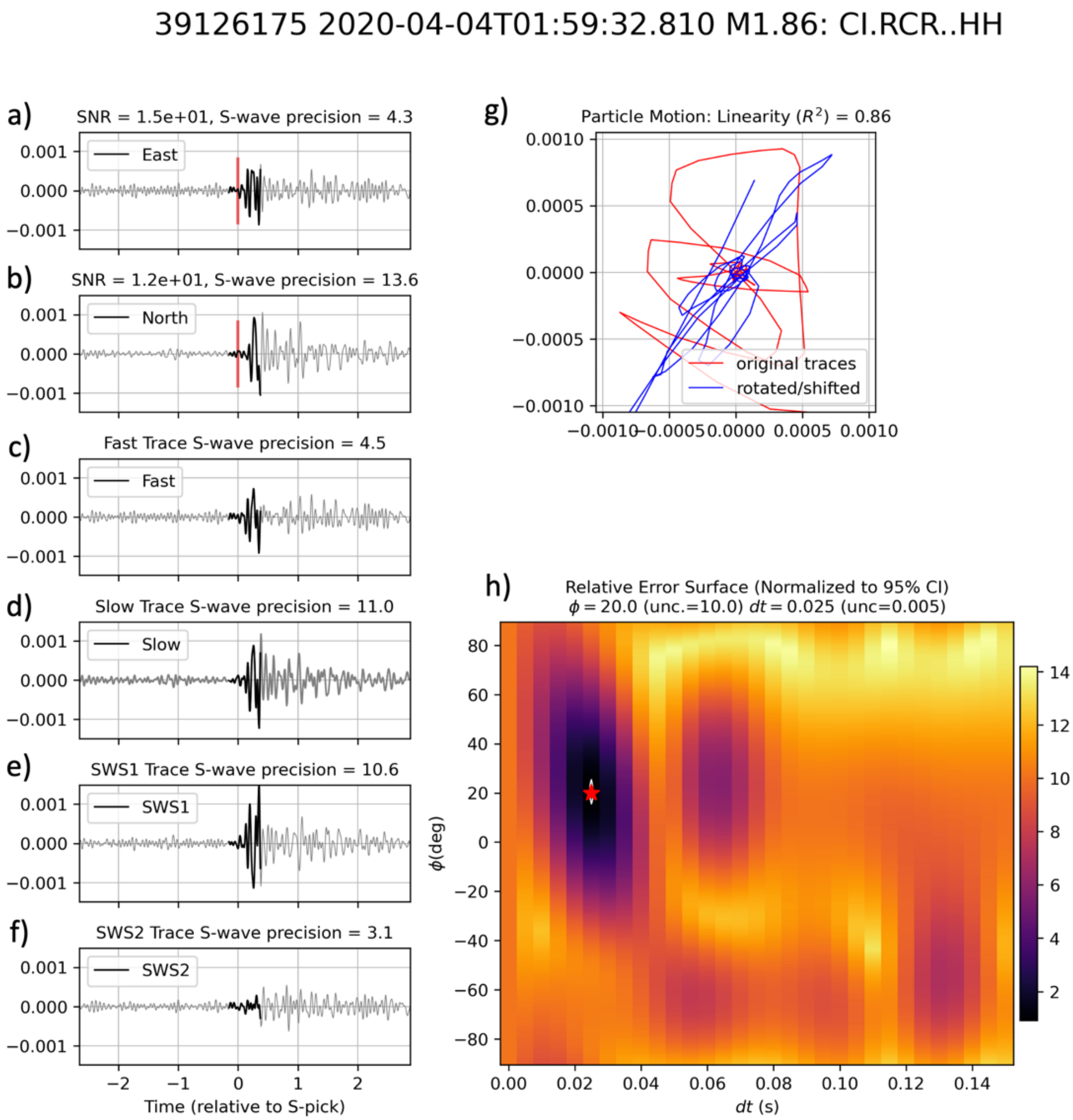

Figure 1: Example of method and quality control assessment. (a-f) rotation of the raw data (a-b) into fast and slow components (c-d), followed by energy maximization of the primary transformed component (e-g) to determine the best pair of splitting parameters (h).

