2026 SCEC Project Report

Numerical Simulations of the Change in Stress-State Inboard of the Mendocino Triple Junction

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Introduction

Mapping observational constraints to the state of stress along the plate boundary of the Western US can help to link the long-term forces driving tectonic plate motion to short-term dynamic earthquake ruptures (Zelst et al. 2019; Wirp et al. 2024). The northward migration of the Mendocino Triple junction along this plate boundary is marked by a fundamental change in boundary conditions from that of a subduction zone to that of a transform boundary; and, this change is recorded by tectonic, geodetic and seismic observations. To translate these observations into constraints on the stress state, we proposed to develop a geodynamic model of the passage of the triple junction. Using experimental constraints on the rock rheology, comparison of the model predictions to kinematic observations allows us to determine the variations in stress that are consistent with these observations. This overall project constitutes Dr. Tian's Xiaochuan's postdoc project on the regional tectonics of Northern California forearc.

For this specific SCEC proposal, we proposed to focus on 1) how the strain rate dependent rheology of the plate boundary shear zone enables the transition from active subduction to coupling of the subducted plate fragment to the overriding plate, and then 2) how the crustal rheology of the overriding plate affects the structural evolution of the new Pacific-North America plate boundary south of the MTJ. The first part is essential for producing the proper plate boundary tractions on the overriding plate, which defines the magnitude and orientations of stress acting on the fore-arc region. The second part is essential for understanding which structures (e.g., pre-existing fore-arc terrane) and/or rock properties lead to the style of strike-slip and reverse faulting observed in the SAF system proximal to the MTJ.

<u>**Change in Scope**</u>: In developing the MTJ model set-up it became clear that a major unknown is how rheology of the plate boundary and rheology of the overlying plate determine the strain partitioning of oblique plate motion. Previous studies, assuming a force-equilibrium condition, found that no upper plate strike-slip deformation occurs until a threshold value of the convergence obliquity is reached (McCaffrey 1992). However, a recent study cast doubt on this *all or nothing* partitioning model by showing that the overriding plate exhibits block rotation and strike-slip faulting regardless of obliquity

angle and that the relationship between obliquity and forearc deformation varies between margins (Morell et al. 2025). By researching models and observational constraints on this question, we decided that it made sense to first better understand the first-order control of this partitioning question before moving forward with fully dynamic models of the MTJ system. Therefore, below we report on the results to date and their implications for the MTJ geodynamics.

We also emphasize that while we have not yet completed the MTJ geodynamic models, we still expect to complete a subset of these models and be able to more directly address the original questions regarding the change in the state of stress imparted by migration of the MTJ.

Research Results

The research result consists of two components: 1) an updated theory for the mechanics of slip partitioning based on an assumption of energy minimization and 2) a global data analysis of strain partition using subduction zone focal mechanism (GCMT), kinematic plate motion model (GSRM) and slab geometry model (Slab2).

First, following on the work by Fitch (1972) and McCaffrey (1992), Dr. Tian re-evaluated their assumptions and reformulated the mechanical analysis using a least-energy assumption, and crucially, including the effects of variable slab dip. Using this approach, the theory predicts a regime diagram for earthquake obliquity (α) as a function of the subduction obliquity (β) and the slab dip (φ). Figure 1 shows the map view and cross-section geometry of the simple analytic model and the regime diagram. The regime diagram is divided into a “partitioned” region (gray) and non-partitioned region (white). The curve dividing these two regions depends on R, the ratio of the average shear stresses on the megathrust (τ_t) and the strike-slip fault in the upper plate (τ_s). The theory predicts that, given a R value, for margins with convergence obliquity below the dip dependent regime boundary, earthquakes on the megathrust can fully accommodate the trench-parallel strain arising from the oblique motion , whereas for conditions in the gray area, no earthquakes with these parameters should exist because it is energetically favorable to accommodate trench parallel motion within the overriding plate. Notice that the position of the regime boundary given by R is predicted to shift depending on the shear stress on the megathrust relative to the upper plate faults. This means that observations may provide a constraint on the strength ratio, R. While this does not provide an absolute constraint on megathrust strength, it allows the relative strength of the megathrust to be compared between subduction zones.

