Physical Limits on Ground Motion at Yucca Mountain and Dynamic Rupture Models with Slip-Weakening Friction Laws

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Outline

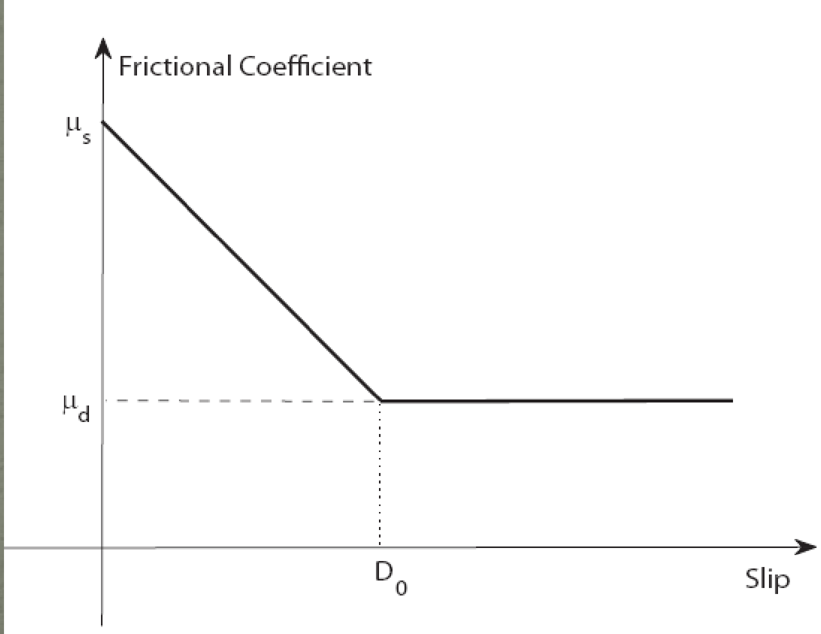
- Day et al. (2005)'s formulation of TSN
- A case study: LVFZ, off-fault yielding & ground motion
- Physical limits on GM at YM: pore-pressure, fault geometry, fault zone structure (with Steve Day)
- Experimental tests on using slip-weakening & elastic off-fault response for physical limit study
  - Ground motion
  - Fault slip rate
- Conclusions

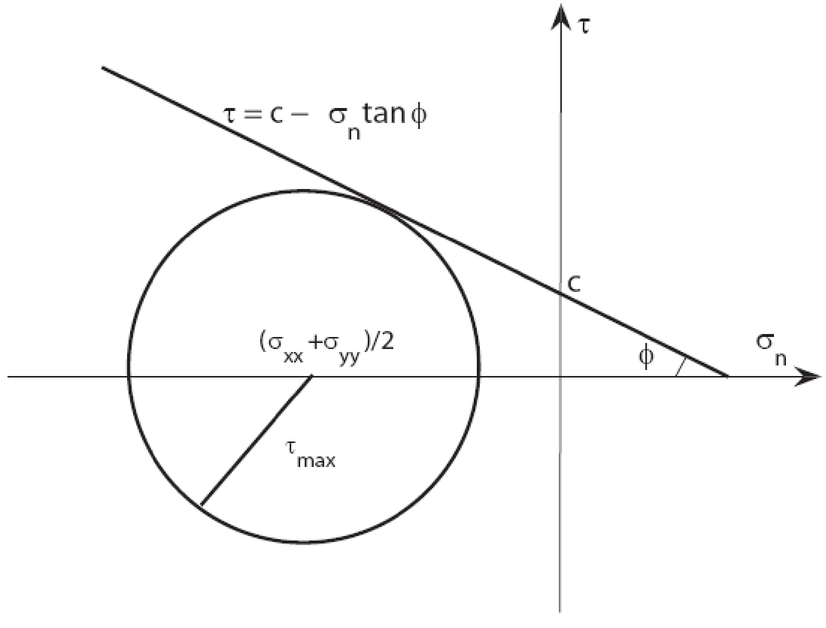
Day et al. (2005)'s TSN

Implemented in EQdyna both 2D and 3D (Duan)

Method: EQdyna (a FEM dynamic code)

- Slip-weakening / Time-weakening Laws on Fault
- Elastic (2D & 3D)or Elastoplastic off-fault Response (2D only)

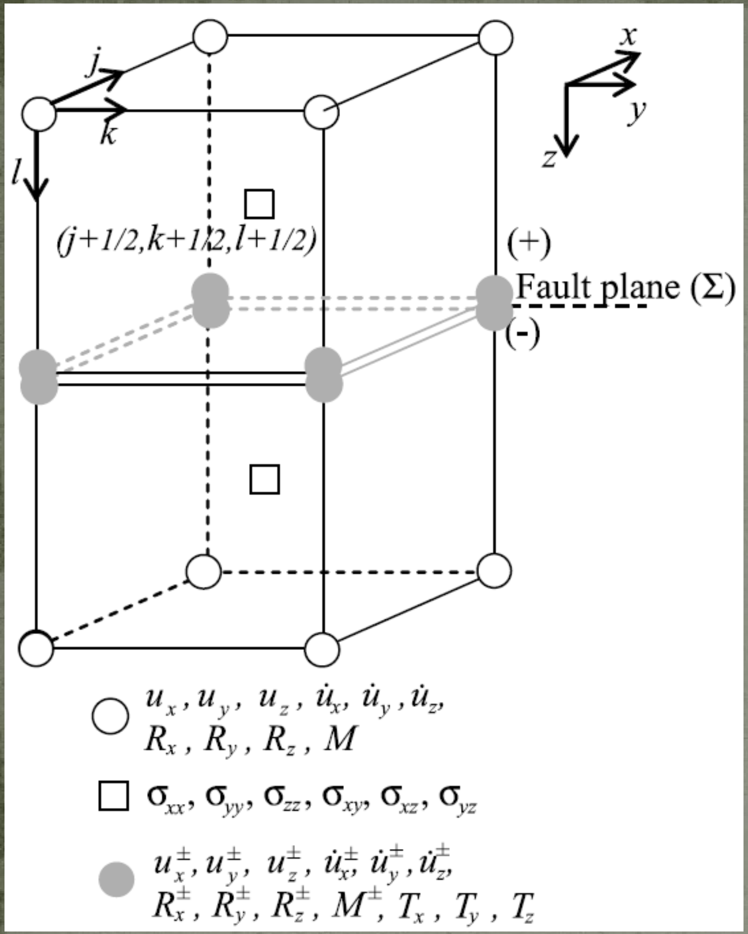




Day et al.' s (2005) TSN formulation

- Treat fault behavior in one theoretical framework at all times, “including prerupture, initial rupture, arrest of sliding, and possible subsequent episodes of reactivation and arrest. … it is unnecessary to test for the conditions nor to construct separate fault plane equations for these different conditions.”

- Andrews (11-14-08): “more robust, can be coded to behave appropriately with zero friction.”



$$\tilde{T}_\nu \equiv \frac{\Delta t^{-1}M^+M^-\left(\dot{u}_\nu^+ - \dot{u}_\nu^-\right) + M^-R_\nu^+ - M^+R_\nu^-}{a(M^+ + M^-)} + T_\nu^0, \quad \nu = x, y,$$

$$\tilde{T}_\nu \equiv \frac{\Delta t^{-1}M^+M^-\left[\left(\dot{u}_\nu^+ - \dot{u}_\nu^-\right) + \Delta t^{-1}\left(u_\nu^+ - u_\nu^-\right)\right] + M^-R_\nu^+ - M^+R_\nu^-}{a(M^+ + M^-)} + T_\nu^0, \quad \nu = z, \tag{11}$$

$$T_\nu = \begin{cases} \tilde{T}_\nu & \nu = x, y, \ \left[\left(\tilde{T}_x\right)^2 + \left(\tilde{T}_y\right)^2\right]^{1/2} \leq \tau_c, \\ \tau_c \dfrac{\tilde{T}_\nu}{\left[\left(\tilde{T}_x\right)^2 + \left(\tilde{T}_y\right)^2\right]^{1/2}} & \nu = x, y, \ \left[\left(\tilde{T}_x\right)^2 + \left(\tilde{T}_y\right)^2\right]^{1/2} > \tau_c, \\ \tilde{T}_\nu & \nu = z, \quad \tilde{T}_z \leq 0, \\ 0 & \nu = z, \quad \tilde{T}_z \geq 0, \end{cases} \tag{12}$$

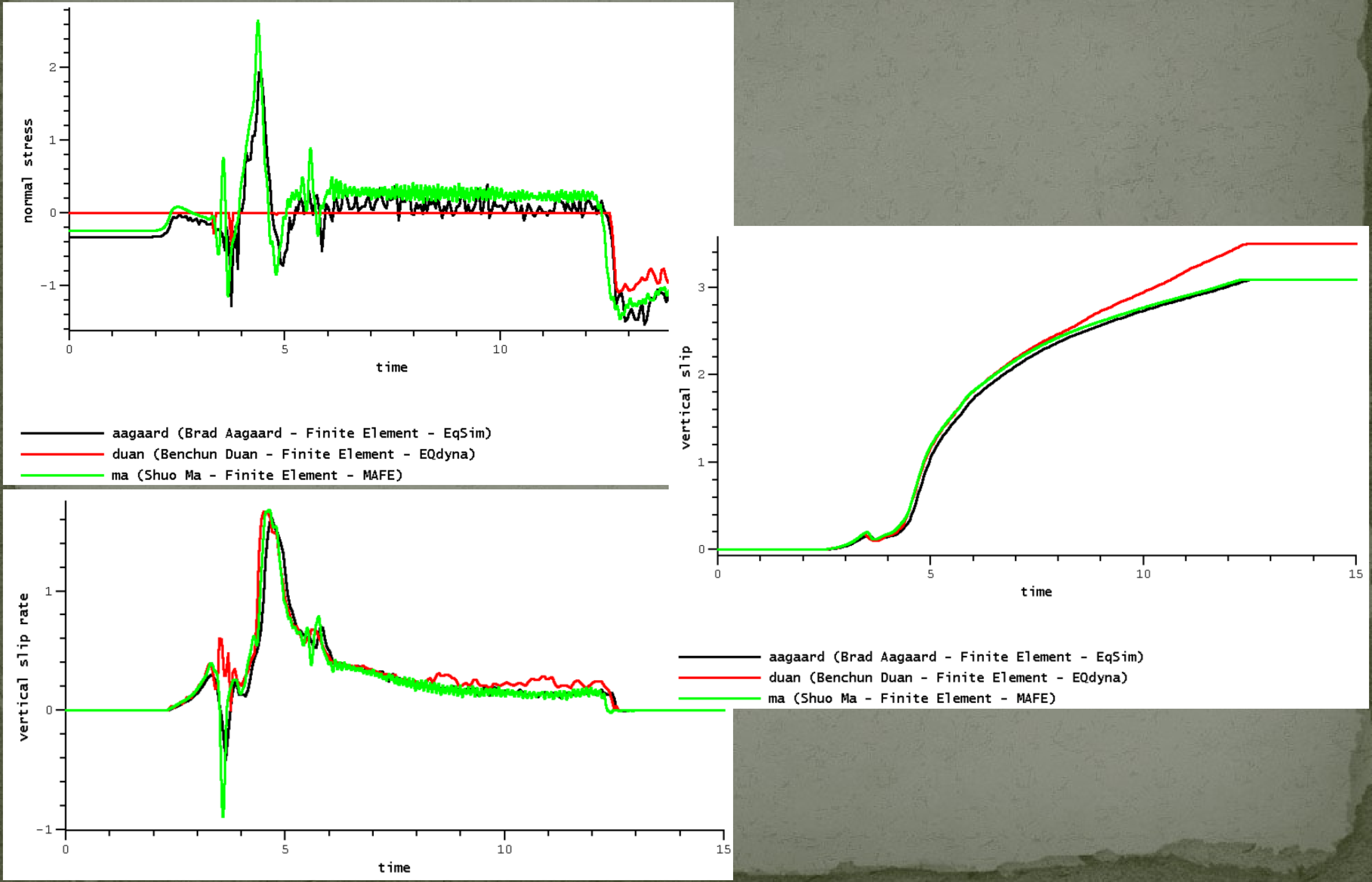
- ➢ Treat multiple episodes of fault opening and closure.
- ➢ No interpenetration.

