Kinematic inversion of physically plausible earthquake source models obtained from dynamic rupture simulations

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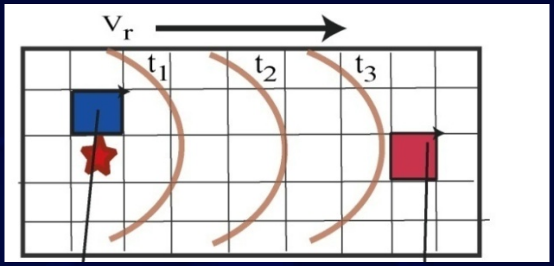
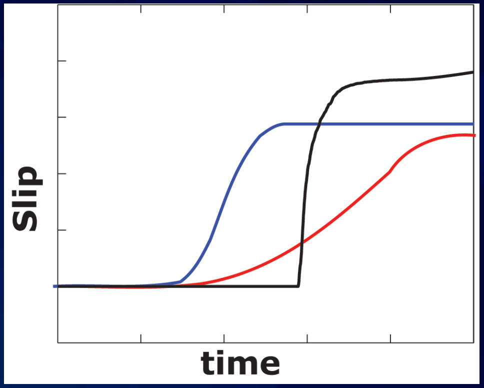
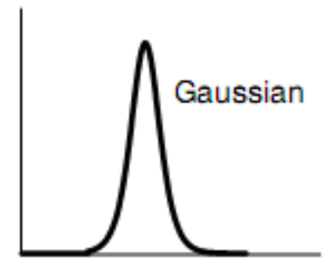
Objective

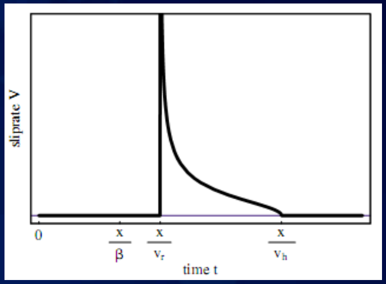
- We make many assumptions in producing kinematic models:
- Fault: grid of rectangles. Each box has a slip value.
- Every point on the fault ruptures once, at a time determined by its rupture velocity. The limits on the duration of slip at each point is constrained a priori, rather than by a physical law.

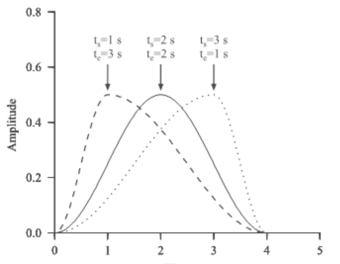




- Simple shapes of slip rate (rise time), single triangle (Archuleta, 1984), several triangles (Kikuchi and Kanamori 1982), single parameter smooth ramp (Cotton and Campillo, 1995), two cosine functions , Yoffee function (Nielsen & Madariaga 2003)







Objective

- In addition to these assumptions we need to regularize and/or constrain the parameters in order to limit the solution space.
- Smoothness of slip
- smoothness in time
- Moment constraint
- Constraints on rake angle
- Constraints on rupture velocity (constant, constrained)

- FUNDAMENTAL QUESTION: With all these assumptions and constraints, how realistic are our source models? What can be reliably inferred from our inversions?

Approach

- Use synthetic sources obtained from simulations of spontaneous dynamic ruptures (Kaneko, Lapusta, Ampuero).
- Compute synthetic seismograms and static displacements
- Invert this “dataset” to obtain kinematic models.

Dynamic Earthquake Modeling

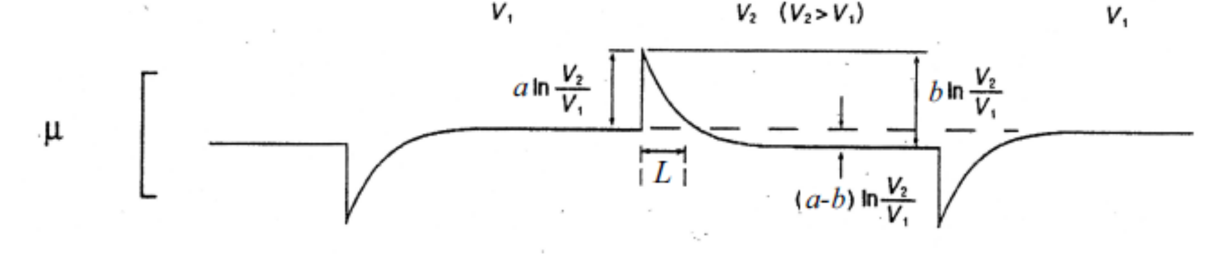
- More physics based approach to earthquake.
- Models earthquakes as frictional sliding
- The initial stress distribution on the fault must be known
- The friction law on the fault must be known.
- Then the equation of motion is solved to get a simulated earthquake

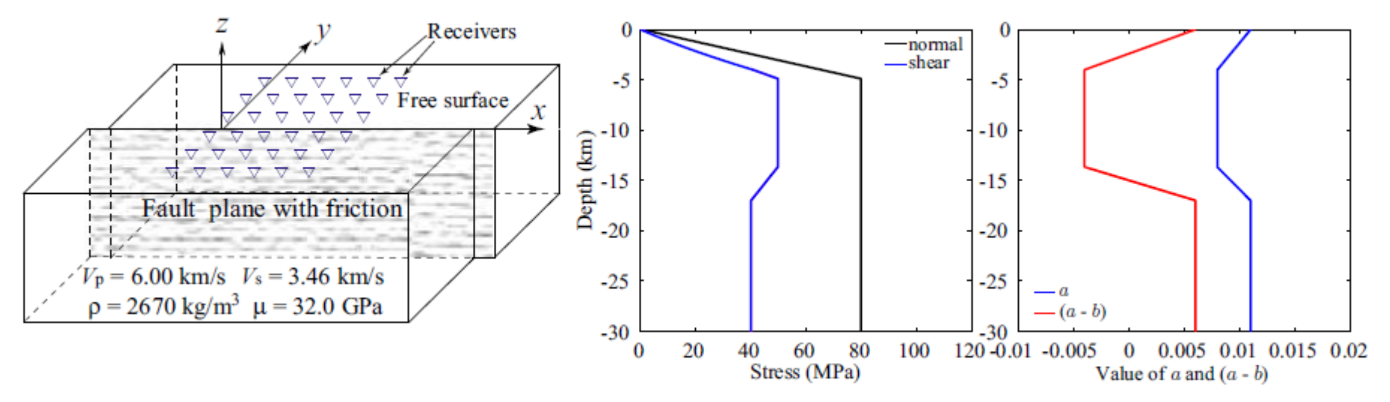
$$\rho\partial_t^2\mathbf{u} = \nabla\cdot\mathbf{T} + \mathbf{F}$$

Friction Law

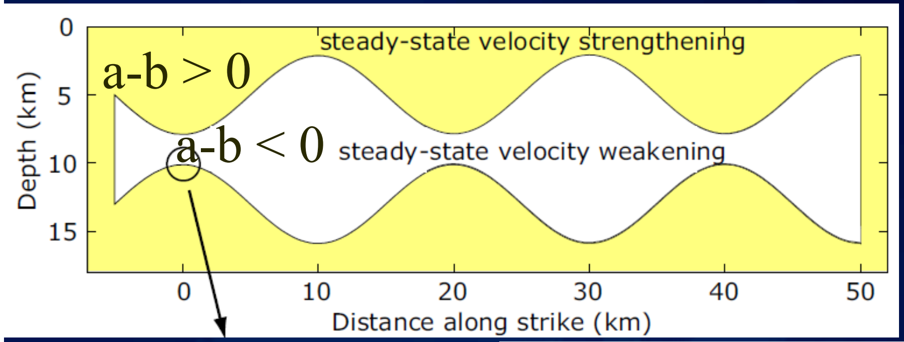
- We are using the Spectral Element Dynamic Simulation code (Kaneko, Lapusta, Ampuero, 2008)
- Friction law on the fault is rate and state Dietrich 1979, Ruina 1983)

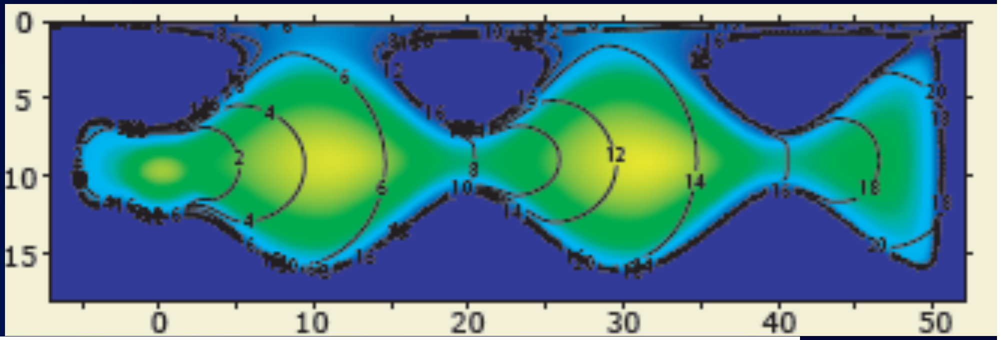
$$\tau \;=\; \bar{\sigma}\left[\mu_0 \;+\; a\ln\left(V/V_0\right) \;+\; b\ln\left(V_0\theta/L\right)\right]\;,\quad d\theta/dt = 1 - V\theta/L$$

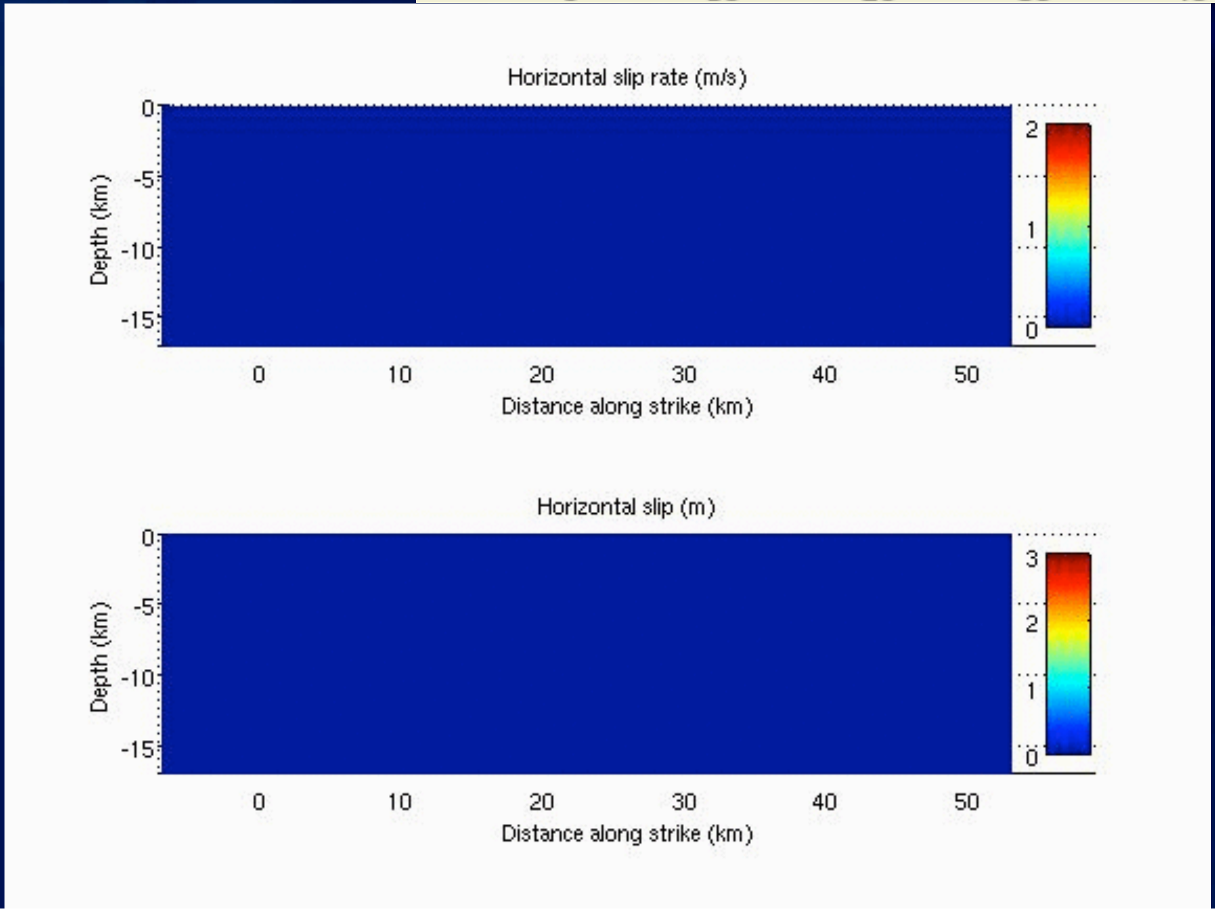




Dynamic Simulation: Example

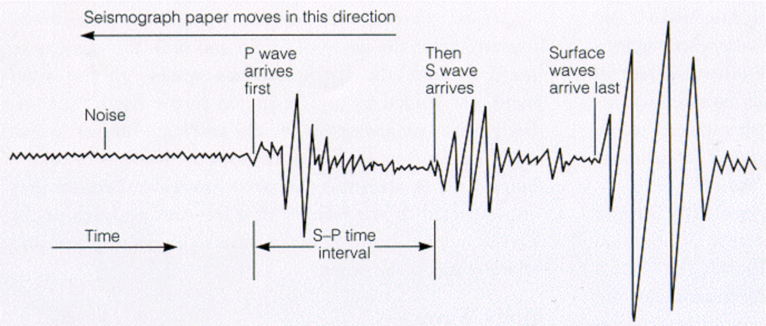





Horizontal slip rate (m/s)

Horizontal slip (m)

Kinematic Source Modeling: From Data to Source



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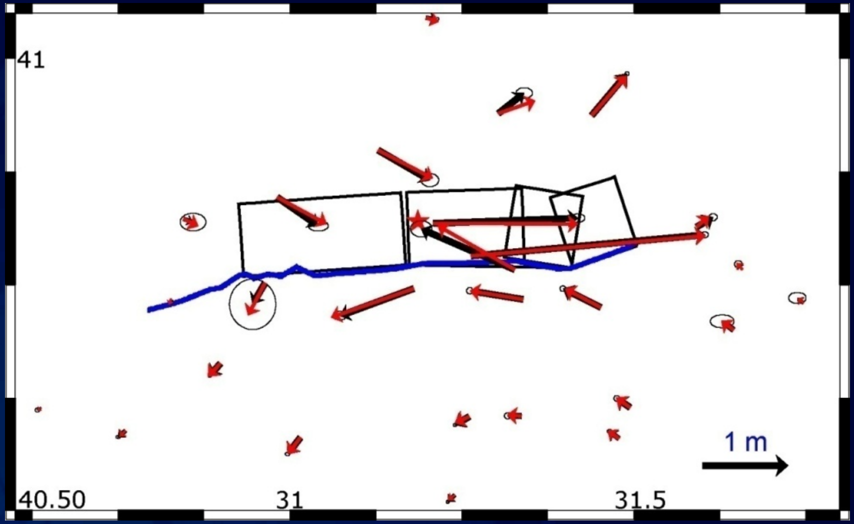
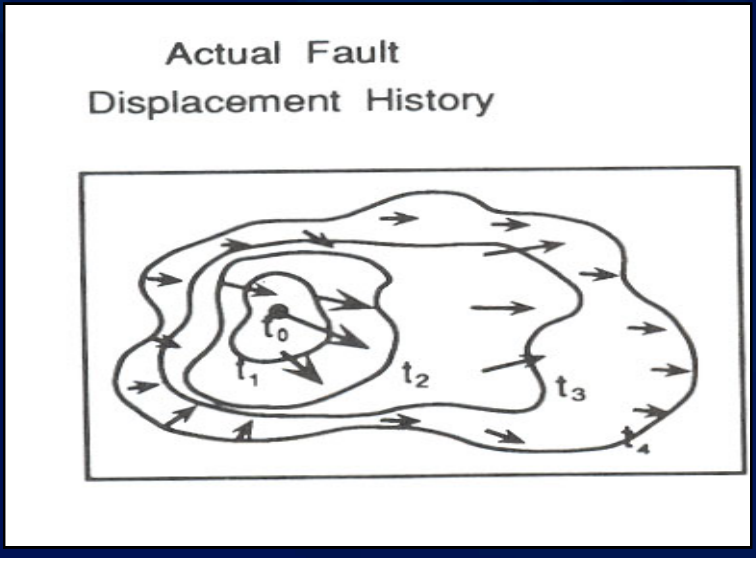


