Comment on “Material contrast does not predict earthquake rupture propagation direction” by R. A. Harris and S. M. Day

Yehuda Ben-Zion

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1. Introduction

[1] Harris and Day [2005] (hereinafter referred to as HD) concluded from some numerical simulations and low resolution analysis of 8 M4-M6 earthquakes near Parkfield, CA, that material contrast in fault zone structures is not important for earthquake propagation direction. The limited theoretical and observational results of HD do not justify such a general conclusion. Considerations of a larger body of results suggest that material contrast may produce a statistically preferred direction of earthquake ruptures. The inferred diversity of the 8 discussed events is consistent with their small number and relatively small size. In addition, the behavior has a natural explanation in a structure with two material interfaces – the San Andreas Fault (SAF) and the Southwest Fracture Zone (SFZ) – on the opposite sides of a deformation/damage region. Large earthquakes propagating predominantly as mode II ruptures, and affected primarily by properties of the bounding crustal blocks (rather than the local structure), are likely to exhibit a smaller amount of diversity.

2. Theoretical Considerations

[2] Analytical and numerical studies indicate that mode II rupture along a bimaterial interface produces dynamic changes of normal stress ($\sigma_n$) that depend on the slip function, material properties and direction of rupture propagation [e.g., Weertman, 1980; Ben-Zion, 2001]. For sub-shear ruptures the change of $\sigma_n$ at the tip propagating in the direction of slip of the compliant solid (referred to below as the positive direction) is tensile, while the change at the tip propagating in the opposite direction is compressive. For supershear ruptures the senses of changes of $\sigma_n$ are reversed [Weertman, 2002; Shi and Ben-Zion, 2006]. The amplitudes of the near-tip changes increase with propagation distance along the bimaterial interface, due to a continual transfer of energy to shorter wavelengths [e.g., Adams, 1995; Ben-Zion and Huang, 2002]. When the bimaterial interface is governed by slip-independent friction, the above dynamic effects produce a wrinkle-like slip pulse that propagates preferentially in the positive direction. In more general cases, the dynamic bimaterial effects compete with other effects. However, since the bimaterial effects increase with propagation distance, mode II rupture on a bimaterial interface is expected to evolve for ranges of conditions to a wrinkle-like pulse in the positive direction.

[3] Numerical studies of this problem using slip-weakening friction employed two classes of nucleation procedures. Class (I) involves relatively small and strong nucleation phases mimicking the initiation of a cascade-type process by a failure of an asperity, coalescence of micro-cracks from the bulk, etc. see also Ben-Zion [2006]. Such cases generate for ranges of conditions ruptures that evolve after initial transients to wrinkle-like pulses similar to those generated with slip-independent friction [Shi and Ben-Zion, 2006]. Class (II) involves relatively large nucleation phases mimicking the final stage of a stable growth of a slip patch to a critical size needed to produce macroscopic instability in the absence of material contrast. The required critical patch size scales in lab experiments with the largest wavelength of the roughness characterizing the sliding surfaces [e.g., Ohnaka, 1996]. Such cases generate bilateral cracks with a wrinkle-like pulse superposed at the tip propagating in the positive direction (e.g., A. M. Rubin and J. P. Ampuero, Aftershock asymmetry on a bimaterial interface, submitted to J. Geophys. Res., 2006). The superposed wrinkle-like pulse produces strong asymmetry of slip velocities at the opposite rupture tips. Incorporating in such simulations rate-dependent friction compatible with experiments of rock friction at high slip rates [e.g., Tsutsumi and Shimamoto, 1997] is likely to produce larger stress drop in the positive direction, leading to asymmetric rupture with larger energy release (and possible pulse spawning) in the positive direction.

[4] Dynamic ruptures may be initiated by both classes of nucleation phases. On polished surfaces having roughness only over very short wavelengths class (II) may be dominant, whereas on fractal-like surfaces class (I) may be realized first. On realistic natural surfaces with roughness (possibly of small amplitude) over broad bandwidth, a nucleation phase of class (II) in a small spatial domain may trigger a stronger nucleation phase of class (I). The same may hold for other types of heterogeneities. Ruptures initiated with nucleation type (II) on a fault governed by the slip version of rate-state friction may produce (J. P. Ampuero, personal communication, 2006) a nucleation phase of type (I). These cases are likely to excite on a bimaterial interface the wrinkle-like mode of rupture. Accounting for realistic rate-dependent friction is likely to enhance, as mentioned, the generation of wrinkle-like ruptures in the positive direction.