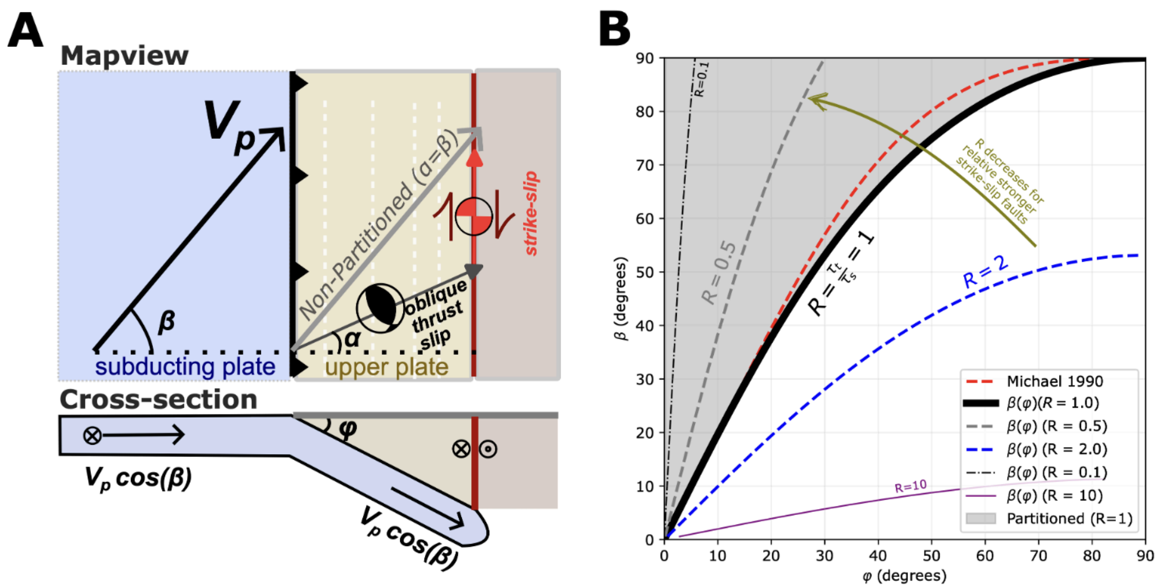

Figure 1: A. Geometry used for analysis of earthquake slip partitioning. B. Regime diagram for energy minimization analysis of slip partitioning. See text for explanation.

Second, motivated by the above mechanical analysis and following on the work by (Morell et al. 2025) we decided to examine partitioning of oblique subduction motion by evaluating subduction zone focal mechanisms for events shallower than 80 km in the vicinity of the megathrust. First, we used the present-day plate motion, the Slab 2.0 model of subducting slab geometry, and the trench location to determine the obliquity of plate convergence at the location of each event. Next, also using the Slab 2.0 model, events above magnitude 5 were classified relative to the megathrust interface to identify events most likely occurred on the megathrust, rather than above or within the subducting plate. For each event the focal mechanism was used to determine the slip obliquity relative to the local subducting plate geometry. At the same time, the Slab 2.0 model was used to determine the slab dip at the location of each event. Finally, a statistical analysis was performed to quantify how well the data fit the analytical predictions of the model. Figure 2 shows the results for Java-Sumatra and Aleutians subduction zones.

