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Relationships between along-fault heterogeneous normal stress and fault slip patterns during the seismic cycle: Insights from a strike-slip fault laboratory model

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ABSTRACT

We use a strike-slip fault analog model to study experimentally the role played by along-fault non-uniform and asymmetric applied normal stress on both coseismic slip and long-term fault behavior. Our model is based on a visco-elasto-plastic multi-layered rheology that allows to produce several hundreds of scaled analog microquakes and associated seismic cycles. Uniform or heterogeneous applied normal stress along the fault plane is imposed and maintained constant during the whole experiment durations. Our results suggest that coseismic slip patterns are strongly controlled by spatial normal stress variations and subsequent accumulated shear stress along fault strike. Major microquakes occur preferentially in zones of major shear stress asperities. Coseismic slip distributions exhibit a pattern similar to the along-fault applied normal stress distribution. The occurrence of isolated low to moderate microquakes where residual stresses persist around secondary stress asperities, indicates that stress conditions along the fault also control the whole variability of fault slip events. Moreover, when fault slip stability conditions are modulated by normal stress distribution, our experiments suggest that the along-fault stress heterogeneity influences the seismic cycle regularity and, consequently, long-term fault slip behavior. Uniform applied normal stress favors irregular seismic cycles and the occurrence of earthquakes clustering, whereas non-uniform normal stress with a single high amplitude stress asperity generates strong characteristic microquake events with stable return periods. Together our results strengthen the assumption that coseismic slip distribution and earthquake variability along an active fault may provide relevant information on long term tectonic stress and could thus improve seismic hazard assessment.

1. Introduction

One of the main measurable parameters that allow characterizing earthquake dynamics is short- and long-term fault slip kinematics. Studying coseismic fault slip distribution provides crucial data to better constrain earthquake mechanics (e.g. Scholz, 1982; King and Wesnousky, 2007), and has also strong implications on seismic hazard assessment (e.g. Stein et al., 1997). Nowadays, recent technological advances in remote sensing measurements as well as the development of dense and permanent geodetic networks provide a detailed analysis of surface deformation along active faults. The 2013 Mw = 7.7 Balochistan earthquake is a typical example. The inversion of near and far field ground deformation obtained from InSAR and sub-pixel optical images correlation provided coseismic slip distribution on the fault plane and led to a better understanding of the mechanical processes activated during this earthquake (Avouac et al., 2014). From such studies, coseismic slip distribution along the fault rupture appears usually heterogeneous, with zones of high slip, referred as asperities, separated by zones of low to zero slip (e.g. Peltzer et al., 2001; Mai and Beroza, 2002; Avouac et al., 2014).

The observed variability in earthquake fault slip distributions can be attributed to many factors (Bizzarri, 2009) including tectonic context, fault plane geometry (e.g. Robinson et al., 2006), earthquake triggered processes such as fluid pressurization (Faulkner and Rutter, 2001), inelastic deformation in the ambient rocks (e.g. Bürgmann et al., 1994; Kaneko and Fialko, 2011) or interactions between nearby faults (e.g. Andrews, 1994). Investigations based on the analysis of earthquakes data catalog

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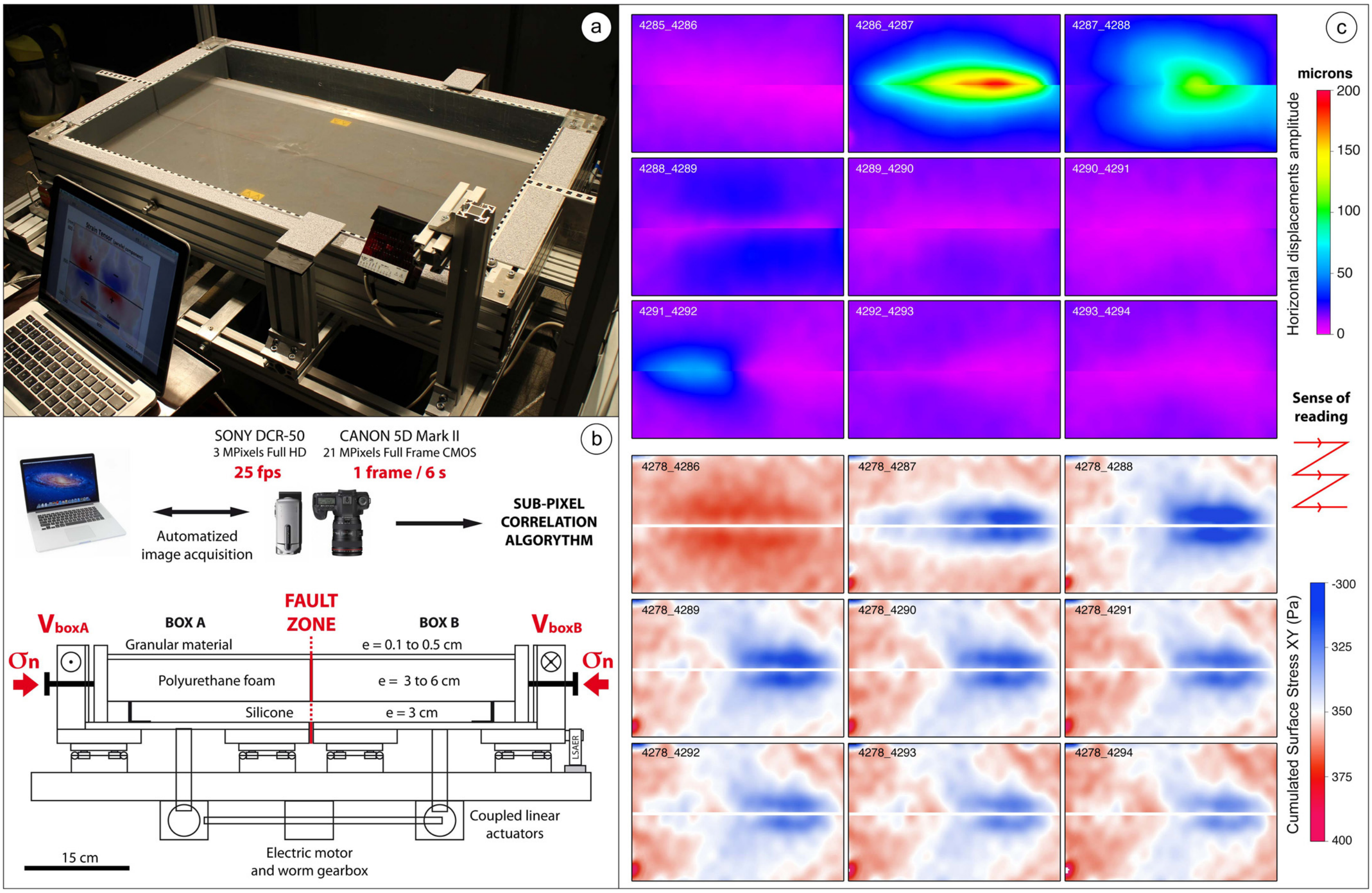

