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Role of the brittle–ductile transition on fault activation

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ABSTRACT

We model a fault cross-cutting the brittle upper crust and the ductile lower crust. In the brittle layer the fault is assumed to have stick–slip behaviour, whereas the lower ductile crust is inferred to deform in a steady-state shear. Therefore, the brittle–ductile transition (BDT) separates two layers with different strain rates and structural styles. This contrasting behaviour determines a stress gradient at the BDT that is eventually dissipated during the earthquake. During the interseismic period, along a normal fault it should form a dilated hinge at and above the BDT. Conversely, an over-compressed volume should rather develop above a thrust plane at the BDT. On a normal fault the earthquake is associated with the coseismic closure of the dilated fractures generated in the stretched hangingwall during the interseismic period. In addition to the shear stress overcoming the friction of the fault, the brittle fault moves when the weight of the hangingwall exceeds the strength of the dilated band above the BDT. On a thrust fault, the seismic event is instead associated with the sudden dilation of the previously over-compressed volume in the hangingwall above the BDT, a mechanism requiring much more energy because it acts against gravity. In both cases, the deeper the BDT, the larger the involved volume, and the bigger the related magnitude.

We tested two scenarios with two examples from L'Aquila 2009 (Italy) and Chi-Chi 1999 (Taiwan) events. GPS data, energy dissipation and strain rate analysis support these contrasting evolutions. Our model also predicts, consistently with data, that the interseismic strain rate is lower along the fault segment more prone to seismic activation.

1. Introduction

Fault activation is crucial for the understanding of earthquakes and their prediction (e.g., Scholtz, 1990; Stein and Wysession, 2003; Peresan et al., 2005). Earthquakes are usually interpreted as the rupture of an asperity along a fault, when the shear stress overcomes the fault strength. But why do faults move episodically? Why is seismicity not more randomly distributed if an earthquake is simply associated with an asperity, which should be smeared out after fault motion? The origin of the earthquake recurrence or seismic cycle (e.g., Thatcher and Rundle, 1979; Savage, 1983; Cattin and Avouac, 2000; Sieh et al., 2008), consisting of a long interseismic period followed by a coseismic (and postseismic) period, remains quite obscure. The length of the interseismic period between two earthquakes along the same fault has been proposed to be controlled by a number of physical parameters, e.g., the relative velocity between the two walls of the fault, the composition of the crust, the mineralogy and foliation of the fault rocks, the morphology and length of the fault plane, the thermal state, the friction on the fault, the fluid pore-pressure, etc. (e.g., Scholtz, 1990; Collettini et al., 2009). All these parameters entail first a long, static accumulation of energy during the interseismic period, which is eventually radiated coseismically when the friction on the fault has overcome. In this article we contribute to this topic with a geological model to explain the activation of a crustal fault, where the aforementioned physical parameters could determine the timescale of the recurrence or the magnitude. In particular, we investigate the role of the brittle–ductile transition (BDT) in the evolution of crustal seismicity. The BDT depth generally represents the lower limit of most crustal seismicity. We propose a model that links the continuous ductile deformation at depth with the brittle episodic behaviour of shallow crustal layers, and show how the BDT may play a triggering role in fault movement. The model is tested numerically and applied to two areas where normal fault and thrust related earthquakes occurred, i.e., in the central Apennines (2009) and Taiwan (1999). GPS interseismic and coseismic data, dissipated energy from the two cases are shown to be consistent with model predictions, where normal faults and thrusts have opposite behaviour. Similar to the effects of the lithostatic load, which enhances the rupture of normal faults and inhibits faulting along thrusts (Carminati et al., 2004), the two types of faulting are asymmetric in terms of geological and mechanical behaviour.

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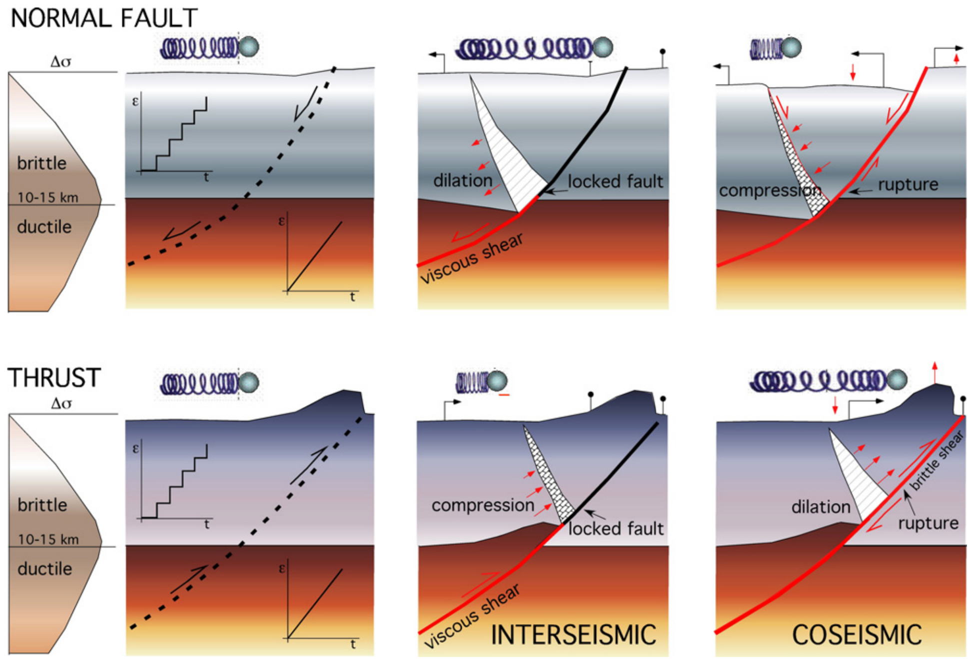

