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Differences in Earthquake Source and Ground Motion Characteristics between Surface and Buried Crustal Earthquakes

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Abstract

In previous work, we have shown that the ground motions from crustal earthquakes that break the ground surface are weaker than the ground motions from buried faulting crustal earthquakes. In this paper, we describe differences in kinematic and dynamic source parameters that may give rise to these differences in ground motion levels. From kinematic rupture models, we show that the slip velocity of surface faulting earthquakes is less that the slip velocity of buried faulting earthquakes. From dynamic rupture models, we infer that rupture in the shallow part of fault (upper few km) is controlled by velocity strengthening, with larger slip weakening distance D_c, larger fracture energy, larger energy absorption from the crack tip, lower rupture velocity, and lower slip velocity than at greater depths on the fault. Dynamic rupture modeling using these properties results in lower ground motions for surface faulting than for buried faulting events, consistent with the observations.

Key words: ground motions, crustal earthquakes, surface rupture events, buried rupture events

1. Observed Differences in Ground Motions

At short and intermediate periods (0.3–3.0 s) the recorded ground motions from crustal earthquakes that produce large surface rupture are systematically weaker than the ground motions from crustal earthquakes whose rupture is confined to the subsurface (Somerville, 2003; Kagawa *et al.*, 2004). The large differences in ground motion levels between surface and buried faulting events are evident in Figure 1, which shows the response spectra of near-fault recordings of recent large earthquakes. The left panel shows recordings from four surface faulting earthquakes in the M_w range of 7.4 to 7.9, and the right panel shows recordings from two buried faulting earthquakes of magnitude M_w 6.7 and 7.0. The response spectra of the deep earthquakes are much stronger than those of the larger shallow earthquakes for periods less than 1.5 sec. Figure 2 shows the event terms for larger sets of surface rupture earthquakes at the top, and subsurface rupture earthquakes at the bottom. The unit line represents the Abrahamson and Silva (1977) model, and lines above this line indicate that the event's ground motions on average exceed the model (Abrahamson *et al.*, 1990). The ground motions of the subsurface rupture earthquakes are systematically stronger than average, and those of the surface rupture earthquakes are weaker that average, over a broad period range centered at one second, which dominates peak velocity. This phenomenon is not region dependent, since the data used in the analyses are from crustal earthquakes in different tectonically active regions around the world (Kagawa *et al.*, 2004).

2. Observed Differences in Kinematic Source Characteristics

Somerville (2003) and Kagawa *et al.* (2004) have shown that earthquakes with surface rupture have asperities (regions of large slip, as defined by Somerville *et al.*, 1999) at depths shallower than 5 km (and possibly others that are deeper), while earthquakes with subsurface rupture have asperities that are all

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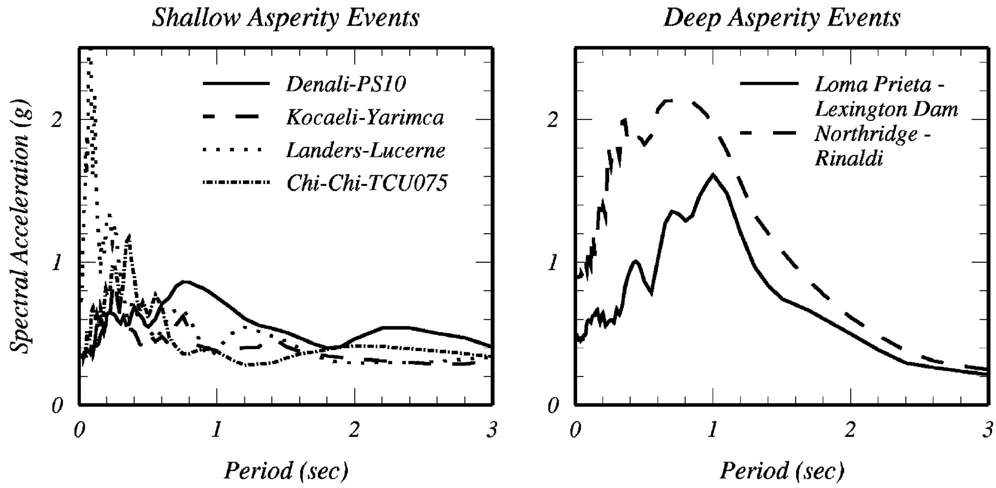

Fig. 1. Near-fault response spectra of recent large earthquakes. Left: Four earthquakes, Mw 7.2 to 7.9, with shallow asperities and large surface faulting. Right: Two earthquakes, Mw 6.7 and 7.0, with deep asperities and no surface faulting.

