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Dynamic triggering of earthquakes is promoted by crustal heterogeneities and bimaterial faults

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ABSTRACT

Remotely triggered earthquakes and aftershocks constitute a great challenge in assessing seismic risk. A growing body of observations indicates that significant earthquakes can be triggered by moderate to great earthquakes occurring at distances of up to thousands of kilometres. Currently we lack the knowledge to predict the location of triggered events. We present numerical simulations showing that dynamic interactions between material heterogeneities (e.g. compliant fault zones, sedimentary basins) and seismic waves focus and enhance stresses sufficiently to remotely trigger earthquakes. Numerical simulations indicate that even at great distances (>100 km), the amplified transient dynamic stress near heterogeneities is equivalent to stress levels near the source rupture tip (<5 km). Such stress levels are widely considered capable of nucleating an earthquake rupture on a pre-stressed fault. Analysis of stress patterns in dynamic rupture simulations which include a heterogeneous zone with a range of material and geometrical properties reveals various mechanisms of stress enhancement. We conclude that both stiff and weak heterogeneities may focus stress waves to form zones of enhanced stress, and that bimaterial interfaces distort under static and dynamic loading in a way that induces local stress concentrations. Our work provides insights for understanding non-uniform distribution of remotely triggered seismicity and recurrence of such events along complex fault-systems and near magmatic intrusions and geothermal zones.

1. Introduction

Earthquake triggering is the process by which stress changes associated with an earthquake can induce or retard seismic activity in the surrounding region. Static stress changes are permanent and produce increased seismicity rates where stress increases (stress triggering), or decreased seismicity rates where stress decreases (stress shadowing). Calculations of static Coulomb stress transfer have proven to be a powerful tool in explaining near-field aftershock distributions (King et al., 1994; Stein et al., Mar 1997; Harris and Simpson, 1998; Pondard et al., 2007; Sumy et al., 2014). Dynamic stress changes due to the passage of seismic waves cause transient dynamic stress oscillations and as such are positive everywhere at some point in time. The physical origin of dynamic triggering remains one of the least understood aspects of earthquake nucleation. We assess some of the mechanisms involved in dynamic triggering. The majority of previous studies have focused on near-field static stress changes that trigger aftershocks, and some studied dynamic stress patterns near fault tips (Finzi and Langer, 2012a,b; Lozos et al., 2012). However in this work we focus on dynamic triggering far away from the fault and aim to elucidate some of the path-dependent mechanisms occurring in remotely triggered seismicity (RTS). While these mechanisms are also present in near field we focus on remote triggering far away from the earthquake source where the contributions from the static stress changes are small and the path-dependent dynamic effects are dominant. The current work reveals how certain fault-zone structures may dynamically amplify and focus seismic waves and induce nucleation of RTS. While a great amount of attention has focused on forecasting near-field aftershocks the topic of RTS remains a great challenge in seismic hazard analysis.

Remotely triggered seismicity has been reported following numerous large earthquakes such as the 2002, M7.9 Denali and the 1992, M7.3 Landers earthquakes (Eberhart-Phillips et al., 2003; Steacy et al., 2005; Hill et al., 1993). RTS at extremely large distances (> 1000 km) has been associated with passing S and surface waves (Gomberg and Davis, 1996; Kilb et al., 2000; Gomberg et al., 2003; Lei et al., 2011). In fact, RTS is often described as the

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result of extremely weak stress perturbations acting on critically stressed faults (van der Elst and Brodsky, 2010). We investigate another mechanism of importance in RTS, where low amplitude stress perturbations may be amplified sufficiently by certain tectonic structures or heterogeneities to induce nucleation along faults that are not necessarily critically stressed.

Dynamic stress waves also affect induced seismicity in the near-field as they do far from the source event. Examples include reported seismicity following moderate ($M < 7$) earthquakes (Hough, 2005) and dynamically triggered complex multi-segment earthquake sequences (Finzi and Langer, 2012a; Hill and Prejean, 2007; Hough, 2005). In fact, dynamic stress waves and their interaction with various fault structures is often considered as an explanation for aftershock patterns that deviate from those of static stress patterns (Freed, 2005).

To date, the underlying mechanisms for remote triggering remain a matter of continuing debate (Brodsky and Prejean, 2005; Prejean and Hill, 2009; Lei et al., 2011; Gomberg, 2013). It is well established that directivity effects can cause enhanced RTS in the rupture direction (Gomberg, 2013). However directivity and other source related effects cannot always fully explain why in some cases faults close to the source remain inactive whereas for the same earthquake distant faults are triggered. Therefore additional information such as path-dependent effects and local stress amplifications are required in order to determine if a fault-zone is likely to experience RTS. Recently, stress amplification on remote faults was also shown to be associated with dynamic interactions between seismic waves and geological structures (Gomberg, 2013). In her paper, Gomberg (2013) proposes that certain fault structures repeatedly experience RTS due to local dynamic interactions with passing seismic waves. In this paper we elucidate the mechanisms underpinning these interactions.