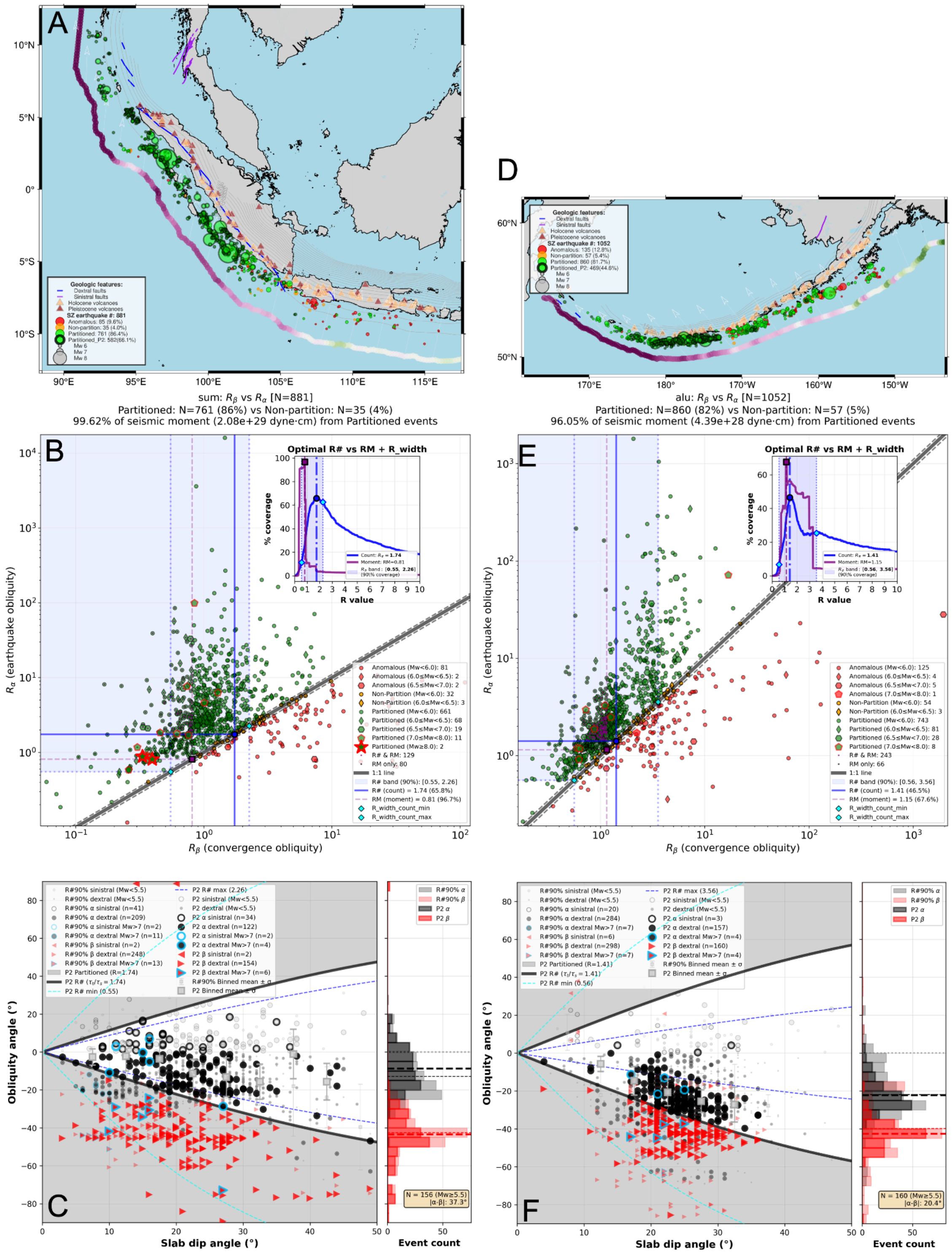

Figure 2: A-C: Java-Sumatra, D-F: Aleutians. A,D: Map of each subduction zone showing megathrust events and plate obliquity. B,E: statistical analysis of earthquake partitioning. C,F: Regime diagram showing best-fitting stress-ration (R) based on the statistical analysis. For each event, a red triangle shows the plate convergence obliquity and dip, while black circle shows the earthquake slip obliquity.

Intellectual Merit

The results for Java-Sumatra and the Aleutians demonstrate that the new analytical model captures the key physical processes controlling slip partitioning along the megathrust. First, for these two locations we find that less than 4 and 5% of events plot in the non-partitioned gray region of regime diagram agreeing with the prediction that at these conditions trench-parallel slip has been transferred to the overriding plate. Second, for the rest of the events occurring in the partitioned region (accounting for 99 and 96% of moment release) we find that the obliquity of these events are less than the convergence obliquity, but these events are not necessarily trench-perpendicular. These results show that 1) rather than there being a critical value for partitioning to occur, most events are in fact partially partitioned - some component of oblique motion is always being transferred to the upper plate; and 2) events are rarely fully partitioned. In addition, we find that the amount of partitioning increases with subduction obliquity. Global analysis of an additional 12 subduction zones confirms these results.

Finally, the statistical analysis of each region provides a predicted R value, which provides an averaged relative strength of the megathrust compared to the shear strength of the upper plate strike-slip fault. For Java-Sumatra the best fitting R-value is 1.7, whereas for the Aleutians the value is 1.4. Both of these values predict that the shear strength supported by the continental crust in the upper plate is similar to the shear stress supported by the megathrust. For comparison, the R-values for Japan and the Tonga-Kermadec are 5.8 and 3.7: these higher values indicate that the shear stress supported by the upper plate is substantially less than that supported on the megathrust.

