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How Fast is Rupture during an Earthquake ? New Insights from the 1999 Turkey Earthquakes

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Abstract.
We report that during the two devastating 1999 earthquakes in Turkey, rupture propagated over a large part of the nearly 200km long fault zone at supershear speed approaching 5km/s. We present observations and modeling which confirm the original inference of supershear rupture during the Izmit earthquake and we show that supershear rupture also occurred during the Düzce earthquake. We show that the rupture velocity measured - about $\sqrt{2}$ times the shear wave velocity - is the value predicted by theoretical studies in fracture dynamics. We look for clues to explain these observations.

Introduction

Classical work in fracture dynamics has shown that the Rayleigh wave speed of the material is the limiting speed of propagation for mode I (tensile) cracks and it had long been assumed to be the case for mode II (inplane shear) cracks as well. A little over two decades ago, however, *Burridge* [1973], *Andrews* [1976], and *Das and Aki* [1977] showed that shear cracks can either propagate at sub-Rayleigh velocity ($V < V_R$) or at intersonic velocity ($V_S < V < V_P$) depending on the cohesive strength of the fault. Subsequent studies in fracture dynamics have confirmed these findings but have shown that crack propagation at most of the intersonic velocities is unstable [*Freund*, 1979; *Burridge et al.*, 1979].

Rupture velocities have been determined for several earthquakes and, when well resolved, they are all sub-Rayleigh with the exception of the 1979 Imperial Valley earthquake in California, for which *Archuleta* [1984] showed strong indications that rupture propagated at supershear velocity over part of the fault. *Archuleta*'s results are also supported by observations made by *Spudich and Cranswick* [1984]. Recent studies suggest that during the 1992 Landers earthquake, rupture locally exceeded the shear wave velocity over fault patches a few kilometers across, but rupture velocity over such limited distance ranges is poorly resolved.

The Izmit earthquake

Figure 1a shows the horizontal ground acceleration recorded at two sites near the fault during the Izmit earthquake. One station (ARC), located about 55km west of the hypocenter (Figure 1c), was operated by Boğaziçi University while the other (SKR), situated about 40km east of the hypocenter, was set up by the Turkish General Directorate of Disaster Affairs. The fault which ruptured during the earthquake is vertically dipping and extends from the earth surface down to a depth of about 20 km [*Toksöz et al.*, 1999; *Özalaybey et al.*, 2001]. It is nearly 150km long and trends almost E-W. During the earthquake, the northern side of the fault moved eastward relatively to the southern side by an average amount of about 3 m [*Barka et al.*, 1999].

Although ARC is located a little further away than SKR, the roughly symmetric location of the two stations with respect to the epicenter and to the fault and the similarity of slip amplitudes to the east and west of the epicenter lead us to expect comparable E-W ground motion at the two sites. As shown in Figure 1a, however, the records display strikingly different time histories. To the west, the P and S wave trains can be clearly identified. To the east, the two wave trains seem mixed together and the strong shaking closely follows the first P arrival. This is even more apparent on the ground velocity traces displayed in Figure 1b. While the ground motion slowly increases for several seconds following the first P arrival at ARC, motion at SKR becomes suddenly very large only 1.8s after the P arrival.

As most of the seismic energy released in earthquakes is radiated in the form of shear waves, these records imply that, while rupture propagated westward at the "classical" sub-Rayleigh velocity, allowing for the clear separation of P and S waves, it propagated eastward at supershear speed, producing shear arrivals at SKR much before their arrival from the hypocenter.

To further support this interpretation, we compare in Figure 1d the main shock accelerations at SKR with those of the largest aftershock ($M = 6.2$), located only a few kilometers away from the main shock focus. For the aftershock the strong shaking begins at the expected arrival time of the S waves from the hypocenter (Sh) while for the main shock it starts several seconds earlier.