3. Parkfield Earthquakes

[5] A good observational test of the theoretical prediction of a preferred propagation direction of mode II ruptures on
faults that separate different solids should employ a large population (for statistical significance) of earthquakes that propagate predominantly as mode II rupture (for which the prediction is made). The 8 M4-M6 Parkfield events discussed by HD satisfy neither the first nor the second requirement. However, since they play a central role in their conclusion, they are discussed in more detail below.

[6] The 8 earthquakes considered by HD are all small to moderate so they are likely to be dominated by the local structural properties rather than properties of the bounding crustal blocks. A sliver of high-velocity rock immediately to the NE of the SAF, associated with the Gold Hill fault, may produce near the hypocenter of the M6 2004 event a local reversal of the velocity contrast across the SAF from that associated with the bounding blocks. In that case, small to moderate ruptures on the SAF in that area are expected to propagate to the NE, as inferred for the 2004 event. In addition, the Parkfield region has two large faults, the main SAF and the SFZ, separated by ~1.5 km wide deformation/damage zone [Rymer et al., 2006]. The hypocenters of the M6 2004 event and many of its aftershocks appear to be located on the SFZ rather than the main SAF [see http://www.consrv.ca.gov/CGS/geologic_hazards/earthquakes/09282004_field_obs.htm]. Detailed near-fault seismic data [Shakal et al., 2005], along with the mapped surface fractures associated with the SAF and SFZ [Rymer et al., 2006], suggest that the M6 2004 event may have consisted of two separate pulses, one propagating on the SFZ to the SE and the other propagating on the SAF to the NW.

[7] In a three-media structure consisting of two crustal blocks separated by a damage zone, the predicted preferred propagation direction depends on which side of the damage zone the rupture has nucleated or migrated to, the rupture velocity, and on the sense of contrast at the two material interfaces. For example, if the region between the SAF and SFZ has lower shear wave velocity than both bounding blocks, the predicted propagation direction of subshear ruptures is SE on the SFZ and NW on the SAF. The predicted directions for supershear ruptures are opposite. As small events grow they may migrate to both interfaces and consist of two unilateral pulses, propagating simultaneously in the two opposite preferred directions of the two different interfaces [G. B. Brietzke and Y. Ben-Zion, Examining tendencies of in-plane rupture to migrate to material interfaces, submitted to Geophys. J. Int., 2005]. If the region between the main SAF and the SFZ has intermediate (or higher) velocity compared to those of the bounding blocks there will be other sets of preferred propagation directions. All such cases, and others accounting for additional structural details, can be generated as a direct consequence of the predicted mechanical behavior of rupture along a bimaterial interface. A more detailed analysis of the structure and earthquakes at the Parkfield region than that done by HD may support, rather than contradict, the preferred direction hypothesis (although, as mentioned, a conclusion one way or the other for 8 earthquakes is not statistically significant).

4. Discussion

[8] The dynamic breaking of symmetry along strike for mode II rupture on a bimaterial interface is expected to produce a statistical preference for rupture propagation in the positive direction. Testing this theoretical prediction with data of individual small to moderate events requires (in addition to good statistical samples) high resolution information on the structure and rupture properties. While the data available at the Parkfield region allow high resolution tests, the analysis of HD does not take into account the local velocity structure, precise event locations, rupture velocities, etc. Thus their analysis does not provide a meaningful test of the predicted theoretical behavior.

[9] Far stronger tests than that of HD were done using stacked catalog data and rock damage generated by many large ruptures. See Ben-Zion [2006] for a brief summary of such published results. Additional related observations emerge for the North Anatolian fault, where a sequence of large 20th century earthquakes exhibited an overall westward migration attributed to successive failures of fault segments due to stress transfer from earlier failures. Surprisingly, the 1943 earthquake did not nucleate in the region of largest stress increase, but rather at the opposite end of the final rupture far to the west, and then ruptured eastward. The following 1944 event nucleated at the far west of the 1943 earthquake and propagated to the west. The “unexpected” nucleation and propagation directions of the 1943 and 1944 earthquakes may be explained by a reversed sense of velocity contrast across the 1943 and 1944 rupture zones. This interpretation is supported by observations of a reversed damage asymmetry across these sections of the North Anatolian fault [Dor et al., 2005; Yildirim et al., 2005].

[10] The discussed results suggest that material contrast in fault zone structures may produce a preferred propagation direction for earthquake ruptures. More observational and theoretical work is needed to test further this hypothesis. At present it is best to keep an open mind on this issue.

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References


Y. Ben-Zion, Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089–0740, USA. (benzion@usc.edu)