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Reply to comment by Y. Ben-Zion on "Material contrast does not predict earthquake rupture propagation direction"

Ruth A. Harris[1] and Steven M. Day[2]

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[1] Normal stress perturbations near the tip of a propagating mode II rupture along a bimaterial interface can introduce asymmetries in the rupture velocity and/or the slip-velocity function. In an informative theoretical study, *Andrews and Ben-Zion* [1997] demonstrated through numerical simulations that, for a constant coefficient of friction, these asymmetries can lead to emergence of a self-sustaining unilaterally propagating slip pulse. They called the phenomenon the ''wrinkle pulse.'' The *Andrews and Ben-Zion* [1997] simulations are for a simplified dynamics in which the friction coefficient never weakens at or following the onset of sliding. This allowed the asymmetrical wrinkle pulse to dominate the dynamics, leading to unilateral rupture in the simulations.

[2] The existence of the wrinkle pulse phenomenon itself is not in question here. Indeed, the wrinkle-pulse phenomenon plays an important part in our own bimaterial rupture simulations [*Harris and Day*, 1997, 2005], and we performed our own analytical study of slip-induced normal-stress perturbations to explain asymmetries in those simulations [*Harris and Day*, 1997]. The utility of the wrinkle-pulse concept is also clear in the work of A. M. Rubin and J.-P. Ampuero (Aftershock asymmetry on a bimaterial interface, submitted to *J. Geophys. Res.*, 2006, hereinafter referred to as Rubin and Ampuero, submitted manuscript, 2006), who use it to suggest a mechanism to explain the existence of asymmetric aftershock distributions [*Rubin and Gillard*, 2000]. It might also provide all or part of the slip-velocity and stress-field asymmetry required to explain observations that damage is concentrated preferentially on one side of strike slip faults in southern California [*Dor et al.*, 2006], as discussed by Rubin and Ampuero (submitted manuscript, 2006). The question under discussion here, however, is simply whether the wrinkle pulse effect is likely to induce unilateral rupture in large, natural earthquakes.

[3] The first suggestion that it might not do so derives from the numerical simulations of *Harris and Day* [1997]. These simulations were for mode II rupture, just as were those of *Andrews and Ben-Zion* [1997], and they used a similar methodology and a similar range of seismic velocity contrasts at the interface, yet *Harris and Day* [1997] found bilateral rupture in all cases. The wrinkle pulse was present and induced the expected asymmetry, but did not give rise to a preferred direction of unilateral rupture propagation.

[4] This difference in conclusion about the relationship of the wrinkle pulse to rupture directivity, contrary to the implication of *Ben-Zion*'s [2006] commentary (and the suggestion given by *Shi and Ben-Zion* [2006]), has nothing to do with the use of artificial viscosity to regularize the numerical solution, but rather results from radically different assumptions about the frictional physics. *Andrews and Ben-Zion* [1997] considered the case of a constant coefficient of friction, while *Harris and Day* [1997] considered a friction coefficient that drops in value following the onset of sliding. The Harris and Day numerical simulations, and all others done since then [e.g., *Andrews and Harris*, 2005, 2006; *Harris and Day*, 2005; *Shi and Ben-Zion*, 2006; Rubin and Ampuero, submitted manuscript, 2006] are consistent in showing bilateral rupture whenever the friction coefficient is allowed to fall to a dynamic friction value that is below the minimum required to stabilize the fault under the initial static stress conditions, that is, to below τ_0/σ_0, where τ_0 and σ_0 are the initial values of shear and normal stress. When the friction coefficient does not weaken to below τ_0/σ_0, the wrinkle pulse dominates and a unilateral rupture mode can occur, albeit with very small slips and very short rise time (of the order of milliseconds) [see *Shi and Ben-Zion*, 2006]; when the friction coefficient does weaken in the above sense, the rupture is invariably bilateral.

