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Spatiotemporal evolution of a fault shear stress patch due to viscoelastic interseismic fault zone rheology

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ABSTRACT

We conducted numerical studies to explore how shear stress anomalies on fault planes (shear stress patches) evolve spatiotemporally during the interseismic period under the influence of viscoelastic rheology assigned to fault zones of finite thickness. 2-D viscoelastic models consisting of a fault zone and host rock were sheared to simulate shear stress accumulation along fault zones due to tectonic loading. No fault slip along a distinct fault planes is implied in the model, thus all fault shear motion is accommodated by distributed deformation in the viscoelastic fault zone. Results show that magnitudes of shear stress patches evolve not only temporally, but also spatially, especially when the stress anomaly is created by a geometrical irregularity (asperity) along the interface of an elastic host rock and viscoelastic fault zone. Such shear stress anomalies diffuse spatially so that the spatial dimension of the shear stress patch appears to grow over time. Models with varying fault zone viscoelastic properties and varying fault zone viscosity both show that such spatial diffusion of shear stress is enhanced by increasing the contribution of the viscous behavior. The absolute rate at which shear stress patches grow spatially is generally not influenced by the size of the shear stress patch. Therefore shear stress patches with smaller dimensions will appear to grow quicker, in the relative sense, compared to larger stress patches. These results suggest that the minimum dimensions of shear stress patches that can exist along a fault could be governed by the effective viscosity of the fault zone. Therefore patterns of accumulated shear stress could vary along faults when viscous properties are heterogeneous, for instance due to depth or material heterogeneity, which has implications on how earthquake rupture behavior could vary along faults.

1. Introduction

Earthquake fault slips are spontaneous phenomenon driven by shear stresses acting on fault planes. Therefore mechanical understandings of earthquake ruptures require the knowledge of (1) the stress condition along faults prior to an earthquake, and (2) conditions leading to fault frictional instability. In the past decades, there have been many studies addressing the latter aspect, which have investigated the cause of fault instability (Brace and Byerlee, 1966) and revealed various fault weakening mechanisms such as rate and state friction (Dietrich, 1979), thermal pressurization (Lachenbruch, 1980), and rock dynamic weakening at high velocities (Tsutsumi and Shimamoto, 1997; Mizoguchi et al., 2006). On the other hand, relatively fewer studies have dealt with the former aspect of characterizing the origin and distribution of fault-resolved shear stress which accumulates between earthquakes.

The importance of understanding fault shear stresses is evident from geophysical observations and theoretical studies. Geodetic studies from subduction zones reveal heterogeneous distribution of fault locking degree which indicates that slip deficits relative to the steady plate motion accumulates unevenly along faults (Burgmann et al., 2005; Chlieh et al., 2008), creating a heterogeneous fault shear stress distribution. Such patterns of locking degree have been shown to exhibit close spatial correlation with the distribution of coseismic fault slip inverted from seismic waveforms of megathrust earthquakes (Moreno et al., 2010; Loveless and Meade, 2011). Recent dynamic rupture models incorporating fault roughness and initial stress heterogeneities (Ampuero et al., 2006; Ripperger et al., 2007; Dunham et al., 2011c; Fang and Dunham, 2013) also show that the final slip distributions of modeled earthquake ruptures are heavily influenced by the initial distribution of stress along modeled faults.

It is also suggested that the degree of the stress heterogeneity varies along a fault based on frequency contents of radiated waves. Recent observations from megathrust earthquakes shows that sources of high-frequency radiation revealed from back-projection methods tend to locate at the deeper regions of the seismogenic zone, although fault slip is generally greater at shallower depths (e.g., Wang and Mori, 2011; Yao

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et al., 2011, 2013; Kiser and Ishii, 2012; Lay et al., 2012). Results by Yao et al. (2013) specifically suggest that there may be a continuous deepening trend of radiation source locations, from the trench to the down-dip limit of the seismogenic zone, as the frequency of the band-passed waveforms increase. If high-frequency waves are to be emitted from the acceleration and deceleration of rupture fronts, these observations suggest that the degree of heterogeneity of fault shear stress and/or frictional properties increases with depth. Along-strike contrast in frequency content of radiated waves was also seen from strong motion data during the Chi-Chi earthquake (Ma et al., 2001). Whether this case should also be interpreted as a consequence of difference in stress or fracture energy heterogeneity is unknown, but suggests that fault stress heterogeneity could have bearing on ground motions caused by earthquakes.

The development of fault shear stress is typically considered to result from steady elastic loading on a fault interface, which is either fully or partially locked obeying some fault friction law. As mentioned above, geodetic observations allow us to invert for the locking degree distribution along a fault, but the limited resolution only yield first order patterns of fault locking. Alternatively, interseismic fault behavior can be forward modeled in numerical models capturing fault slip behavior spanning multiple earthquake cycles (Lapusta et al., 2000; Hetland et al., 2010). These studies provide one complete picture of how interseismic and coseismic processes influence each other, but spatial scales of the heterogeneities produced in these models are often restricted to the length scale of the heterogeneity provided a priori in the model (e.g. the distribution of frictional properties, segmentation between seismic and aseismic regions). We also argue, as discussed below, that interseismic fault behavior may not be best represented by friction laws that govern localized deformation along zero-width fault planes. We still have limited knowledge about how fault stress heterogeneity develops at various scales.