Fig. 1. Assuming a steady stated strain rate in the ductile lower crust, stick–slip motion in the brittle upper crust, tensional and compressional faults generate opposite kinematics and mechanic evolution. In the tensional tectonic environment, the triangle of crust above the BDT remains "suspended" while a dilated area forms during the interseismic period. Once shear stress along the locked part of the fault becomes larger than fault strength, the hangingwall will collapse. Conversely, along a thrust plane, an area over-compressed separates the ductile shear from the overlying locked fault during the interseismic period. The hangingwall is expelled as a compressed spring during the coseismic period.

2. Geological model

It is widely accepted in the literature that the rheology of the crust can be simplified with an upper brittle layer and a deeper ductile crust (e.g., Rutter, 1986). The transition between the brittle shallow crust and the ductile deep crust is thought to determine differing tectonic behaviours between the two domains. The steady state deformation in the ductile layer is, in fact, at odds with the stick–slip behaviour of the shallower brittle levels. The constant strain rates measured by GPS during interseismic periods (e.g., Kreemer et al., 2002) suggest that the locked status of faults in the brittle layer does not inhibit continuous ductile shear below the BDT. Therefore, we speculate that the episodic stick–slip behaviour of the brittle crust coexists with steady-state shear in the lower crust. In the volume across the BDT, strain is transferred from one mechanism to the other. This differential behaviour implies that during the interseismic period the absence of motion in the brittle layer contrasting with the continuous slip in the ductile layer generates a pressure gradient, which will be eventually dissipated during the activation of the fault in the brittle segment at the coseismic stage.

We assume a simple fault plane cross-cutting both the brittle and the ductile layers of the crust. In normal faulting, deep ductile deformation generates a dilation at the interface with the brittle shallow locked part of the fault. Dilatancy (i.e., the phenomenon in which fractures and cracks form and open when rocks are stressed; e.g., Frank, 1965) should reach its maximum at the BDT. Conversely, compression should form in the footwall of the normal fault. One example could be the antithetic normal fault that slipped during the 40 s sub-event of the Irpinia 1980 earthquake (Pingue and De Natale, 1993). During the coseismic stage, the hangingwall instantaneously subsides down, closing the fractures in the dilated volume (e.g., Axen, 1999). This can be explained by the weight of the brittle hangingwall that overcomes the strength of the weakened dilated band (Fig. 1). The triangle suddenly falls when the shear stress along the locked part of the fault is equal to the fault strength. Moreover the area stretched during the interseismic period may become the location for the development of a conjugate normal fault (Melosh and Williams, 1989, Fig. 1). Cracks and veins close to the BDT transition have been described by Nuchter and Stockhert (2008). They inferred their generation during the coseismic stage, but such veins could also have formed during the interseismic period.

Unlike the normal fault case, along a thrust the hangingwall above the BDT is over-compressed during the interseismic, and should dilate at the coseismic stage (Fig. 1). The opposite distribution of stress is expected in the footwall. During the coseismic stage, elastic rebound is expected with uplift of the hangingwall along the brittle segment of the thrust, and internal subsidence should ensue above the BDT where some dilatancy should develop instantaneously (Fig. 1). This is compatible with the data and model presented by Burrato et al. (2003) for fault-propagation folding and it has been detected during the great Sumatra earthquake (Meltzner et al., 2006).

Our model can be simplified as follows. Let us imagine a spring located across the BDT, with its terminations attached to the ductile and the brittle parts of the hangingwall. During the interseismic period, along a normal fault the motion of the ductile lower part will elongate the spring and accumulate energy. In the coseismic stage, energy will be released and the spring will contract (Fig. 1). Along a thrust, the opposite behaviour is expected, i.e., the spring will be shortened during the interseismic, whereas it will extend during the coseismic stage (Fig. 1).

3. Numerical modelling

In order to evaluate the physical feasibility of the proposed geological model, the results of some numerical simulations will be discussed. Finite element dynamic modelling was performed using the commercial COMSOL Multiphysics 3.5 software (http://www.comsol.com/).