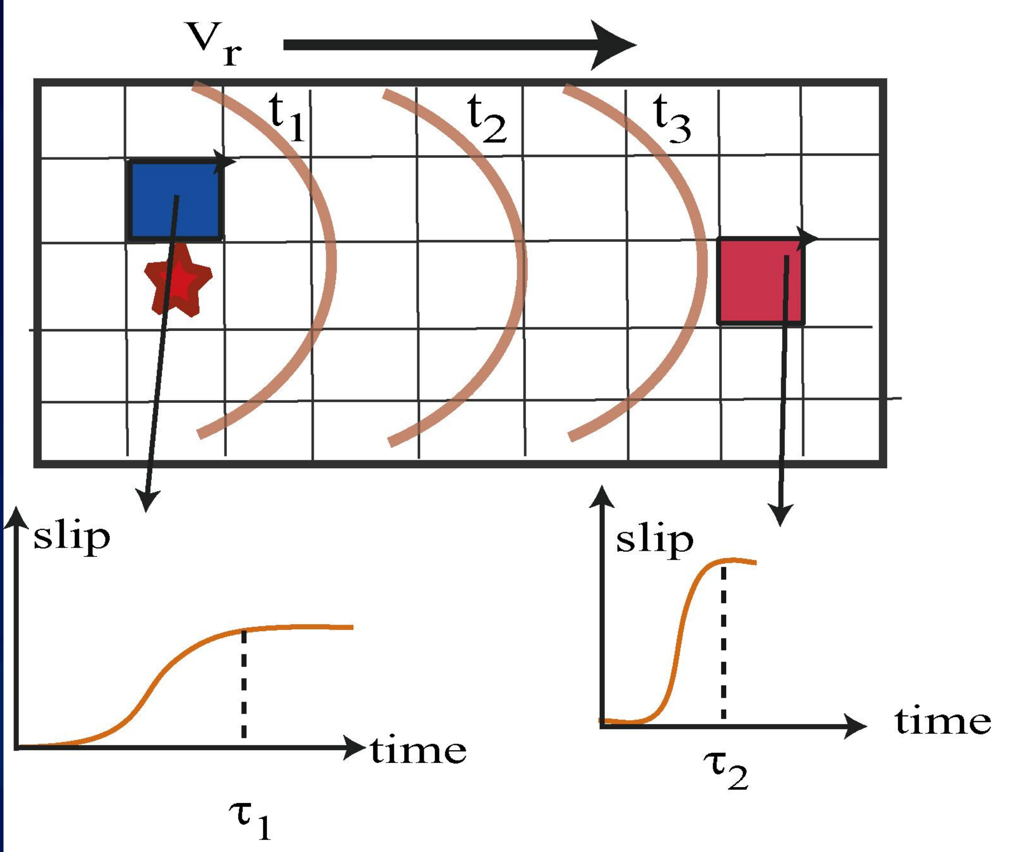


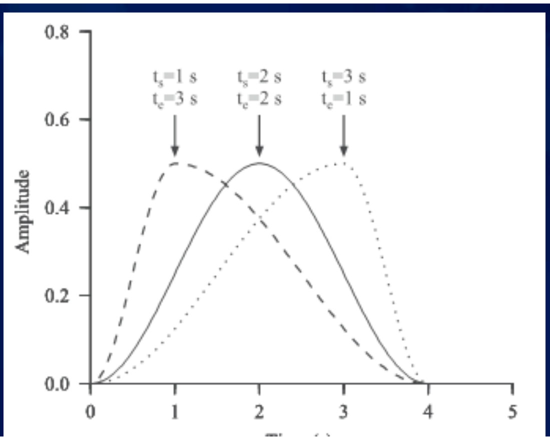
I. Method for Modeling Earthquakes

- **Inversion method:**

  Joint inversion of seismic waves and static offsets (Ji *et al.* 2002) using “Simulated Annealing Method”.

- **Parameters to find out**
  - Slip at each subfault on the fault
  - Rise time (the time that takes for slip to occur at each point on the fault). (1 or 2 parameters)
  - Rupture velocity (how fast does the rupture propagate)

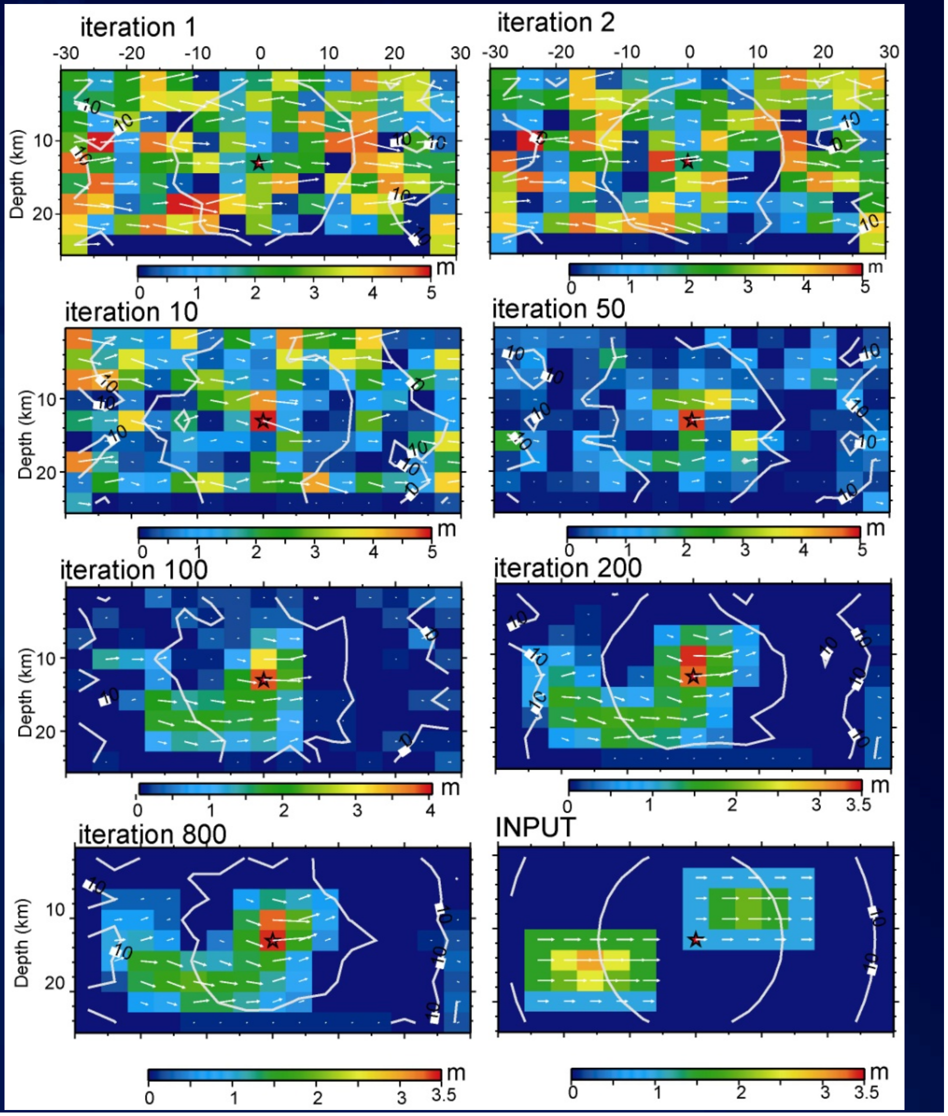




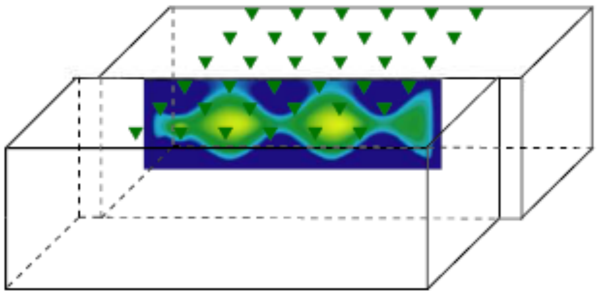
$misfit = e_{WF} + W_{ST} e_{ST} + Wsm \cdot e_{SM} + W_{TS} \cdot e_{TS} + W_{MO} \cdot e_{MO}$

Approach: Search for the Best-fit Model From Data

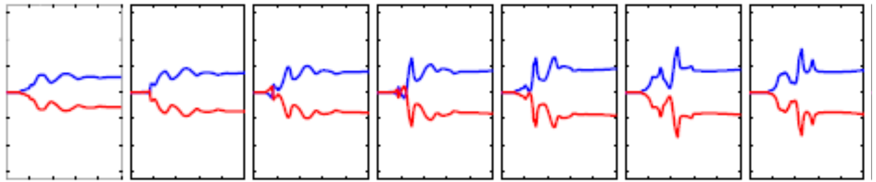
- Misfit to be minimized $$misfit = e_{WF} + W_{ST} e_{ST} + Wsm \cdot e_{SM} + W_{TS} \cdot e_{TS} + W_{MO} \cdot e_{MO}$$
- Search for the minimum misfit in the bounded parameter range:
  - Start with a random model
  - Calculate misfit
  - Move around that random model randomly, calculate misfit for the new model
  - Choose the new best model.
  - At every iteration the randomness decays.
  - Converge to a model

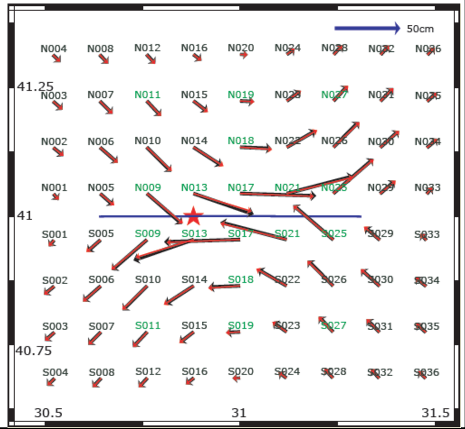


Procedure



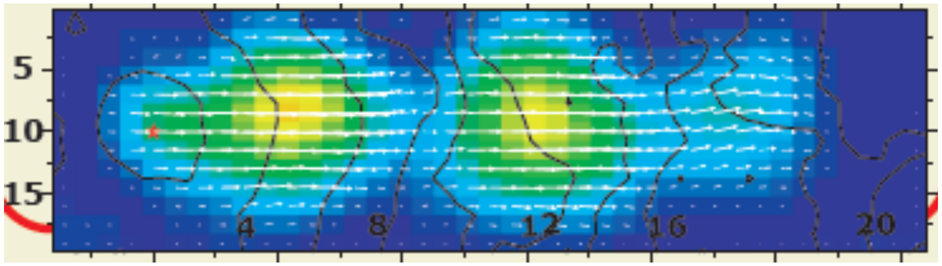
Create dynamic rupture model





Create synthetic GPS and strong motion data

Use synthetic GPS and strong-motion data to obtain kinematic model of the input.



Given:

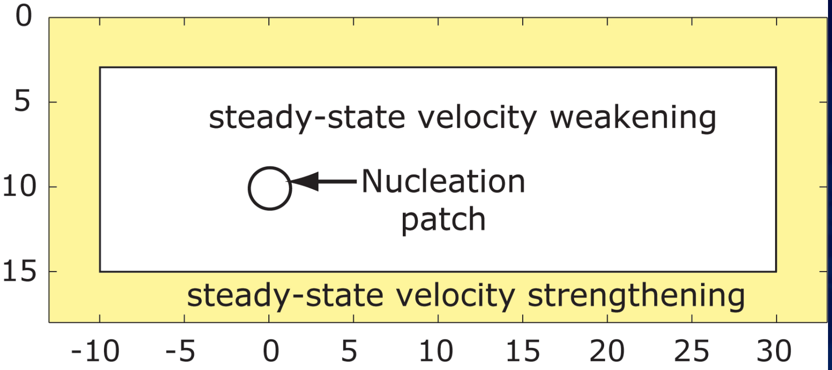
- hypocenter location,
- point source solution: strike, dip, rake
- velocity model

Not given:

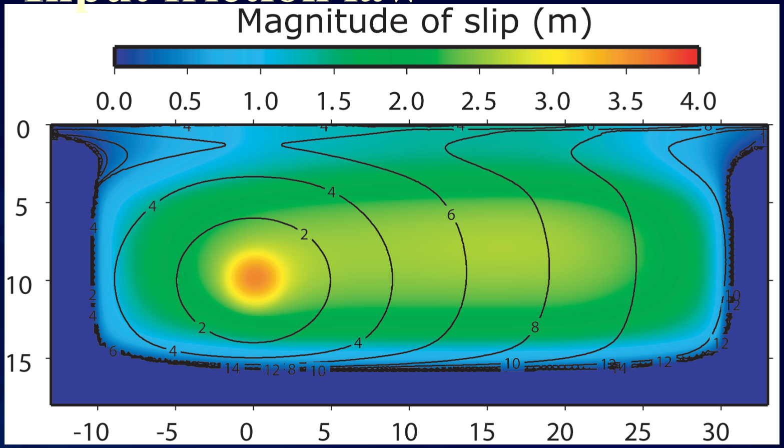
- Fault length,
- slip distribution, moment,
- rupture velocity