$$\sigma_n \leq 0, \tag{7}$$

$$U_n \geq 0, \tag{8}$$

$$\sigma_n U_n = 0, \tag{9}$$

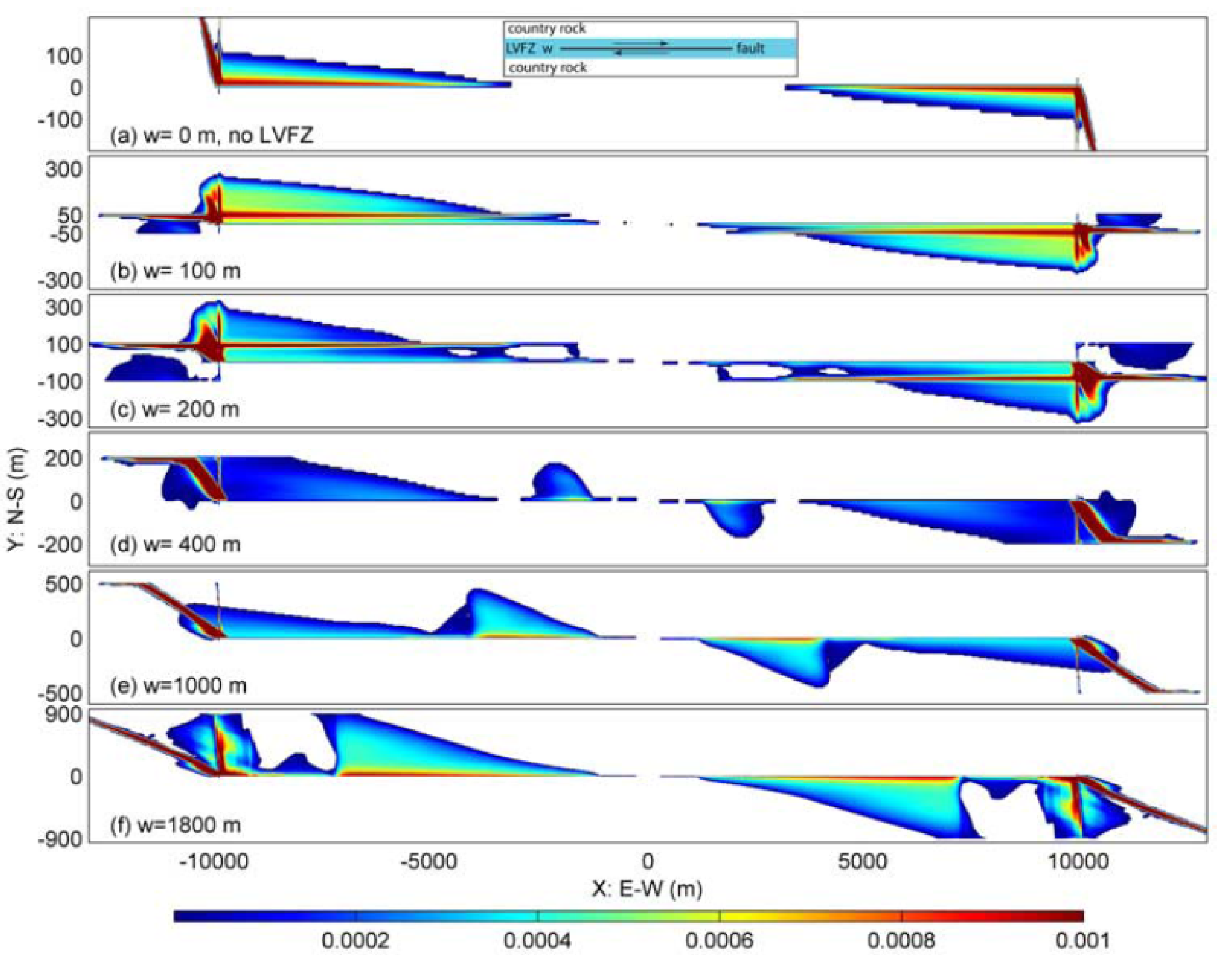
Fault opening effects: TPV10 ftepi



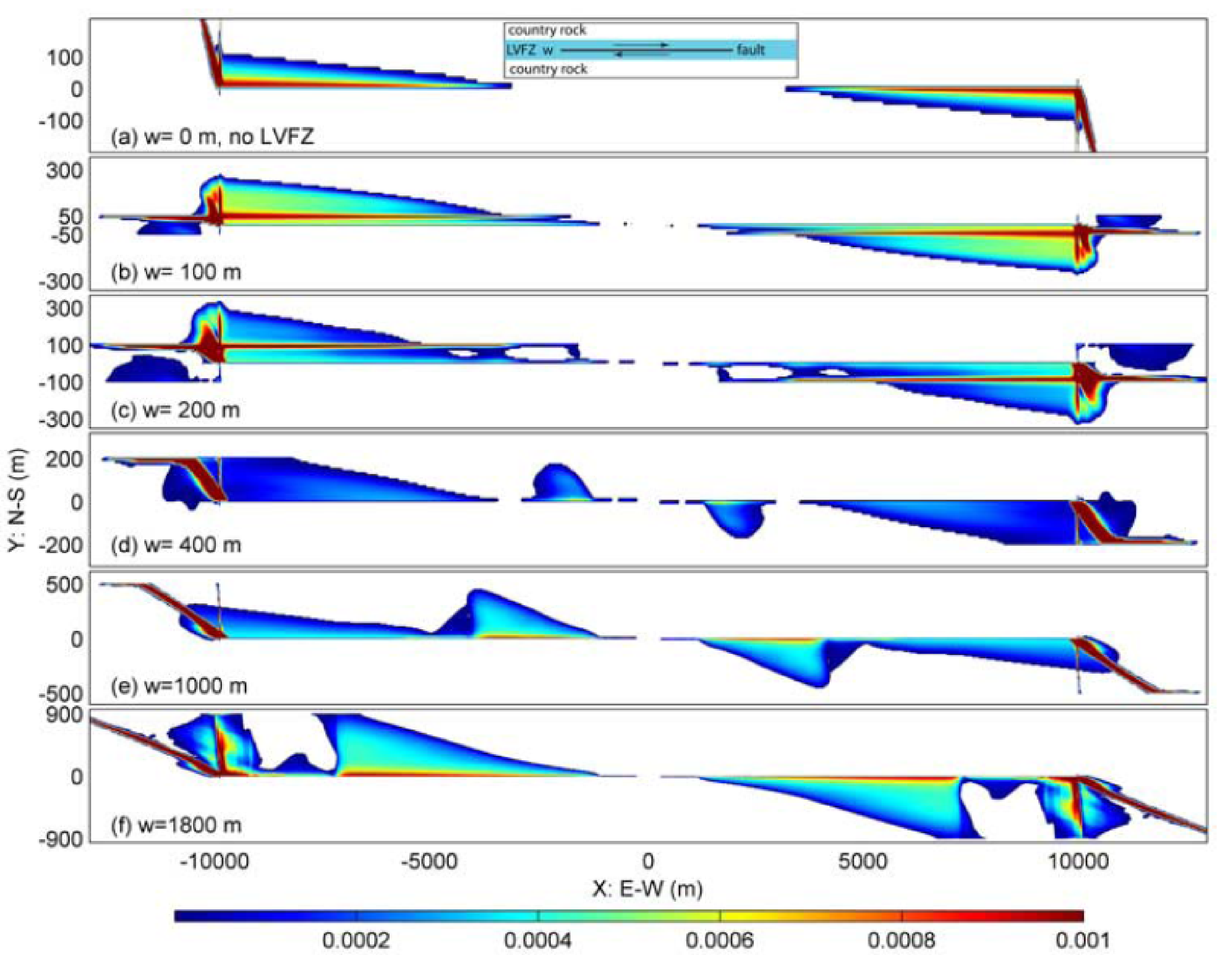
A case study: LVFZ, Off-fault Yielding & Ground Motion

Duan (2008), Effects of low-velocity fault zones on dynamic ruptures with nonelastic off-fault response, GRL.