[5] This conclusion holds irrespective of whether the solution is regularized by viscous loss [*Harris and Day*, 1997, 2005] or by the addition of memory effects to the normal-stress dependence of the shear resistance [e.g., *Ranjith and Rice*, 2001; *Cochard and Rice*, 2000; Rubin and Ampuero, submitted manuscript, 2006]. It even holds for unregularized numerical solutions [*Shi and Ben-Zion*, 2006], although such solutions are highly suspect (because they include wavefield components with wavelength too short to be accurately modeled by grid-based numerical methods—the resulting numerical noise is very evident in the results in *Shi and Ben-Zion* [2006]). Nor is the conclusion altered when 3D effects are considered [*Andrews and Harris*, 2005; *Harris and Day*, 2005]. Furthermore, laboratory experiments allow for controlled material contrasts and controlled nucleation and initial stress conditions, and so provide a test of numerical and theoretical assertions about spontaneous rupture dynamics (e.g., A. Rosakis et al., Dynamic shear rupture in frictional interfaces: Speeds, directionality, and modes, submitted to *Treatise on Geophysics*, edited by H. Kanamori, 2006). Laboratory experiments of spontaneous rupture propagation on a fault that is the interface between two plastics, homalite and polycar-

[1]U.S. Geological Survey, Menlo Park, California, USA.
[2]Department of Geological Sciences, San Diego State University, San Diego, California, USA.

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bonate, show convincing evidence of bilateral rupture propagation where friction drops during rupture [*Xia et al.*, 2005]. These laboratory experiments further confirm and support the theoretical results cited above.

[6] The world's best recorded small, moderate, and large earthquakes have occurred in a material contrast setting, the Parkfield earthquakes on the San Andreas fault in central California [*Bakun et al.*, 2005; *Langbein et al.*, 2005]. The most recent large event, the 2004 M6 earthquake, and its predecessors, studied as part of the Parkfield Earthquake Prediction Experiment [e.g., *Bakun and Lindh*, 1985], provide a key test of the material contrast hypothesis [*Harris and Day*, 2005; *Xia et al.*, 2005]. In the Parkfield region, tomographic images of the P-wave velocity structure [*Eberhart-Phillips and Michael*, 1993; *Thurber et al.*, 2006] show a material contrast near the San Andreas fault. This contrast however did not lead to unilateral rupture propagation in the direction predicted if rupture propagation direction were controlled by the wrinkle pulse. Instead, *Harris and Day* [2005] show that a range of propagation directions occurred during 70 years of Parkfield earthquakes, based on findings from other researchers' high-resolution studies of earthquakes at Parkfield [see *Harris and Day*, 2005 and references therein]. Thus, our best available observations appear to be consistent with the foregoing theoretical and experimental predictions.

[7] The Ben-Zion [this issue] commentary proposes that the Parkfield region does not represent a material contrast across a single fault, the San Andreas fault, but is instead a trimaterial setting with a damage-zone between two parallel fault planes. The commentary also proposes, without citing any evidence, that earthquakes at Parkfield have nucleated on one or the other of these parallel fault strands and propagated in the directions dictated by the surrounding materials. This suggestion, however, is not consistent with high-resolution Parkfield observations. Instead, using relocated seismicity [*Thurber et al.*, 2006], *Simpson et al.* [2006] reveals the fault zone at Parkfield to be a single fault, the San Andreas fault, at >6 km depth, that then branches into two fault planes, the San Andreas fault, and the Southwest Fracture Zone, as one travels updip, above 6 km depth. This fault zone geometry forms the shape of a 'Y', and is not two parallel faults [*Simpson et al.*, 2006]. Since nucleation during the 2004 M6 Parkfield earthquake occurred below 6 km depth [*Langbein et al.*, 2005], the M6 earthquake must have nucleated, then propagated [*Custódio et al.*, 2005; *Liu et al.*, 2006] on the single fault plane that is the San Andreas fault, before it could encounter the shallow two-fault setting. This observation of a single fault at depth transitioning to two faults closer to the earth's surface shows a much more complex picture of fault geometry than the comment-author's simple scenario of rupture in opposite directions on two parallel faults, and does not appear to offer any support for rupture in a preferred direction controlled by the wrinkle pulse.

[8] To summarize, we find consistent results from three sources: theoretical results from high-resolution numerical simulations with a realistic drop in friction during rupture, laboratory experiments on shear faults at a bimaterial interface, and high-resolution observations of earthquake ruptures. These results are consistent in finding that material contrast alone does not lead to a predictable preferred rupture direction.

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S. M. Day, Department of Geological Sciences, San Diego State University, San Diego, CA 92182, USA. (day@moho.sdsu.edu)

R. A. Harris, U.S. Geological Survey, M.S. 977, 345 Middlefield Road, Menlo Park, CA 94025, USA. (harris@usgs.gov)