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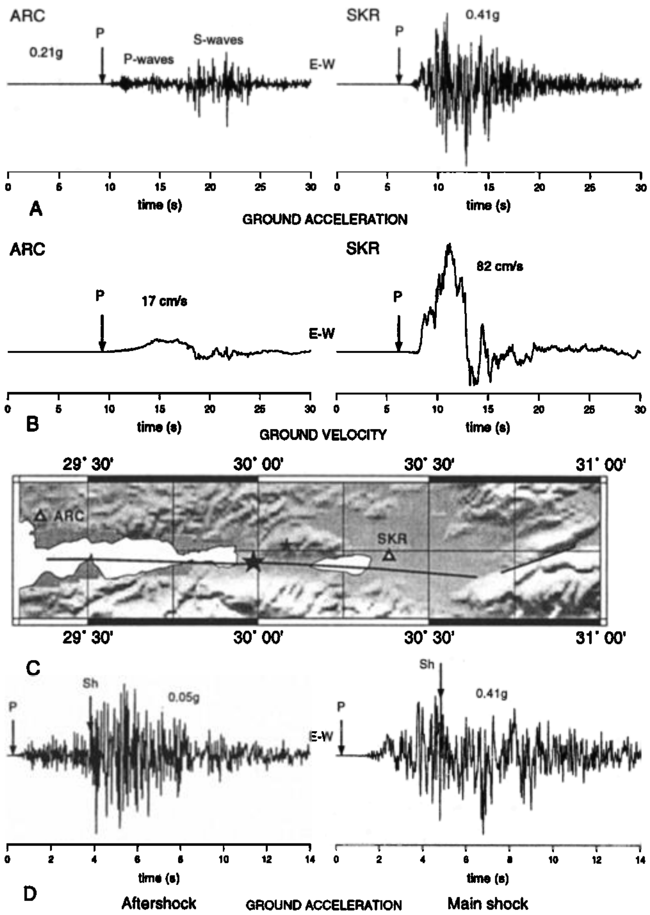

Figure 1. (A) Comparison of the E-W accelerations recorded at two sites during the Izmit earthquake. Traces start at the inferred earthquake origin time. P arrivals are indicated. Values show peak accelerations. (B) Same as above for the velocity. (C) Map showing the epicenter (large star), the surface breaks (solid line), the recording sites (triangles), and the aftershock (small star) whose records are shown below. (D) Comparison of the main shock records at SKR with those of the strongest aftershock (September 13). The traces start 0.2s before the P arrival. Sh shows the expected arrival time for S waves coming from the hypocenters.

The rupture velocity can be directly inferred from the S-P time on the SKR records (1.8s). As shown by *Ellsworth and Çelebi* [1999] and *Bouchon et al.* [2000], this yields an apparent velocity of 4.7km/s. As the station is located a few kilometers from the fault, what it really sees, however, is the passage of the conical shock wave front. Thus, by the time the wave front reaches the station, rupture has already passed by it. Correcting for this yields a rupture velocity of 4.8 to 4.9km/s.

The inversion of the full records gives a value of about 4.7 to 4.8km/s. This rupture speed explains remarkably well the SKR records (Figure 2). Records at ARC, on the other hand, are best explained by a rupture propagating westward at 3km/s [*Bouchon et al.,* 2000].

A unique feature of intersonic crack growth is that the stress singularity at the crack tip is not the classical square root singularity, as it is for sub-Rayleigh speed, except for a specific value of the rupture speed: $\sqrt{2}V_S$. The specificity of this intersonic velocity was originally showed by *Eshelby* [1949] for a moving glide dislocation and has been confirmed for shear cracks by subsequent investigations [*Freund,* 1979; *Burridge et al.,* 1979]. The nature of the stress discontinuity at the crack tip is directly related to the energy release rate supplied by the elastic field for crack growth. *Freund* [1979] has shown that the stable growth of shear cracks at intersonic speed is only possible at $\sqrt{2}V_S$, because the energy flux into the crack tip, which provides the fracture energy to advance the rupture, is zero at all the other intersonic velocities. This result has been recently confirmed by *Huang et al.* [1999] and *Gao et al.* [1999].

Until a little over a year ago, however, no experimental confirmation of supershear rupture had been reported in the scientific or engineering literature. The first successful experiment was made recently by *Rosakis et al.* [1999, 2000] who observed the intersonic propagation of a shear crack. The rupture velocity they measured is about $\sqrt{2}V_S$. In the present case of the Izmit earthquake, the velocity inferred (about 4.8km/s) corresponds to the one predicted for stable crack growth.

Recent numerical simulations by *Andrews and Ben-Zion* [1997], *Rice* [1997], *Harris and Day* [1997], *Ben-Zion and Andrews* [1998], and *Cochard and Rice* [2000], suggest that shear rupture is facilitated when the two sides of the fault have different elastic properties. In this case, the normal stress near the crack tip may be reduced due to the non-symmetry of the stress field.

