Material contrast does not predict earthquake rupture propagation direction

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[1] Earthquakes often occur on faults that juxtapose different rocks. The result is rupture behavior that differs from that of an earthquake occurring on a fault in a homogeneous material. Previous 2D numerical simulations have studied simple cases of earthquake rupture propagation where there is a material contrast across a fault and have come to two different conclusions: 1) earthquake rupture propagation direction can be predicted from the material contrast, and 2) earthquake rupture propagation direction cannot be predicted from the material contrast. In this paper we provide observational evidence from 70 years of earthquakes at Parkfield, CA, and new 3D numerical simulations. Both the observations and the numerical simulations demonstrate that earthquake rupture propagation direction is unlikely to be predictable on the basis of a material contrast. Citation: Harris, R. A., and S. M. Day (2005), Material contrast does not predict earthquake rupture propagation direction, Geophys. Res. Lett., 32, L23301, doi:10.1029/2005GL023941.

1. Introduction

[2] What allows large earthquakes to occur repeatedly on faults, without generating much heat? One mechanism proposed in the 1990's invoked a contrast in compliance between different rocks on the NE side of the fault, then this 'preferred-direction' hypothesis would have the earthquakes on the NW-SE striking fault rupturing both to the NW and to the SE (Figure 1a). Such predictions are possible because the numerical simulations, the lab experiments also do not predict results that depend on the assumed friction formulation. Instead we propose that propagation direction at Parkfield and elsewhere is controlled by fault geometry and rheology.

2. Computer Simulations of Earthquakes: Preferred Direction Hypothesis

[3] To address the question of what determines rupture propagation direction, scientists have explored computer simulations of earthquakes. One set of computer simulations has examined earthquake behavior for the case of a fault that bounds two different rock types. These 2D simulations predict results that depend on the assumed friction formulation. Some numerical experiments have suggested that there would be a preferred direction of rupture as a consequence of these normal stress fluctuations. Since increased ground motion [Boatwright and Boore, 1982; Somerville et al., 1997] damage, and triggered seismicity [Gomberg et al., 2001] are often observed in the forward direction of a propagating earthquake rupture, predicting propagation direction would be a step towards deterministic hazard prediction. Here we show that earthquakes on the Parkfield section of the San Andreas fault do not support the hypothesis that rupture propagation direction is predictable from rock compliance contrast. A series of magnitude 4 to magnitude 6 Parkfield earthquakes from 1934 to 2004 did not all propagate in the direction predicted by their surrounding rock types. Nor do numerical simulations that include a reduction in friction coefficient during sliding [Harris and Day, 1997] predict a preferred rupture direction. Instead we propose that propagation direction at Parkfield and elsewhere is controlled by fault geometry and rheology.

3. Computer Simulations of Earthquakes: No-Preferred Direction Hypothesis

[4] Concurrent work [Harris and Day, 1997] has examined a second end-member case of computer simulations in which the friction coefficient transitions between static and kinetic states when fault sliding begins. For this second end-member case generally predicts that the preferred propagation direction for earthquakes should be in the slip direction of the ‘softer’ (lower shear modulus) rock [Andrews and Ben-Zion, 1997; Ben-Zion and Andrews, 1998; Cochard and Rice, 2000; Ranjith and Rice, 2001]. As an example, if a right-lateral strike-slip fault strikes NW-SE and has softer rocks on the NE side of the fault, then this ‘preferred-direction’ hypothesis would have earthquakes on this fault rupturing from NW to SE (Figure 1a).
show a preferred propagation direction in the presence of a material contrast.

4. Observational Evidence

[5] Although much can be learned from computer and lab simulations of earthquakes and cracks, the observations of actual earthquakes serve to test the computational- and lab-based hypotheses. For the material contrast case the observational evidence has been relatively sparse, with one exception. This exception is the San Andreas fault near Parkfield, California. The Parkfield site has been intensely monitored for more than 20 years due to its recurring M6 earthquakes, the most recent of which occurred in 2004 [Langbein et al., 2005]. Observational data from Parkfield earthquakes extend to the 1800’s, but the best recorded events have occurred since the 1930’s. Next we show how Parkfield earthquakes from 1934 to 2004 and with magnitudes ranging from M4 to M6, disagree with the preferred-direction hypothesis (Figure 2).

