Progress report for 2013 SCEC Proposal

Title of Project

Heterogeneity, rotations and volumetric strain near faults from focal mechanism data

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***Proposal Categories*:**

Integration and Theory

Science Objectives:

2d, 3c, 3d

Abstract

We performed several observational studies of spatio-temporal patterns in earthquake source mechanisms that accounted for possible effects of rock damage and sampled the range of seismogenic depths in close proximity to faults. The focus was on quantifying large-scale heterogeneities, rotations, and volumetric changes of seismic strain fields around large rupture zones. The research was conducted along two primary directions: analysis of spatio-temporal variations of double-couple-constrained focal mechanisms, and derivation of earthquake source tensors with a waveform inversion procedure that includes isotropic and CLVD components. Analysis of rotations of double-couple-constrained mechanisms in the Eastern California Shear Zone indicates that the most immediate aftershocks have focal mechanisms most unlike like the mainshock. This may be explained by neglecting a small isotropic component (0.03-0.15 of the total moment) in the focal mechanism determination process. Analysis of full source tensors of seven M > 4 earthquakes in the trifurcation area of the San Jacinto fault zone indicates that each event has a small but statistically significant explosive isotropic component. The obtained isotropic components are 0.04-0.23 of the total moment, which is consistent with the estimates from analysis of rotations.

1. Project Objectives

Most studies on the physics and properties of crustal earthquakes focus on deviatoric stress/strain components. While deviatoric stress-strain changes are likely to be dominant in most circumstances, even small changes of volumetric and normal stress-strain can have fundamental implications for many aspects of earthquake and fault mechanics. The primary objective of this project was to find signatures of radiation produced by rock damage in earthquake source volumes of regular tectonic earthquakes in geometrically complex areas.

We approached this subject from two independent directions and found results that were consistent between the two. The first direction focused on indirect evidence for isotropic components using focal mechanisms of the 1992 Landers aftershock sequence (Ross and Ben-Zion, 2013). The focal mechanisms were constrained *a priori* to be double couple (DC), and we searched for results that could indicate effects related to possible isotropic source components. This was done by looking at the evolution of rotation angles of focal mechanisms over space and time in the Landers region, and comparing the results to those of synthetic tests. We showed that the observed rotations can result from neglecting small isotropic components in the derivation of focal mechanisms, and estimated the size of a possible neglected isotropic component.

Since the analysis of DC-constrained catalogs only provides indirect evidence on possible isotropic components, we also performed direct inversion of source tensors that do not include these constraints. We focused on the trifurcation area of the San Jacinto fault zone (SJFZ), where the large geometrical complexity of the fault zone structure suggests likely production of rock damage in earthquake rupture zones. The earthquake mechanisms were derived with a generalized ‘Cut and Paste’ (gCAP) inversion scheme (Zhu and Ben-Zion, 2013), using 3-component waveforms typically recorded by >100 stations at regional distances. The possible error in the isotropic components due to station variability was quantified with bootstrap resampling for each event. Tradeoff and correlation between isotropic and CLVD components were quantified using synthetic tests with realistic station configurations. Two different tests with velocity model perturbations were conducted to quantify the uncertainty due to inaccuracies in the Green’s functions.

2. Methodology and Results

2.1 Spatio-temporal variations of double-couple constrained focal mechanisms

We computed seismic potency tensors using geometrical relationships (Aki and Richards, 2002, p. 212) and an empirical potency-magnitude scaling relation (Ben-Zion and Zhu, 2002) from the strike, dip, and rake of fault plane solution (FPS) and local magnitude recordings. The employed FPS, locations and magnitudes were taken from the improved recent DC focal mechanism catalog of Yang et al. (2012). We focused on aftershocks of the 1992 Landers earthquake. The rotation angle (Kagan, 1991) between two sets of principal axes of P_{ij} based on DC mechanisms can quantify the geometric differences between two sources. We computed sets of rotation angles between the FPS of the Landers mainshock and each of the aftershocks in various spacetime windows to quantify the degree of source heterogeneity and temporal rotations in various fault sections. We chose three sub-regions of the Landers rupture zone (Figure 1) to analyze the distribution of rotation angles near the ends of the rupture and in the central section. This was done with the expectation that damage production should be stronger near the edges than in the center. We used this to quantify whether the focal mechanisms were scattering or focusing with

