Overview Numerous field observations indicate the existence of complex crustal structures with heterogeneous fault zones that evolve due to damage accumulation from repeated earthquakes. A realization of damaged fault zones is the so called low-velocity fault zones (LVFZs) which exist in most mature faults. Within these zones, the wave velocity is estimated to be reduced by 20 to 60% relative to the host rock [1]–[6]. The existence of damage within the fault zone may impact the long-term behavior of the earthquake cycles, resulting in complex patterns, as well as an increase in the slip due to the added compliance. Thus, highlighting the need to incorporate accurately complex fault geometries in our seismic modeling. Accompanying the rise of numerical observations, computational tools capable of modeling earthquake complexities has emerged integrating field observations with high end computational methods. However, explicitly modeling damaged fault zones present a complex challenge due to the vastly different spatio-temporal scales leaving much to explore. The multiscale nature of the problem arises spatially due to the geometrical complexities and rupturing occurring on small sections of the faults, and temporally with the damage, prestress, and frictional properties evolving over different seismic time scales. Accordingly, earthquake cycle models that are capable of efficiently integrating damage and resolving different time scales remain crucial to obtain accurate predictions for seismic hazards.

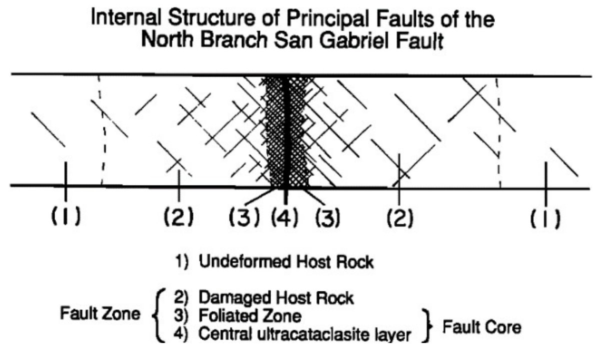

Figure 1 Schematic section across the north branch San Gabriel fault zone illustrating the different structural zones within the fault zone, adapted from article Chester et al. 1993 [4].

Traditionally, bulk methods such as finite difference (FD) and finite elements (FE) as well as Boundary Integral (BI) Method have been used extensively to model spontaneously propagating shear cracks in a variety of engineering and geophysical applications. More recently Hajarolasvadi and Elbanna [7] proposed a "hybrid scheme" that benefits from the strengths of each individual scheme without the drawbacks associated with it. This allowed for numerical modeling of earthquake ruptures at fraction of the cost, while accurately incorporating fault zone complexities. Abdelmeguid et al. [8] extended hybrid method to model the sequence of earthquakes and aseismic slip on rate and state faults within the quasi-dynamic limit. **Here we propose the extension of the hybrid method to earthquake cycle simulations of complex fault zone geometries studying the role of preexisting and evolving damage. Through the hybrid scheme numerical efficiency, we will be able to resolve the spatial scales associated with damaged fault zones, and by combining a quasi-dynamic and dynamic approaches be capable of resolving the temporal scales.**

The main motivation of the proposed work is to utilize the hybrid scheme superior computational capabilities to efficiently and accurately model earthquake cycles of faults with high resolution fault zone physics, focusing primarily on faults within damaged regions. For this specific thrust the commonly used approximation of quasi-dynamic is restrictive due to the substantial role reflected waves play within the damaged region. Accordingly, it is vital to have a scalable approach that captures the slow periods of aseismic slip and rapid occurrence of earthquake rupture accurately. The proposed scheme involves merging the quasi-dynamic hybrid approach for inter-seismic periods and aseismic slip with the dynamic hybrid scheme for earthquake ruptures. ensure continuity.

Main Results:

Problem Description: We choose a domain with the same dimensions, elastic properties, and frictional parameters as SCEC SEAS-BP2. We implement a pressure sensitive visco-plastic rheology for the off-fault material with cohesion = 20 MPa, tangent of angle of internal friction = 0.6, and viscosity coefficient = 2 * elastic shear modulus.

The normal stress in the bulk is assumed to vary linear with depth. The normal stress on the fault is assumed to vary linear with depth down to 2.5 km and then remains constant after that at a value of 50 MPa. This distribution of the fault normal stress corresponds to the pore pressure increasing hydrostatically in the shallow layer (~ 2.5 km) and then increasing litho-statically after that.