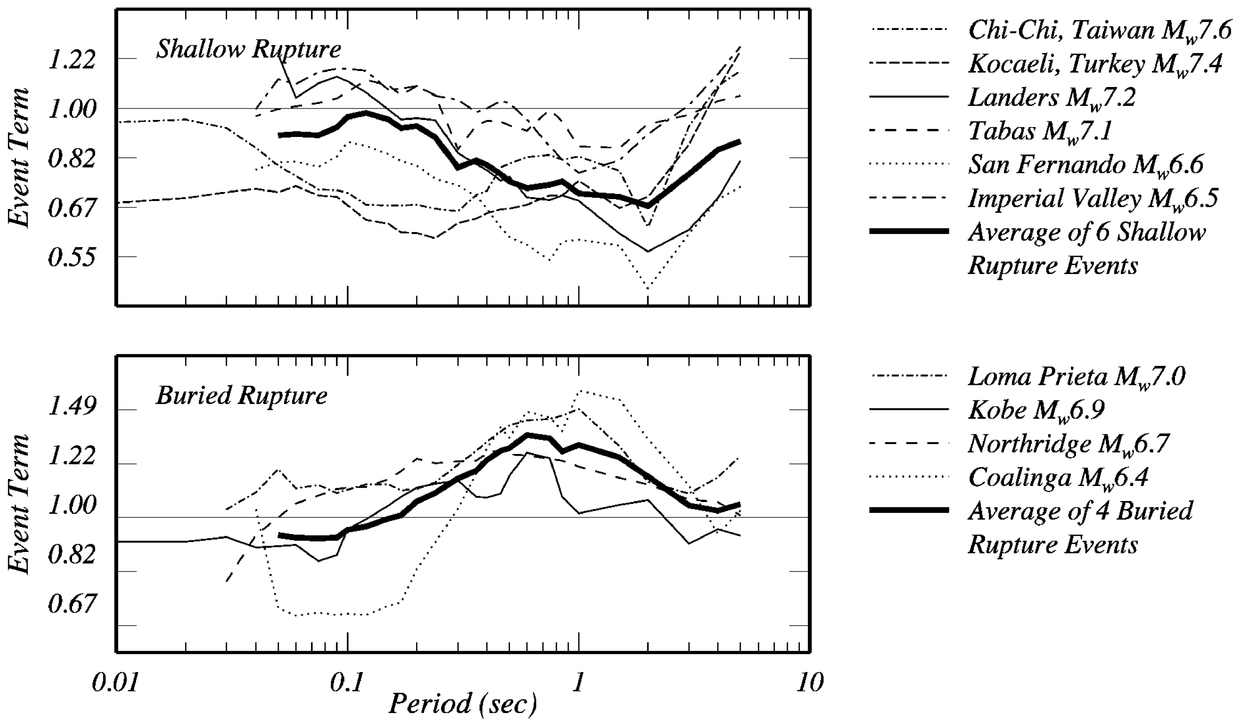

Fig. 2. Comparison of response spectral amplitude of individual earthquakes having surface rupture (top) and buried rupture (bottom), averaged over recording sites, with the amplitude of the average earthquake as represented by the model of Abrahamson and Silva (1997), represented by the unit line, which accounts for magnitude, closest distance and recording site category. The event terms (residuals) are shown as the ratio of the event to the model. Source: Somerville (2003).