To integrate quality control in the program, we incorporated the following (Figure 1):

1. S-wave pick buffer: there are instances where the S-wave pick is offset from the true arrival, which introduced issues in the windowing. A buffer was added to include the data prior to the S-wave pick, and the calculation of the delay time was adjusted accordingly.
2. Hodogram linearity: after rotation the hodogram should be nearly linear (g) due to objective of maximization of energy on the primary transformed component (e).
3. S-wave precision measurement after rotation: this is a measure of the amplitude of the S-wave relative to the window of data prior to the assumed S-wave. In panel (e), a high S-wave precision is sought since it means the energy is maximized on that component, whereas in (f) a low S-wave precision would indicate successful minimization on the secondary transformed component.
4. Error surface analysis: visual inspection of the error surface (h) would show the stability of the solution, with a clear global minimum rather than multiple modes.

Combining these quality control measures into a display panel for visual inspection allowed for an assessment of the quality of each measurement. We utilized a scale of 0-3, with 0 being for unusable measurements, and 3 being for high-quality measurements, such as in Figure 1. Our codes are set up so that the user selects the quality of the measure after visual inspection, which is then written to a database for later analysis.

III. Key Results

As part of the workflow, we split the seismicity into localized clusters using DBSCAN (Pedregosa et al., 2011), which clusters events based on spatial density and excludes outliers. Figure 2a shows the clusters, which were determined using their 3D coordinates. We have a total of 45 clusters with an average of 60 events per cluster. The map view also shows the station distribution (blue triangles). Since precise S-wave arrivals are central to the method, preliminary analysis was done with the S-wave arrivals in the catalog to ensure that they were not mis-picked. Figure 2b shows travel-time over distance, with colors corresponding to the phase in the downloaded event file.

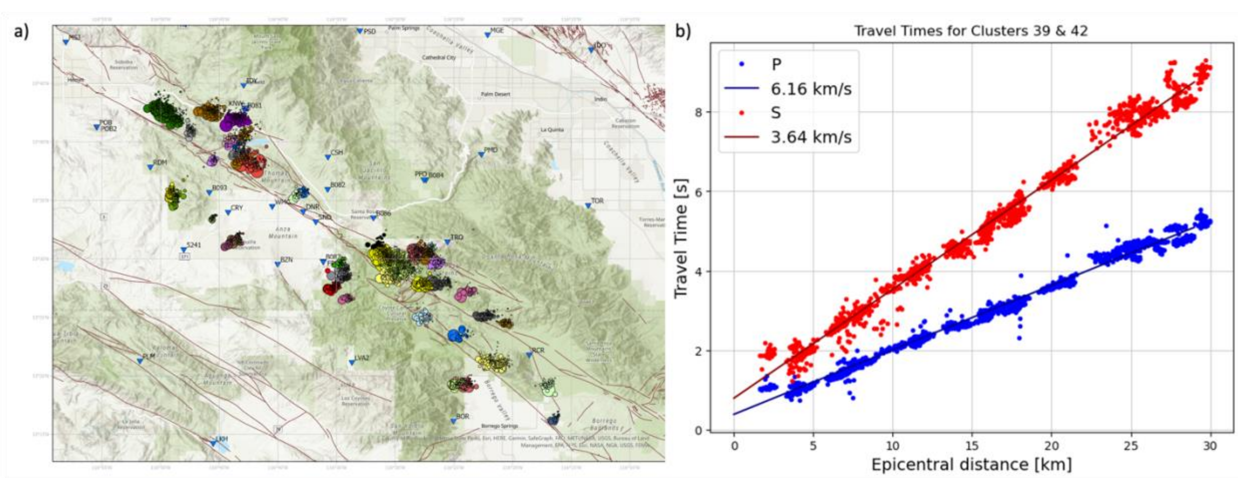

Figure 2: a) Map view of station distribution (blue triangles) and clusters (colored circles) for the San Jacinto Fault Zone; b) Travel times versus distance for events in two select clusters.

Figure 3 shows map views of the anisotropy at nearby stations for different clusters, with the station colored by the degree of anisotropy and the opacity of the station corresponding to the uncertainty. Since delay time increases for longer ray paths, a correction for distance was applied to the delay time measurements using the known travel time between the station and the earthquake. Figure 3a shows one of the consistent trends observed in this study: a radial decrease in anisotropy. This decrease may imply that most of the anisotropy sampled by the ray path is located near the damaged, highly complex main fault zone.