[6] The San Andreas fault is a right-lateral strike-slip fault. Near Parkfield the fault mainly offsets Franciscan assemblage rocks on the NE side of the fault from Salinian granitic rocks on the SW side of the fault [Dibblee, 1971; Eberhart-Phillips and Michael, 1993], leading to predominantly ‘softer’ rocks on the NE side, and predominantly ‘stiffer’ rocks on the SW side. Using this simple model of material contrast across a fault, the preferred-direction hypothesis would have all Parkfield San Andreas earthquakes rupturing the fault from NW to SE (Figure 1a). Many earthquakes at Parkfield have shown this behavior. In 1934 an M6 Parkfield earthquake occurred and regional seismograms show that it nucleated in the NW and subsequently ruptured along the San Andreas fault to the SE [Bakun and McEvilly, 1979, 1984]. A similar event occurred in 1966 when the San Andreas fault once again slipped in an M6 Parkfield earthquake that ruptured from NW to SE [Bakun and McEvilly, 1979, 1984]. However neither the 1934 nor the 1966 M6 earthquakes were solo events. Instead both M6 earthquakes had M5 foreshocks, the closest event in time to each M6 being a 17-minute earlier M5 foreshock. In both 1934 and 1966 the M5 foreshocks nucleated in the same region as their subsequent M6 mainshocks, but rather than propagating from NW to SE, both of the M5 foreshocks propagated along the San Andreas fault from SE to NW [Bakun and McEvilly, 1979].

[7] Taken together, the M6 1934 and 1966 Parkfield mainshocks appear to endorse the preferred-direction hypothesis, since both earthquakes propagated in the predicted direction for this section of the San Andreas fault. However, the M5 foreshocks, whose rupture directions were opposite to their hypothesized pathways, conflict with the preferred-direction hypothesis. The evidence against the preferred-direction hypothesis mounts as one marches forward in time and examines other Parkfield earthquakes.