Model 1

Input friction law

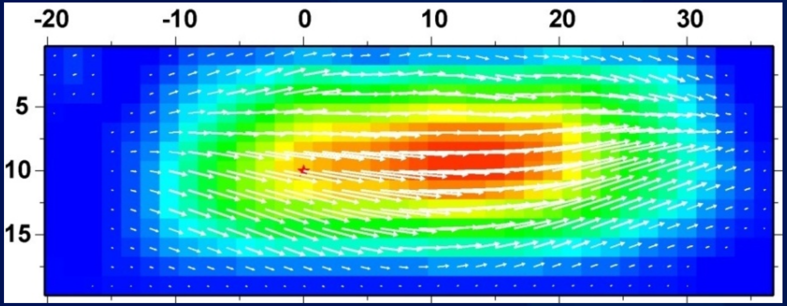


Input friction law

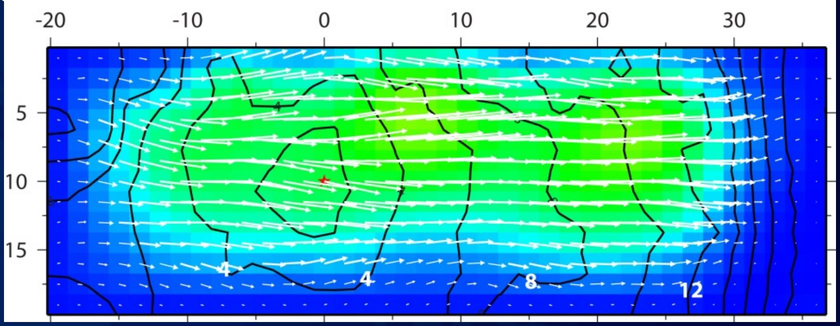


Inverted Kinematic Models

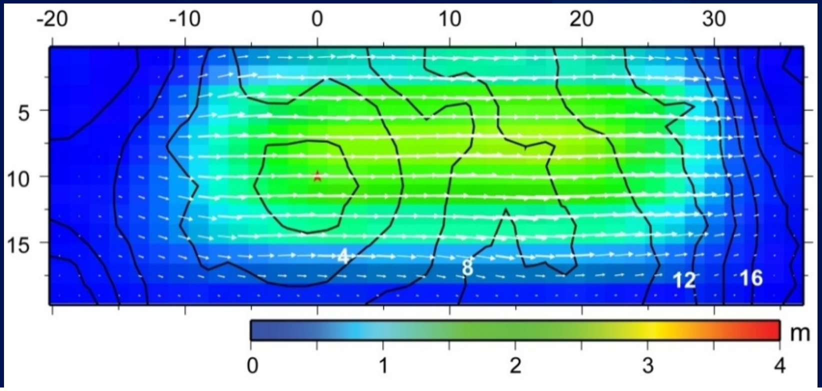
GPS



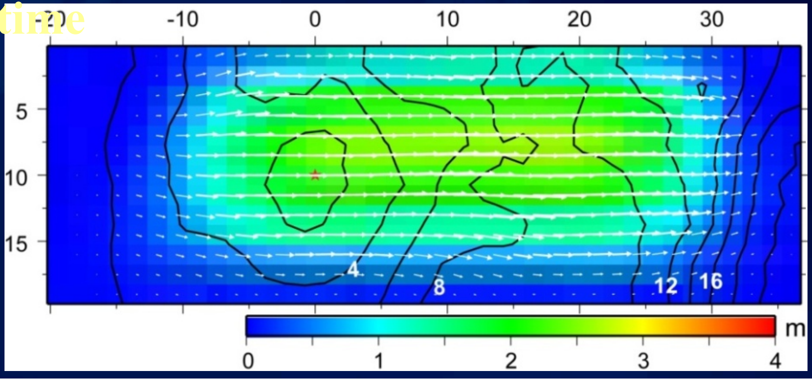
Seismic



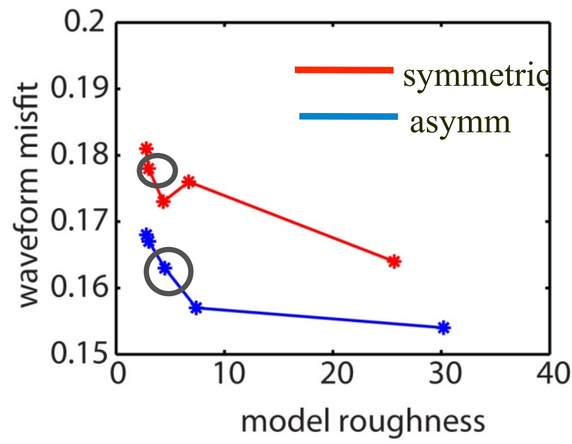
Joint:Symmetric Rise time

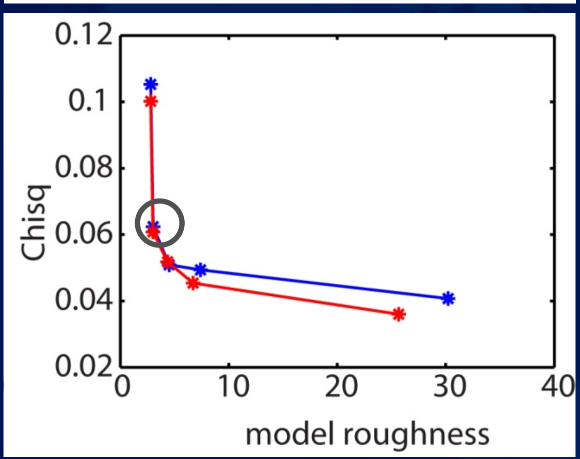


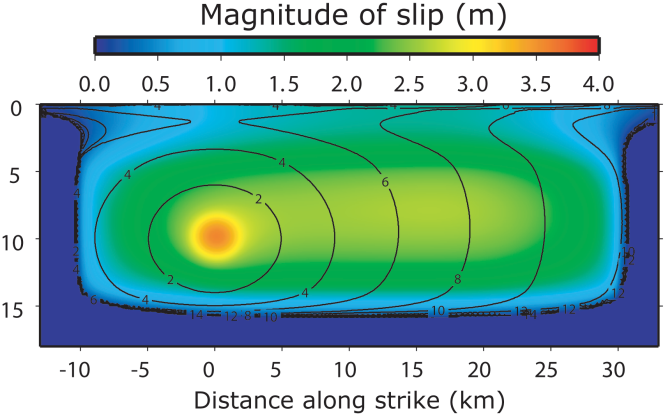
Joint: Asymmetric rise time

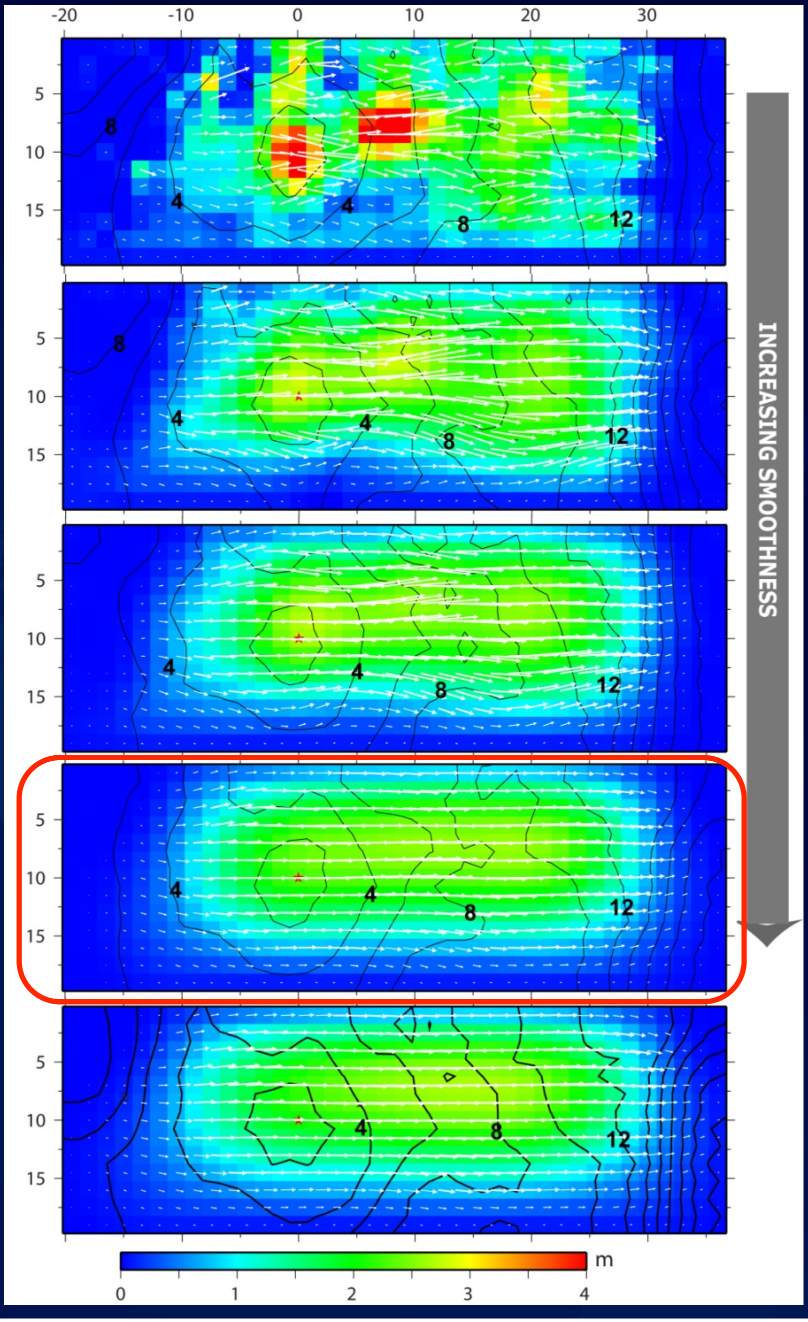


Model 1 – How do we decide best fit models

