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Earthquake rupture propagation inferred from the spatial distribution of fault rock frictional properties

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ABSTRACT

The frictional properties of fault rocks that rupture during earthquakes are expected to affect the nucleation and propagation of seismic slip, but these properties and their variation under in-situ earthquake conditions are typically unknown. Here, we present experimental results on the variation of frictional properties of fault rocks from the Alhama de Murcia Fault (AMF) in SE Spain, which ruptured in the 2011 Lorca earthquake. In the epicentral area, the fault zone is characterized by the presence of abundant phyllosilicate-rich gouges that surround more competent, fractured lenses of the phyllitic basement. Measurements of lineaments and orientations of R-shears in the gouges are consistent with CMT-solutions of the 2011 Lorca earthquake, suggesting that the bulk of displacement on the AMF was accommodated within similar gouges at depth. In order to evaluate the frictional properties of the fault rocks of the AMF, we performed rotary shear experiments under hydrothermal conditions of samples obtained from surface outcrops of the AMF zone, progressively simulating deeper levels in the crust by stepping temperature, effective normal stress and fluid pressure. A negative velocity-dependence of friction, expressed as a negative value of the Rate-and-State Friction (RSF) parameter $(a - b)$ and which is a prerequisite for the nucleation of an instability, was observed only for samples derived from competent lenses under hydrothermal conditions. Gouge-derived samples exhibited only velocity-strengthening properties, i.e. positive values of $(a - b)$, which increase with deeper conditions, in particular with increasing effective normal stress. Combined with our outcrop observation of the anastomosing nature of gouges surrounding more competent lenses of fractured protolith, our results suggest that the 2011 Lorca earthquake nucleated in the competent lenses, followed by propagation of slip into the frictionally weaker gouges. The inferred upward propagation direction of the 2011 Lorca earthquake is consistent with propagation of the rupture into the velocity-strengthening gouges which at shallower levels provide a smaller barrier to seismic slip due to lower values of effective normal stress and $(a - b)$. Our results suggest that the spatial variation of the frictional properties along the AMF was an important factor controlling the nucleation and propagation of seismic slip which, together with the shallow hypocenter close to the city of Lorca, led to serious damage. We infer that understanding of such variations in frictional properties may significantly improve seismic hazard evaluations in tectonically active regions.

1. Introduction

In view of its modest magnitude, the 2011 M_w 5.1 Lorca earthquake in the Betic Cordillera of SE Spain was much more destructive (9 casualties, remediation costs estimated at 1.2 billion euros) than might have been expected. Initial real-time locations of the earthquake by the Instituto Geografico Nacional and the Instituto Andaluz de Geofisica suggested a shallow hypocenter (2–4 km) close to the Lorca city center, which may in part explain the destructive nature of the earthquake. In addition, analyses of the main and aftershocks reveal that the propagation of slip was directed towards the southwest as well as towards the surface (López-Comino et al., 2012). The upward direction of movement of the Lorca earthquake was confirmed in a fault slip model based on geodetic data (González et al., 2012). Both studies yield a hypocentral depth of 4–5 km, slightly deeper than the initial estimates. The distribution of fault slip in the model of González et al. (2012) correlates with the pattern of positive Coulomb stress change calculated to result from extensive groundwater extraction in the area over the past decades. This led González et al. (2012) to infer that the Lorca earthquake nucleated in fault rock that was on the

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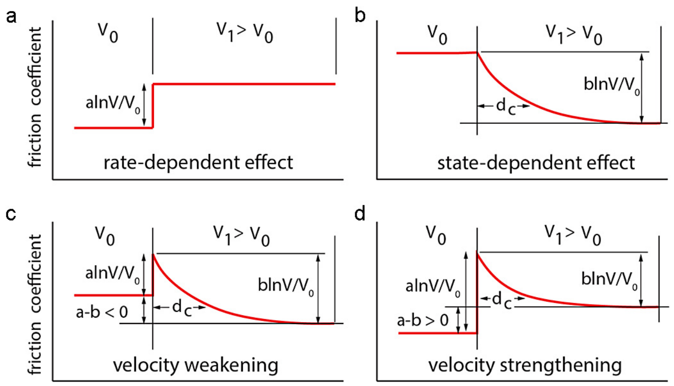

Fig. 1. Theoretical effect of an instantaneous step in sliding velocity on the coefficient of friction in the framework of Rate and State Friction (RSF). (a) Instantaneous increase of friction with an increase in velocity, quantified by parameter a (scaled by the size of the velocity step $\ln V/V_0$). (b) Evolution of friction after a velocity increase, with d_c the critical distance required for the friction to decrease to $1/e$ of its original value, and b the total decrease of the frictional resistance (scaled by $\ln V/V_0$). (c) Net effect of a and b when $a - b < 0$, resulting in velocity-weakening. (d) If $a - b > 0$ then friction increases, resulting in velocity strengthening.

transition from velocity-strengthening to velocity-weakening and then propagated to the southwest and upwards due to the lower pre-seismic stress state as a results of crustal unloading. However, the frictional properties of the fault rocks that ruptured during the earthquake are unknown, whilst these are expected to exert first-order control on the nucleation and propagation of earthquakes (e.g. Dieterich, 1992; Scholz, 1998, 2002).