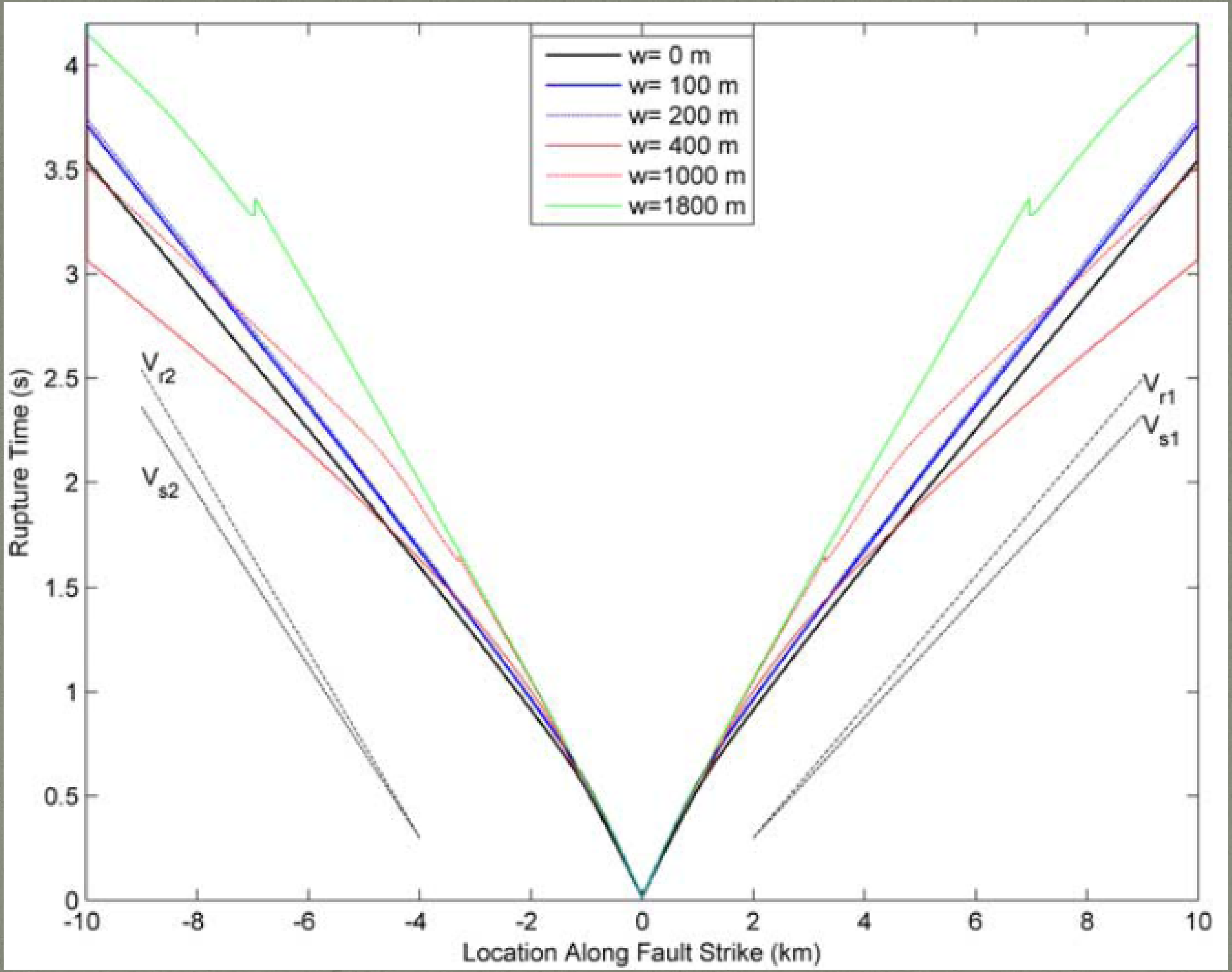
Plastic strain distribution w/ varying LVFZ (in width)



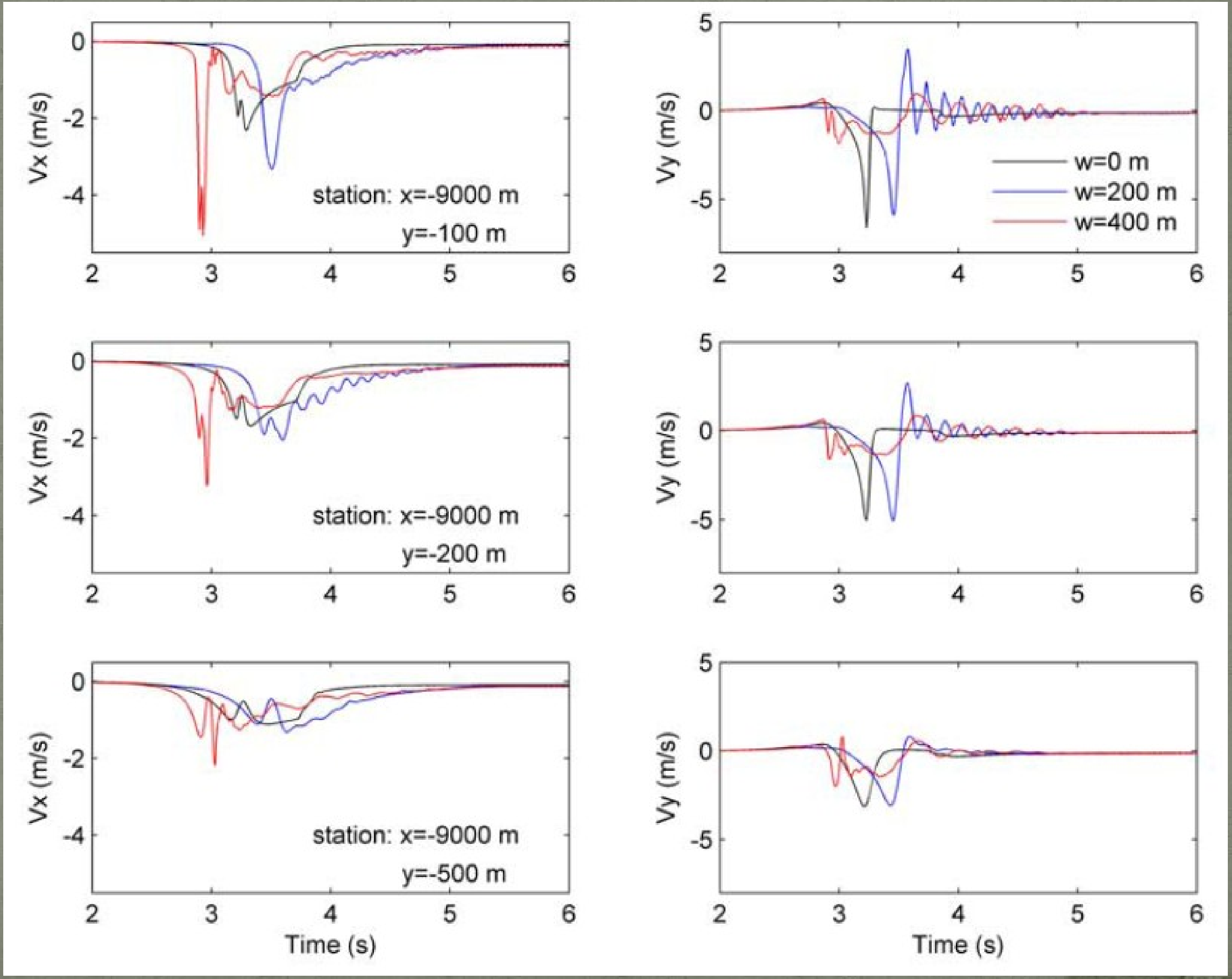
Plastic strain distribution with varying LVFZ (in width)



Rupture velocity



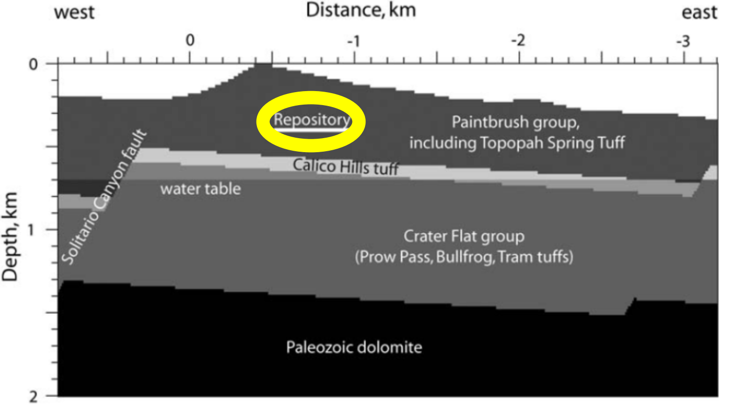
Ground Motion: pre-existing fault zone & dynamic yielding do have significant effects on GM !

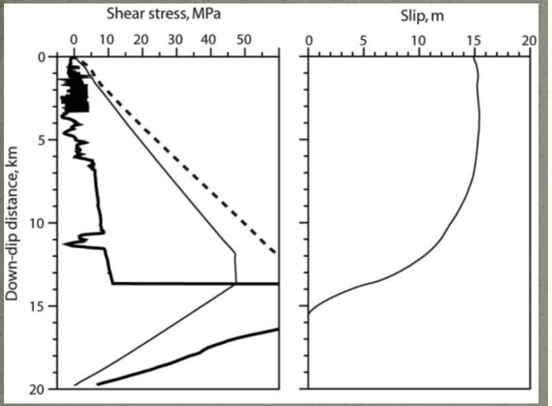


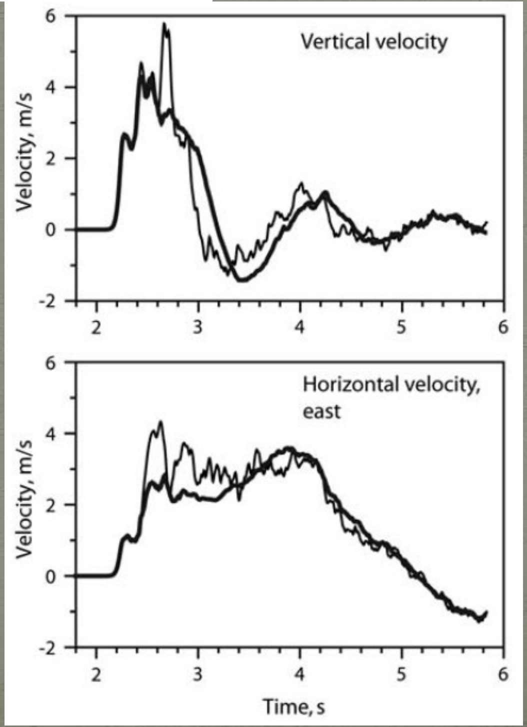
Physical limits on GM at YM

Verification, effects of pore-pressure, fault geometry, and fault zone structure (With Steven M. Day)

Starting point: Andrews et al. (2007)







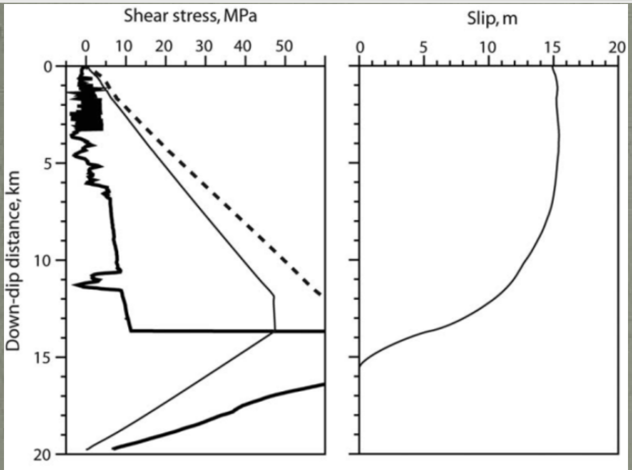
Andrews, Hanks, and Whitney (2007): max-slip 15 m case as our starting point.