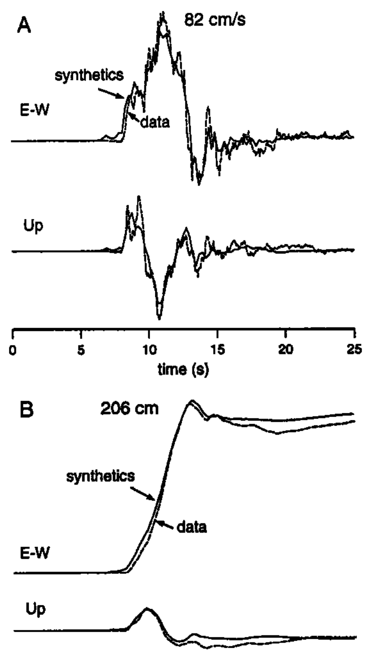

Figure 2. (A) Comparison of the ground velocity recorded at SKR with the one calculated for the rupture model which best fits the strong motion records. In this model, rupture propagates eastward at about 4.7 to 4.8km/s for nearly 50km. Traces start at the origin time of the earthquake. Peak recorded velocity is indicated. (B) Same as above for the displacement.

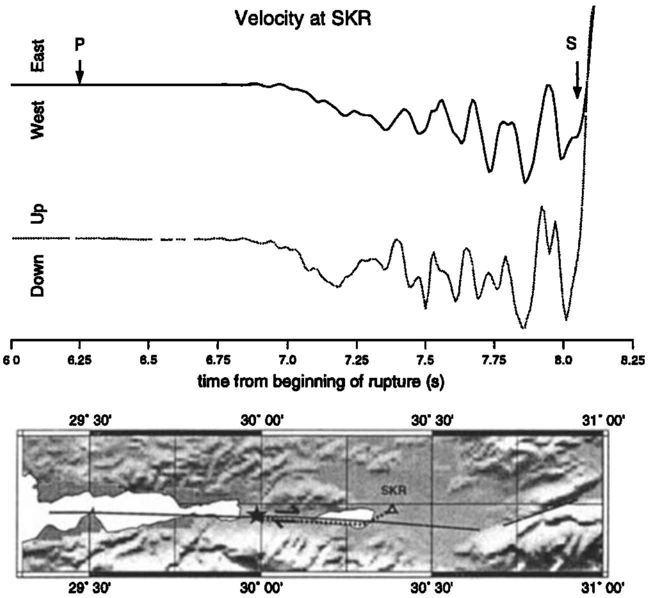

Figure 3. (Top) P wave train at SKR. The upper trace is a zoom of the record of Figure 1b. The lower trace is the corresponding vertical velocity. Arrival times of P and S waves are indicated. (Bottom) Map showing the epicenter (star), the fault (solid line), and the station (triangle). The arrows indicate the directions of motion of the two sides of the fault. The dotted line illustrates the path followed by P waves traveling from the central segment of the fault to the station.

This, however, will only occur when rupture propagates in the direction in which the more compliant medium is moving. These findings may be relevant here. Figure 3 is an enlarged picture of the P wave train at SKR. It shows that the station moved westward and downward for the whole duration of the wave train. As seen at the bottom of the figure, this is not what is expected at this location. The station should have moved eastward and up. During the first 1.8s of rupture, the station saw the rupture as if it were located on the southern side of the fault. The likely and simple explanation for this is that rocks to the south of the fault have higher velocity than rocks to the north, so that P waves arrive at the station after having traveled along the south side of the fault, as schematically shown. According to the above studies, the presence of lower velocity material to the north of the fault and the fact that this side was sliding eastward, would have facilitated the eastward propagation of the rupture. This may explain why rupture propagated at supershear speed eastward while it propagated westward at sub-Rayleigh velocity.

As seen in the field and on the Spot images [*Michel and Avouac,* 2001], the segment over which rupture propagated at supershear speed makes a remarkably linear scar, often no more than a meter wide. The simple planar morphology of the fault that this implies may have contributed to it. The two may indeed be related, supershear speed during previous earthquakes on this segment may have led to its simple morphology. In contrast, west of the epicenter the rupture enters the more complex faulting system of the Marmara Sea.

