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The effect of plate-scale rheology and plate interactions on intraplate seismicity

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A B S T R A C T

We use finite element modeling to investigate on the stress loading-unloading cycles and earthquakes occurrence in the plate interiors, resulting from the interactions of tectonic plates along their boundary. We model a visco-elasto-plastic plate embedding a single or multiple faults, while the tectonic stress is applied along the plate boundary by an external loading visco-elastic plate, reproducing the tectonic setting of two interacting lithospheres. Because the two plates deform viscously, the timescale of stress accumulation and release on the faults is self-consistently determined, from the boundary to the interiors, and seismic recurrence is an emerging feature. This approach overcomes the constraints on recurrence period imposed by stress (stress-drop) and velocity boundary conditions, while here it is unconstrained. We illustrate emerging macroscopic characteristics of this system, showing that the seismic recurrence period τ becomes shorter as Γ and Θ decreases, where $\Gamma = \eta_I/\eta_L$, the viscosity ratio of the viscosities of the internal fault-embedded to external loading plates, respectively, and $\Theta = \sigma_Y/\sigma_L$ the stress ratio of the elastic limit of the fault to far-field loading stress. When the system embeds multiple, randomly distributed faults, stress transfer results in recurrence period deviations, however the time-averaged recurrence period of each fault show the same dependence on Γ and Θ, illustrating a characteristic collective behavior. The control of these parameters prevails even when initial pre-stress was randomly assigned in terms of the spatial arrangement and orientation on the internal plate, mimicking local fluctuations. Our study shows the relevance of macroscopic rheological properties of tectonic plates on the earthquake occurrence in plate interiors, as opposed to local factors, proposing a viable model for the seismic behavior of continent interiors in the context of large-scale, long-term deformation of interacting tectonic plates.

1. Introduction

Growing paleoseismological and historical evidence shows episodic seismicity in the interiors of many stable continental regions, such as the North China, North East America, and other major continental plates (Yin, 2010; Wallace and Eyles, 2015), which remains at odd with the fundamental tenet of rigid plate interiors, implying that deformation concentrates along margins (Isacks et al., 1968). As a consequence, a working model for the occurrence of intraplate seismicity is, to date, lacking. Unlike their plate margin counterpart, where earthquakes are reconciled with our understanding of plate tectonics, intraplate earthquake occurrence remains a highly debated issue, and whether these can possibly be explained in the plate tectonics context remains unclear (Calais et al., 2016). In fact, far-field tectonic stress propagates from surrounding plate boundaries, firstly, from the upper mantle, and arising from topographic load and are accommodated on the whole intraplate interiors, through stress feedback among faults, upper and lower crusts and the underlying mantle (Zoback, 1992; Liu and Stein, 2016), thus suggesting that the macroscopic seismic behavior must reconcile with the large scale picture of plate tectonics.

While geodetic and geophysical observations help constraining interplate earthquakes focusing on plate boundary faults (e.g., megathrust) and adjacent areas, for intraplate setting, a vastly different approach is required. This is because the broad distribution of faults are supposed to collectively and slowly accommodate far-field tectonic stress (Stein et al., 2009). Moreover, the periods between the recurrence of intraplate seismic activity are very long, i.e., 1000–10,000 yr (Guo et al., 2011), likely due to substantially lower strain rate across the intraplate faults (i.e., <1 mm/yr), as opposed to their counterpart along plate margins, inferred from field works (Ritz et al., 1995) and geodetic observations

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(Calais and Stein, 2009). Therefore, the lack of such long instrumental seismic record does not allow establishing a spatiotemporal recurring pattern of intraplate seismicity.

Two different approaches are followed in the understanding of intracontinental seismicity, the plate tectonics and local load approach. Several studies have addressed interplate seismicity following the plate tectonics approach, where the single fault along the plate margin is loaded directly by boundary conditions mimicking the action of interacting plates, through either constant strain rate or stress, resulting in recurrent slip (e.g., Toth and Gurnis, 1998; Fialko and Khazan, 2005). However, in plate interiors, many faults with different sizes and mechanical strengths coexist, which result in a complex pattern of non-simultaneous slip along faults, and by a relevant stress field perturbation due to near/far and co-/post-seismic stress transfer between faults and surrounding plates (Freed and Lin, 2001). The second approach, emphasizes the role of more local perturbations. According this approach, the intraplate stress and the subsequent faults activity can be affected by local perturbations due to pre-existing weak zones below the fault (e.g., Kenner and Segall, 2000), topography load change due to surface erosion (e.g., Calais et al., 2010), glacier removal (e.g., Grollimund and Zoback, 2001), fluid flow along the fault plane (e.g., Audin et al., 2002), and shear tractions from mantle convection (e.g., Forte et al., 2007). Because accounting for all these factors has been proved challenging, the role of plate-scale as opposed to local load perturbation has remained poorly understood.

A historical study on seismic patterns in the North China (Liu et al., 2011) suggests that two different fault clusters along Weihe and Shanxi rifts have released seismic moment in an alternate fashion. In addition, in plate interiors recurrence periods and duration of aftershocks show a systematic dependence of on the distance of faults from plate boundaries (Xu and Deng, 1996; Stein and Liu, 2009). The temporal variation of the far-field tectonic stress from extension to compression has been correlated with paleo-stress fields of the intraplate region (e.g., the Central Europe, Kley and Voigt, 2008), which suggests that the tectonic boundary forcing affects the stress field of very distant regions (e.g., Calzolari et al., 2016). Some studies have addressed the vertical (e.g., Perfettini and Avouac, 2004), horizontal (e.g., So and Capitanio, 2016), and three dimensional (Hieronymus et al., 2008) stress transfer between the lithosphere and fault during seismic cycles, illustrating that feedback in a lithospheric plate can be relevant for the immediate surrounding as well as the plate-scale stress evolution. In particular, So and Capitanio (2016) showed how the stress loading cycle within continent interiors may result from large-scale interactions between deforming plates. Based on a semi-analytical one-dimensional (1D) model in which two deformable plates (i.e., internal fault-embedded and external loading plates) and a single fault were implemented, this system allows for realistic slip, plate boundaries deformation rates, and seismic recurrence periods. These studies suggested that the control of averaged plate-scale rheologies with the appealing advantage of reducing the complexity of the system to macroscopic lithospheric properties.