- Validate against Andrews et al. (2007)
- Time-Dependent Pore Pressure
- Fault Geometry: change in dip at depth
- Fault Zone Structure: low-velocity fault zone (damage)

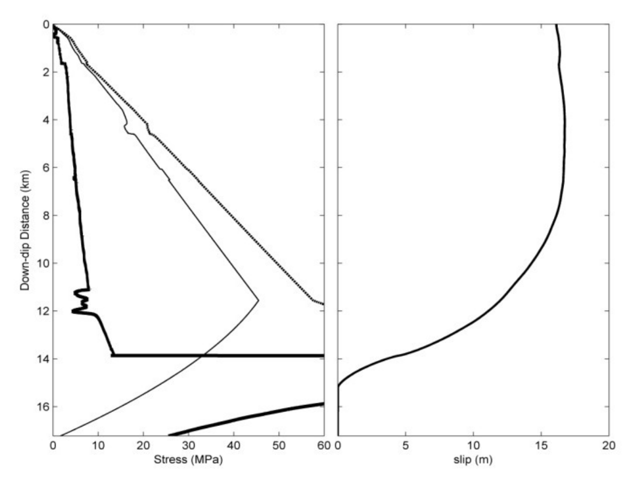
Verifiaction against Andrews et al. (2007)

Initial Stress & Final Slip

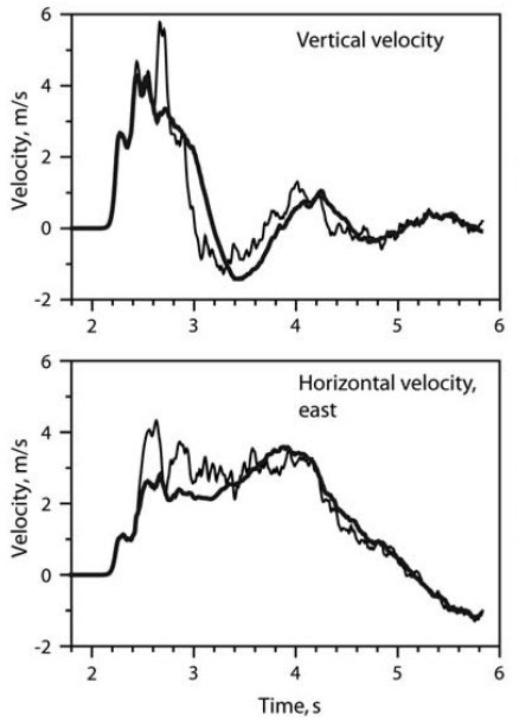
Andrews et al.

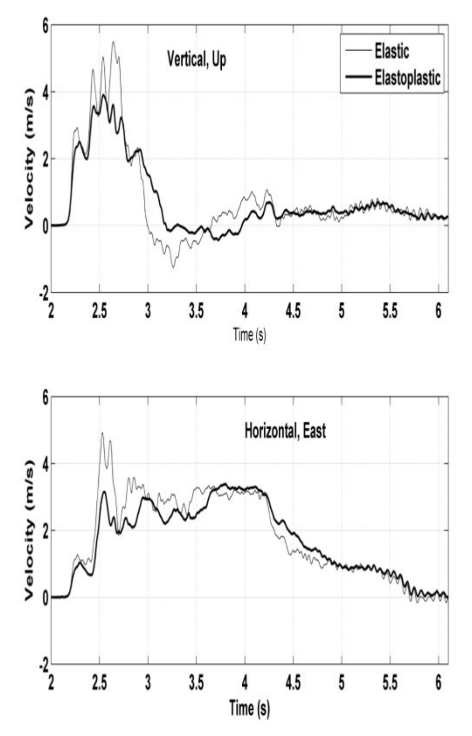


Duan & Day



Ground Motion at Site



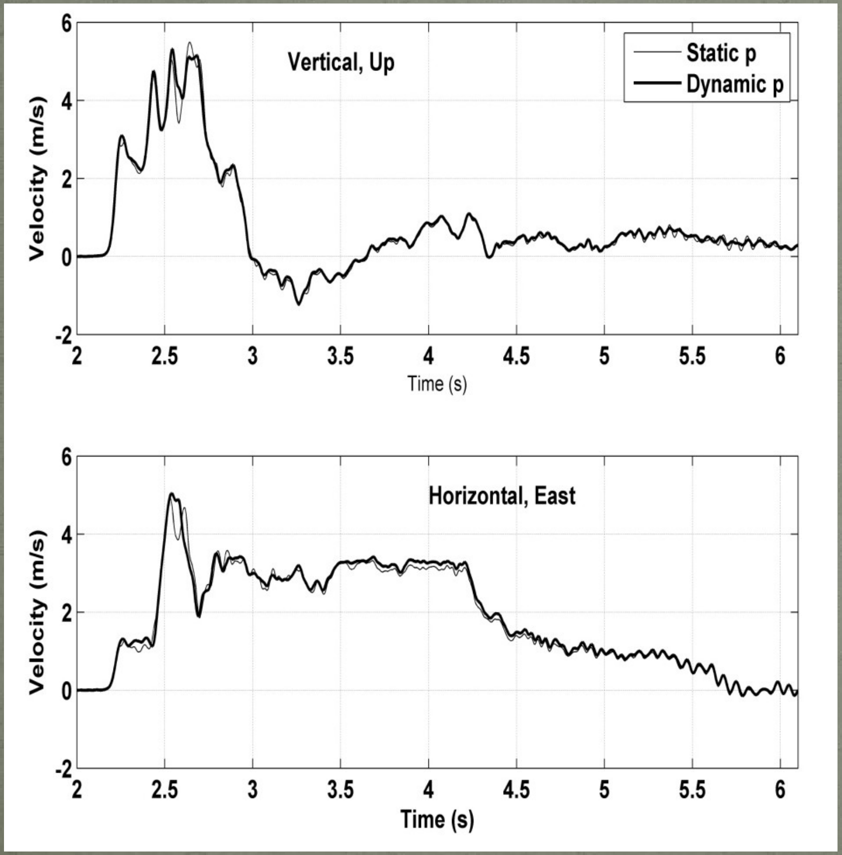


Andrews et al. (TW)

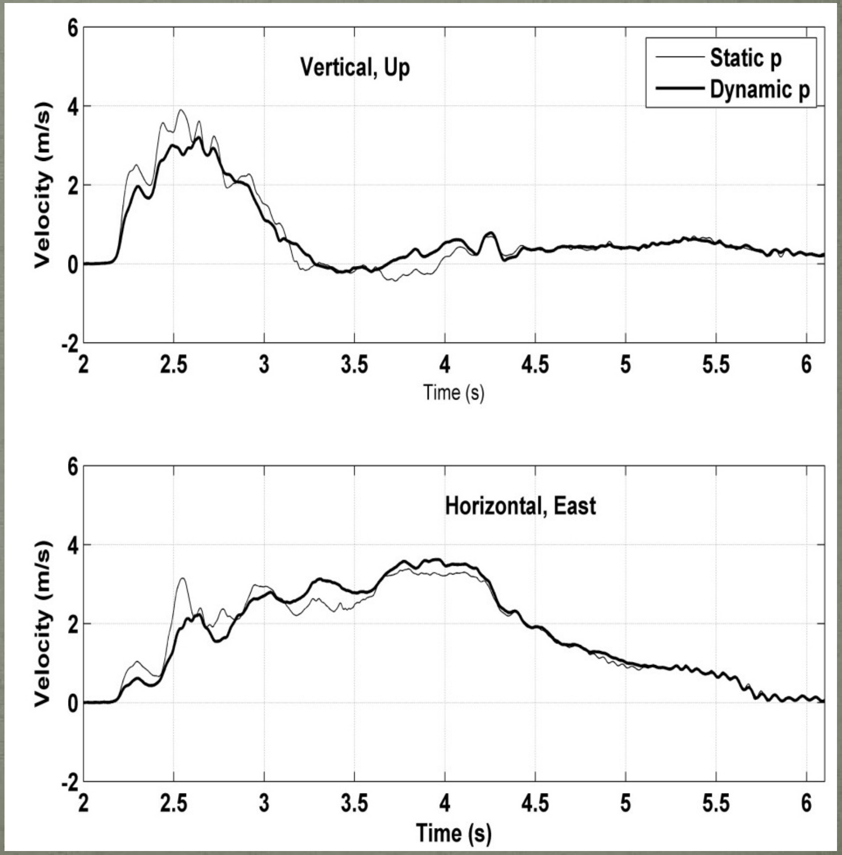
Duan & Day (SW)

Pore Pressure: Time-dependent? (Skemption's coefficent B = 0.8)

