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The emergence of seismic cycles from stress feedback between intra-plate faulting and far-field tectonic loading

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A B S T R A C T

Using numerical modeling we show the emergence of cyclic slip behavior of faults from stress feedback through an idealized fault, its surrounding plates and far-field tectonic stress. The tectonic stress is exerted on the fault through a force applied along an idealized plate margin, acting on the fault, resulting from the interactions of viscous embedding and external plates. We find that, in such coupled system, the interaction of plates results into feedback with periodic deformation, slip along the fault and episodic plate margin motions. The viscosity of the embedding and loading plates primarily control the stress-loading time and hence the slip recurrence interval. For an Earth-like range of lithospheric viscosities, we derive a power-law with negative exponent, −0.99 to −0.5, scaling the recurrence period with loading-rate, providing an explanation for the observables from paleoseismology and geodesy. The feedback between single fault and far-field stress that arises from interactions of deforming plates provides a context to understand the earthquake cycle within continents, while reconciling the short-term seismic deformation to the long-term plate tectonics frame.

1. Introduction

Mechanical rupture and sliding on faults in continental interiors and along plate boundaries are governed by similar processes (Stein et al., 2009). However, the recurrence period (Scholz et al., 1986; Newman et al., 1999; Yin et al., 2014) and aftershock duration (Tuttle et al., 2002; Stein and Liu, 2009) of many mid-continent earthquakes are much longer compared to those occurring along convergent plate boundaries, and the reason for that has remained elusive. This affects directly seismic hazard assessment within continent interiors, due to the occurrence of several unpredictable and destructive seismic events in mid-continental regions (Gupta et al., 2001; Newman et al., 1999; Liu and Wang, 2012) such as North China (e.g., 2008 M_w 7.9 Wenchuan earthquake), western India (e.g., 2001 M_w 8.0 Bhuj earthquake) and central North America (e.g., 1811–1812 M_w 8 New Madrid earthquakes).

Although likely governed by the same mechanisms, differences between earthquakes occurring in mid-continent and plate boundary environments are many. The most distinct difference in mid-continental region is the markedly slower loading-rate, i.e. <1 mm/yr, which was inferred from geodetic studies of seismogenic faults in mid-continental regions (e.g., Craig and Calais, 2014). Loading-rates on faults are correlated with the large distance between the fault and the nearest plate boundary yielding a longer recurrence period (e.g., Scholz et al., 1986). The correlation among the distance, recurrence period and slip-rate is in agreement with the idea that tectonic stresses propagate from the plate margins, where tectonic forces apply, into deforming continent interiors. Many studies provide evidence of intraplate stress field primarily governed by the propagation of stress from tectonic plate margins (e.g., Zoback et al., 1989; Sandiford et al., 2004). These stresses are likely sustained over long-term, determining features of intraplate deformation (Calzolari et al., 2016). This idea is further corroborated by GPS evidence of co- and inter-seismic deformation observed at a distance of 1,500 to 3,000 km from the Sumatran–Andaman plate boundary in Southeast Asia (Vigny et al., 2005; Trubienko et al., 2013), and possibly continuing over the long-term, as in the case of the post-seismic deformation in South America caused by the 1960 earthquake (e.g., Hu et al., 2004; Khazaradze et al., 2002). However, to date the controls of tectonic forces and deformation on the occurrence and recurrence of earthquakes in continental interiors remains unaddressed.

Stein and Liu (2009) illustrated an almost inverse proportional relationship between the aftershock duration, which generally becomes longer with increasing recurrence period (Dieterich, 1994),

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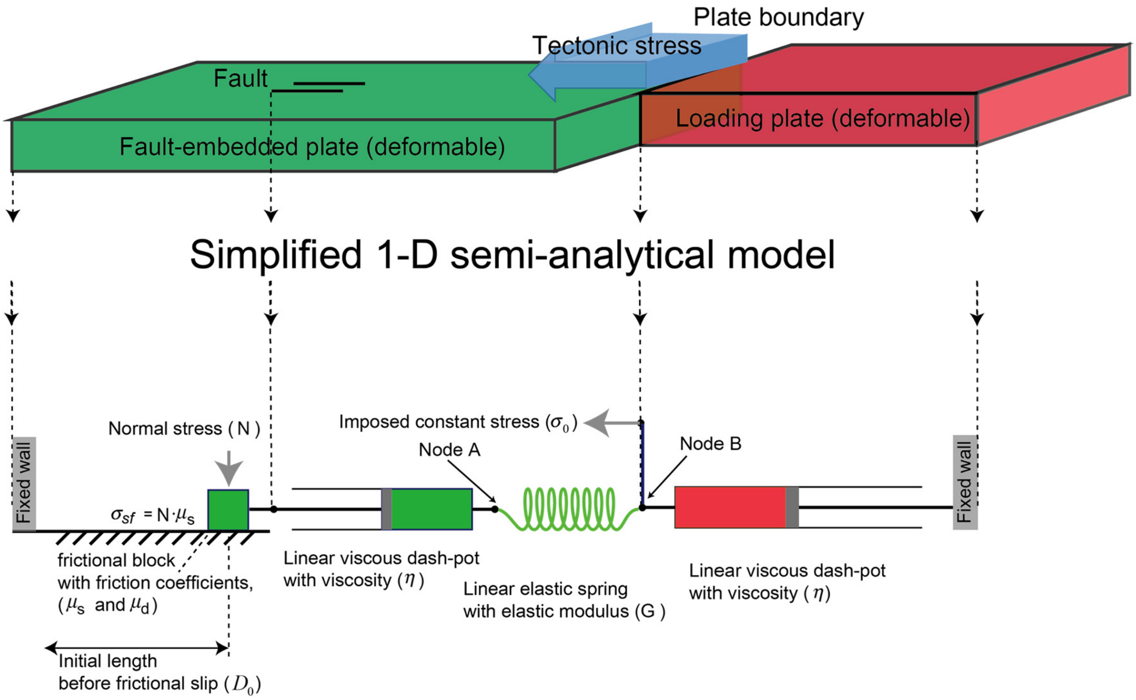