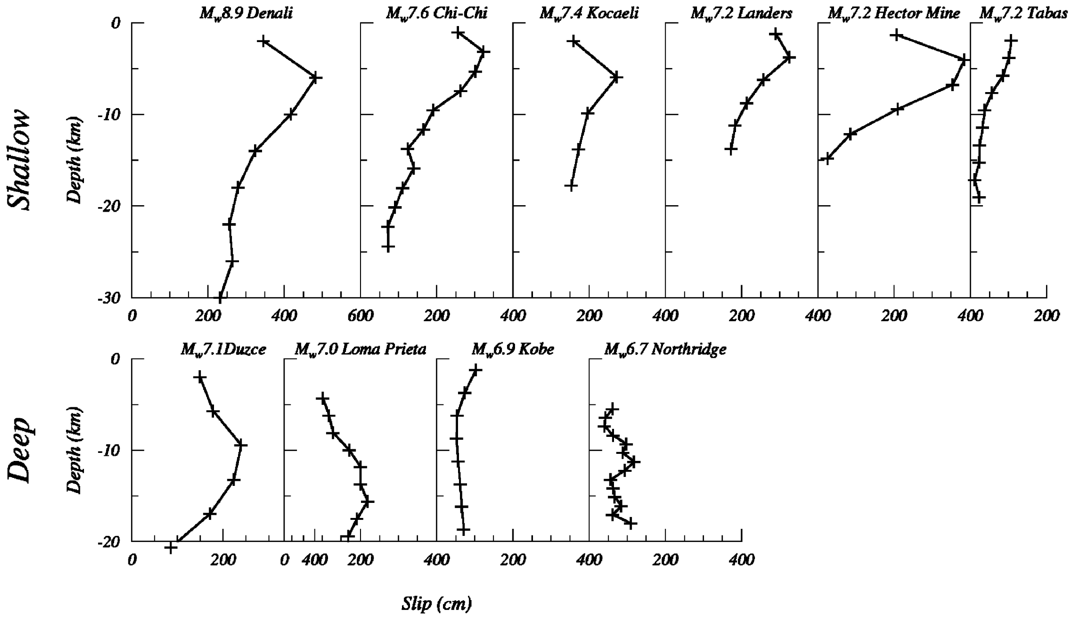

Fig. 3. Distribution of slip for shallow (top) and deep (bottom) earthquakes.

deeper than 5 km. The observation of weaker ground motions for surface than for buried faulting earthquakes seems paradoxical, because the shallow events have much larger near-surface displacements. This can be seen by comparing the distribution of slip with depth, averaged along strike, for surface faulting earthquakes, shown at the top of Figure 3, with that for buried faulting earthquakes, shown at the bottom of Figure 3.

However, slip velocity is a much more important determinant of strong motion levels than fault slip (Dan and Sato, 1999). The effective slip velocity is defined by Ishii *et al.* (2000) as the slip velocity averaged over the time in which the slip grows from 10% to 70% of its final value, and represents the dynamic stress drop. As shown in Figure 4, the distribution of effective slip velocity with depth for shallow events is quite different from the distribution of slip with depth. The shallow events have large near-surface displacements, but they do not have correspondingly large slip velocities. The slip velocities of the deep events, as high as 2 m/sec, are larger than those of the shallow events, causing larger ground motion levels because slip velocity strongly controls strong motion levels. Averaged over 9 shallow events and 8 deep events, the slip velocity of shallow events is about 70% that of deep events. This is true both for the fault as a whole and for the asperities on the fault. We consider that this difference in slip velocity between shallow and deep events is an important aspect of earthquake source characterization for the simulation of strong ground motion.

3. Observed Differences in Dynamic Source Characteristics

In a systematic analysis of dynamic rupture models of crustal earthquakes, Mai *et al.* (2005) found that the fracture energy is large for surface faulting events, and small for subsurface faults, as shown in Figure 5, in which the events on the left side are for surface faulting, and the events on the right side are for buried faulting. The large fracture energy of shallow events reduces the amount of energy available for seismic radiation, causing such events to produce mainly long period seismic radiation. This is consistent with surface faulting events producing weak high frequency ground motions as described in Figures 1 and 2. Abercrombie and Rice (2005) and Tinti *et al.* (2005) both show that fracture energy increases with seismic moment. This would cause a corresponding decrease in radiated energy, inhibiting the growth of strong motion amplitudes with increasing seismic moment for earthquakes that are large enough to break the surface, and thus tending to limit the growth of ground motion amplitudes with magnitude.