[8] In 1992, 1993, and 1994, magnitude 4 (M4+) earthquakes occurred in the area of the San Andreas fault where the 1966 M6 mainshock started. These moderate 1990’s earthquakes were shown to have propagated upwards and to
Spudich
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predecessors, the 2004 M6 earthquake propagated on the
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occurred, on the same portion of the fault as 1934 and 1966.
the observational evidence seems to require another expla-
predicted by this hypothesis (Figures 1 and 2). Therefore
propagated in the direction that would be predicted by the
in the middle of the fault at 0 seconds then spontaneously
propagates. (a) Schematic showing the 3D finite-difference
grid used for the simulations. The simulated earthquake
nucleates at the circles. (b) Spontaneous rupture simulations.
On the near side of the fault Vp = 6000 m/s, Vs =
3464 m/s. On the far side of the fault Vp = 5000 m/s, Vs =
2887 m/s. The density 2670 kg/m3 is the same for both
sides. Each frame shows a snapshot of the rupture at
0.5 second intervals. Contours show the differential
horizontal slip-velocity (m/s). Note that the rupture
propagates in both along-strike directions, to the right
and, left. (c) Same as b) except that on the far side of the
fault Vp = 4000 m/s, Vs = 2309 m/s. Note that the rupture
propagates in both along-strike directions, to the right and,
left. To the left the propagation speed is supershear, >Vs, as
observed in 2D simulations by Harris and Day [1997].
the SE (one earthquake), and upwards and to the NW (two
earthquakes), rather than NW to SE [Fletcher and Spudich,
1998].
In 2004 the most recent M6 Parkfield earthquake
occurred, on the same portion of the fault as 1934 and 1966.
A surprise for those anticipating the recent M6 earthquake
was its propagation direction. Unlike its 1934 and 1966 M6
predecessors, the 2004 M6 earthquake propagated on the
San Andreas fault primarily from SE to NW [Fletcher and
Spudich, 2004; Langbein et al., 2005].
To summarize, two M6 Parkfield earthquakes have
propagated in the direction that would be predicted by the
preferred-direction hypothesis, and one M6, two M5 and
two M4 earthquakes have propagated in directions not
predicted by this hypothesis (Figures 1 and 2). Therefore
the observational evidence seems to require another expla-
nation for the propagation directions of earthquakes.
5. New 3D Computer Simulations of Earthquakes
Before abandoning the computationally-based pre-
ferred-direction hypothesis, one more numerical test needs
to be done. Since all of the aforementioned numerical
studies were for the 2D case of a fault bounded by
contrasting materials, here we also examine 3D simulations
to test if including the third dimension might alter our
hypotheses about rupture propagation direction. The third
dimension is of large significance for the material contrast
scenario because only in the 2D in-plane (along-strike, for a
strike-slip fault) situation are the shear and normal stresses
coupled. In 3D the anti-plane (along-dip for strike-slip)
contribution can also be significant, and the anti-plane
solution behaves differently than the in-plane solution.
For numerical comparison with earlier 2D simula-
tions [Harris and Day, 1997], we use the same initial
conditions and friction parameters, and the same method-
ology. The 3D numerical simulations use a 3D finite-
difference computer program [Day, 1982; Day and Ely,
2002] and invoke artificial nucleation at the hypocenter
followed by spontaneous (unforced) rupture propagation.
The slip-weakening fracture criterion [Ida, 1972] allows the
rupture to propagate as long as points on the fault plane
meet or exceed the slip-dependent failure threshold. Since
there is a material contrast across the fault, the normal stress
does not remain constant, but instead varies. We take the
frictional stress to be proportional to the normal stress.
Because of the instantaneous response of frictional stress
to normal stress change, the perfectly elastic problem is ill-
posed, in the sense that steady sliding is unstable to
perturbations of all wavelengths [Adams, 1995]. We regu-
larize the problem by making the medium Kelvin-Voigt
viscoelastic, which eliminates the exponential growth of
short-wavelength perturbations and makes the problem
analytically well-posed, as well as numerically well-
behaved. The finite-difference simulations use a node-
sizing of 50 m (similar results were produced using
25 m), a slip-weakening critical distance of 0.1 m, and
static and kinetic friction coefficients of 0.6 and 0.5,
respectively. The initial shear and normal stresses are
107.5 MPa and 200 MPa, respectively.
Figure 3 shows the simulations for the cases of 17%
and 33% contrast across a vertical right-lateral strike-slip
fault with faster material on the ‘closer’ side of the fault, and
slower material on the ‘farther’ side of the fault. Even
though the full 3D solution incorporates many more features
than are permitted in 2D, we find that the behavior in the
along-strike direction is the same for the 3D and 2D cases.
The 3D case shows along-strike rupture speeds and rupture
patterns that are the same as those presented by Harris and

Figure 3. 3D computer simulations of an earthquake propagating on a right-lateral vertical-strike-slip fault. The rock on the far side of the fault is softer than the rock on the near side. The simulated earthquake is artificially nucleated at 0.5 seconds then spontaneously propagates. (a) Schematic showing the 3D finite-difference grid used for the simulations. The simulated earthquake nucleates at the circles. (b) Spontaneous rupture simulations. On the near side of the fault Vp = 6000 m/s, Vs = 3464 m/s. On the far side of the fault Vp = 5000 m/s, Vs = 2887 m/s. The density 2670 kg/m3 is the same for both sides. Each frame shows a snapshot of the rupture at 0.5 second intervals. Contours show the differential horizontal slip-velocity (m/s). Note that the rupture propagates in both along-strike directions, to the right and, left. (c) Same as b) except that on the far side of the fault Vp = 4000 m/s, Vs = 2309 m/s. Note that the rupture propagates in both along-strike directions, to the right and, left. To the left the propagation speed is supershear, >Vs, as observed in 2D simulations by Harris and Day [1997].
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