The initial shear stress distribution is computed assuming initial slip rate of 1 nm/s and steady state conditions for the state variable.

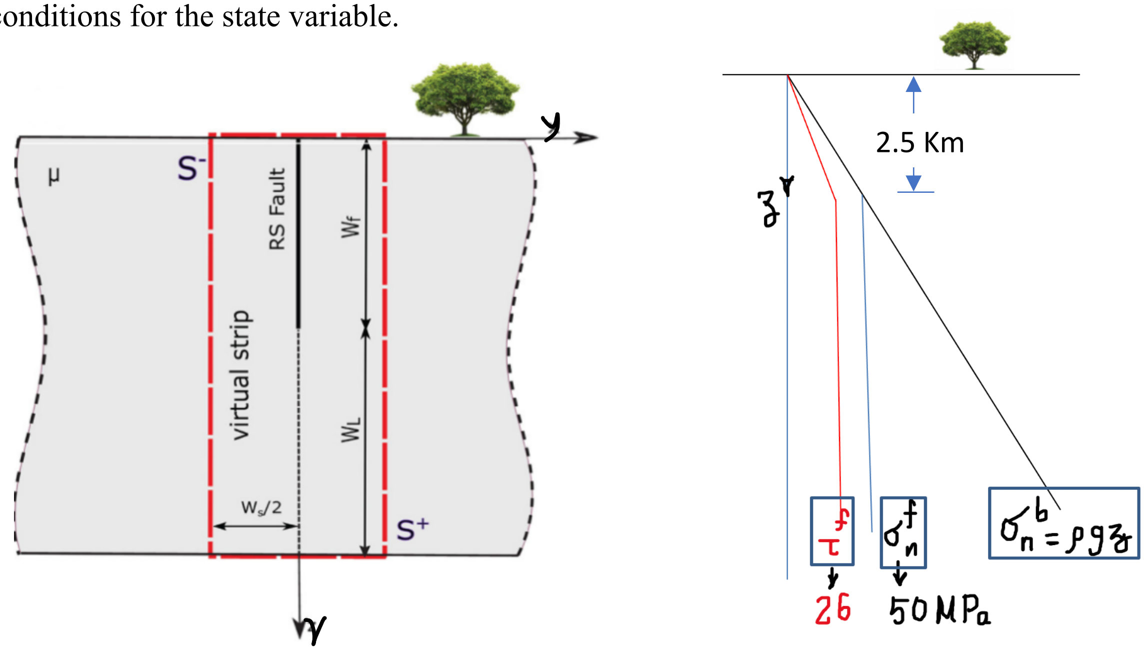

Figure 2: Problem setup. (a) Problem geometry identical to SEAS-BP2. (b) A schematic representation of the variation in the bulk normal stress, fault normal stress, and fault shear stress with depth.