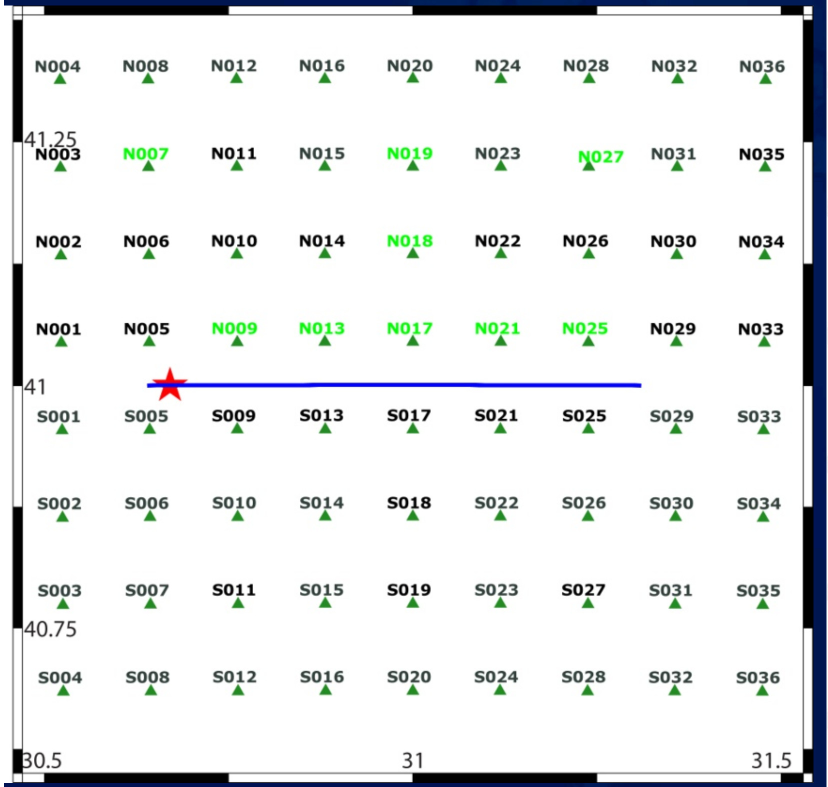


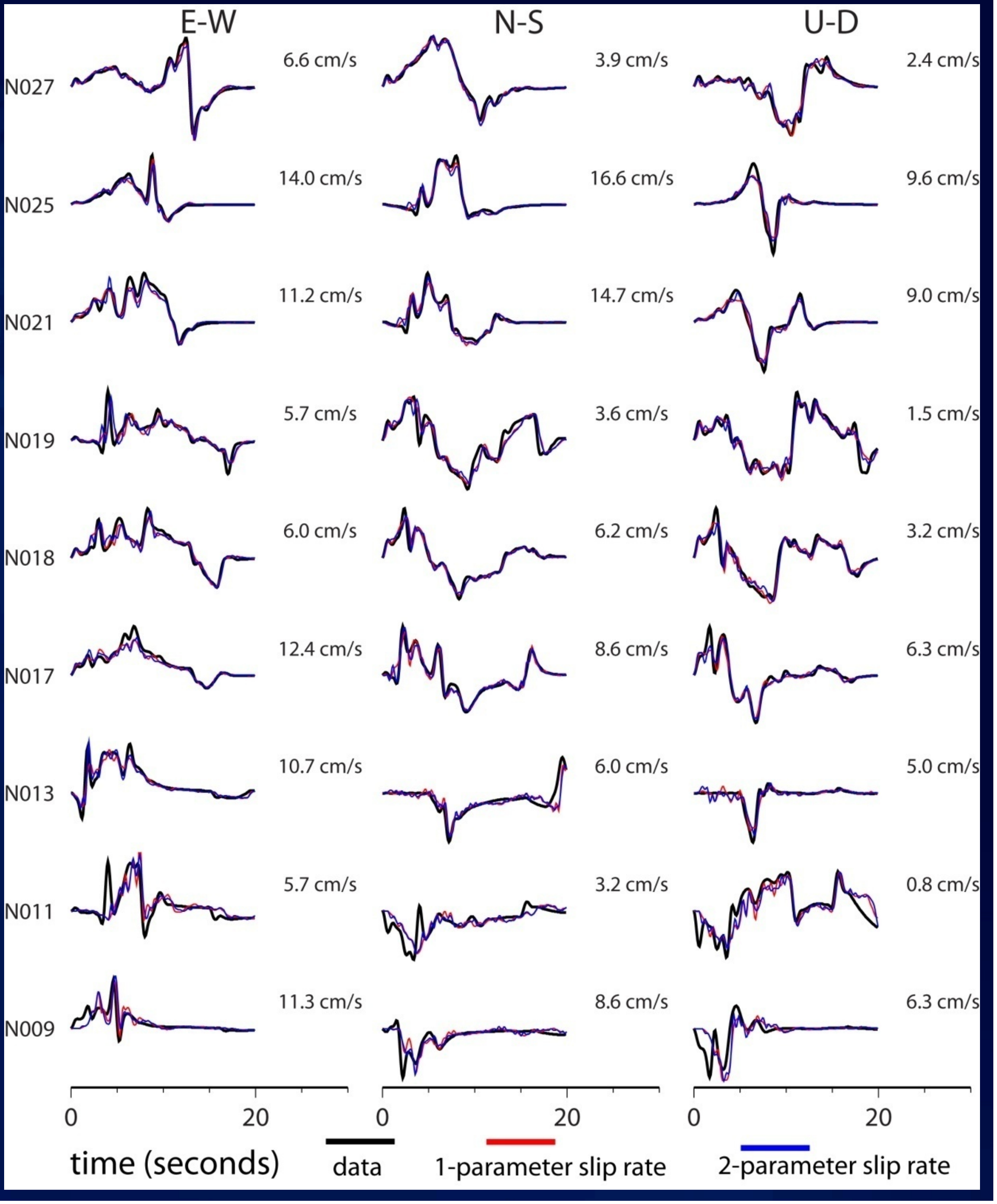




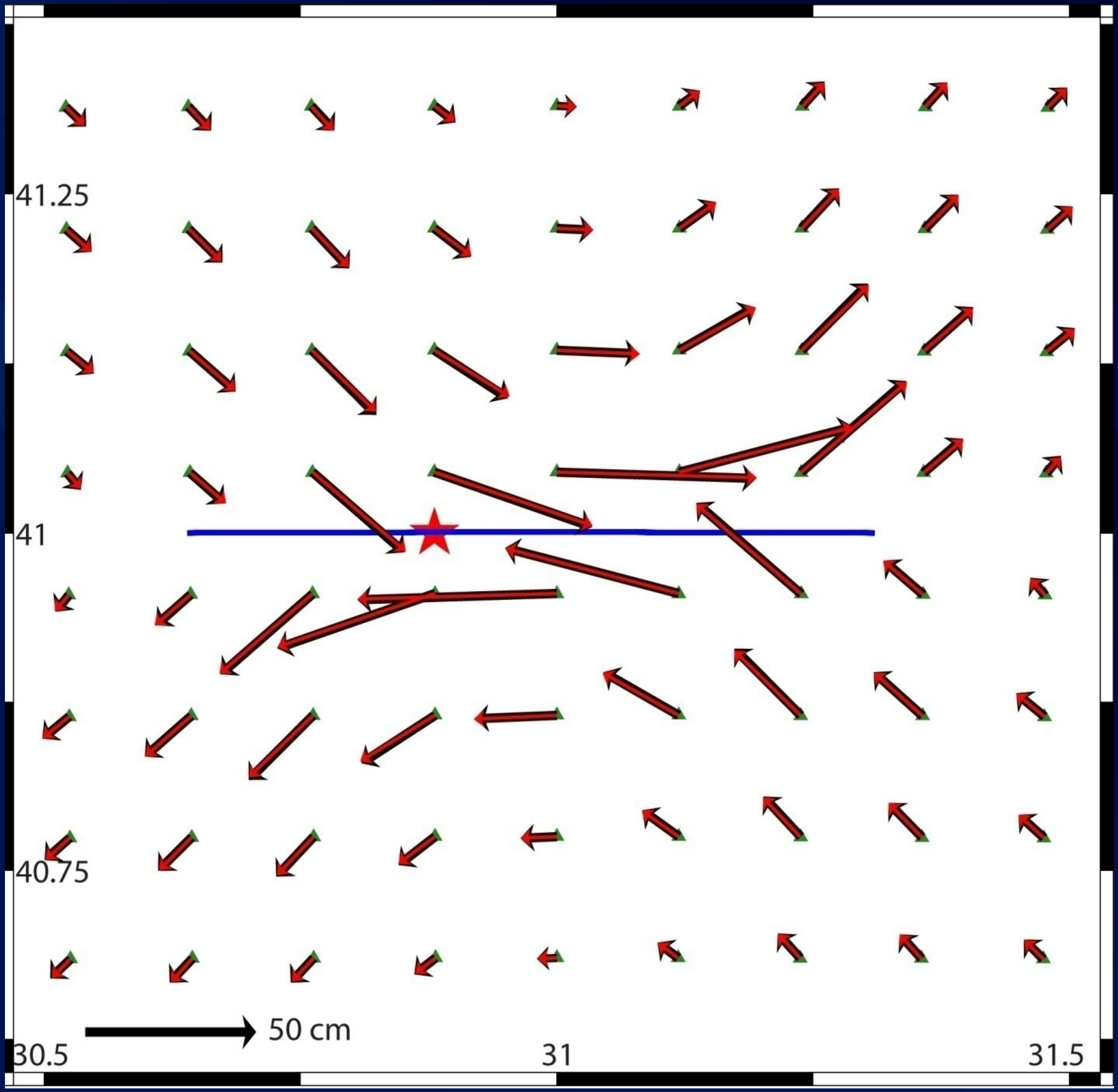


Strong-Motion Fits

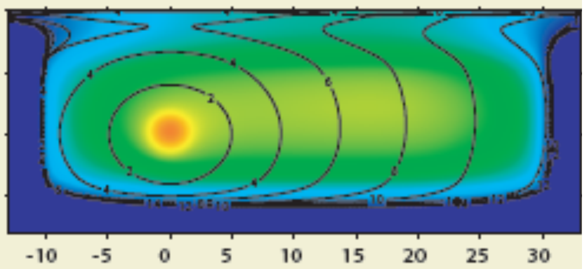




GPS fits



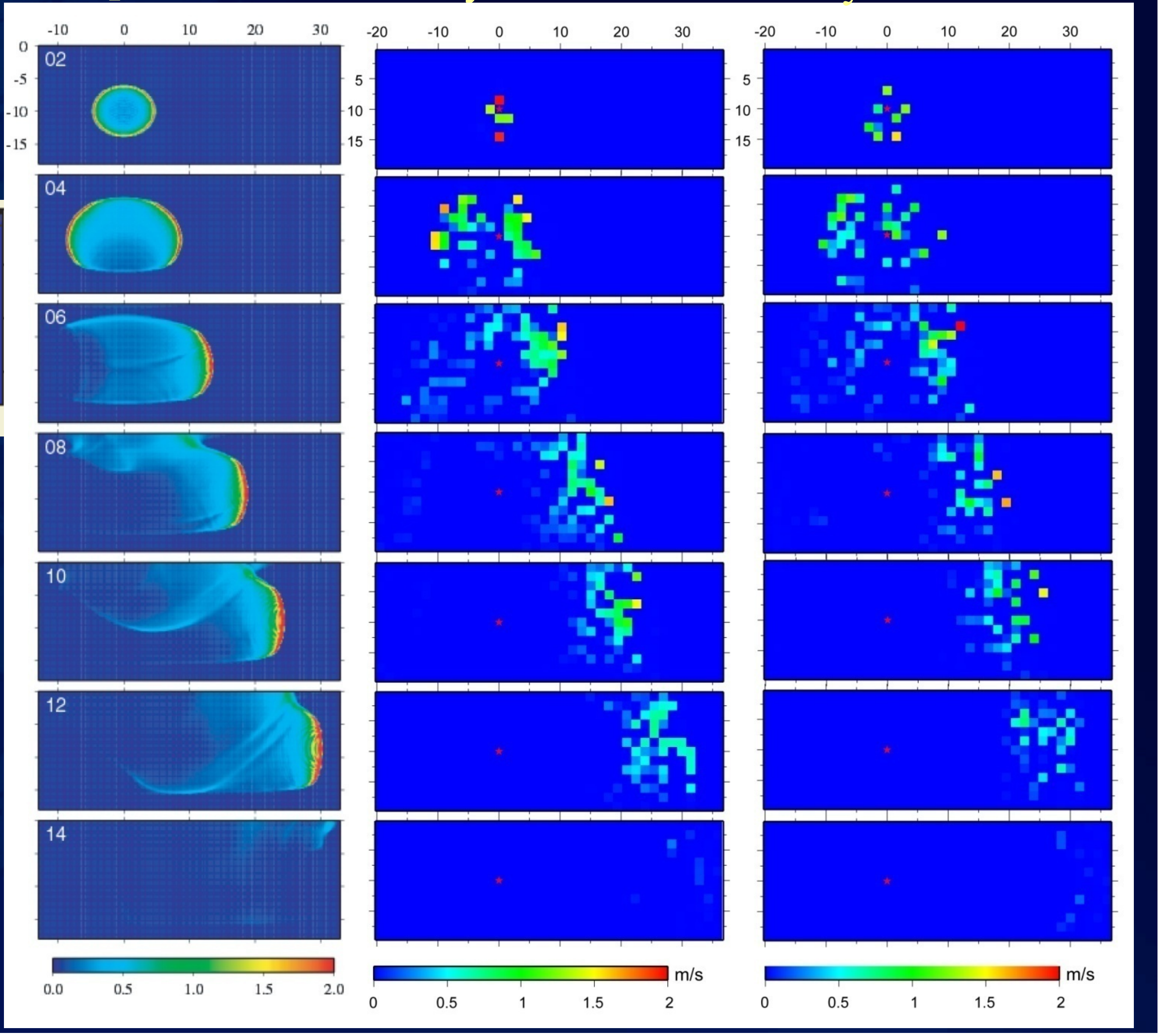
Model 1 Snapshots



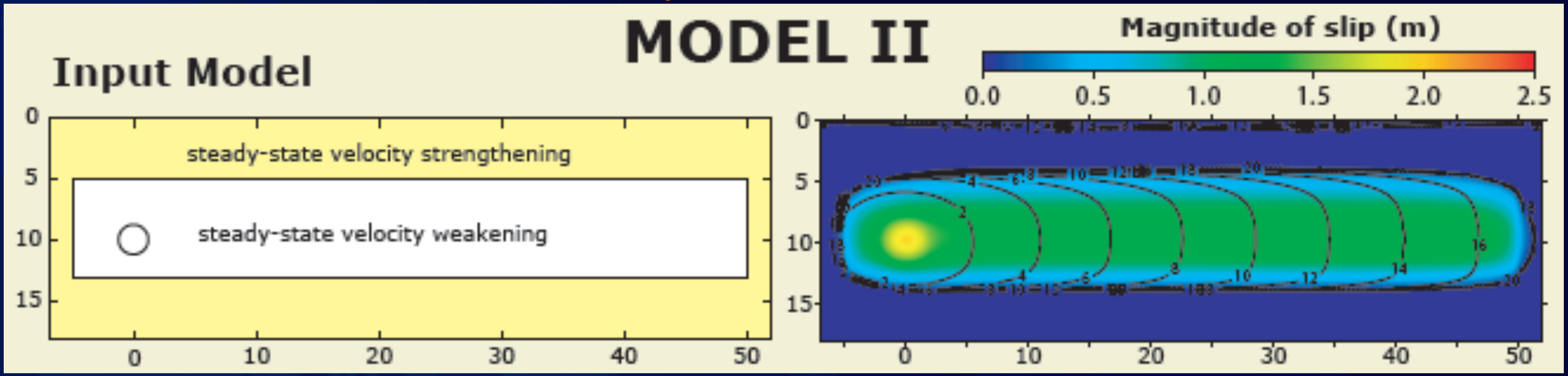
Input

Symmetric

Asymmetric

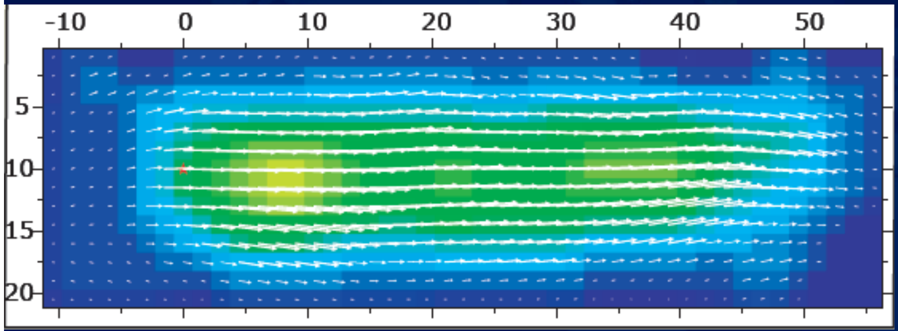


Model 2

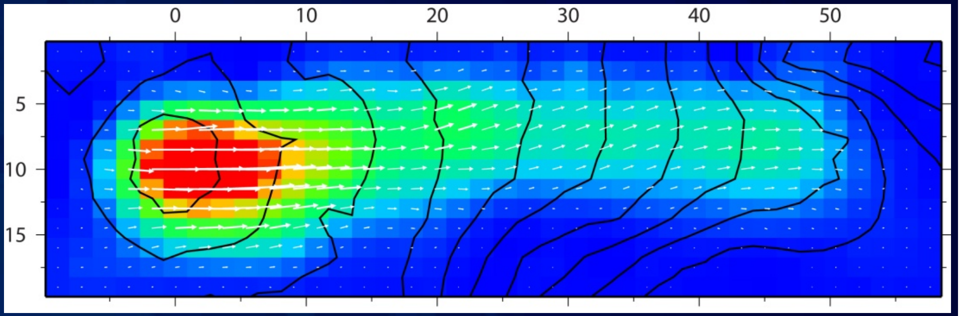


Inverted Kinematic Models

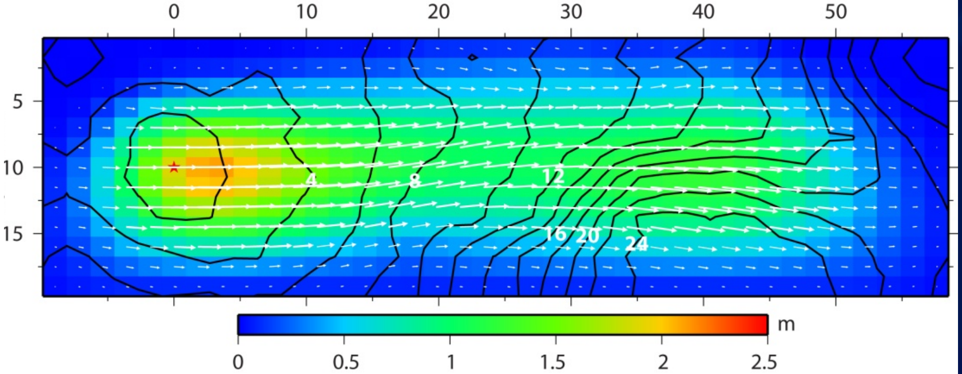
GPS model



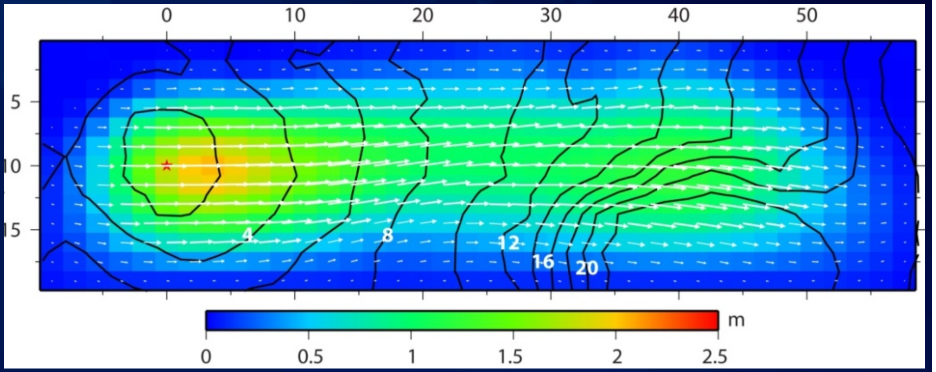