In this study, we focus on one fundamental aspect of interseismic fault shear stress development. We investigate numerically how a single stress anomaly on a fault plane evolves over time when viscoelastic rheology is introduced for materials constituting fault zones. The aim is to gain a basic understanding of a source process, namely the behavior of a single stress patch on a fault, which shall lead to our comprehension of fault stress heterogeneities and their development in general.

There are several reasons why we focus on the influence of viscoelastic rheology in contrast to common fault models which consider frictional interfaces embedded in elastic host rocks. First of all, rocks do exhibit viscoelastic properties even at depths shallower than the brittle–ductile transition without occurrence of crystal plastic creep of silicate minerals. The process of fault stress loading takes place over long time scales on the order of decades to centuries which suggests that slow bulk deformational processes such as volumetric creep assisted by compaction (Dudley et al., 1998; Hagin and Zoback, 2004; Chang and Zoback, 2009; Sone and Zoback, 2013) or pressure solution (Weyl, 1959; Durney, 1972; Gratier and Guiguet, 1986) can also become an important process that influences the stresses loaded on faults during the interseismic period. Sone and Zoback (2014) studied the time-dependent deformational properties of shale gas reservoir rocks and showed that rocks with Young's modulus as high as 20–60 GPa can exhibit enough time-dependent behavior to relax significant fractions of differential stresses applied to the rock over engineering time scales (i.e. less than decades).

These time-dependent rock behaviors caused by the presence of some porosity are usually considered to be effective at shallower conditions compared to seismogenic depths (few tens of km). However, if we acknowledge the facts that (1) rock materials within and around faults are highly damaged (Chester et al., 1993), (2) many tectonic and petrophysical evidences point to pore pressure ratios (pore pressure divided by lithostatic stress) close to 1 along subduction plate boundaries (Audet et al., 2009; Saffer and Tobin, 2011), and (3) temperature along plate boundaries are significantly lower than the surroundings (Hyndman and Wang, 1993; Hyndman et al., 1995; Wang et al., 1995), it is not unreasonable to expect that rock rheological behaviors typically considered at engineering depths (<few km) also apply to seismogenic depths along subduction zones. Studies of postseismic crustal deformation have also indicated that either time-dependent afterslips or off-fault viscous deformation is needed to explain transient crustal deformations observed after large earthquakes (Thatcher and Rundle, 1984; Savage, 1995). Thus it is plausible to believe that many rock materials at seismogenic depths can also exhibit significant viscous behavior over geological time scales. If fault rocks and the surrounding host rock exhibit time-dependent behavior, tectonic loading of fault stresses may not be as simple as described by frictional surfaces embedded in elastic mediums. Time-dependent viscous deformation relaxes stress simultaneously as it is also being loaded steadily over time.

In this paper, we argue that viscous deformation around asperities can alter the spatial pattern of stress anomalies along faults in addition to its effect on stress magnitudes. We also study how differences in fault rheological properties (e.g. viscosity, type of constitutive law) affect the spatial evolution of fault stress anomalies during interseismic loading. This is motivated by the possibility that change in fault rock properties may help explain the difference in fault stress heterogeneity with depth, and possibly along-strike, suggested by seismological observations.

2. Finite element model setup

2.1. General description

We conducted 2-D time-dependent quasi-static calculations using the finite element modeling software PyLith 2.0.3 for Windows (Aagaard et al., 2013, 2015) to investigate how a patch of shear stress anomaly on a locked fault plane evolves over time when viscoelastic rheology is introduced to the materials within and around a fault zone. The models consist of a 2-D (plane strain) rectangular block of 200 m by 30 m dimension where one of the long edges is considered to be the fault plane and the other side considered to be some boundary

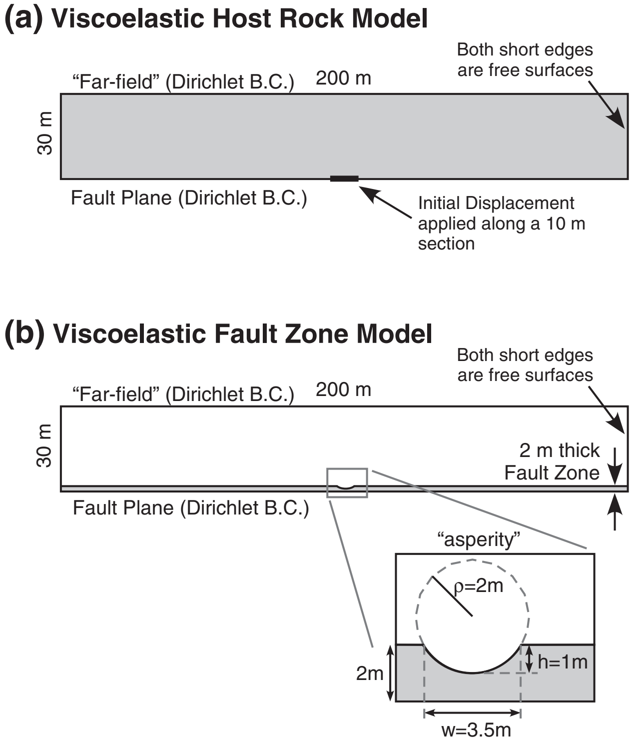

Fig. 1. Schematic diagrams of the 2-D finite element model used in this study. (a) Viscoelastic host rock model. (b) Viscoelastic fault zone model.