We do not find a systematic correlation between the strength ratio, R, and other first-order subduction zone characteristics such as subducting plate age, oceanic versus continental overriding plate, trench motion (rollback versus advance) or subducted sediments (type or thickness). This lack of obvious correlation may indicate that there are a combination of factors affecting the strain partitioning, which may include time-dependence arising from spatial and temporal heterogeneity in stress. Such heterogeneity may arise from earthquake-cycle stress redistribution (Wang et al., 2012), episodic slow slip and tremor (Obara & Kato, 2016), fluid-related variations in effective normal stress (Audet & Kim, 2016), and geological timescale trench motion variations due to deeper slab dynamics (Billen & Arredondo, 2018). Consequently, instantaneous strain partitioning may represent a transient snapshot of an evolving subduction system rather than a fixed response to static subduction-zone parameters.

Broad Impacts

Because the Cascadia subduction zone has very low seismicity, the above analysis provides limited direct constraints for this margin. However, the global results do allow us to make some predictions for the partitioning of deformation and provide insight into the relative strengths of the megathrust and the overriding plate. The first prediction from the global result is that megathrust events do not accommodate the full convergence vector and instead, a substantial component of the trench-parallel motion is accommodated as permanent strain in the upper plate. The second prediction is that the southerly portion of the plate is more likely to have large partitioning of slip because this is the region with higher obliquity.

Although we have not found any systematic correlation between the R values and other subduction parameters, Cascadia is most commonly compared to the Nankai-Ryukyu subduction zone because both locations have young subducting plates with continental overriding crust and subducted sediments. The R value for Nankai is 0.70, which indicates larger shear stress in the upper plate compared to the megathrust and predicts that earthquakes on the megathrust will include a substantial component of the trench-parallel strain, rather than more complete partitioning of the deformation.

Next Steps: the MTJ Geodynamic Models

From the above analysis, we've learned that our geodynamic simulations should reproduce partial coupling of trench-parallel strain regardless of the observed obliquity of convergence. This observation provides a constraint on the material parameters (friction, cohesion and viscosity) controlling the strength of the shear zone between the subducting and overriding plate. Figure 3 shows the basic model set-up for the geodynamic simulations. The main suite of experiments will vary the obliquity of the subducting plate and shear zone parameters. We will then examine the partitioning of oblique motion into upper plate strain, how this varies across the triple junction and how this affects the stress state in the upper plate.

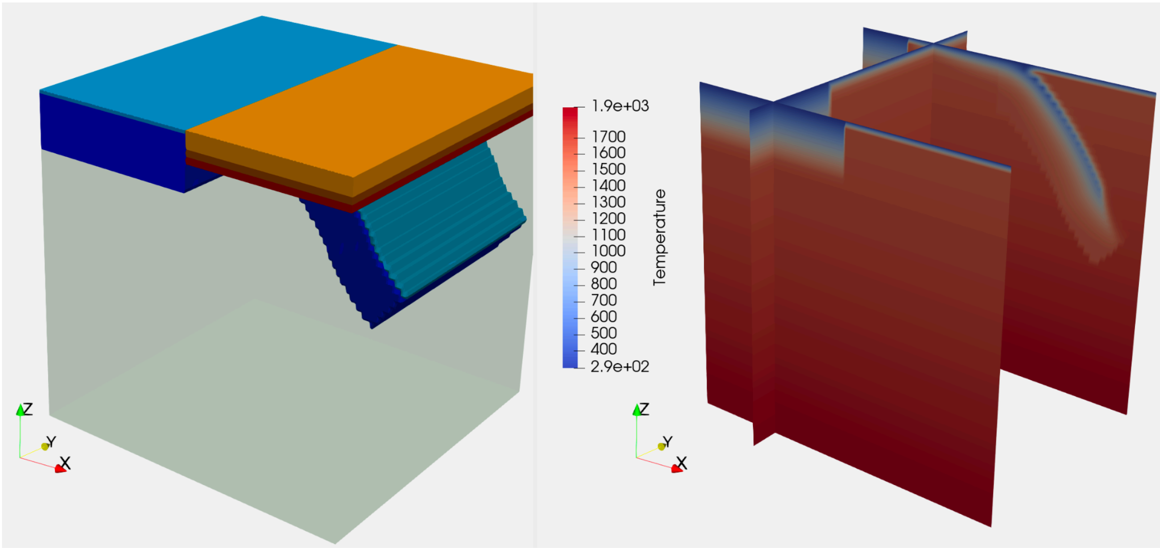

Figure 3: 3D perspective view of the plate geometries for the Mendocino Triple Junction geodynamic model. Left: The blue plates are portions of the modeled Pacific and Juan de Fuca Plates: the Juan de Fuca plate is connected to a subducted slab. The orange plate is a portion of the North America plate. Right: Cross sections showing only the oceanic plate thermal structure.

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