Fig. 1. The top row shows a schematic diagram of fault-embedded (green-colored region) plate, loading plate (red-colored region), and tectonic stress (blue-colored arrow). In comparison to traditional approaches (i.e., constant velocity and stress conditions applied by rigid boundary), our model allows the loading-plate to deform, and the stress to distribute to both the fault-embedded and loading plates following stress accumulation/release on the fault. The bottom row represents the simplified 1-D semi-analytical model which is comprised of frictional, viscous and elastic elements. The fault is described as a frictional block with static (μ_S) and dynamic (μ_d) friction coefficients. Viscous and elastic behaviors are modeled by dash-pot and linear spring, respectively.

and loading-rate based on the data from paleo-seismological (e.g., Atwater et al., 2003) and geodetic studies (e.g., Sauber et al., 1994). A more detailed analysis of various regional tectonic settings (Stein and Liu, 2009) showed that loading-rates decrease in domains located at an increasing distance from the plate margins to intraplate regions, although the correlation flattens around plate margins. This observation is also matched by the GPS-constrained tectonic deformation within the whole Tibetan Plateau (Clark, 2012) and several subduction zones (Trubienko et al., 2013). This evidence suggests that, over the long-term, a scaling law between the recurrence period and the background loading-rate exists which must follow from the basic tenet of plate tectonics which prescribes stress propagation from plate margins towards their interiors (Molnar, 1988).

Alternative mechanisms proposed for the occurrence of mid-continent earthquakes include local shear/vertical stress perturbation caused by mantle circulation (e.g., Heimpel and Olson, 1996; Becker et al., 2015), topography (van der Pluijm et al., 1997), surface erosion (e.g., Calais et al., 2010) and glacier removal (Grollimund and Zoback, 2001), which are related to local factors and do not reconcile with the large-scale plate tectonics framework.

Here, we consider far-field stress propagation from plate boundaries as a viable process to constrain the observed relation between the loading-rate and recurrence interval of mid-continent earthquakes, and their link to regional stress fields. Previous studies (Li et al., 2009; Kenner and Segall, 2000; Liu et al., 2014) suggested the relevance of time-dependent stress transfer between the fault and surrounding region (e.g., other faults, upper crust and lower crust and upper mantle) on the recurrence interval and spatio-temporal clustering of intraplate seismicity. Here, we follow the same principle and consider the transfer of far-field stresses, instead, resulting from the balance across scales between plate interiors, margin and neighboring plate. We illustrate a self-consistent framework to model the recurrence of slip along idealized faults and their loading-rate, under the effect of far-field stress propagation from plate boundaries. This system comprises an idealized deforming visco-elastic plate loading a frictional plastic fault and an external, viscous loading plate. Therefore, the stress in the internal and the external plate must balance, redistributing in time to deforming fault, internal or external plates. A 1-D semi-analytical numerical approach is used to calculate loading-rates and slip cycles based illustrating the emergence of stress feedback through the fault, deforming lithospheres, and plate boundary. We show a scaling law that encompasses a wide range of timescales, including both plate boundary and mid-continent earthquakes, and discuss the relevance for short- and long-term continental deformation.

2. Modeling approach

We investigated the role of self-consistent stress transfer in seismic recurrence periods, in terms of the feedback between the idealized fault, its surrounding plates (i.e., internal fault-embedded and external loading plates), and the far-field tectonic forces. Our model is generalized to a tectonic setting where the stresses within a single plate are in balance with the surrounding plates. In this case, we consider a visco-elasto-frictional lithospheric region, the internal plate, loaded through its margin by a constant tectonic stress applied through a continuous, external deforming viscous plate (see Fig. 1). The tectonic stress is self-consistently distributed to both plates and redistribute in time. As the internal plate yields and slip occurs on the fault, the internal and the external plates must deform to accommodate the slip. Then, the viscous deformation of the external plate, which now sustains larger stresses, limits the compression rate to the internal plate, hampering the slip on the fault, which eventually vanishes as stress along the fault is below its strength. As stress transfers to the external plate, the loading along the plate margin increases, then causing another slip event, as the stresses in the internal plate are larger than its