Elastic off-fault response

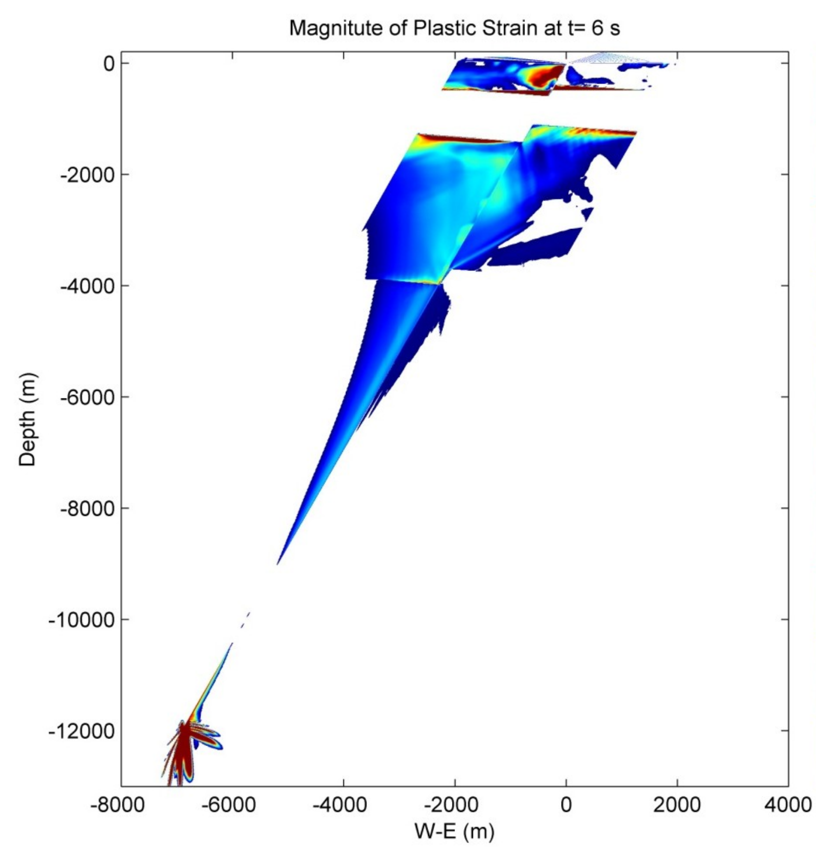


Plastic yielding allowed

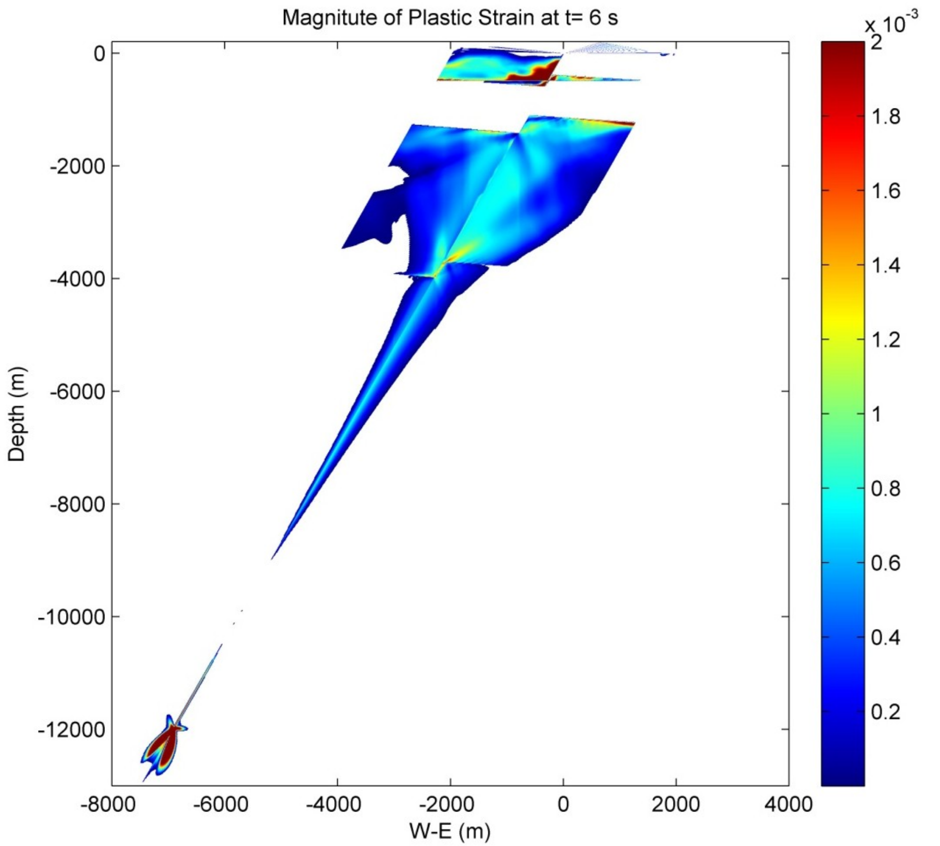


Pore Pressure: Off-fault Plastic Strain

Static Pore Pressure



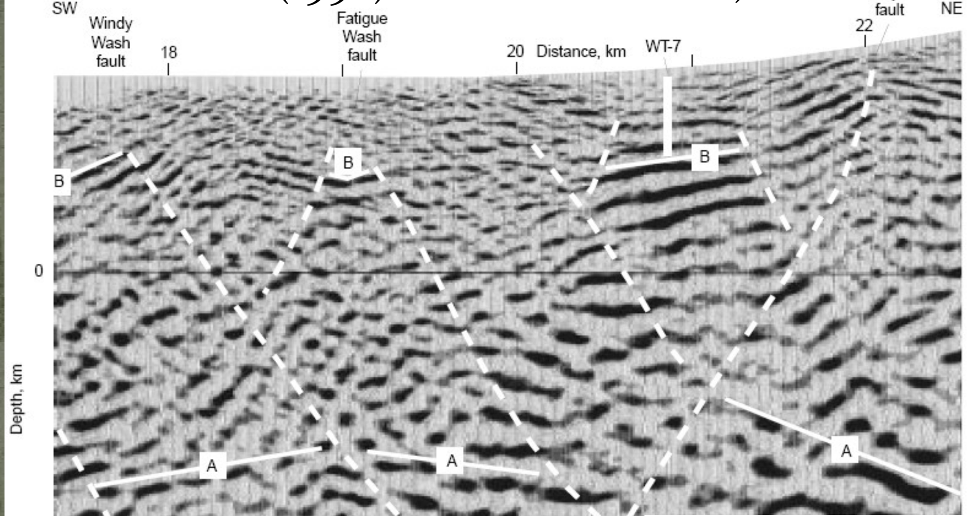
Dynamic Pore Pressure: varying



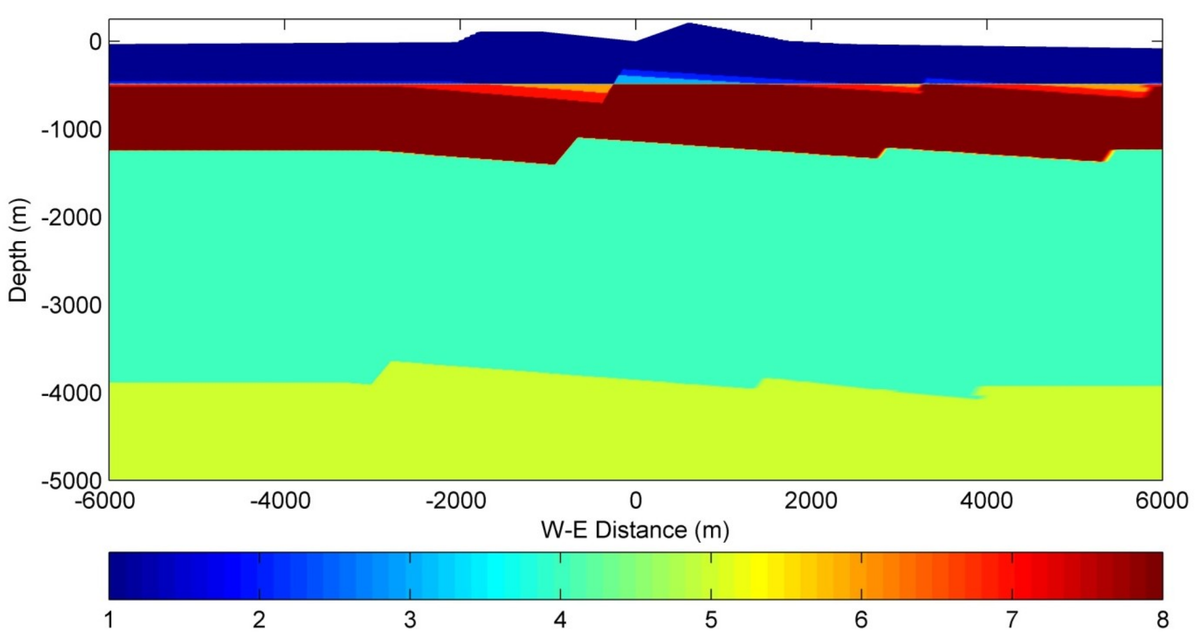
Pore pressure affects off-fault material strength, thus plastic yielding!

Uncertainty in Fault Geometry: dip at depth

Brocher et al. (1998): seismic reflection, GSA Bull.

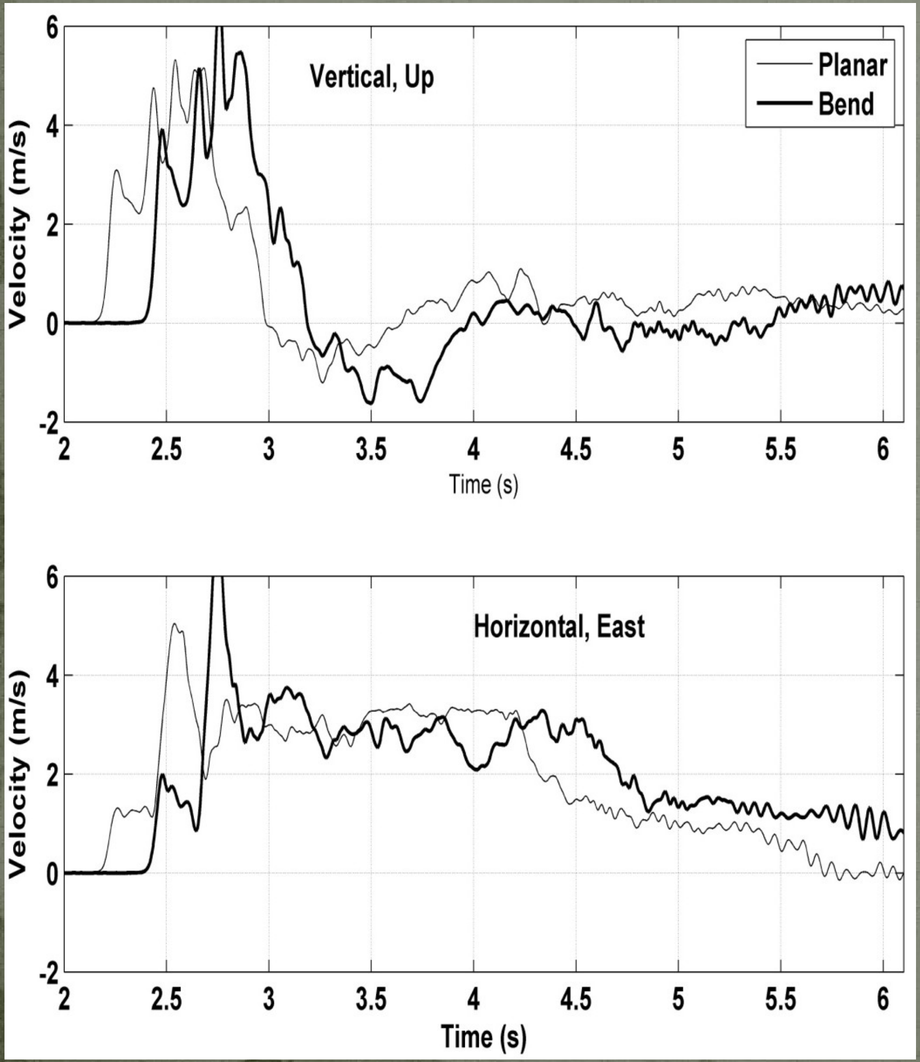


A shallower dip at depth is likely!!