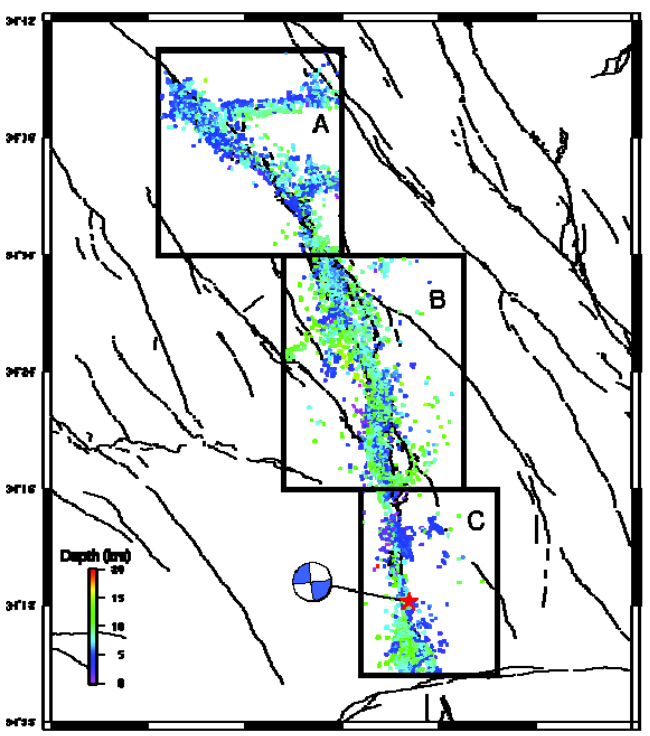

Figure 1. Aftershocks of the 1992 M 7.3 Landers in the eastern California shear zone. The study area is divided into three regions surrounding the two rupture ends and the central section. The epicenter locations are from the regional 1980-2010 focal mechanism catalog of Yang et al. [2012].

respect to the regional tensor.

We studied rotation angles in each of the three regions separately as a function of time. It was found that the most immediate aftershocks had the largest mean rotation angle, which then decayed as a function of time for all three regions. This meant that the aftershock focal mechanisms became more aligned with the mainshock focal mechanism as time increased. If the most immediate aftershocks are expected to be more like the mainshock than the later events, this would suggest that something is producing extra scatter in the rotation angles. In particular, we found that the temporal extent of the decay was strongest in the two edge regions, and weakest in the center, which is consistent with the expectations for brittle damage in rupture zones.

One explanation for the observed behavior was that a small isotropic component was present in the earliest aftershocks and neglected in the focal mechanism determination process. In such a situation, the error introduced by forcing the solution to be a double-couple would manifest in the form of a small rotation of the principal axes. It is expected that damage, and hence isotropic components, would be strongest in the edges of a rupture zone. We tested this with synthetic polarities, creating realistic station configurations with various amounts of isotropic component. The polarities were then inverted for the focal mechanism, which forced the solution to be a double couple. We calculated the average rotation for each value of isotropic component, and then estimated that the neglected isotropic component was 0.03-0.15 of the total event moment.

2.2 Isotropic source terms of San Jacinto fault zone earthquakes with a gCAP method

We performed full waveform inversion on a set of earthquakes in the SJFZ (Figure 2) using the gCAP procedure (Ross et al., 2014). We focused on the trifurcation area of the SJFZ because the large geometrical complexity of the fault zone structure suggests likely production of rock damage in earthquake rupture zones. The gCAP procedure accounts for isotropic and CLVD source components (Zhu and Ben-Zion, 2013); it involves breaking up each seismogram into Pnl and surface wave phases and performing a joint inversion to increase the estimation precision due to inaccuracies in the Green's function (Zhu and Helmberger, 1996). The two windows were filtered in different frequency bands: 0.05-0.3 Hz for the Pnl and 0.02-0.1 Hz for the surface waves. The southern California velocity model of Hadley and Kanamori (1977) was used. We investigated 7 earthquakes in the SJFZ, which occurred in the complex trifurcation region, each with $M > 4$.