Many studies have shown how structural features such as low-velocity fault zones (Fohrmann et al., 2004) or sedimentary basins (Gomberg et al., 2004; Hartzell et al., 2010) can cause trapped waves and seismic wave amplification. Stress-enhancing interactions were also described in studies of wave reflection off the Moho or the Earth's core (Lin, 2010; Hough, 2007) and dynamic stress concentration along bimaterial interfaces (Stoneley, 1924; Burridge, 1973; Finzi and Langer, 2012a; Lei et al., 2011). While the phenomena of "seismic waves focusing", excitation of bimaterial interfaces and large scale wave reflections have long been studied in various geophysical contexts, only a few recent studies account for such processes in the context of remotely triggered seismicity (Lin, 2010; Lei et al., 2011; Gomberg, 2013).

We extend these studies by showing numerically how significant stress concentrations due to material heterogeneities far from a source earthquake may induce remotely triggered seismicity. We show how even smaller magnitude earthquakes can trigger far-field seismicity by considering the effect of crustal heterogeneities such as fault zones, basins and igneous bodies. While other studies (Fohrmann et al., 2004; Gomberg, 2013) have solely focused on the interactions between seismic waves and low-velocity zones, we demonstrate how dynamic interactions between the seismic waves and both compliant and stiff geological structures may induce remotely triggered seismicity in and around these structures.

2. Methods

2.1. Numerical simulations of dynamic stress transfer in a heterogeneous crust

In order to simulate remotely triggered seismicity we set up a Finite Element model domain where we solve the wave equation for dynamic rupture at a fault. Excitation of distant faults and bimaterial interfaces is studied by calculating Coulomb Failure Stress (CFS) throughout the model domain and by noting potentially significant occurrences of anomalously low and high values. Two principal triggering criteria are used to measure the likelihood of RTS. One is the threshold of peak transient CFS of the radiating seismic waves (Hill et al., 1993; Gomberg et al., 1997). A second criterion calculates the magnitude of the cumulative energy exerted at the fault (Brodsky et al., 2000). In the discussion we compare these two measures and show they give slightly different estimations of the likelihood of RTS.

We show that path effects are as important as source effects for RTS by examining the dynamic stress-enhancing interactions between seismic waves and heterogeneities embedded in the model domain. While most natural heterogeneities represent weakened zones such as damaged fault-zones and sedimentary basins, we also examine stress-enhancing interactions in the presence of a stiff zone (e.g. Vauchez et al., 1998 and Tommasi et al., 1995). This enables a better understanding of the various stress-enhancing mechanisms.

We simulate tectonic loading and dynamic rupture using the same method as our previous study of multi-segment dynamic stress patterns (Finzi and Langer, 2012a). We use the 2D finite element code esys.escript (Gross et al., 2007). The fault (see Fig. 1) is embedded in a homogeneous medium with rigidity $G_0 = 30$ GPa, first Lame parameter $\lambda = 30$ GPa, density $\rho = 2700\ \text{kg/m}^3$ and shear wave velocity $v_S = 3333$ m/s. The model domain is loaded with a stress tensor such that the unruptured source fault is optimally aligned with respect to the Coulomb Failure stress under the condition of a static coefficient of friction $\mu_s = 0.6$ (for more modelling constraints see Supplementary material).

The simulated earthquakes along the source fault are 60 km long with M_w7, an average slip of approximately 5 m and a maximum slip of 9 m at hypocentral depth (values chosen to be consistent with geologic observations; Wells and Coppersmith, 1994). Furthermore, the prescribed fault friction parameters ensure that simulated earthquakes exhibit sub-shear pulse-like ruptures.

A material heterogeneity in the form of a compliant/stiff zone of 8 km by 16 km is located at one fault length or 60 km East of the source fault (model A). Simulation results for two fault lengths separation between model and heterogeneity zone (model B) can be found in the Supplementary material section. The compliant material zone has a rigidity $G_A = 0.7G_0$. As the first Lame parameter and density are kept unchanged, the shear wave speed in the heterogeneity is $v_A = \sqrt{0.7}\,v_S$. The material properties of the stiff zone are $G_A = 1.3G_0$ and $v_A = \sqrt{1.3}\,v_S$. While a material contrast of 30% is large in terms of typical lithology variations in the crust, it represents various tectonic settings in which soft sediments accumulate in a basin or accretionary prisms bounded by stiffer material (Gomberg, 2013; Shani-Kadmiel et al., 2012; Shani-Kadmiel et al., 2014; Hartzell et al., 2010 and DESERT group studies, e.g. Weber et al., 2009) and across large faults such as the San Andreas (Brietzke and Ben-Zion, 2006 and references therein). Fig. 1 shows the configuration of our simulations, and other configurations used to test specific hypotheses are explained further in the discussion (see also Supplementary material for more details). Rupture is initiated at the star location in Fig. 1 and after a short bilateral propagation phase, it proceeds unilaterally East towards the heterogeneous zone.

2.2. Analysis: peak transient CFS as a fault stability criterion

We conduct multiple dynamic rupture simulations assigning different elastic properties and geometrical characteristics to the material heterogeneity. To determine whether a rupture could nucleate on a remote fault in our model domain we calculate the peak transient Coulomb failure stress (peak transient CFS) on