Seismic model



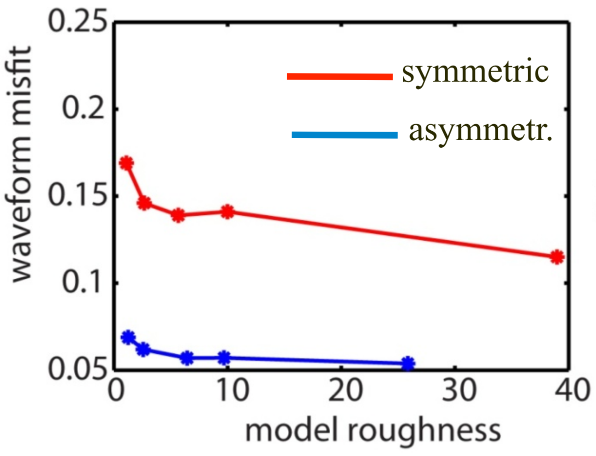
Joint: Symmetric

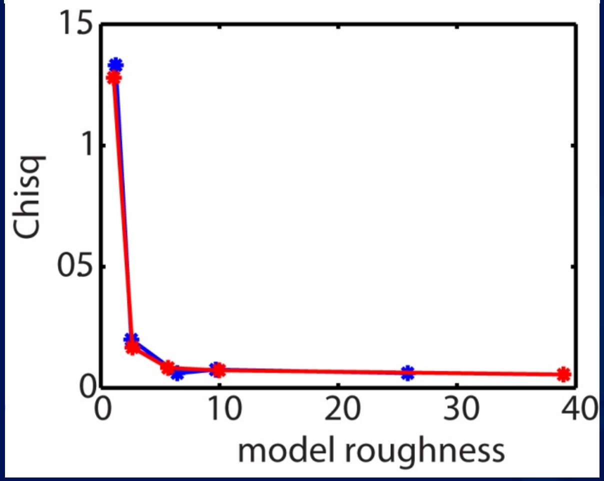


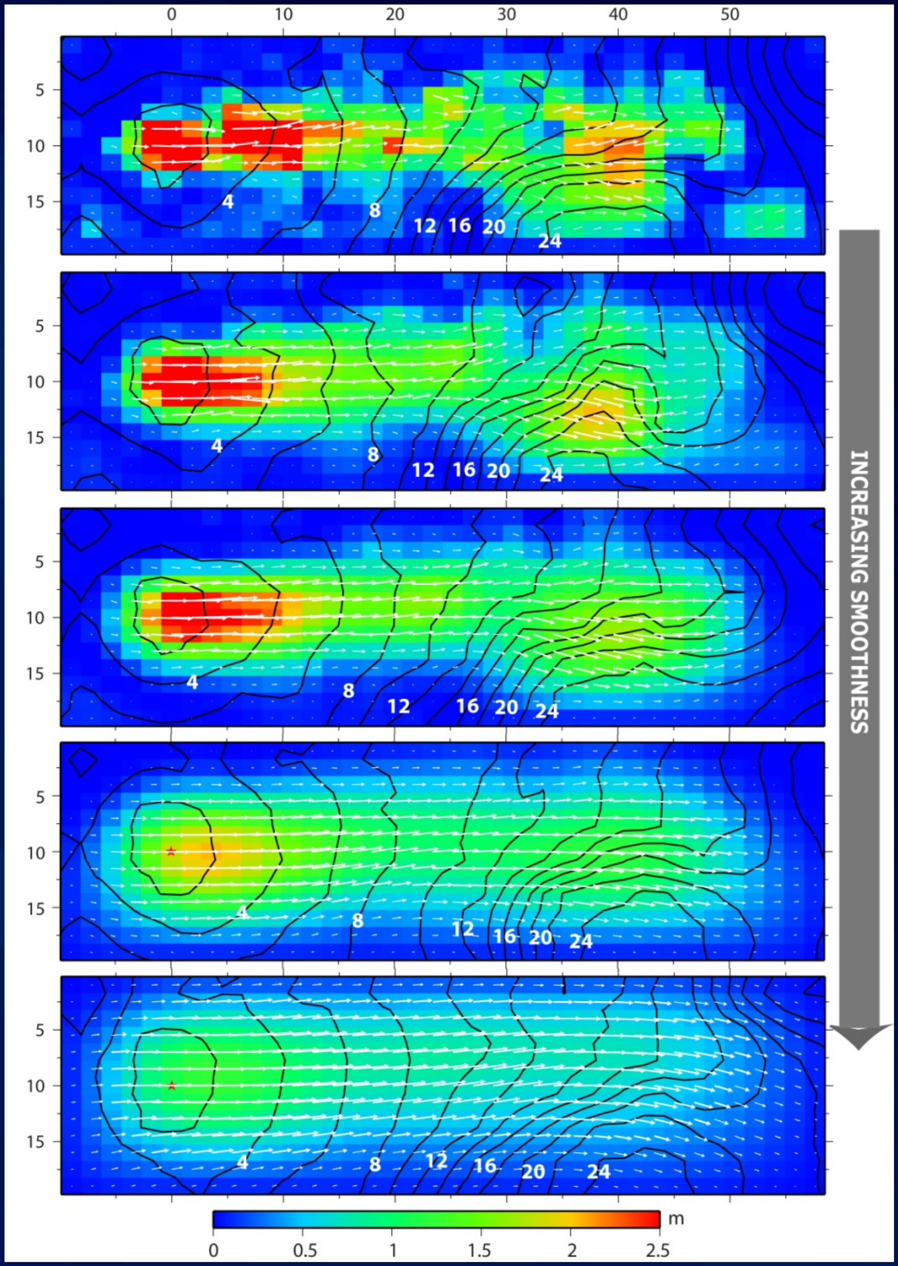
Joint: Asymmetric



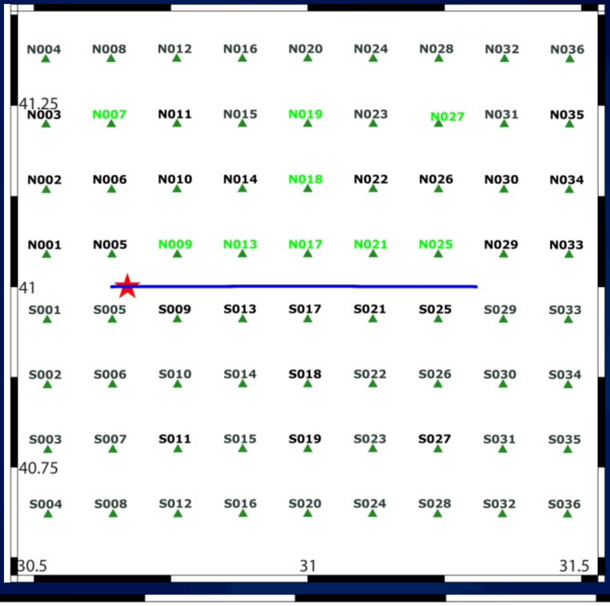
Model 2 – Smoothness vs Misfit

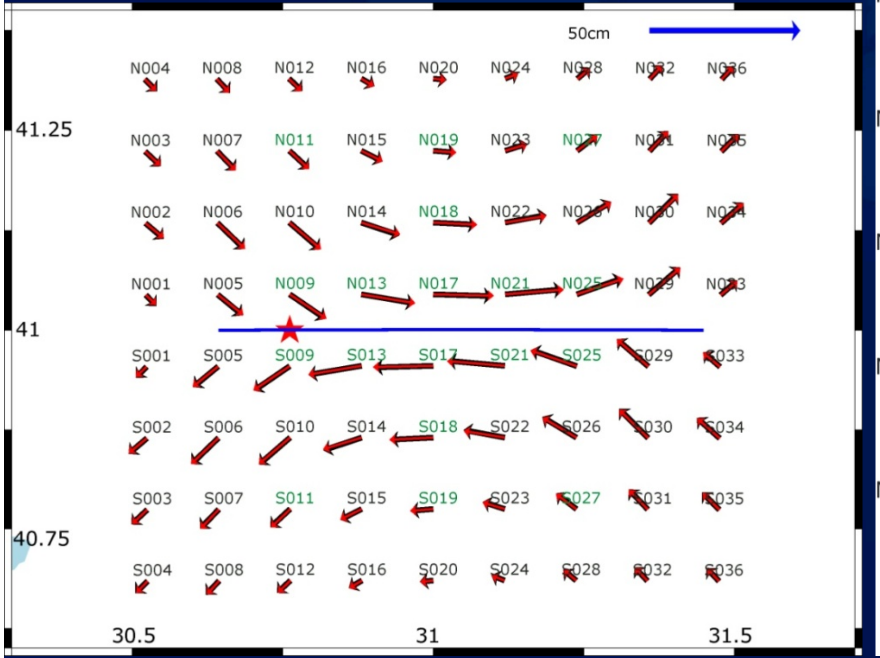


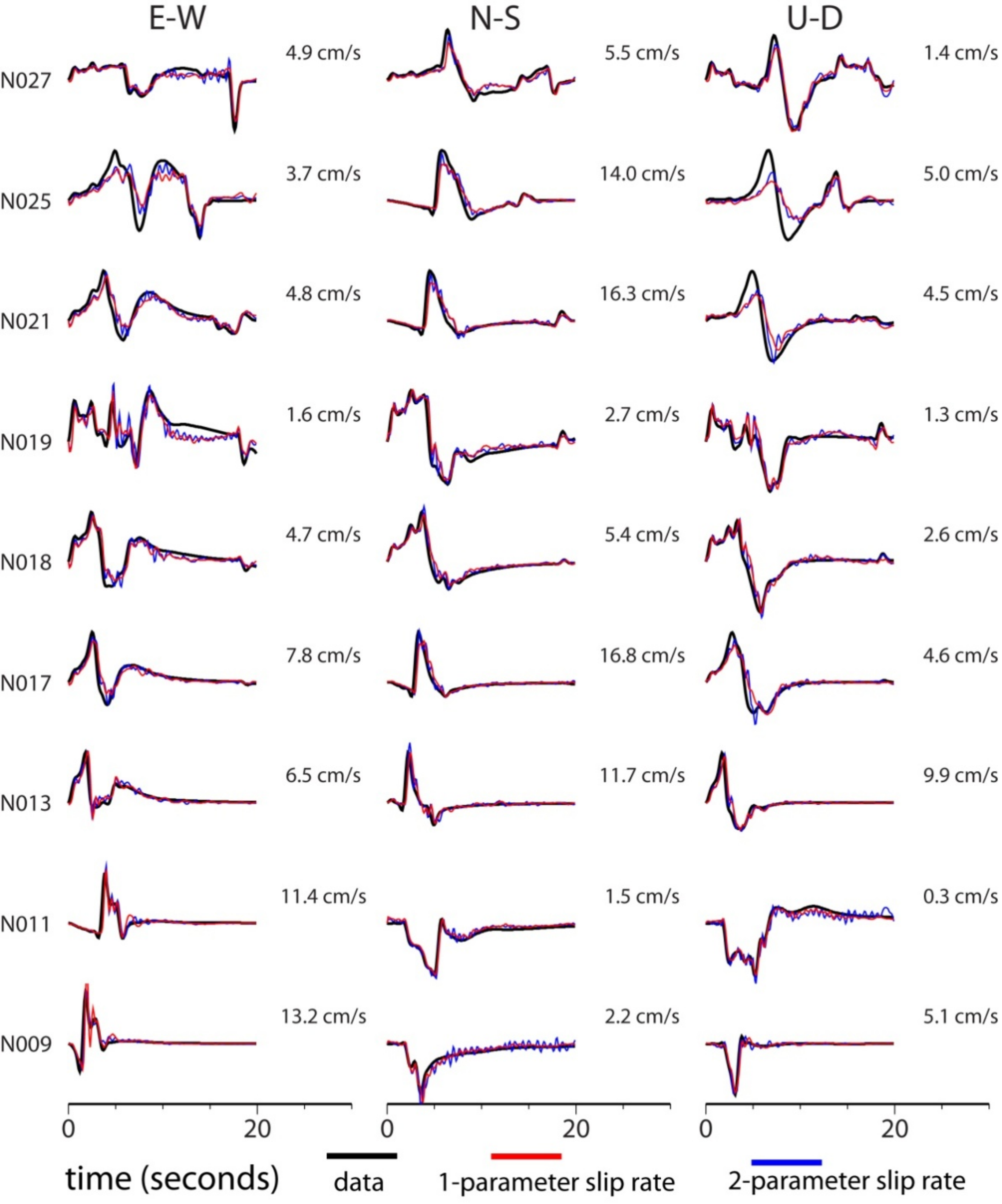




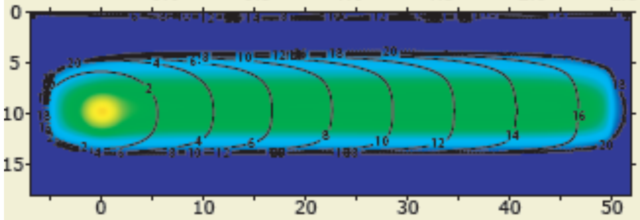
Model 2: Fits to the Data

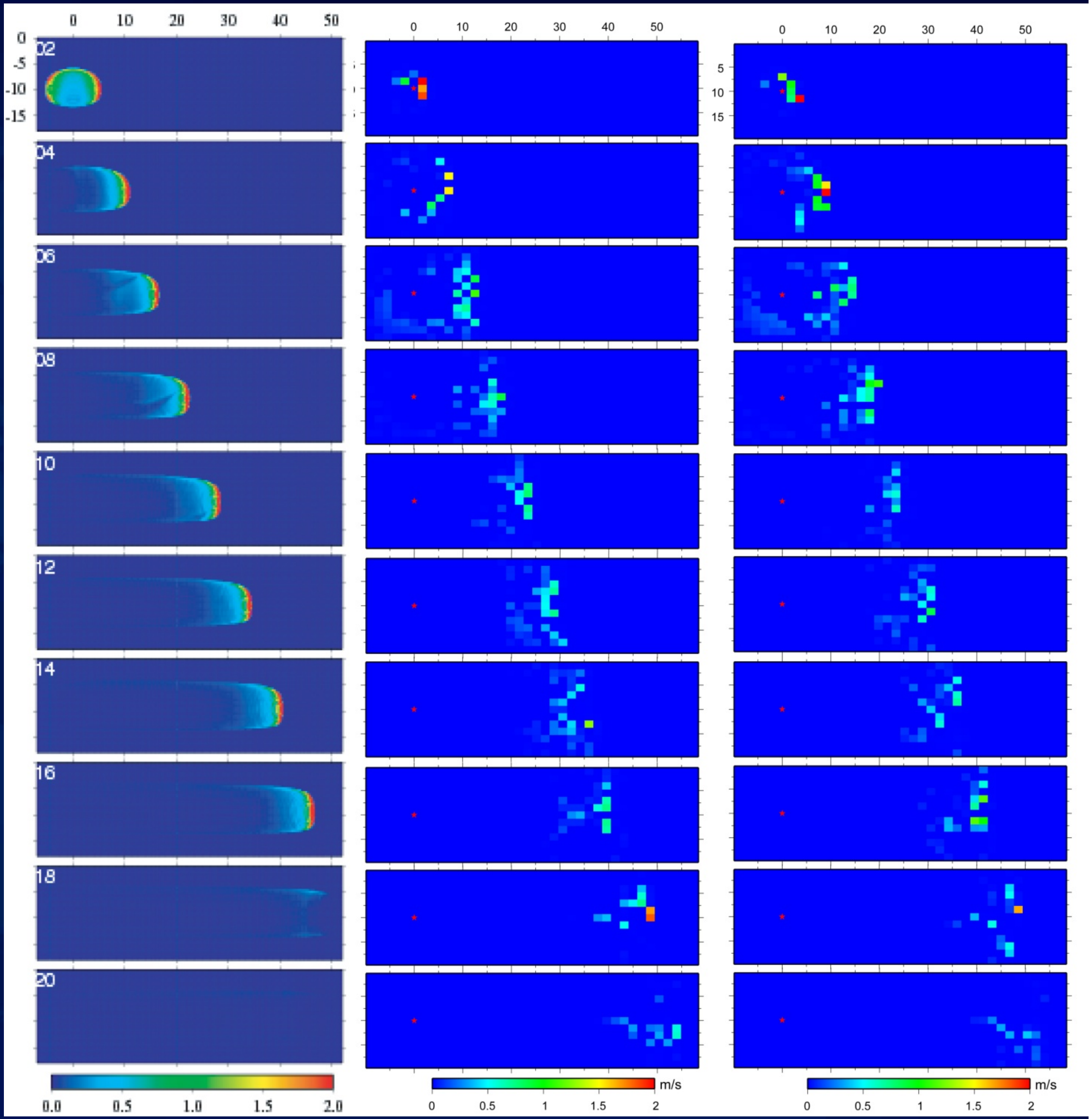






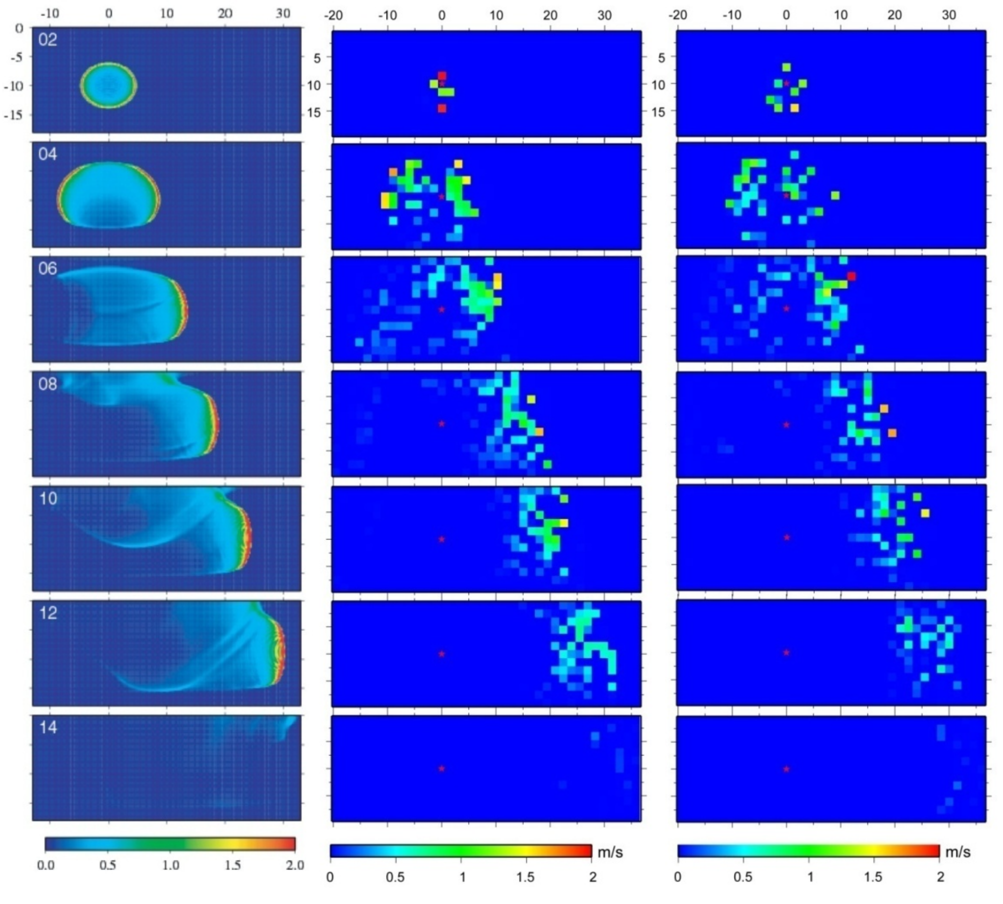
Model 2 Snapshots