We used a grid search over the parameter space of moment magnitude, strike, dip, rake, isotropic component, and CLVD to obtain the best fitting set of parameters. Generally each event was inverted with >100 3-component waveforms to ensure good station coverage. The distance range of the stations used was 40-300 km. For each earthquake, we found an explosive isotropic component in the range of 0.04-0.23.

We performed numerous statistical tests on each earthquake to verify that the isotropic components were statistically robust. The first test was a bootstrap resampling procedure (Efron, 1979) that resampled stations with replacement 1000 times and performed a new inversion for each. From these we derived 95% confidence levels for each earthquake, and found that all but one had a statistically significant explosive isotropic component. The next test we performed analyzed correlation between CLVD and isotropic components. This was done using synthetic deviatoric waveforms with various amounts of CVLD radiation. They were created for a realistic station configuration and inverted by allowing only double-couple and isotropic components (constraining CLVD to be zero). We found that for the range of CVLD values typical of tectonic earthquakes, the artificially retrieved isotropic components were generally smaller than the isotropic components obtained in the inversion of the real data.

The final tests we performed used velocity model perturbations to analyze the effect of velocity model errors on the isotropic components themselves. We generated 500 random velocity models perturbed from the original model and created Green's functions from each. Then each model was used to invert the original event data for a new set of best fitting parameters. We found that for five of the events, 90% of the velocity models led to an isotropic component that was explosive in type. This suggested that velocity model perturbations could not explain the consistency of the explosive isotropic component.

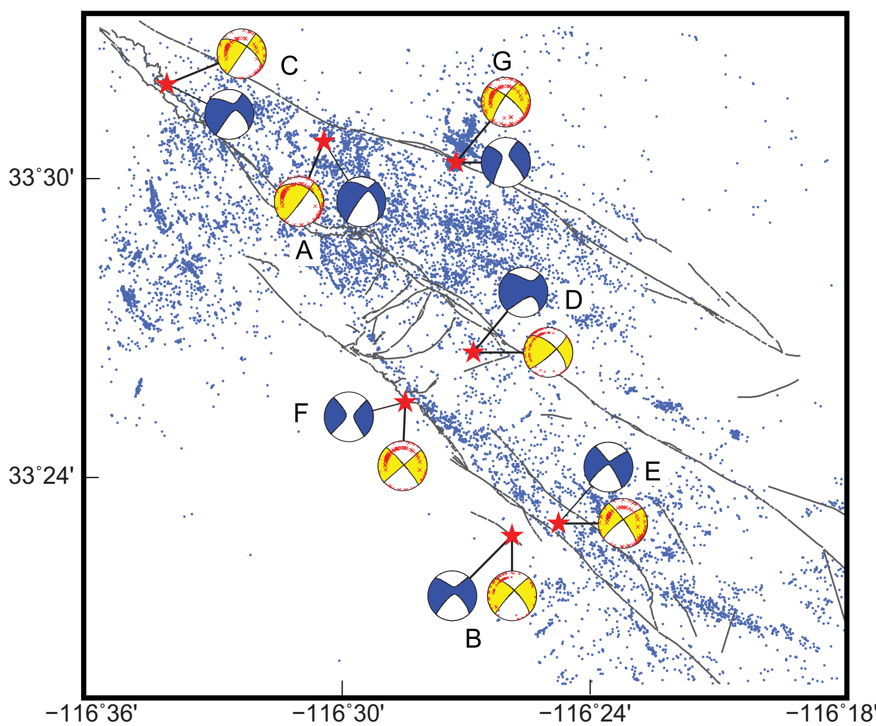

Figure 2. Inversion results for the analyzed earthquakes. The blue focal mechanisms are unconstrained full source tensor solutions determined from gCAP waveform inversions. Each earthquake is found to have a small explosive isotropic component. The yellow focal mechanisms are double-couple-constrained and show with red "+" symbols the locations of stations used in the derivations.

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