Reply to comment on "How fast is rupture during an earthquake? New insights from the 1999 Turkey earthquakes"

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[1] In a previous paper [*Bouchon et al.*, 2001], we presented what we believe are strong indications of supershear rupture over parts of the faults of the 1999 Turkey earthquakes. These findings are based on near-fault recordings and modeling of the ground motion. We also showed that the supershear value inferred for the Izmit earthquake (the only event for which this velocity is well resolved) is close to $\sqrt{2}$ times the shear wave velocity, which is the value theoretically predicted in fracture dynamics for stable shear crack growth in the absence of an extended shear process zone [*Freund*, 1979; *Gao et al.*, 1999; *Huang et al.*, 1999] and is also the one which has been observed in laboratory experiments of shear rupture [*Rosakis et al.*, 1999, 2000]. These are the major findings of the paper and the only results mentioned in the abstract.

[2] Recently *Broberg* [1994] and *Samudrala et al.* [2001] have shown that in the presence of a shear process zone of some realistic magnitude like the one mentioned by *Andrews* [2002] in his comments, $\sqrt{2}Vs$ retains much of its special significance and that for most realistic values of fault strength, the energy release rate has a maximum at values close to $\sqrt{2}Vs$ suggesting the tendency of shear cracks to stably propagate around that speed.

[3] After establishing these results, we tried to find some clues which might help explain why rupture propagated at supershear speed over parts of the fault while it propagated at the "classical" sub-Rayleigh velocity over other parts. We found two possible clues in the observations. We did not pretend that either clue played a role in the supershear rupture, but we thought that they might be relevant to the problem and should be presented and summarily discussed.

[4] One clue comes from the clear observation that, along the Izmit supershear segment, P-waves propagate faster along the southern side of the fault than along its northern side. That such a situation might have affected the rupture dynamics is suggested by theoretical studies [*Weertman*, 1980; *Rice*, 1997; *Andrews and Ben-Zion*, 1997; *Harris and Day*, 1997; *Ben-Zion and Andrews*, 1998; *Cochard and Rice*, 2000] which show that the presence of different materials on the two sides of the fault can greatly modify the characteristics of rupture. As the fault slips, the normal stress on the fault (which for a planar fault in a homogeneous medium is constant and equal to the tectonic loading) continuously changes, reducing or enhancing friction. The major effect theoretically predicted is that rupture will be facilitated in the direction in which the more compliant medium is moving. This, however, as correctly pointed out by *Andrews* [2002] in his comments, only applies to a subshear rupture. In a recent paper motivated by our observations, *Weertman* [2002] investigated the stress field properties of a dislocation moving at approximatively $\sqrt{2}Vs$ on the interface between half-spaces of slightly different elastic constants. His results suggest that, at such a velocity, the reduction in normal stress would occur in the direction in which the harder medium is moving, thus conflicting with our observations. Another study relevant to the problem is the theoretical investigation by *Liu et al.* [1995] of a crack propagating along an elastic/rigid interface at intersonic speeds. The configuration studied represents the most extreme case of a bimaterial mismatch, but it demonstrates the meaning of $\sqrt{2}Vs$ for a bimaterial. The authors found that only at $\sqrt{2}Vs$ is the crack allowed to propagate without any crack face interaction. When applied to the configuration of the Izmit supershear segment (in which case the less compliant medium is considered rigid), their results show that the crack faces will try to open up (pressure release over the tectonically imposed static level) for all speeds between Vs and $\sqrt{2}Vs$, while they will try to interpenetrate (resulting in increase pressure) for all speeds between $\sqrt{2}Vs$ and Vp. In light of the various recent theoretical investigations of the problem which show that the presence of two different materials "*leads to the emergence of a much richer phenomenology than rupture along a plane in a homogeneous continuum*" [*Cochard and Rice*, 2000], we still view the observed velocity contrast across the supershear fault segment as having played a possible role on the dynamics of the rupture on this segment.

[5] The second clue that we presented in *Bouchon et al.* [2001] as a possible factor in the supershear rupture comes from field observations and satellite images of the Izmit rupture. These observations show that the surface break of the fault segment over which rupture propagated at supershear speed is a simple scar, often no more than a meter wide, extending very linearly over several tens of kilometers [*Michel and Avouac*, 2002; *Barka et al.*, 2002]. The surface rupture clearly expresses a narrow linear deformation zone which indicates that the supershear fault segment has a simple planar morphology. In contrast, the western fault segment over which rupture propagated at sub-Rayleigh velocity is part of the complex fault system of the Marmara Sea. Eastward of the supershear segment, where rupture propagated also at sub-Rayleigh velocity, the fault geometry becomes complex and its surface break is discontinuous and changes direction.

[6] A puzzling observation to earthquake engineers, which may be relevant to the supershear problem, is the low ground accelerations recorded near the fault during the Izmit earthquake [*Erdik*, 2000]. The values recorded are surprisingly low for an event of this magnitude and devastation [e.g. *Erdik*, 2000; *Celebi et al.*, 2000]. At first, this may seem in apparent contradiction with the inferrence of supershear rupture as such a rupture will produce a shock-like wavefront near the fault (see *Rosakis et al.* [1999] for an experimental illustration of this phenomenon). However, the ground accelerations are the expressions of the high-frequency radiation of the source and this radiation is mostly controlled by the heterogeneities and irregularities of the rupture process [e.g. *Bernard et al.*, 1996]. The low accelerations recorded near the fault suggest that the rupture process was relatively (and unusually) smooth. Low-acceleration levels and supershear rupture may thus both be related to the simple planar morphology of the central segment of the Izmit rupture.

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[7] As we mentioned in the original paper, supershear rupture during previous earthquakes may also have led to the simple morphology of this segment.

[8] What we offered in *Bouchon et al.* [2001], beyond showing strong indications that supershear rupture occurred in the 1999 Turkey earthquakes and that the velocity inferred is close to the one theoretically predicted and experimentally observed, are some possible clues, based on different sets of observations, of what might have contibuted to this phenomenon. We do not claim to have the definite answer as to why supershear occurred on parts of the faults while other segments broke at the "classical" sub-Rayleigh velocity.

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