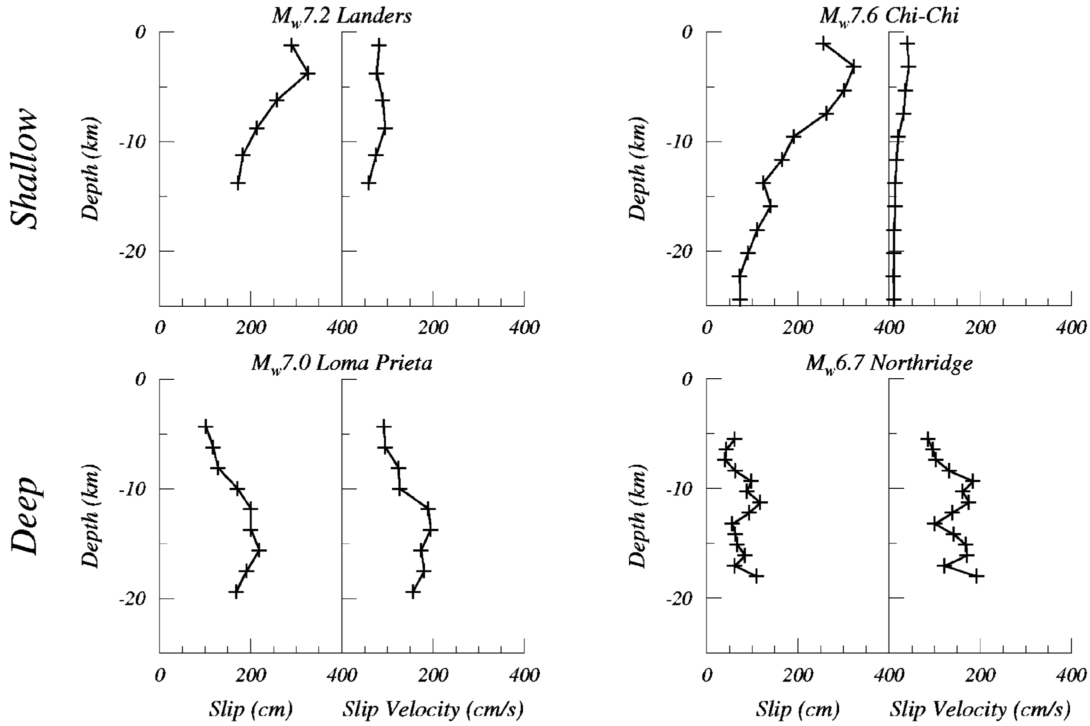

Fig. 4. Distribution of slip (left panel) and slip velocity (right panel) for shallow (top) and deep (bottom) earthquakes. The left hand side compares two strike slip earthquakes and the right hand side compares two thrust earthquakes.

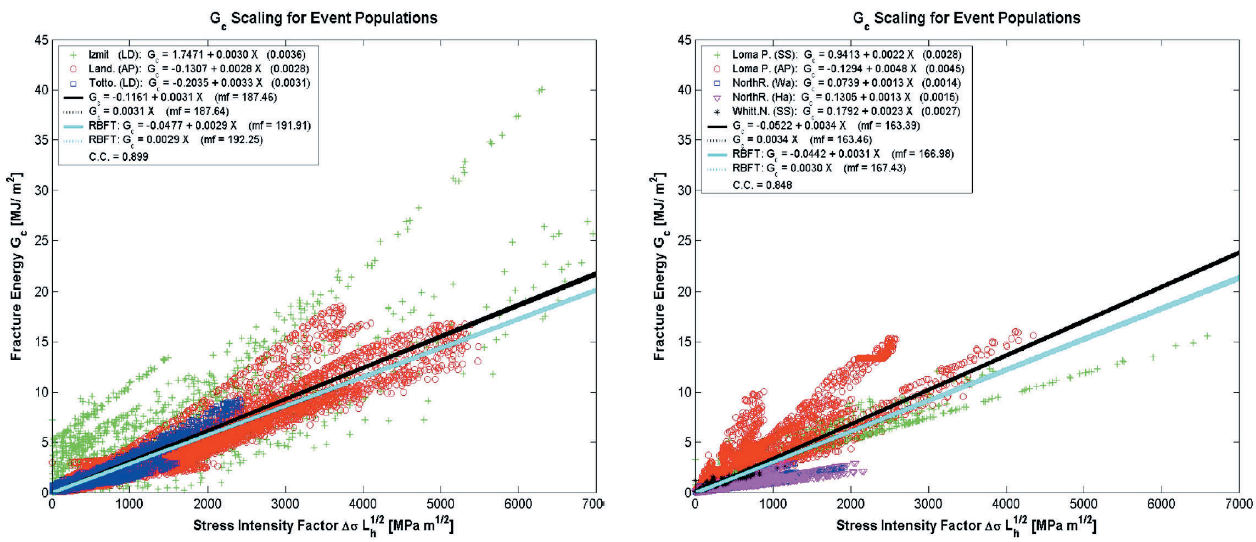

Fig. 5. Distribution of fracture energy (vertical axis) and stress intensity factor (horizontal axis) for surface rupture (left) and buried rupture (right) events. Source: Mai *et al.* (2005).