The Düzce earthquake

The Düzce earthquake extended three months later the rupture zone of the Izmit earthquake 40km eastward. The fault still trends nearly E-W but dips to

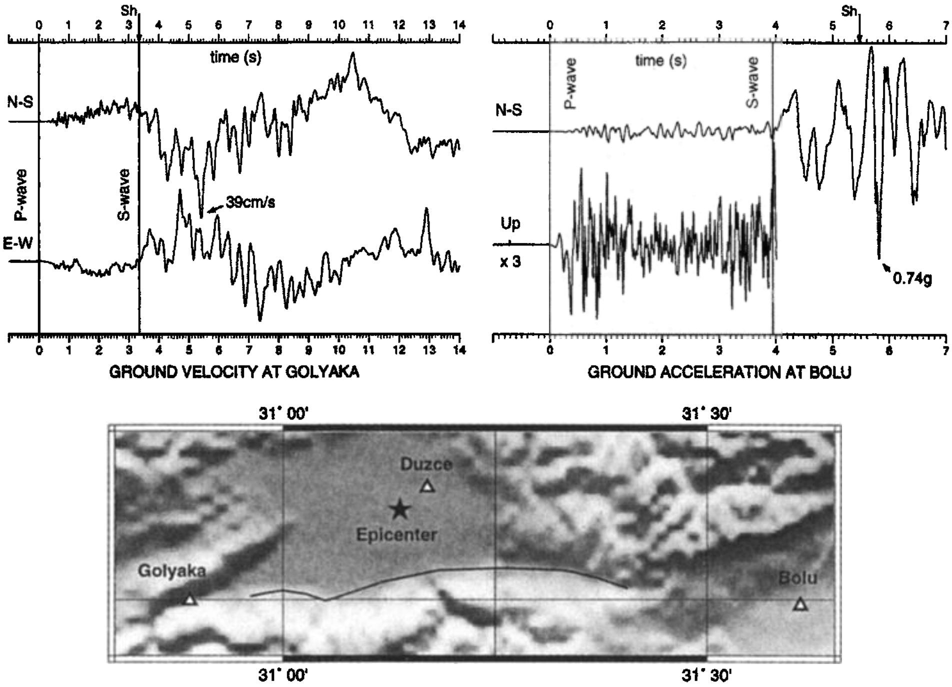

Figure 4. (Top) Ground motion recorded during the Düzce earthquake at two stations located near the two extremities of the fault. The time origin corresponds to the first arrival at the station. Vertical lines are drawn at the observed arrival times of P and S waves. Sh denotes the expected arrival time of S waves from the hypocenter. Values indicate peak amplitudes. The vertical acceleration at Bolu is amplified to clearly show the P onset and is not displayed beyond 4s to prevent it to overlay the horizontal acceleration trace. (Bottom) Map showing the epicenter (star), the surface rupture (solid line), and the strong motion stations (triangles).

the north at about 65° [*Özalaybey et al.*, 2000] (Figure 4). During the earthquake, the northern side moved eastward, relatively to the southern side, by about 4m.

The ground motion was recorded at two stations located near the extremities of the fault. At Gölyaka to the west (Figure 4), a station that we installed a few hours before the earthquake, S waves arrive 3.35s after the first P waves. This delay corresponds exactly to the S-P time expected for waves coming from the hypocenter. On the other hand, at Bolu to the east, S waves arrive 3.95s after the first P waves. The expected S-P time there, however, is 5.25s. Thus, these records show direct evidence that rupture again propagated at supershear speed during the Düzce earthquake.

What that speed was is more difficult to infer than for Izmit because the station is located beyond the fault termination and it seems likely that rupture decelerated before stopping. What can be inferred is the average rupture velocity between the hypocenter and the eastern edge of the surface breaks: about 4.3km/s. Westward, the modeling indicates a velocity of about 3km/s.

Thus, in the Düzce earthquake again, eastward rupture was supershear (on at least a large part of the fault) while westward rupture was sub-Rayleigh. As the fault has played in the past (and partly during the earthquake) as a normal fault [*Armijo et al.*, 2000], rocks to the north have a shallower origin than rocks to the south, thus likely creating a material contrast with the lower velocity medium to the north. Like in Izmit, this may have contributed to the supershear eastward rupture.

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