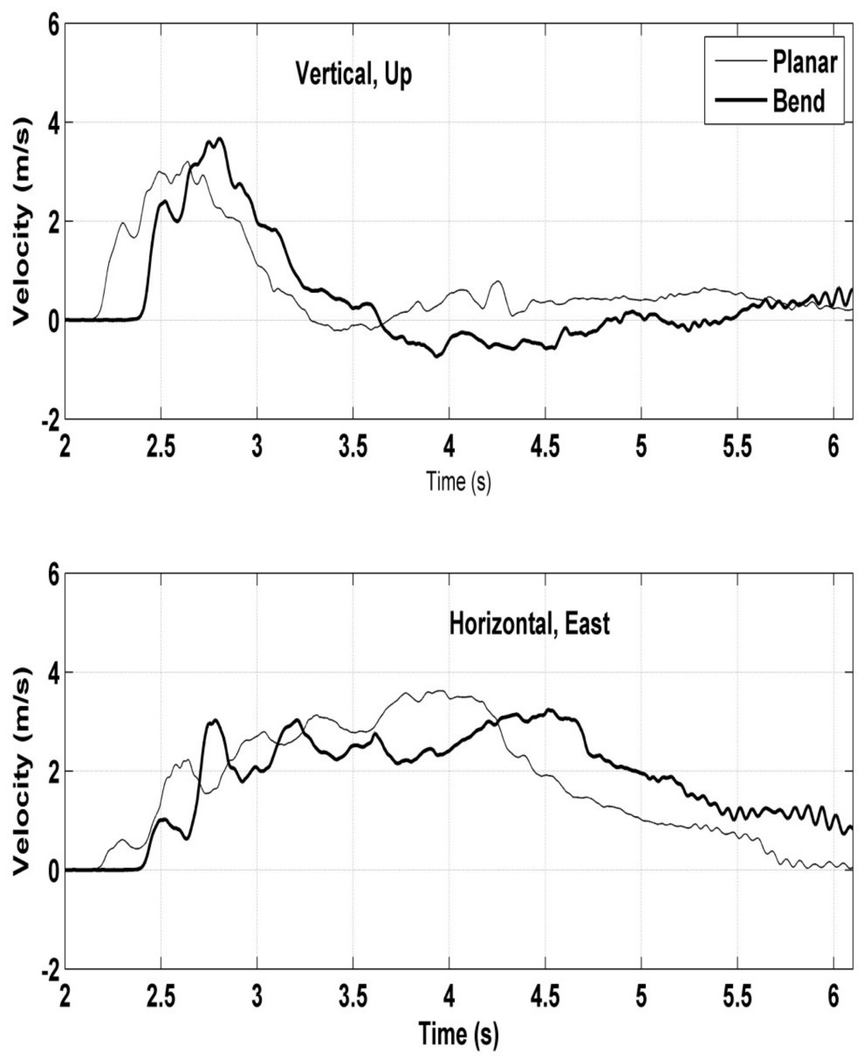


Fault Geometry: Ground Motion

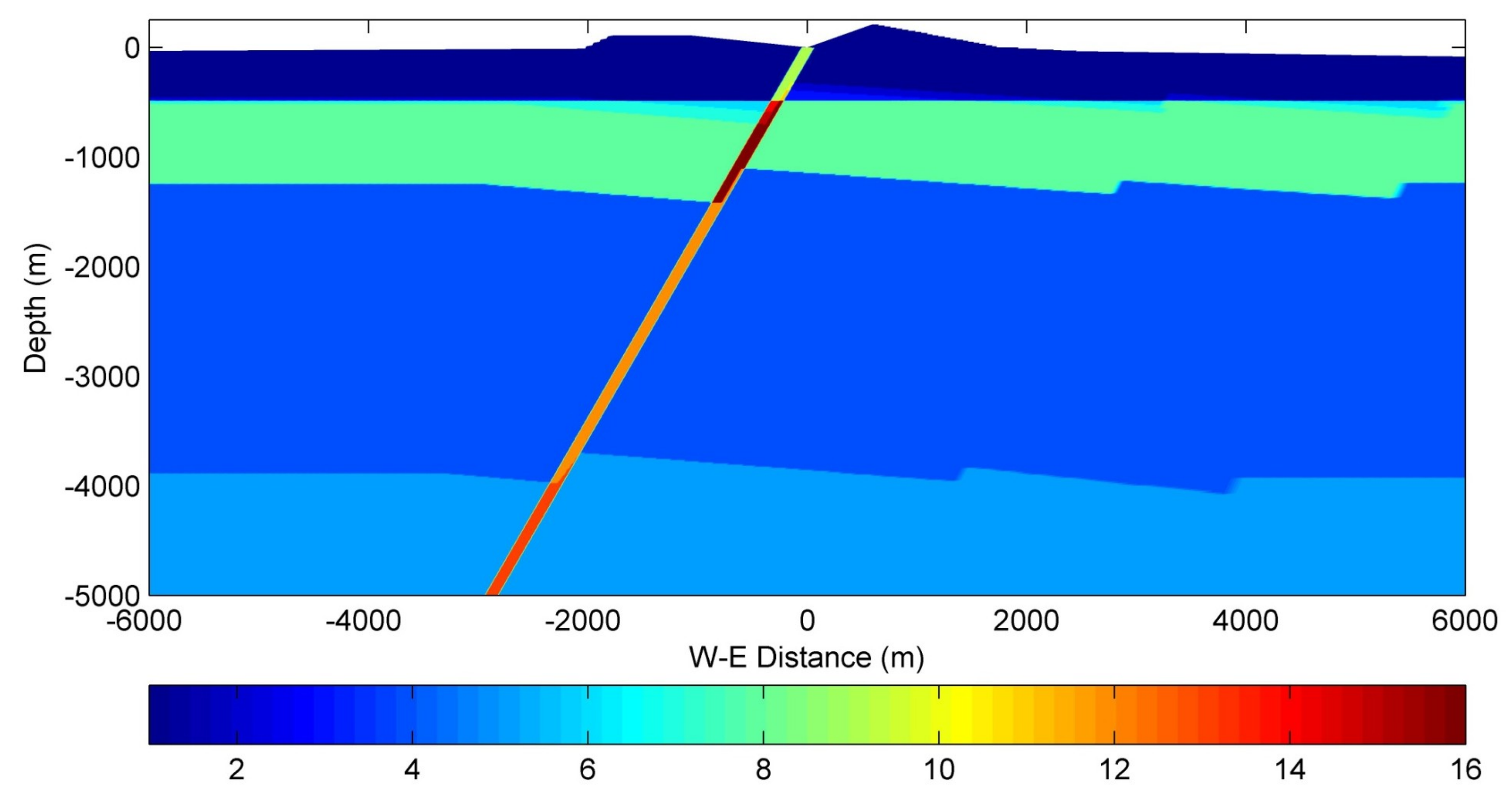
Elastic



Elastoplastic

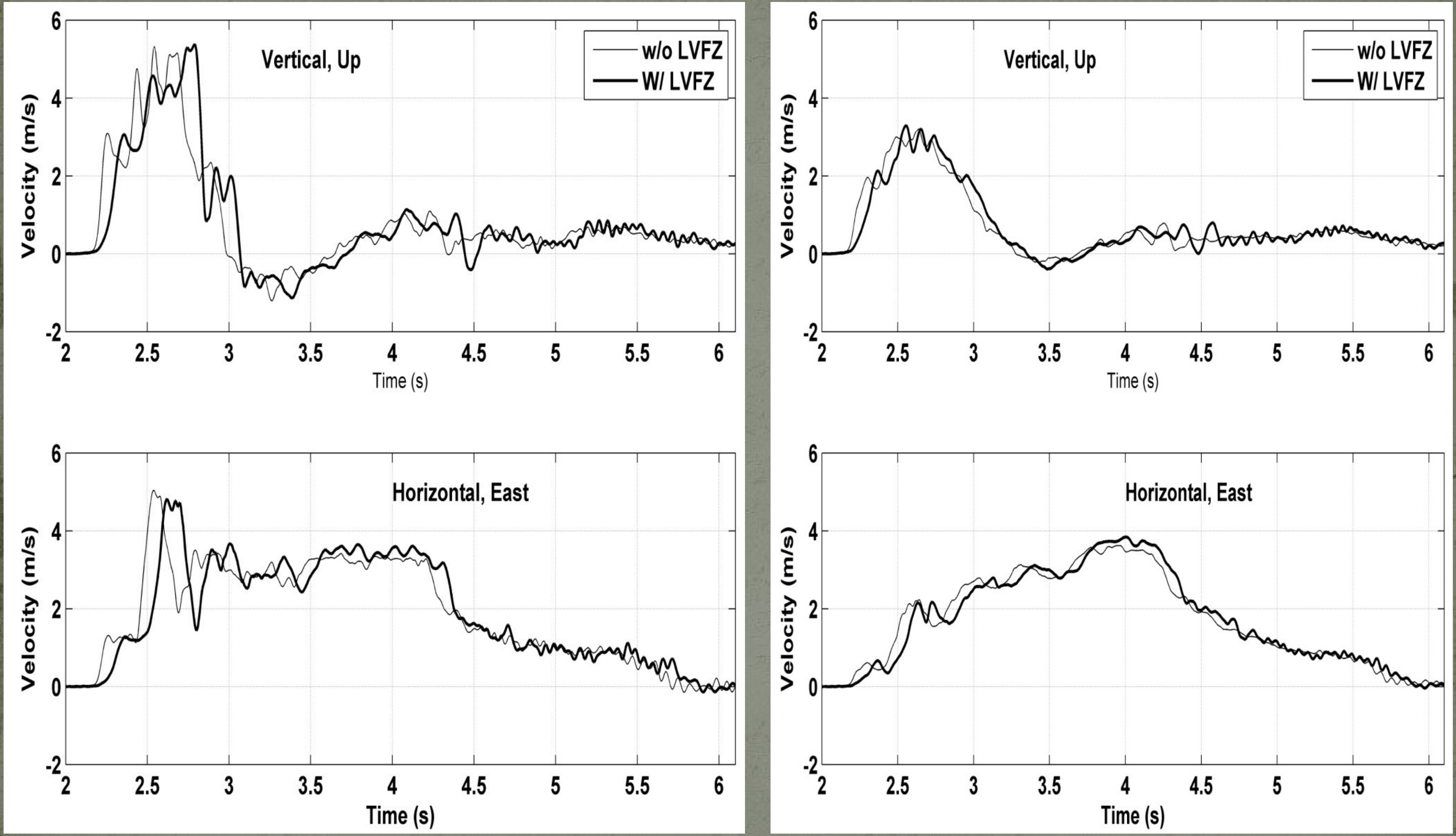


Fault Zone Structure: Damage Zone



A 100 m wide damage fault zone (low-velocity): symmetric about fault.

Fault Zone Structure: Ground Motion



Elastic

Elastoplastic

More high-frequency motion, but peaks stay the same!

Subsection Conclusions

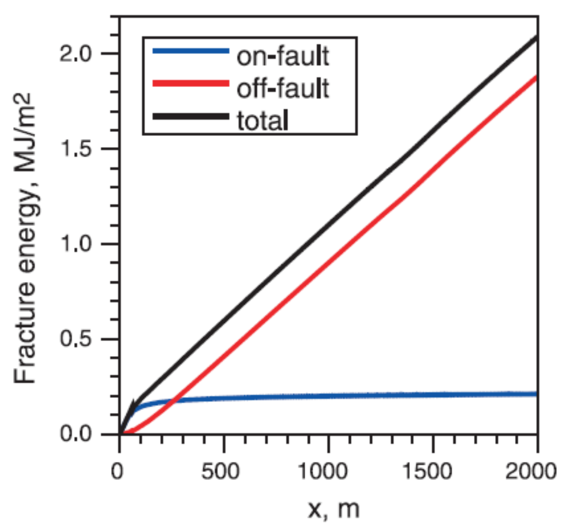
- Time-dependent pore pressure is quite important for peak velocity at the site if off-fault material yields.
- Fault geometry (dip at depths) can have significant effects for peak V at the site if material is strong (elastic response).
- Fault zone structure (damage zone) can introduce more high frequency motion at the site.

Slip-weakening Law, Elastic Response for Physical Limit Study at Yucca Mountain

Can we adequately represent the range of ground motion amplitudes using a slip-weakening law, and off-fault linear elasticity?