Both numerical models (Day and Ely, 2002) and laboratory models (Brune and Anooshehpoor, 1988) of the weak zone have revealed its significant effects on rupture dynamics and near-fault particle motion. In the weak zone, the friction increases with sliding velocity (velocity strengthening), and the dynamic friction is quite low compared with that in the deeper part of the fault. Velocity strengthening causes negative or small positive stress drop, and reduces the radiated seismic energy. Consequently, the contribution to the ground motion from shallow asperities is low. Rock mechanics experiments have shown that the presence of a thick gouge layer produces similar effects (e.g. Marone and Scholz, 1988; Shimamoto and Logan, 1981). We expect that the effect of velocity strengthening is significant for shallow slip on existing faults and in soft sedimentary rocks.

Estimates of the slip weakening distance D_c from dynamic rupture models have been summarized by Mai *et al.* (2005). It is notable that the 1994 Northridge earthquake had an unusually short slip weakening distance, between 0.1 and 0.15 meters, as estimated by three separate studies (Nielsen and Olsen, 2000; Oglesby and Day, 2002; and Hartzell *et al.*, 2005), in contrast with values of 0.4 to 0.9m, 0.4–1.5 m, and 0.8–3.5 m for the Tottori, Kobe and Landers earthquakes respectively. Among the four events analyzed, the Northridge earthquake is the only thrust event, and the only event having no surface rupture. These measurements of fracture energy and slip weakening distance are consistent with rupture in the shallow part of the fault (upper 5 km) being controlled by velocity strengthening, with larger slip weakening distance Dc, larger fracture energy, larger energy absorption from the crack tip, lower rupture velocity, and lower slip velocity than at greater depths on the fault, resulting in lower ground motions for surface faulting than for buried faulting events.

Fluctuations in rupture velocity may affect the frequency content of the seismic energy generated during the rupture. The slowdown in rupture velocity due to velocity hardening and increase of D_c in the shallow part of the fault could cause the suppression of high frequency energy and enhancement of long period ground motion energy. The overall rupture behavior, and consequently the frequency content of near-fault ground motion, may be different depending on whether the hypocenter is shallow or deep.

4. Modeling of Differences using Rupture Dynamics

We have used rupture dynamic modeling (Pitarka and Dalguer, 2003) to shed light on the physics of why surface faulting earthquakes have weaker ground motions than those of buried faulting (Pitarka *et al.*, 2005). The top panel of Figure 6 is a buried rupture, and the panels below it are for increasingly weak shallow zones (represented by decreasing values of stress drop) in the upper 5 km of the crust. With increasing weakness, the shallow zone is increasingly effective at arresting the upward propagation of rupture to the surface, reducing the slip velocity on the fault, and reducing the strength of the ground motion. The ratio of buried to surface spectral acceleration is shown as a function of period in the third column of Figure 6. For increasingly low values of strength of the shallow zone, the ground motion values become increasingly weak. Figure 7 compares buried rupture with the third surface rupture case (shallow stress drop = 1 Mpa) from Figure 6, showing much larger slip velocities on the fault for the buried rupture case than for the surface faulting case. This demonstrates that we can find realistic rheological models of the shallow part of the fault that are consistent with the observation of weaker ground motions from surface faulting than from buried faulting earthquakes.

5. Conclusions

The ground motions from earthquakes that break the ground surface are weaker than the ground motions from buried faulting earthquakes. From kinematic rupture models, we show that the slip velocity of surface faulting earthquakes is less that the slip velocity of buried faulting earthquakes. From dynamic rupture models, we infer that rupture in the shallow part of fault (upper few km) is controlled by velocity strengthening, with larger slip weakening distance D_c, larger fracture energy, larger energy absorption from the crack tip, lower rupture velocity, and lower slip velocity than at greater depths on the fault. Dynamic rupture modeling using these properties results in lower ground motions for surface faulting than for buried faulting events, consistent with the observations.