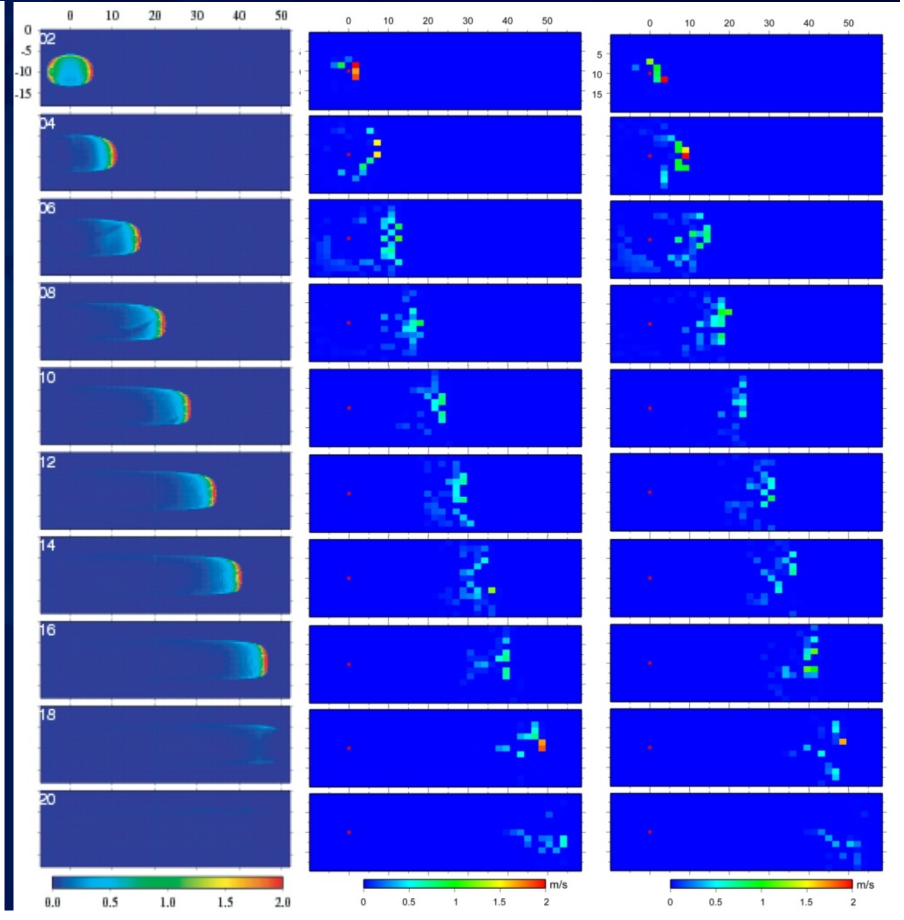


Crack vs Slip Pulse

Model 1

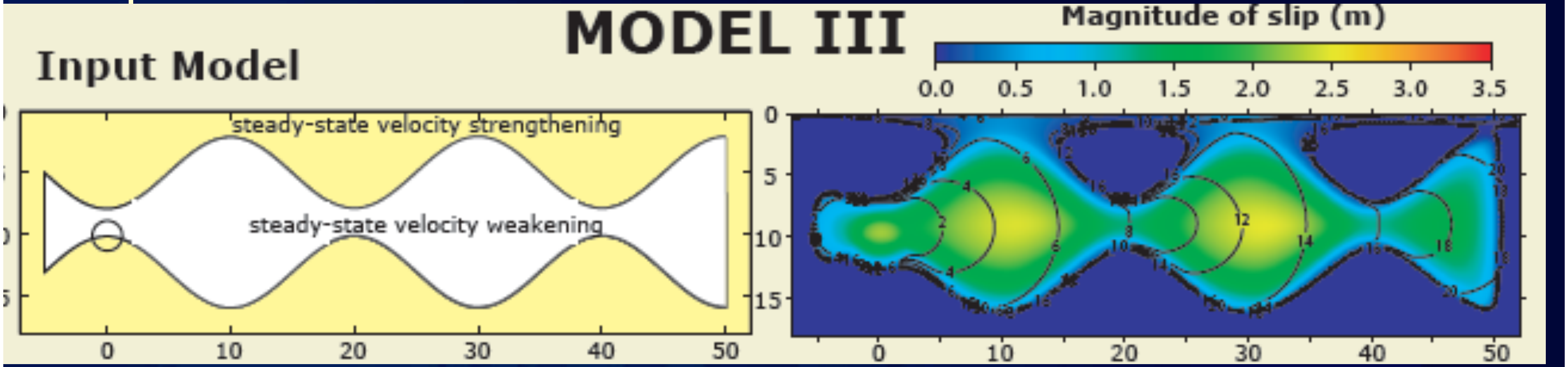


Model 2



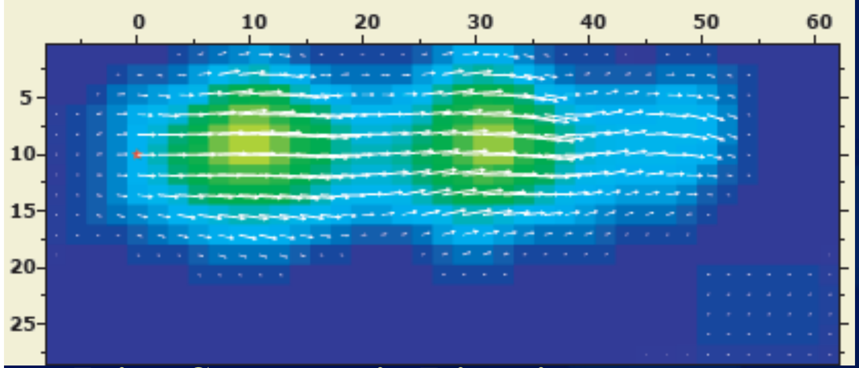
Model 3

- Input

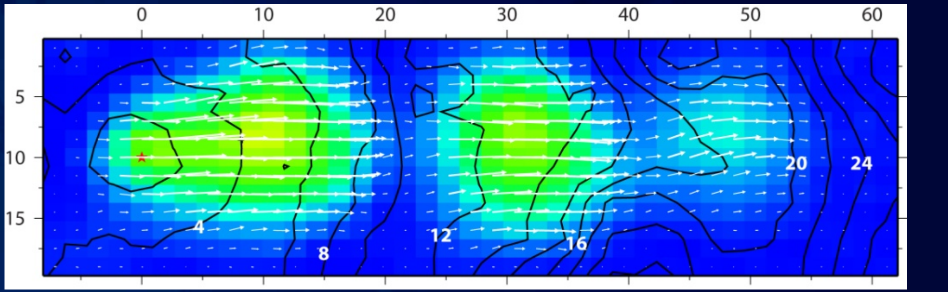


Inverted Kinematic Models

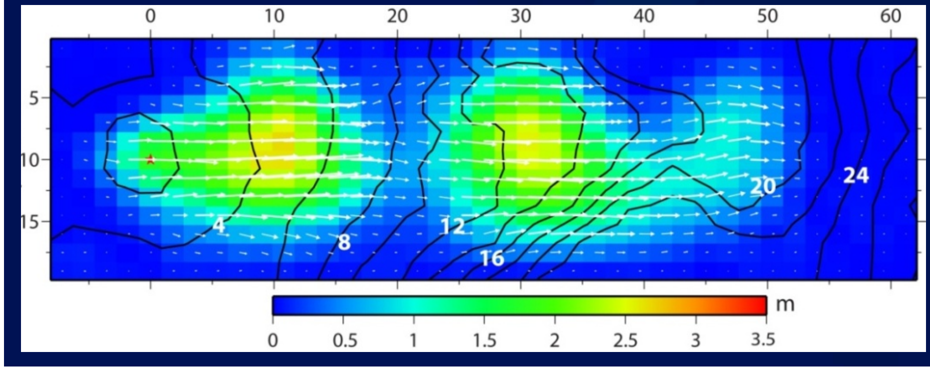
GPS model



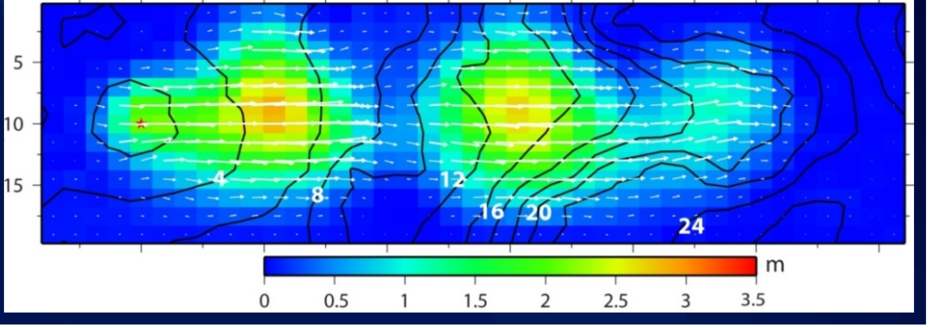
Seismic



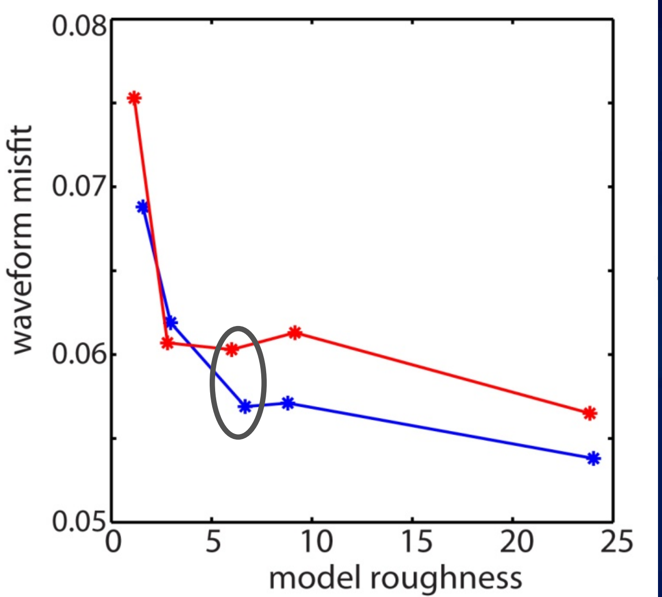
Joint:Symmetric Rise time

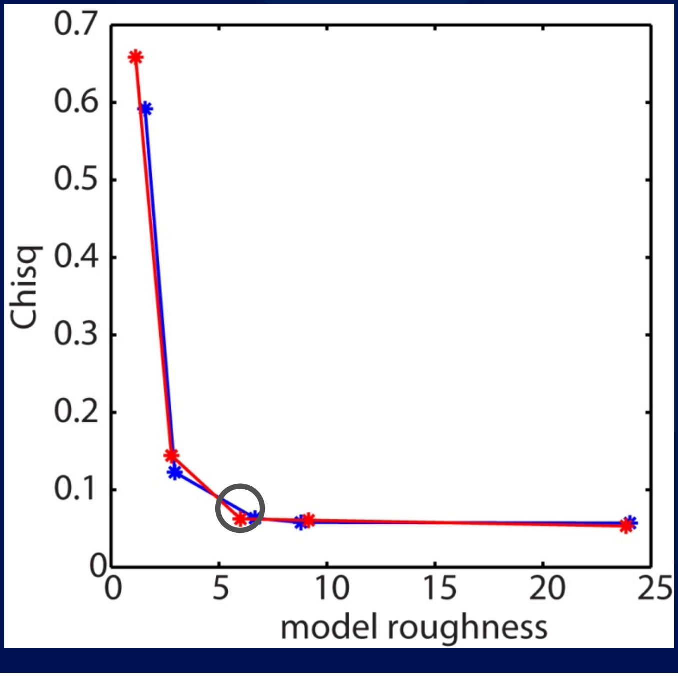


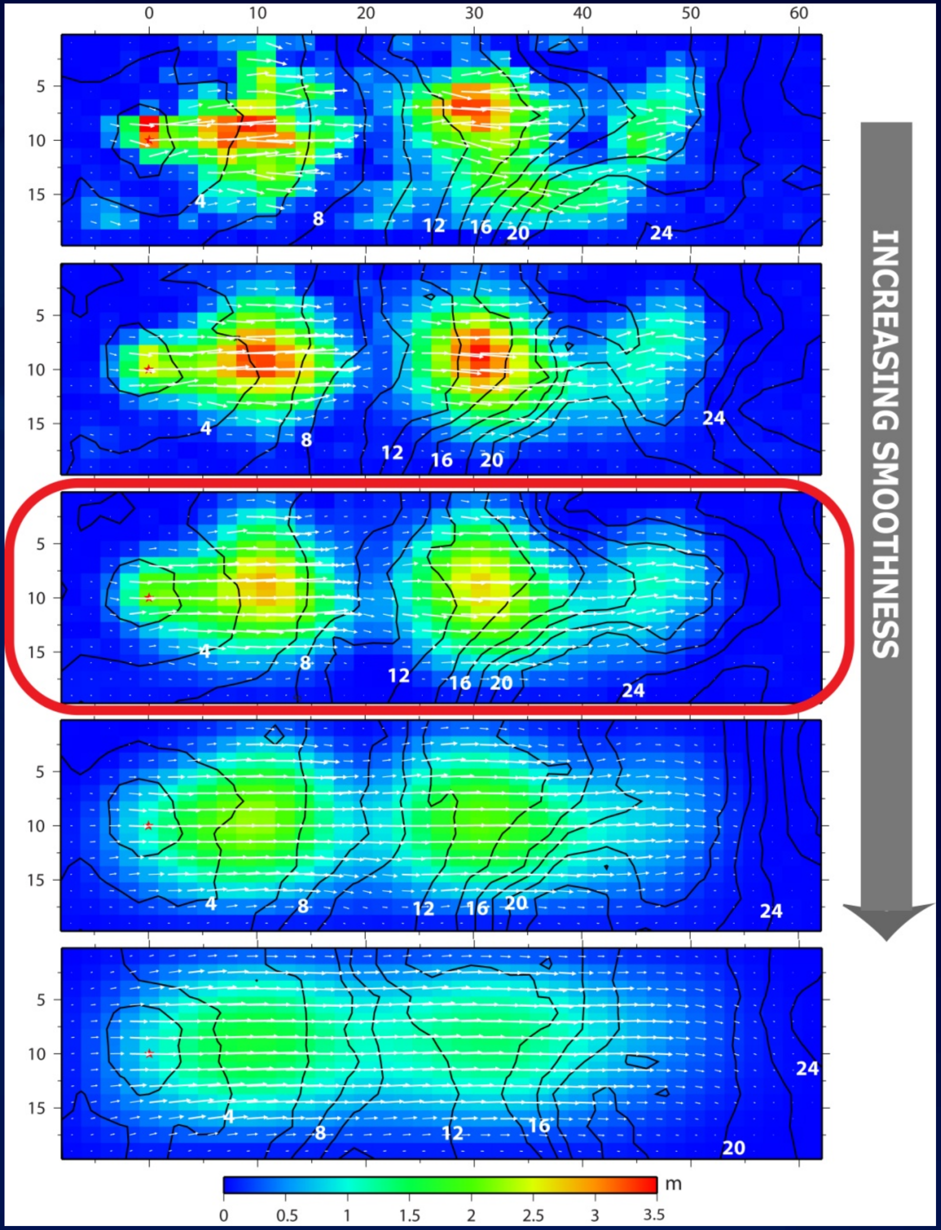
Joint: Asymmetric rise time