Fig. 1. a) General view of the experimental set-up. The device is constituted by a computerized shear box fixed to a rigid aluminum structure. b) Mechanical and kinematical boundary conditions. The model visco-elasto-plastic rheology is achieved by superimposing granular, elastic and viscous layers representing the upper and lower crust. Schematic cross section of the experimental device showing its internal mechanical structure, the geometry of analog material layers and how boundary conditions (σ_n and loading rate) are imposed. c) Model surface horizontal displacements (top) and cumulated shear stress (bottom). Surface displacements are quantified using sub-pixel image correlation technique. Numerical tools are used to analyze model deformation at the surface and at depth. Examples of surface horizontal displacement measurements acquired during a typical experiment. Each stage is separated by 6 s corresponding to 20 μm of far-field simple shear model deformation. Stick–slip behavior is observed; instantaneous incremental fault slip events are separated by long time periods where the fault is locked and model records long wavelength elastic loading, i.e. coseismic and interseismic stages respectively.

(e.g. Wesnousky, 2008) strongly suggest that coseismic slip distribution is essentially controlled by fault strength variations. Furthermore, the study of specific earthquake ruptures reveal that accumulated stress distribution along strike is also a key parameter that must be taken into account (Peyrat et al., 2001; Mai and Beroza, 2002). One of the most recent examples confirming these conclusions comes from the study of the 2008 Mw 7.9 Wenchuan earthquake (Wen et al., 2012b). The simulation of this earthquake rupture, based on the inversion of surface geodetic data, revealed that coseismic slip pattern can be explained by spatial heterogeneities in stress loading on the fault plane inherited from the interseismic period. This heterogeneous loading can also results from spatial variability in the fault frictional behavior linked to the fault rheology. Numerical modeling, based on rate-and-state friction laws (Scholz, 1998), succeed in reproducing these couplings (e.g. Barbot et al., 2012). As observed in the nature, simulated seismic ruptures appear mostly confined within strong patches (asperities) that remain locked during the interseismic period. These asperities seem to play a key role not only on the slip distribution but also in the seismic cycle behavior. The models with a single asperity embedded into a creeping zone produce quite regular seismic cycles, whereas multiple asperity models conduct to more complex cycles.

In the present study, we apply an original experimental approach to investigate the role of fault stress distribution on coseismic slip pattern and seismic cycle behavior. We use a scaled visco-elasto-plastic multi-layered analog model for reproducing seismic cycles on a strike-slip fault (Caniven et al., 2015). This experimental device allows to apply a uniform or a non-uniform temporally constant normal-stress (σ_n) along the fault plane.

The main goal of this paper is to study how spatial variations in normal stress on a fault can influence coseismic slip distribution and fault kinematics at seismic cycle time-scale (equivalent to a few months up to several thousand years in nature).

2. Experimental model

Experimental set-up characteristics and analog model rheological properties are extensively described in a previous publication (Caniven et al., 2015). Hereafter, we only sum up the main points.

2.1. Experimental set-up and boundary conditions

The experimental device consists of a rigid structure (1 m × 1.5 m × 1.8 m) made of aluminum profiles supporting all mechanical and model-monitoring equipment (Fig. 1a). The main structure is made of two compartments, moving in opposite direction at a constant velocity ranging from 1 to 7 μm/s (Fig. 1b). Both compartments have similar sizes of 120 cm × 73 cm × 12 cm and are in contact along their longest dimension. They represent the two