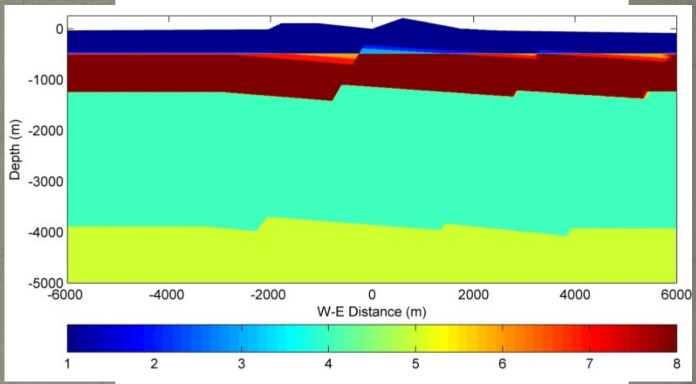
Theoretical bases to tackle the question

- Andrews (2005), Templeton and Rice (2008), Duan and Day (2008): Energy loss off the fault causes fracture energy (on+off fault) to proportional to rupture distance under uniform, homogenous conditions. (Do increase with rupture distance)
- Andrews (2004): Time-weakening (TW) law results in an increase in Do with rupture distance, given elastic off-fault response. (Time-weakening can be a candidate for addressing the question)

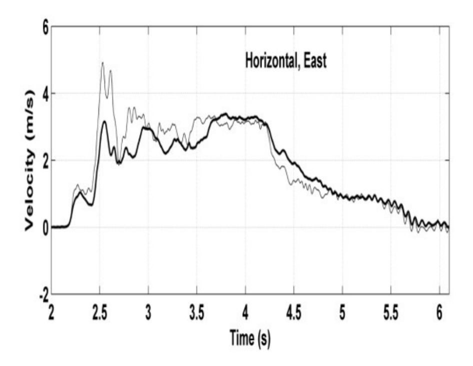


Numerical experiement design

- Reference model: elastoplastic material, planar fault, no LVFZ (Slip-weakening Do = 0.25 m)

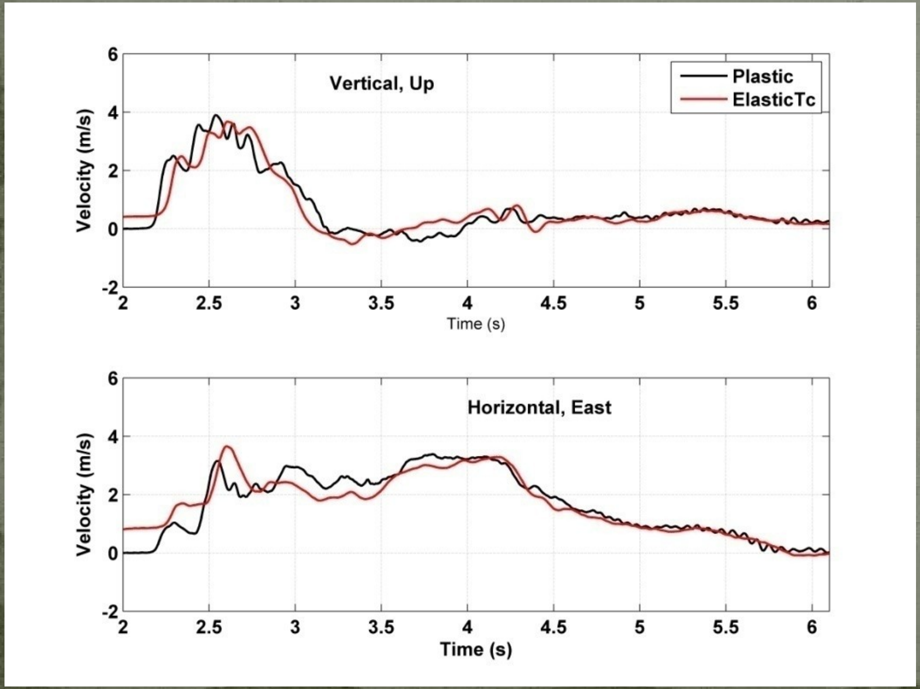


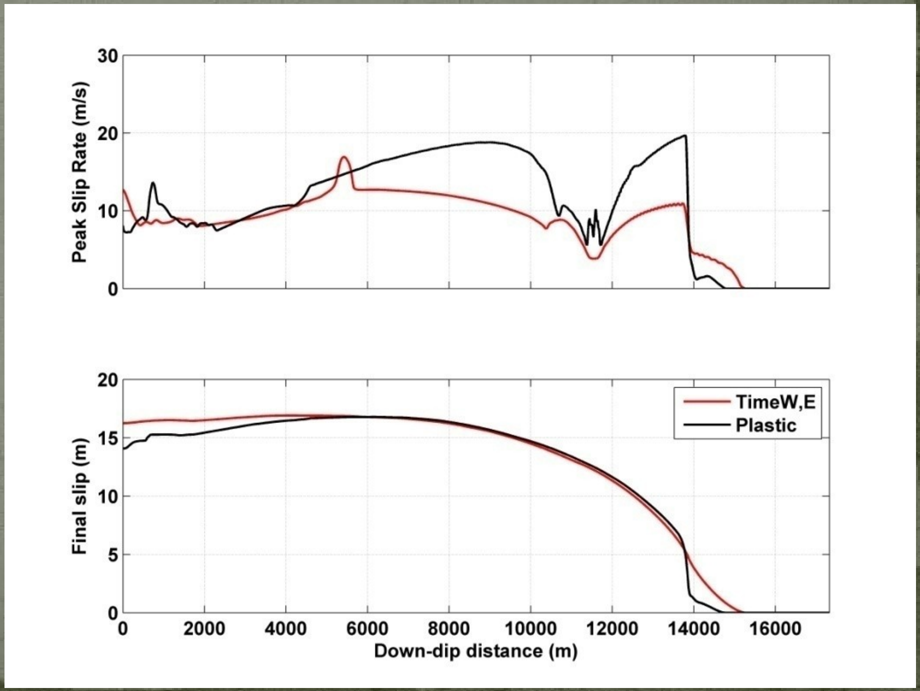
- Tested cases:
  - A time-weakening model
  - Slip-weakening models with rupture-distance-dependent Do
- Examine:
  - Ground motion at the site
  - Peak slip velocity on the fault



A time-weakening model

- A large Tc:
- Ground V amplitudes can be reproduced easily.
- Peak slip rate may be quite different.

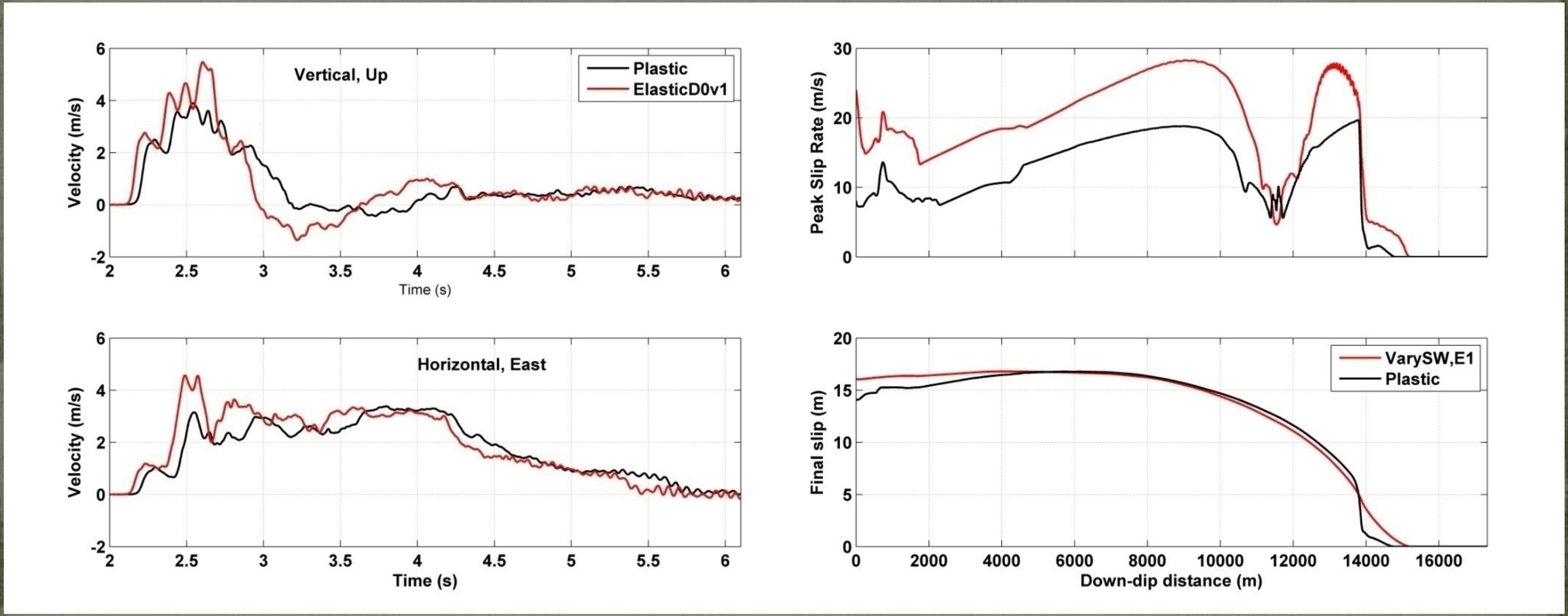




Time-weakening with variable Do

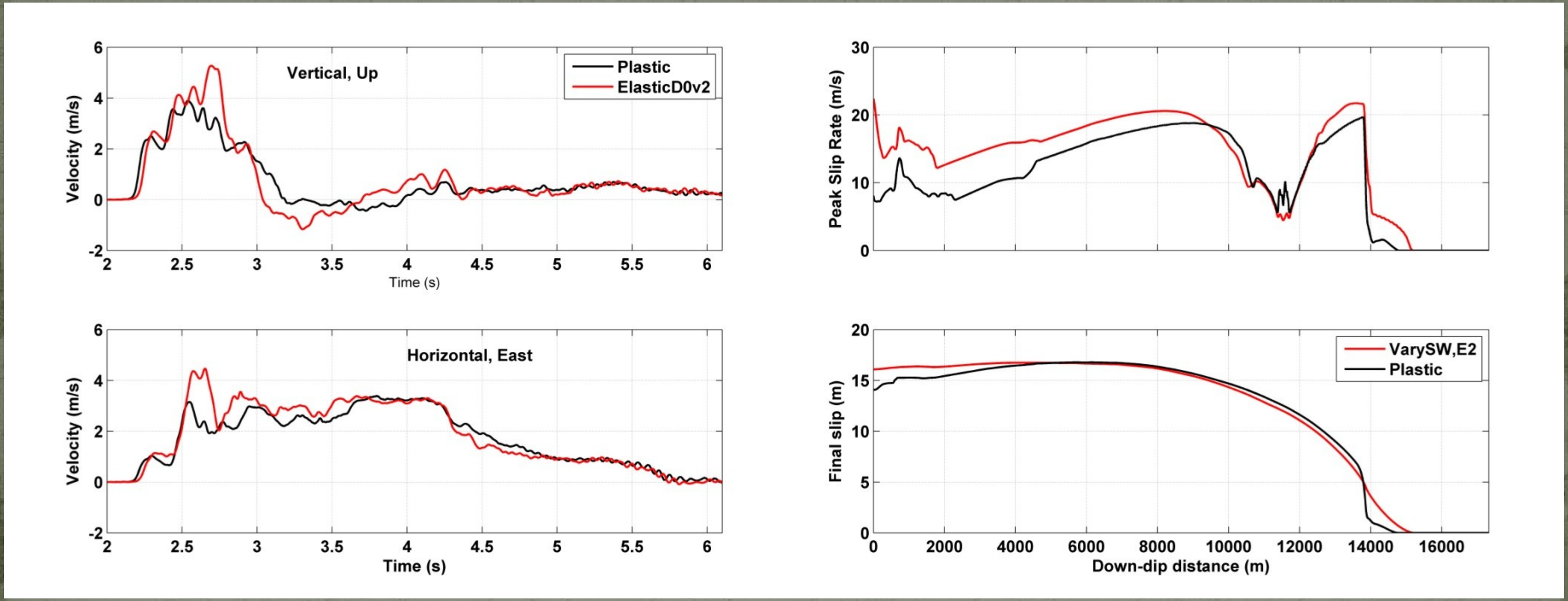
- Linear increase in Do with rupture distance x (in km): Do=ax+do, a-constant, do is value of Do at hypocenter.
- Case 1: a=0.05, do=0.1 m (at surface: Do=0.7 m)
- Case 2: a=0.05, do=0.25 m (0.85 m)
- Case 3: a=0.075, do=0.25 m (1.15 m)
- Case 4: a=0.1, do=0.25 m (1.45 m)