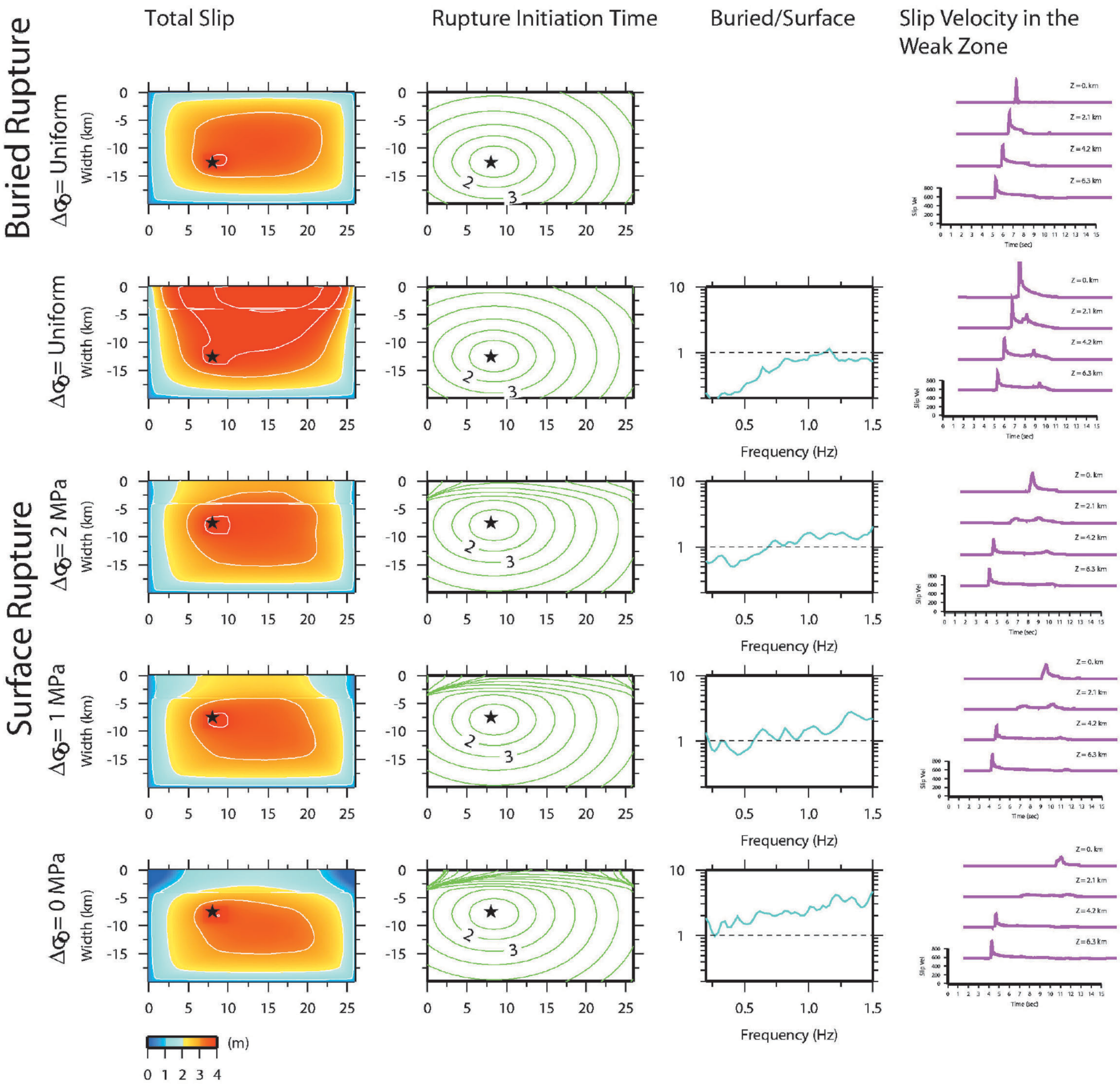

Fig. 6. Dynamic simulation of buried and surface rupture earthquakes. The top panel is a buried rupture, and the panels below it are for surface rupture with increasingly weak shallow zones in the upper 4 km of the crust. The shallow zone is increasingly effective at arresting the upward propagation of rupture to the surface, reducing the slip velocity on the fault, and reducing the strength of the ground motion.