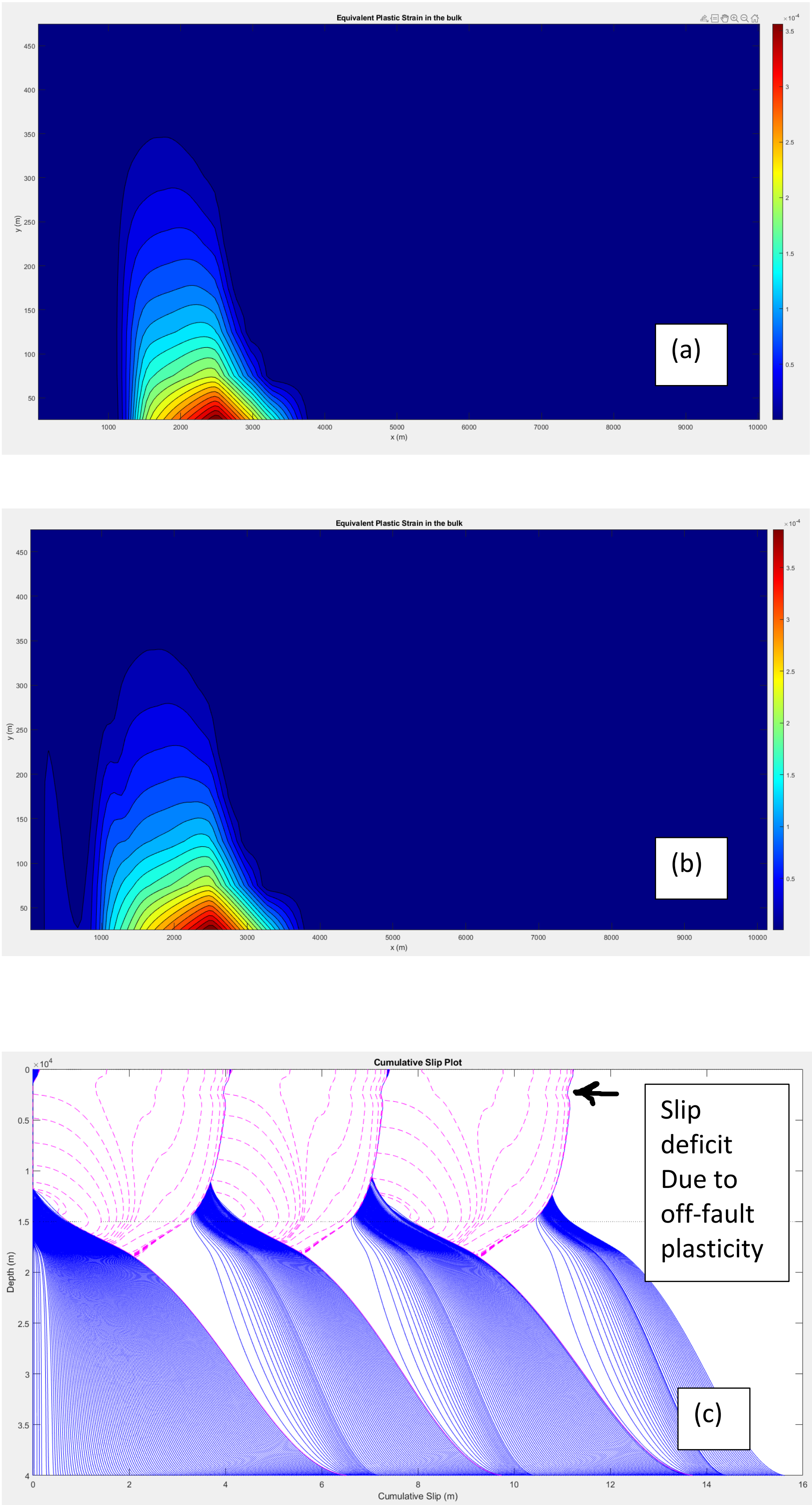

Figure 3: Evolution of off-fault plasticity and fault slip during a sequence of earthquakes and

aseismic slip using the hybrid FEBI method with alternating quasidynamic (during aseismic slip) and full inertial dynamic (during seismic slip). (a) Off-fault equivalent plastic strain after the 1st seismic event. (b) Off-fault plastic strain after the 3rd seismic event. Note that the plastic strain has grown in extension both along the fault strike-parallel direction (denoted here by the x-axis) and the fault strike-normal direction. The equivalent plastic strain has also increased in its magnitude. (c) Fault slip distribution. Blue lines represent aseismic slip drawn every 5 years. Magenta lines represent seismic slip drawn ever 1 minute. Note there is a slight dip in the slip distribution at around depth = 2.5 km, highlighted by the black arrow. This dip represents a deficit in slip accumulation on the fault plane due to an increase in the off-fault plastic strain in this region. In other words, the deformation in this zone has been partially accommodated by bulk inelasticity.

Publications and Presentations: AGU 2020 Presentation: NG010-01 - Modeling Sequence of Earthquakes and Aseismic Slip With High Resolution Fault Zone Physics (Invited)

Broader Impacts: Training of two PhD students: Md Shumon Mia (MechSe) and Mohamed Abdelmeguid (CEE) who are working on developing computational tools for modeling SEAS with high resolution fault zone physics.

Intellectual Merits: Advancing the state of the art of computational earthquake dynamics by enabling simulations of sequence of earthquakes and aseismic slip with off-fault bulk inelasticity on large scale.