- Case 1: a=0.05, d0=0.1 m (at surface: D0=0.7 m)



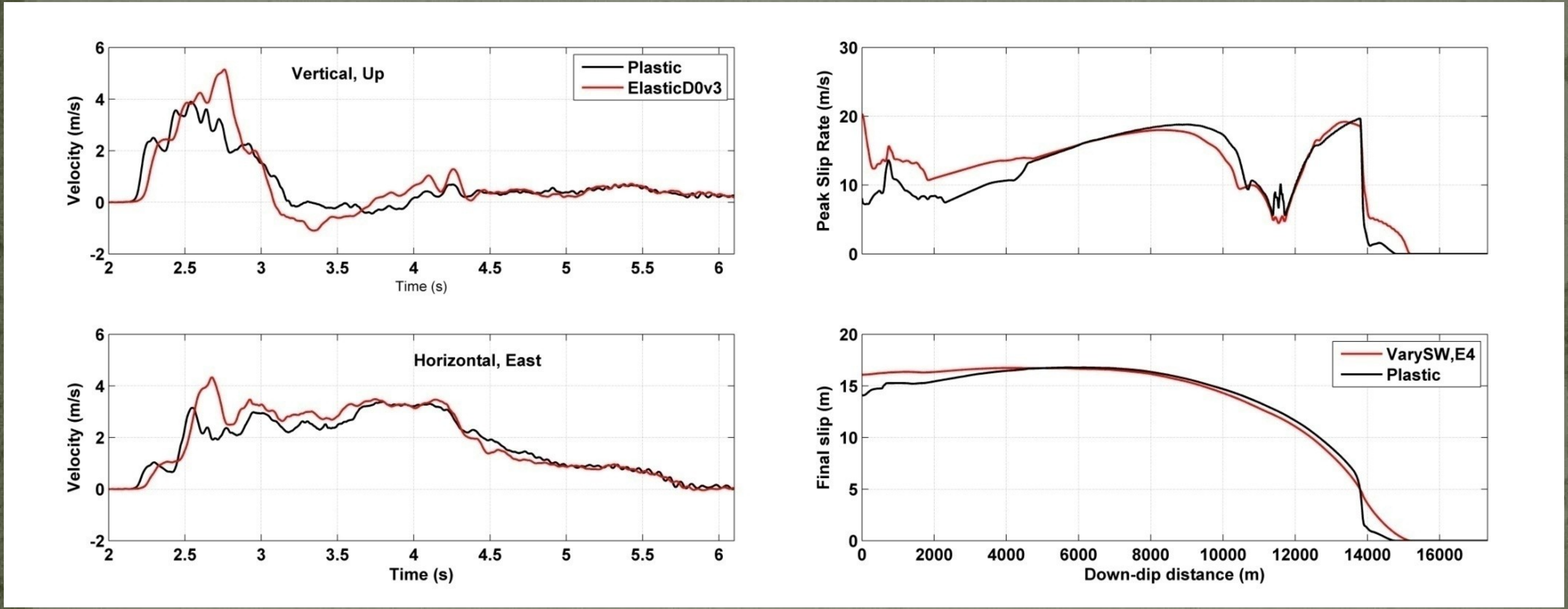
- Average D0 on the fault is comparable
- Peak Slip V much larger
- Amplitude of GM much larger

- Case 2: a=0.05, d0=0.25 m (at surface: D0=0.85 m)



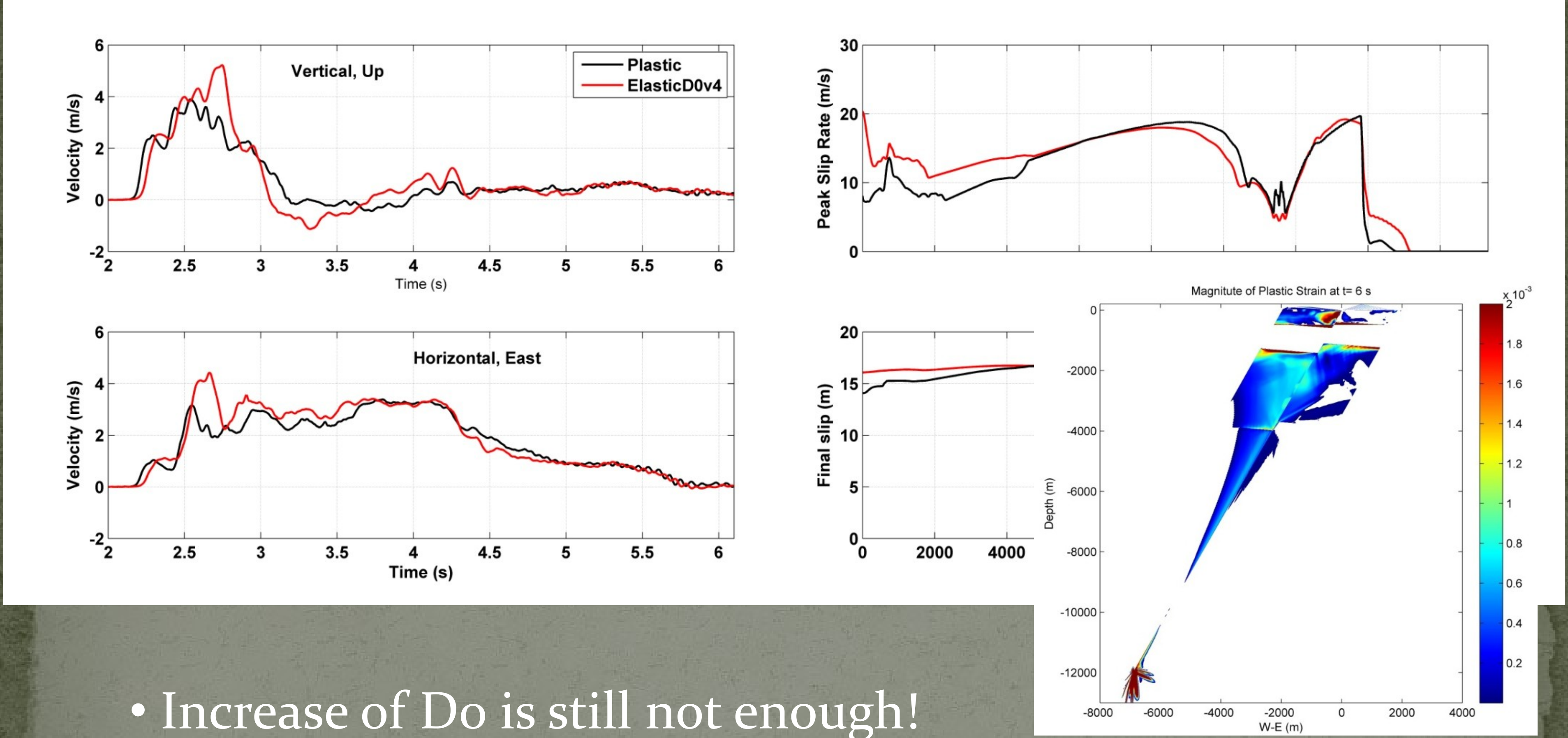
- Increase of D0 is not enough (a too small in D0=ax+d0)
- Peak Slip V much larger at shallow depths
- Amplitude of GM still much larger than reference

- Case 3: a=0.075, d0=0.25 m (at surface: D0=1.15 m)



- Increase of Do is still not enough!
- Peak Slip V still much larger at shallow depths
- Amplitude of GM still much larger than reference

- Case 4: a=0.1, d0=0.25 m (at surface: D0=1.45 m)

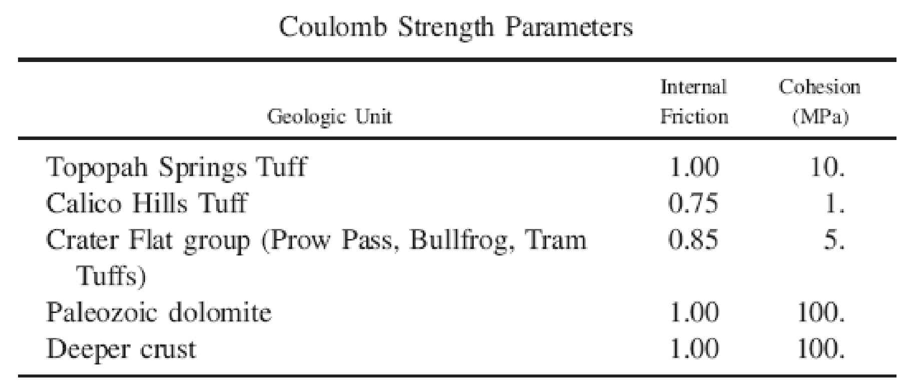


- Increase of D0 is still not enough!
- Peak slip V near surface always much higher:

  strong plastic yielding near surface may require very large D0 => piecewise linear functions?

Subsection Conclusions

- We may be able to reproduce Ground Motion (GM) magnitude & fault slip with elastic material response, by
  - ➢ Time weakening law: much easier than SW with a linear varying Do
  - ➢ Slip weakening law: seems to need very large Do near surface to mimic strong material failure over there!
- Concern
  - Material strength parameters ? near the surface: GM at the site seems very sensiti
faulting, while strength pa
loss off the fault and effect



Coulomb Strength Parameters

Geologic Unit	Internal Friction	Cohesion (MPa)
Topopah Springs Tuff	1.00	10.
Calico Hills Tuff	0.75	1.
Crater Flat group (Prow Pass, Bullfrog, Tram Tuffs)	0.85	5.
Paleozoic dolomite	1.00	100.
Deeper crust	1.00	100.

Comments on future directions

- Drucker-Prager yielding in shear in EQdyna 3D can be achievable in the coming year with some financial support
  - Parallelization of EQdyna is under the way: Multi-level (i.e., MPI and OpenMP)
  - Graduate students, postdocs: supports
- I am willing to attend the nonelastic validation proposed by Andrews (on 11/14/08).