In the present work, we expanded the model of So and Capitanio (2016) to a two-dimensional (2D) model to investigate on the role of large-scale interactions of plates and stress transfer across scales, on the behavior of intraplate earthquakes. Additionally, we address the influence of the initial perturbation to the local stress field, which are here meant to mimic heterogeneous topographic load. We used a high-resolution 2D finite element model of a Maxwell viscoelastic plate embedding single and multiple idealized faults under the load of an external deformable Maxwell viscoelastic plate. We assessed recurrence intervals and stress evolutions in the parametric space of plate-scale rheology and far-field stress magnitude with short wavelength and short timescale stress perturbations such as fault interaction and predefined initial stress. Our work allows illustrating that the intraplate seismicity is mainly controlled by the macroscopic properties of lithospheres and their interactions with neighboring tectonic plates, and provide insight on the large-scale tectonics and local scale loads interactions.

Table 1
Model parameters and symbols.

Descriptions	Symbols	Values
Shear modulus	G	$3.2 \cdot 10^{10}$ Pa
Poisson ratio	ν	0.3
Viscosity of external plate	η_L	10^{21} Pa s
Viscosity of internal plate	η_I	10^{20}–10^{22} Pa s
Viscosity ratio	$\Gamma = \eta_I/\eta_L$	0.1–10
Yield strength of fault	σ_Y	$8 \cdot 10^7$ Pa
Hardening modulus	H	$3.2 \cdot 10^9$ Pa
Far-field tectonic loading stress	σ_L	$2 \cdot \sigma_Y$–$10 \cdot \sigma_Y$
Stress ratio	$\Theta = \sigma_Y/\sigma_L$	0.1–0.5
Characteristic pre-stress	σ_{pre}	$1.5 \cdot \sigma_Y$, $3 \cdot \sigma_Y$, $4.5 \cdot \sigma_Y$ and $6 \cdot \sigma_Y$

2. Modeling technique

We implemented a 2D numerical model with the code ABAQUS (Hibbitt, Karlsson, Sorensen, Inc., 2009), which uses the Finite Element Method (FEM) in a fully Lagrangian frame. The model employs all components of the intraplate system, including single or multiple faults, internal (i.e., fault-embedded) plate, external (i.e., loading) plate, and far-field constant tectonic stress imposed between the two plates. Details on the variables and symbols are presented in Table 1.

The internal plate has a domain size of 1000 × 1000 km and behaves as a Maxwell viscoelastic body. It is contiguous to an external, loading plate. For simplicity, this latter was bound with an analytical elastic spring and a Newtonian viscous dashpot, resulting in a Maxwell viscoelastic plate rheological model (see Fig. 1). The tectonic load is applied along the margin of the two plates. The viscosity ratio of the two plates $\Gamma = \eta_I/\eta_L$ was varied in the numerical experiments. In many studies, the crust is distinguished from the mantle, and is treated as an elastic layer atop a visco-elastic lithospheric mantle (e.g., Nalbant and McCloskey, 2011). Here, we embed the two and use a visco-elastic rheology with values of viscosity between 10^{20} and 10^{22} Pa s, which are common in models including lithospheric shear zones and ductile faults (e.g., Conrad and Hager, 1999). This approach allows reproducing the bulk effect of rheology, capturing the macroscopic behavior of tectonic plates. The fault distribution was set to single (Fig. 1a), in an initial setup, and multiple, in a second setup (Fig. 1b). Single faults are defined on single elements. In order to reduce boundary effects, when the number of faults is set as multiple, no fault is located near the boundaries of the internal plate (the black rectangles in Fig. 1b).

The internal and external plates are mechanically in contact. The constant compressional loading stress σ_L is applied to the boundary as the far-field tectonic stress. σ_L is scaled by σ_Y in $\Theta = \sigma_Y/\sigma_L$, and the range of Θ tested is listed in Table 1. The range of σ_L used is constrained by realistic estimates of horizontal deviatoric stress in the Indian plate (i.e., 50–400 MPa; Cloetingh and Wortel, 1985). In visco-elasto-plastic material, total strain rate tensor ($\dot{\varepsilon}_{ij}^{T}$) is simply approximated by the sum of viscous ($\dot{\varepsilon}_{ij}^{V}$), elastic ($\dot{\varepsilon}_{ij}^{E}$), and plastic ($\dot{\varepsilon}_{ij}^{P}$) strain rate tensors. For viscoelastic internal and external plates, the strain total rate is described by

$$\dot{\varepsilon}_{ij}^{ST} = \dot{\varepsilon}_{ij}^{SE} + \dot{\varepsilon}_{ij}^{SV} = \frac{1}{2G}\frac{\partial \sigma_{ij}}{\partial t} + \frac{\sigma'_{ij}}{2\eta} \quad (1)$$

ST, SE and SV refers to total, elastic and viscous strain rates of the viscoelastic plates. σ_{ij} and σ'_{ij} means the Cauchy and deviatoric