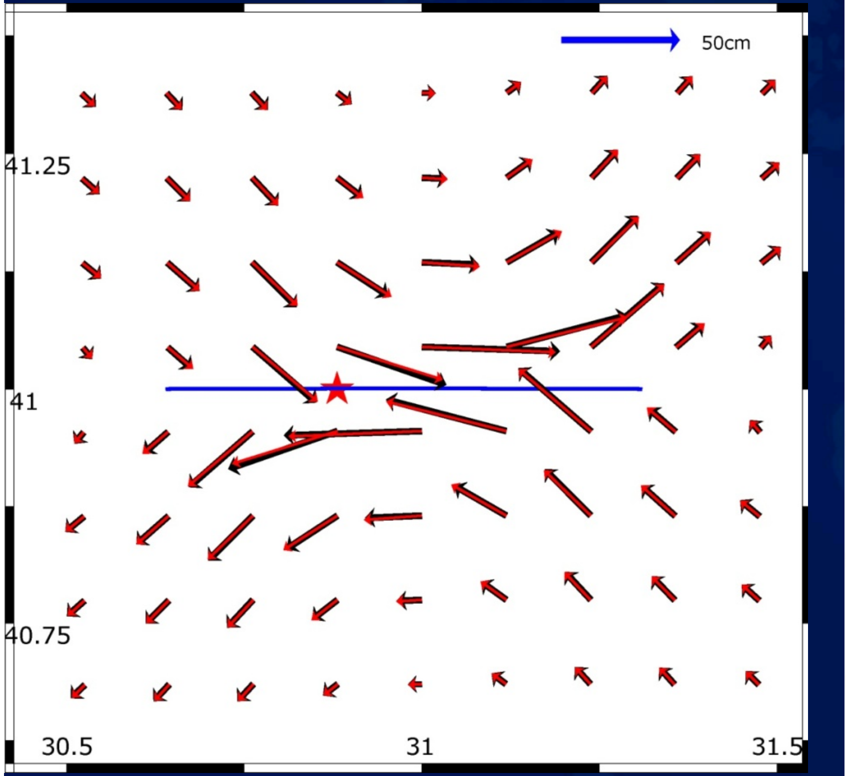
Model 3 – Smoothness vs Slip Models

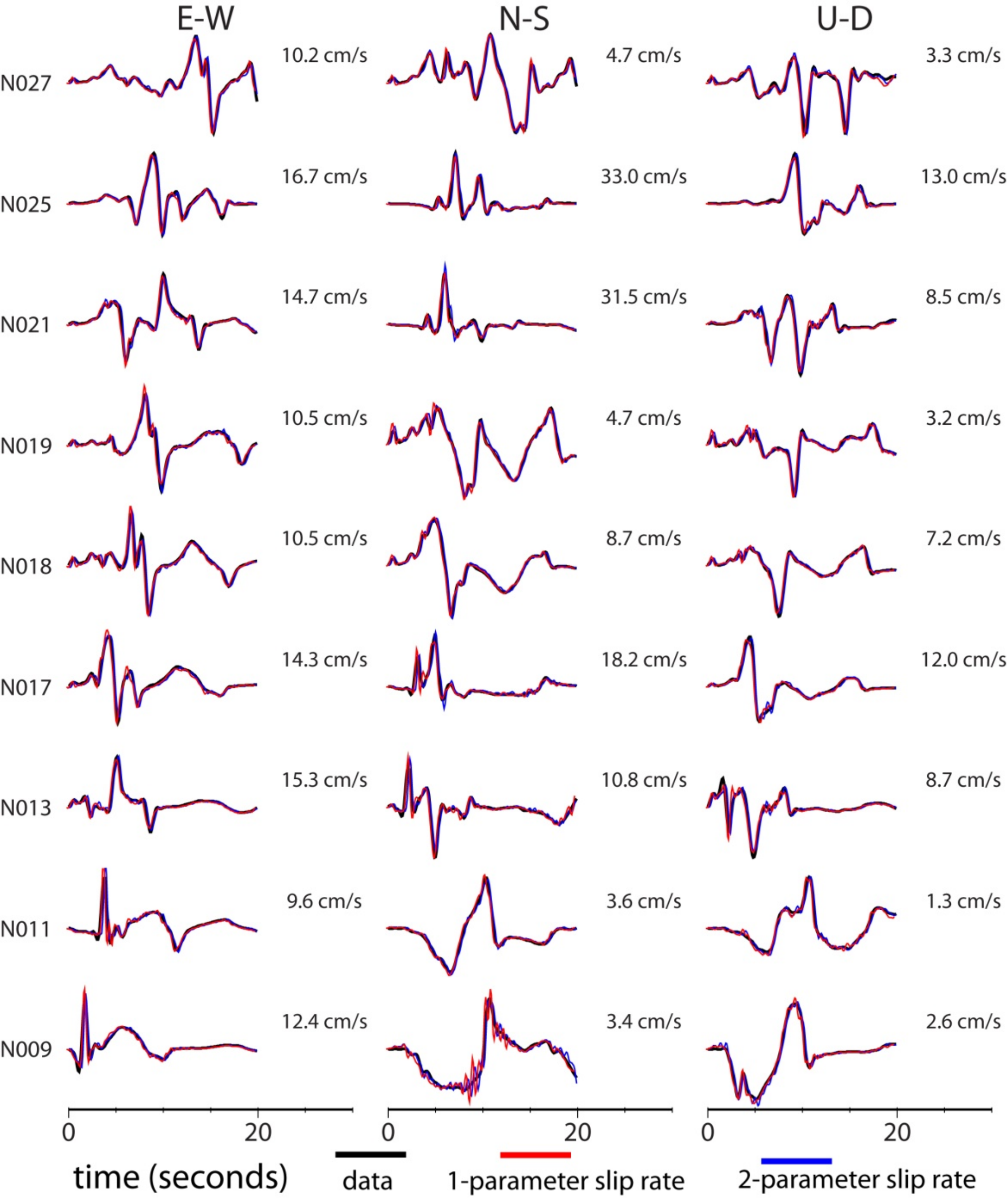




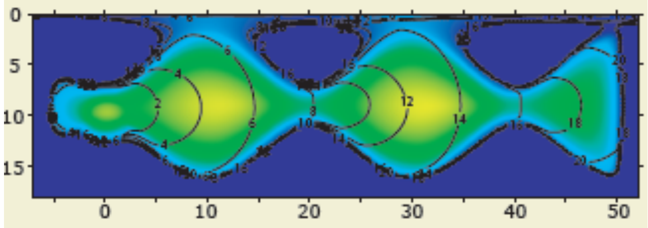


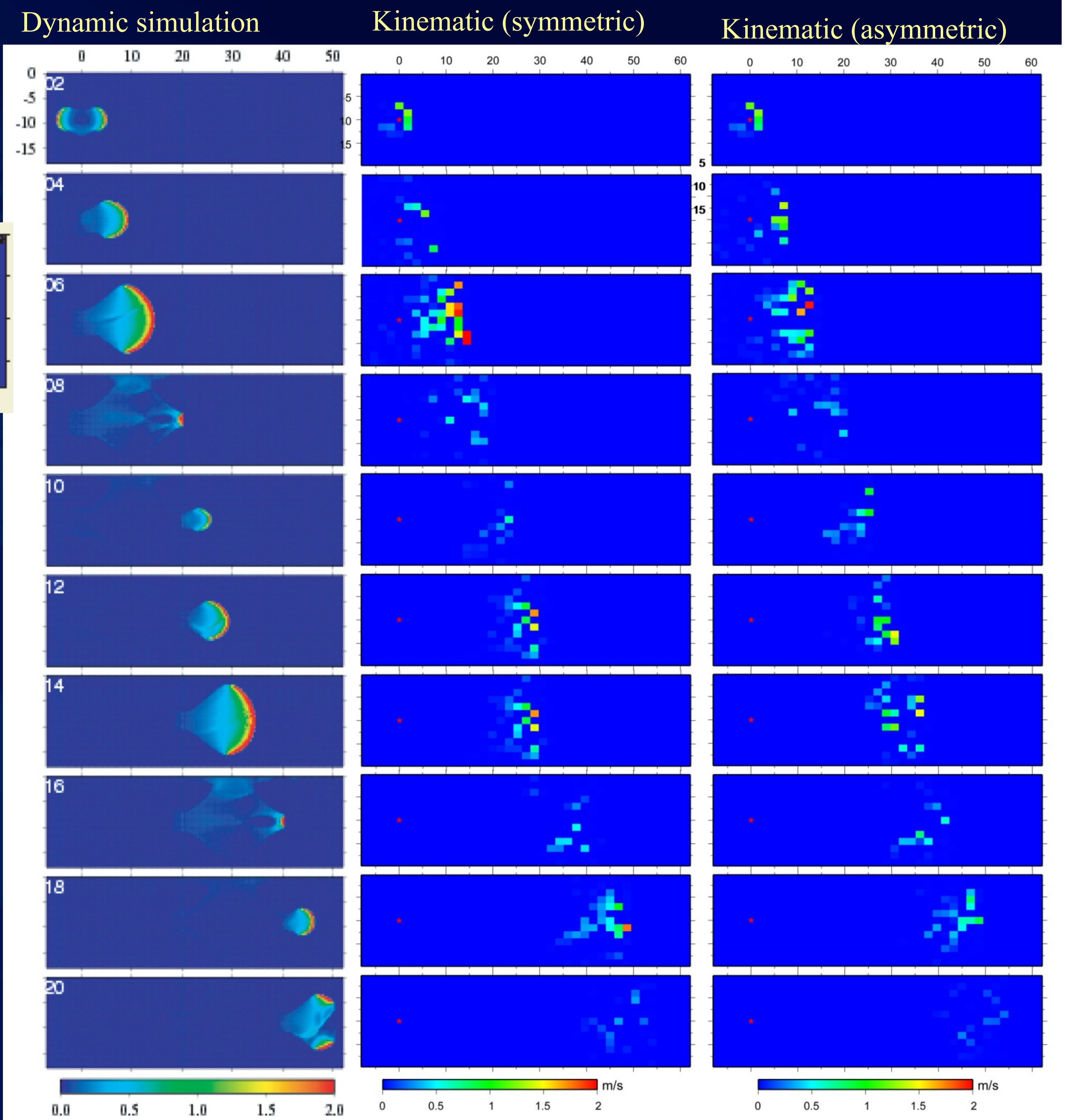
Model 3: Fits to the Data





Model 3
Snapshots

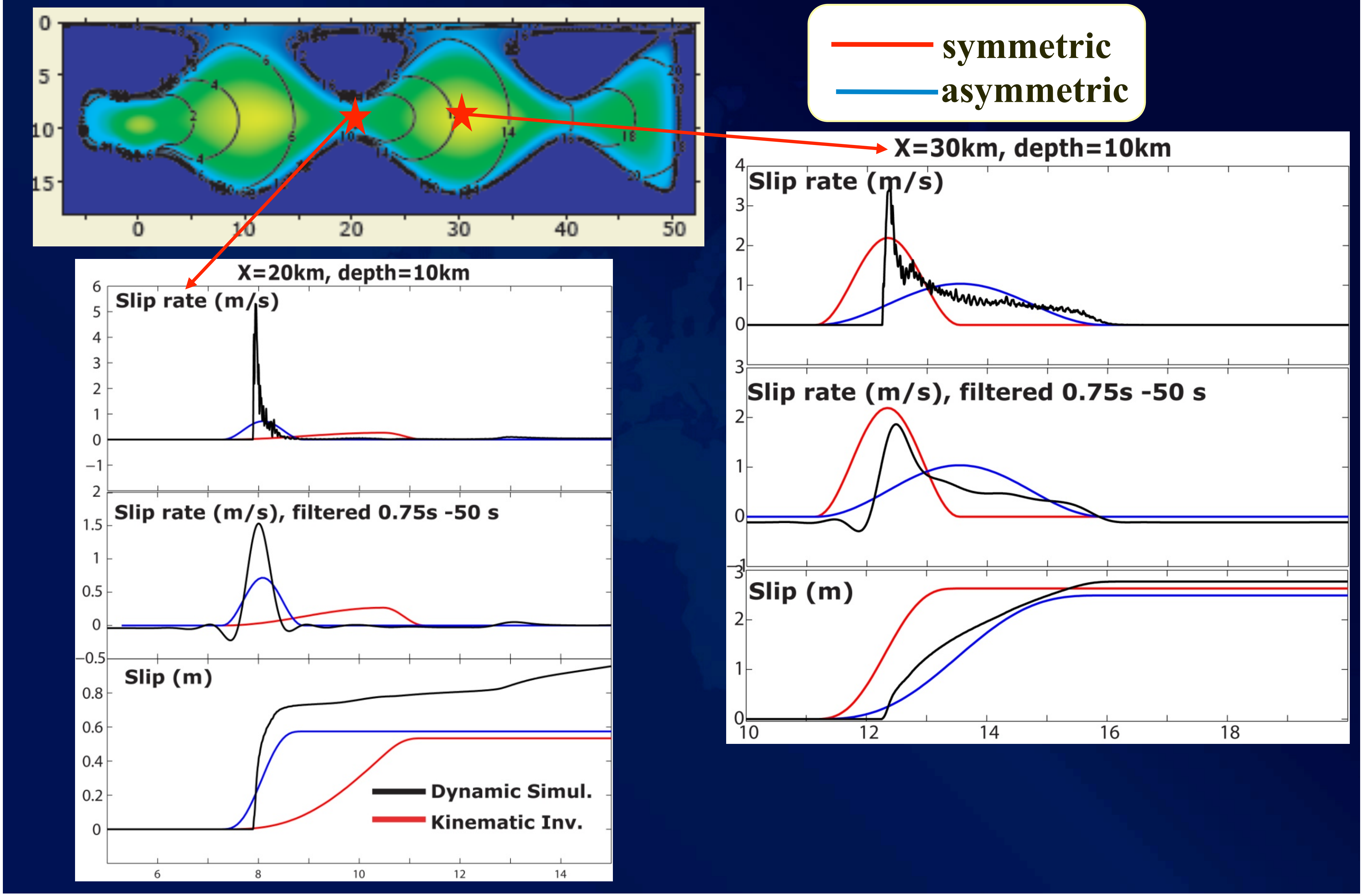



Dynamic simulation

Kinematic (symmetric)

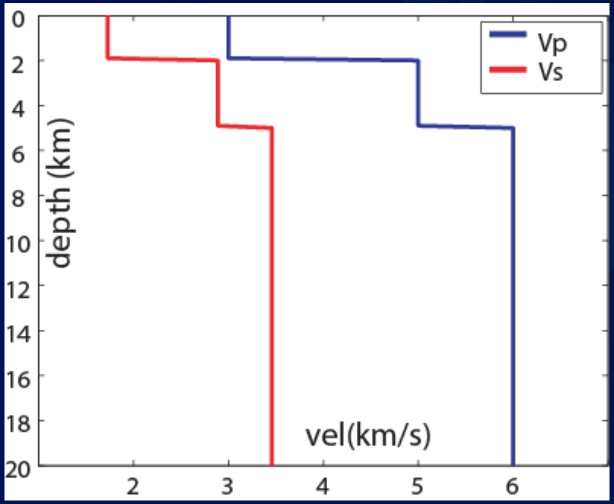
Kinematic (asymmetric)

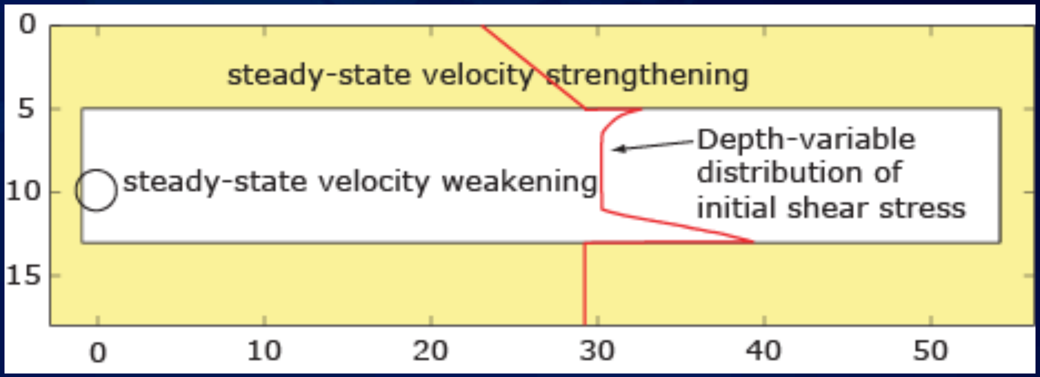
Slip History of Points on the Fault



Model 4: What about more complicated velocity structures?