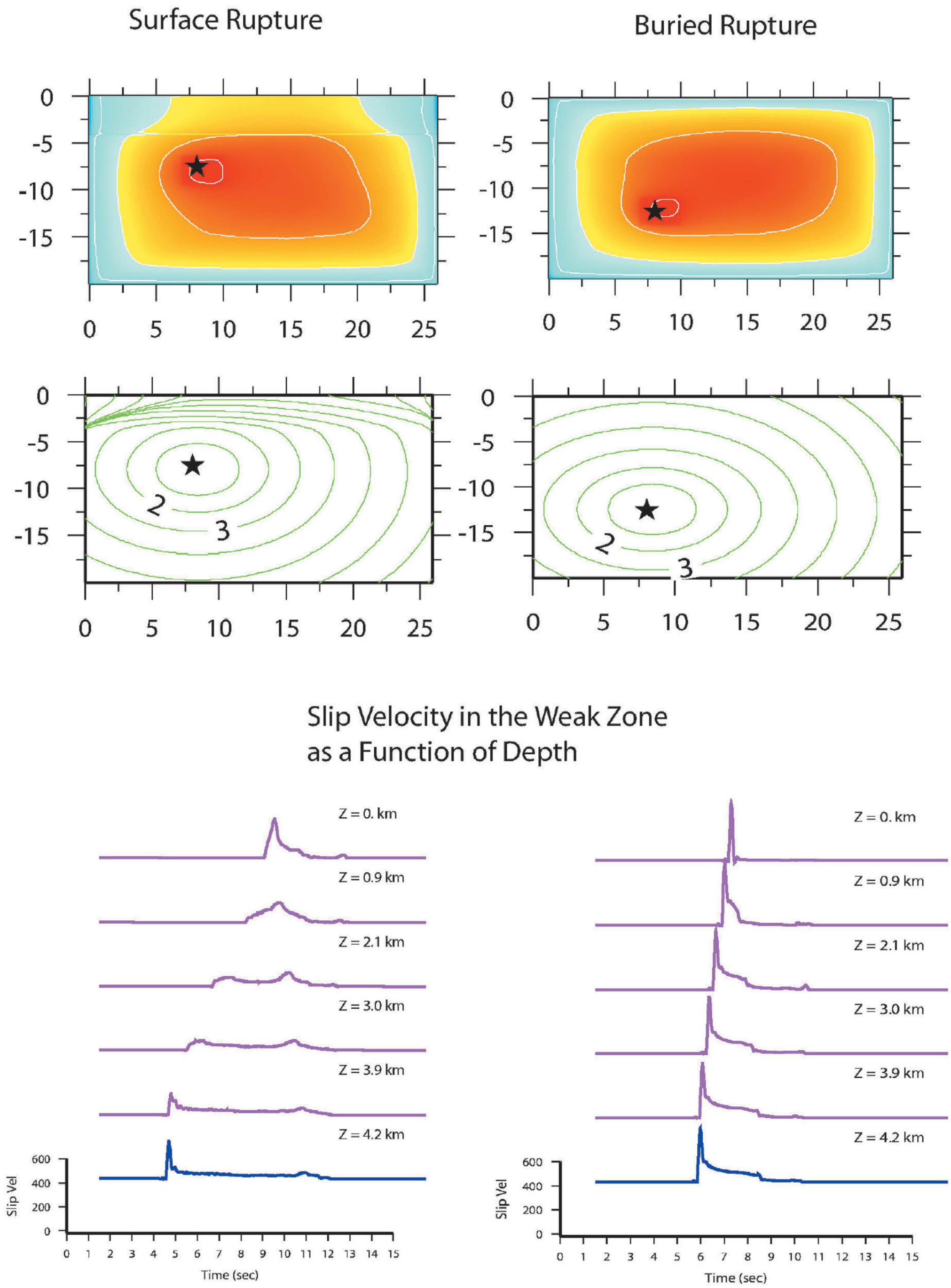

Fig. 7. Detail from Figure 6 comparing buried rupture with third surface rupture case (shallow stress drop=1 Mpa), showing much larger slip velocities on the fault for the buried rupture case.

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