One of the key frictional parameters for earthquake nucleation and propagation is the velocity-dependence of friction, often expressed as $(a - b)$ in Rate-and-State Friction (RSF) terminology (see e.g. Dieterich, 1979; Ruina, 1983), where parameter a quantifies the direct effect of a velocity-change on the coefficient of friction, while b describes the evolution effect of friction (Fig. 1). With increasing GPS station coverage and CPU power, it is now possible to use observations of shallow creep to infer the in-situ values of $(a - b)$ of fault rocks (e.g. Kaneko et al., 2010; Wei et al., 2013; Fukuda et al., 2013). In addition, numerical simulations of the seismic cycle based on rate-and-state friction equations suggest that the distribution of seismic slip can be significantly influenced by along strike and/or along dip variability in $(a - b)$ as well as by the velocity-dependence of $(a - b)$ (e.g. Boatwright and Cocco, 1996; Shibazaki et al., 2011; Noda and Lapusta, 2013). All these models show that variations in $(a - b)$ can have a significant effect on the distribution of seismic slip, but there is little experimental constraint on these variations in natural fault rocks.

Here, we present results of a combined field and experimental study of cataclastic rocks from the fault core and damage zone of the Alhama de Murcia Fault, which ruptured during the 2011 Lorca earthquake. We performed friction experiments on fault rock samples aimed at obtaining the values of $(a - b)$ at earthquake nucleation velocities under the in-situ conditions of pressure, temperature and fluid pressure inferred for the 2011 Lorca earthquake. The combination of our field observations and experimental results shows that a preferred upward direction of rupture propagation is consistent with the fault zone structure observed at the surface in the epicentral area and with the frictional properties of the fault rocks that ruptured during the earthquake.

2. Tectonic context of the Lorca earthquake

The Internal Zone of the Betic Cordillera in SE Spain is a tectonically active alpine terrain made up of elongate mountain ranges of metamorphosed Palaeozoic and Mesozoic rocks (e.g., Platt and Vissers, 1989) separated by intermontane basins filled with Neogene to recent marine and continental deposits (e.g., Sanz de Galdeano, 1990). Current tectonic interpretations of these basins vary, from late-orogenic extensional structures in response to changes in the west Mediterranean lithosphere structure (e.g. Platt and Vissers, 1989; Lonergan and White, 1997; Spakman and Wortel, 2004), to a pull-apart origin associated with strike-slip movements along an NE trending network of prominent faults interpreted as major strike-slip faults (De Larouzière et al., 1988; Montenat and Ott d'Estevou, 1999). Structural analysis, however, indicates that since the latest Miocene to early Pliocene, the Alhama de Murcia and Crevillente faults acted as contractional faults (Meijninger and Vissers, 2006; Martínez-Díaz et al., 2010), and the present-day tectonic activity in the region is commonly viewed in terms of the late stages of transient upper mantle processes, now dominated by ongoing motion between Africa and Eurasia (e.g., Masana et al., 2004).

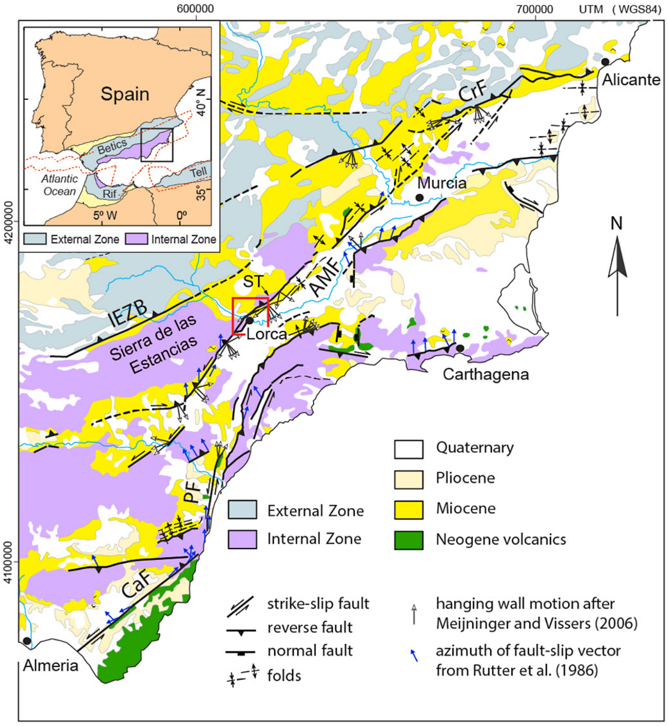

Fig. 2. Structural-tectonic sketch map of south–eastern Spain between Alicante and Almería showing the main Alhama de Murcia–Crevillente fault belt, compiled after Meijninger and Vissers (2006). Abbreviations: AMF Alhama de Murcia fault, CaF Carboneras fault, CrF Crevillente fault, IEZB Internal–External Zone Boundary, PF Palomares fault, ST Sierra de la Tercia. Kinematic data from Meijninger and Vissers (2006) and Meijninger (2006) are supplemented with azimuths of fault slip vectors from Rutter et al. (1986). Area in rectangle around Lorca is shown in Fig. 3.

Along the southern margin of the Lorca basin and along the Sierra de las Estancias SW of Lorca, the Alhama de Murcia Fault (AMF) is a morphologically sharp, NE trending linear structure (Figs. 3 and 5) associated with the contact between basement rocks and mostly Quaternary basin sediments and defined by a steep NW dipping fault. Kinematic indicators on this fault consistently indicate sinistral reverse motion, with a movement sense of the hanging wall towards the south to south–southeast (Meijninger and Vissers, 2006). Scarce outcrops of steeply tilted Miocene sediments of the footwall, oriented parallel to the main fault, reveal both layer-parallel reverse and sinistral shear senses and are cut and displaced by NNE trending sinistral and WNW trending dextral strike-slip faults. The prominent faults form part of a larger-scale zone of essentially post-Miocene shortening, made up of NE trending oblique-reverse faults with top to the SSE and NNW directed motions, and NE to ENE trending folds (Fig. 2), including