One of the key sources of uncertainty in shear-wave splitting analysis is the depth interval that contributes to the anisotropy, and Figure 3b shows that for a deep (>10km) cluster, the anisotropy recorded at the surface is low. More results in agreement with Figure 3b could further isolate the anisotropy to a very shallow layer. Shallow anisotropy would indicate a structural cause related to the number of cracks in the shallow crust. Finally, Figure 3c shows an example of where two stations with different azimuths relative to the cluster location have very different dV (normalized delay time) values. This example points to potential localized regions of increased fracture density.

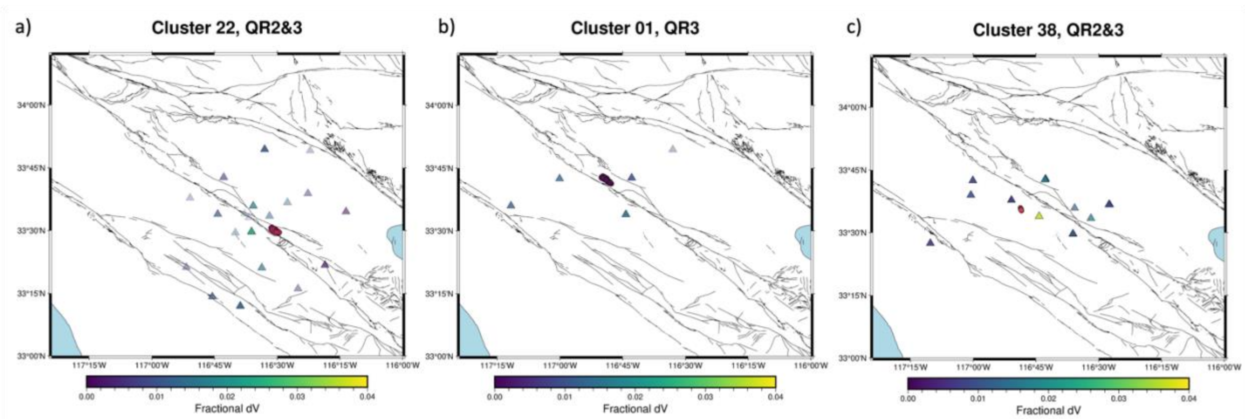

Figure 3: Example results for select clusters including only medium- and/or high-quality measurements: a) radial decrease in anisotropy, b) low anisotropy for a deep cluster, and c) strong azimuthal differences in anisotropy close to the source.

IV. Outlook and Significance

In this report, we focused mainly on the magnitude of anisotropy (dV), whereas another parameter that may be analyzed is the fast S-wave orientation. The orientation of fast direction appears less consistent; we are currently investigating why. With more analysis, however, a better characterization of fast direction could be possible, which would provide a better indication of where anisotropy is controlled by regional crustal stress, and where structure is the main driver of anisotropy. Li et al. (2015) argued that fast directions were mainly oriented north-south across the main fault zone, which generally agreed with the accepted model of maximum horizontal stress from Yang and Hauksson (2013). Jiang et al. (2021) confirmed the findings of Li et al. (2015) but expanded their conclusions to show that off-fault fast directions are instead controlled by the dominant fault orientation.

One important question that remains to be determined is the depth extent of the raypath responsible for the anisotropy is we observed. In our work so far, we have followed previous work in assuming that anisotropy accrues steadily along the raypath as it travels from source to station. Alternatively, anisotropy could be caused dominantly by shallow structure. This is an ideal dataset to test these contrasting hypotheses because we have a diverse range of raypath geometries and also several sites in which borehole and surface stations are nearly collocated. Over the next few months, we will work to isolate these contributions. In either case, our results will provide important insight for future studies and interpretations of local-scale anisotropy measurements.

A promising line of future work related to crustal anisotropy as measured by shear wave splitting would be to characterize its influence on source and seismicity properties, for example rupture directivity and its relationship with spatiotemporal earthquake clustering. Li et al. (2015) showed differing trends across the bi-material interface of the San Jacinto Fault Zone. Ben-Zion and Zaliapin (2019) calculated the damage area of the SJFZ for use in earthquake clustering applications. Successfully linking rupture directivity with areas experiencing higher stress has important implications for earthquake forecasting, and can be supplemented with further study on the effect that the extent of the damage zone has on earthquake clustering and triggering, as well as the potential difference in seismic hazard across the bi-material interface of the SJFZ.

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