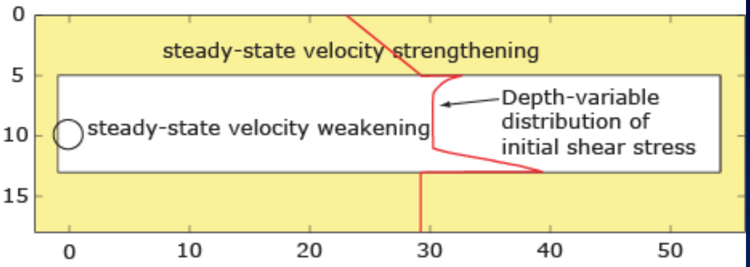
- All above tests are done with half-space models.
- Heterogeneities create more complicated waveforms and it becomes harder to resolve what is happening on the fault
- Stress heterogeneities also contribute to complexity in rupture behavior

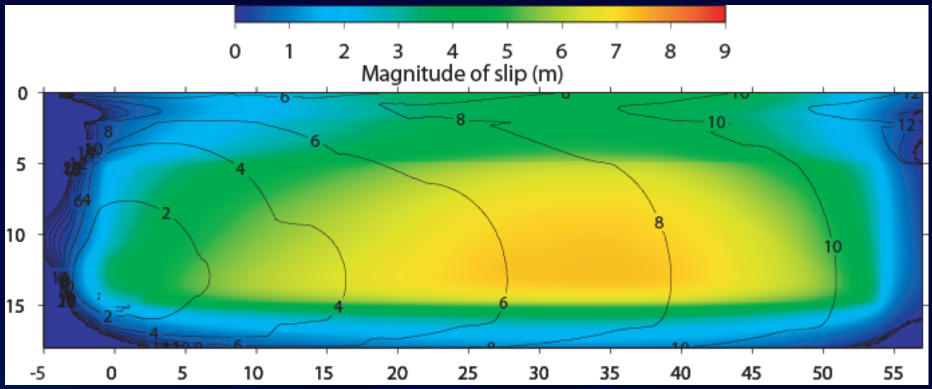




Model 4

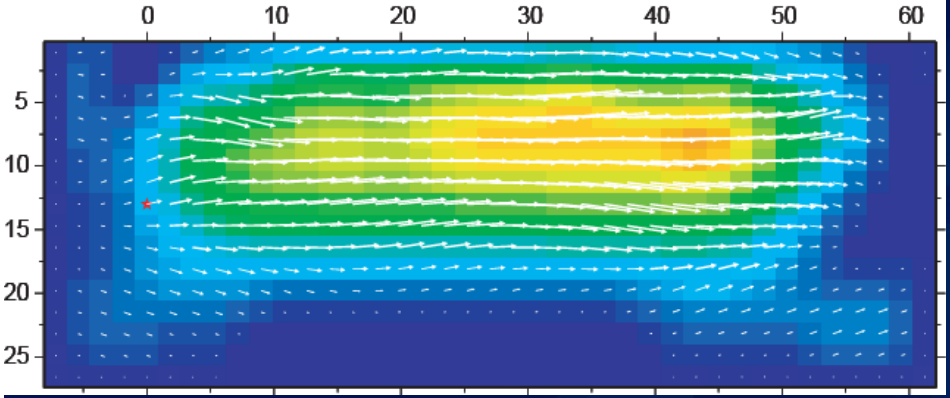
Input model



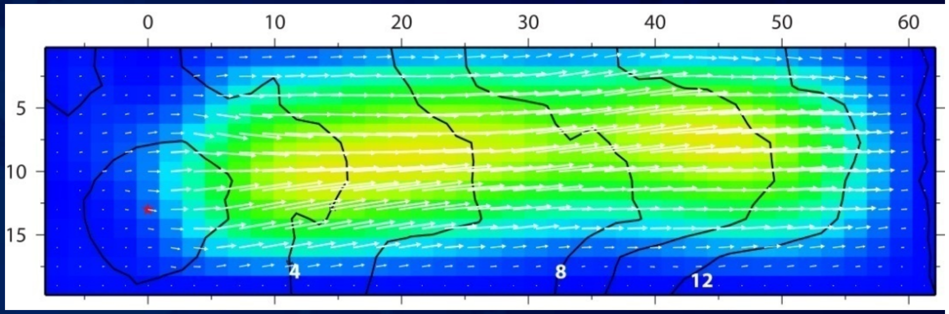


Inverted Kinematic Models

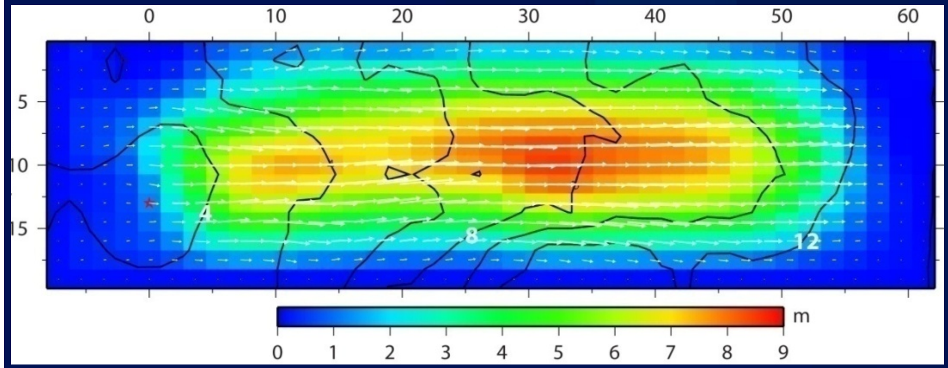
GPS model



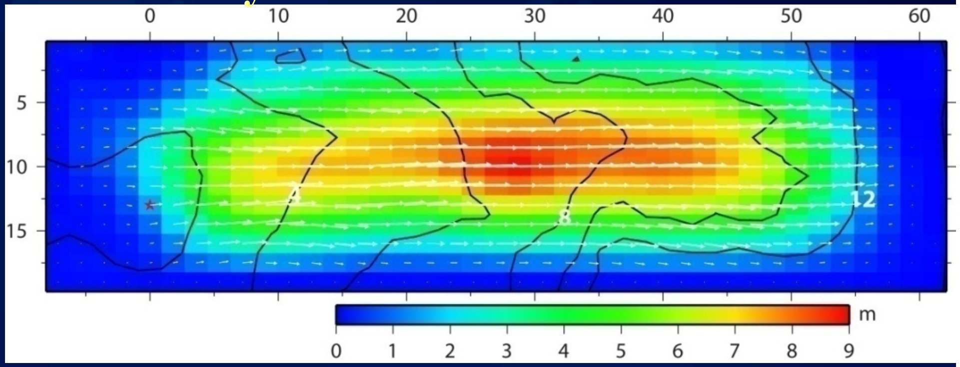
Seismic



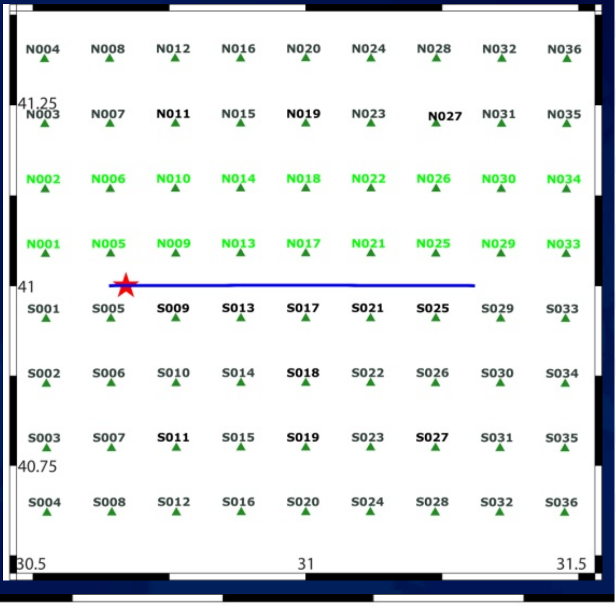
Joint:Symmetric Rise time

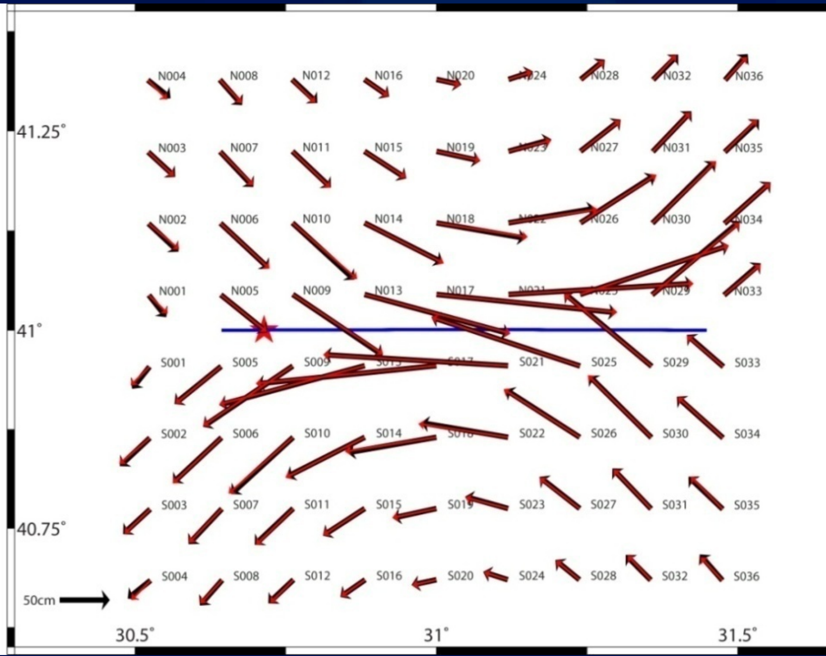


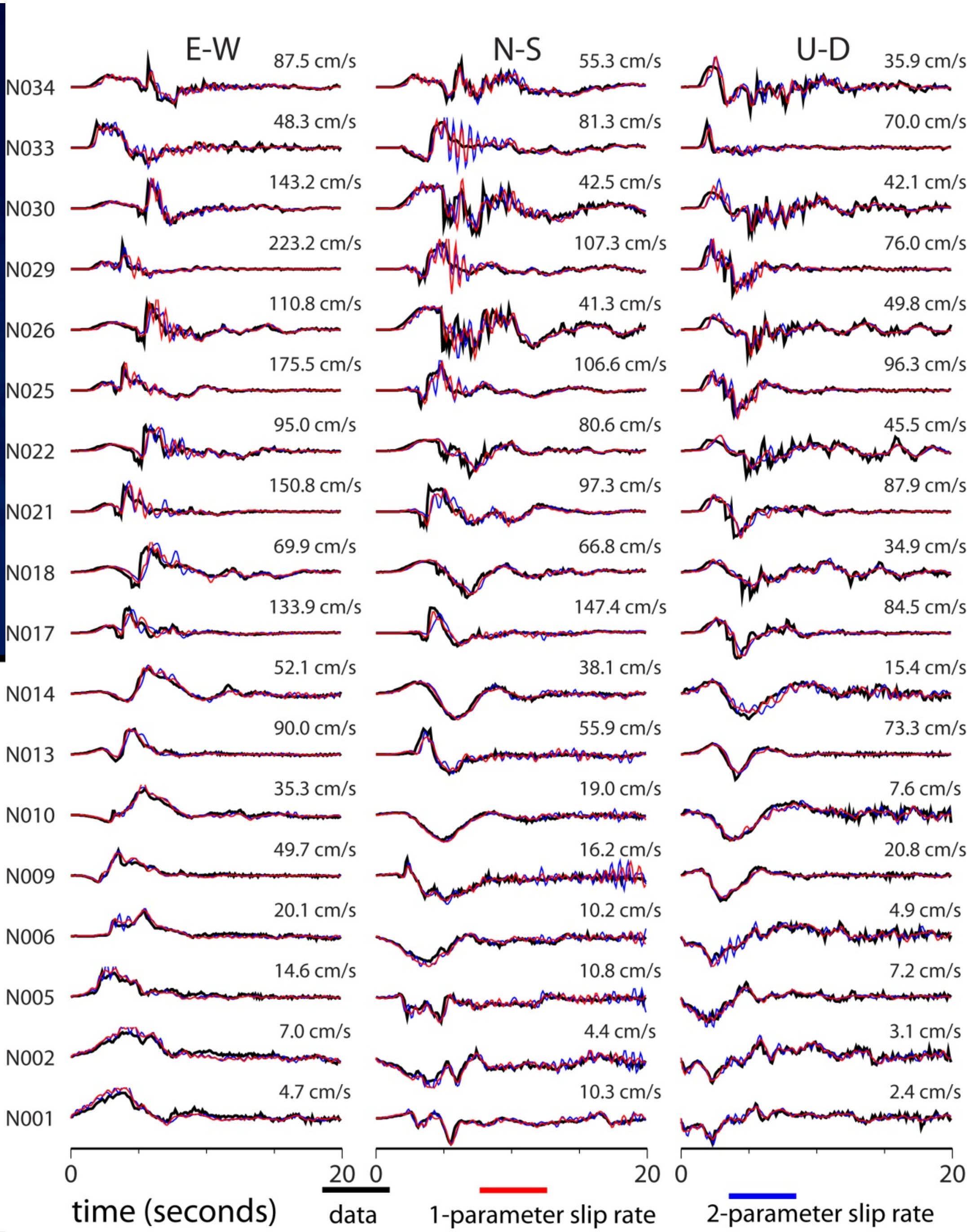
Joint: Asymmetric rise time



Data fits

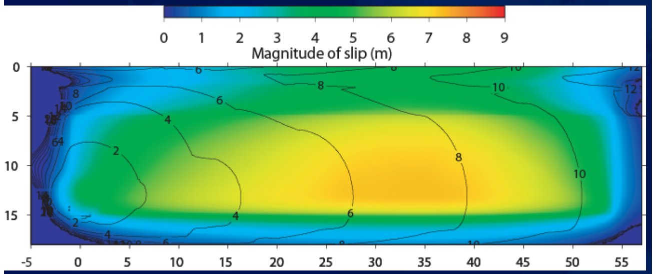

N004 N008 N012 N016 N020 N024 N028 N032 N036
41.25
N003 N007 N011 N015 N019 N023 N027 N031 N035
N002 N006 N010 N014 N018 N022 N026 N030 N034
N001 N005 N009 N013 N017 N021 N025 N029 N033
41
S001 S005 S009 S013 S017 S021 S025 S029 S033
S002 S006 S010 S014 S018 S022 S026 S030 S034
S003 S007 S011 S015 S019 S023 S027 S031 S035
40.75
S004 S008 S012 S016 S020 S024 S028 S032 S036
30.5
31
31.5

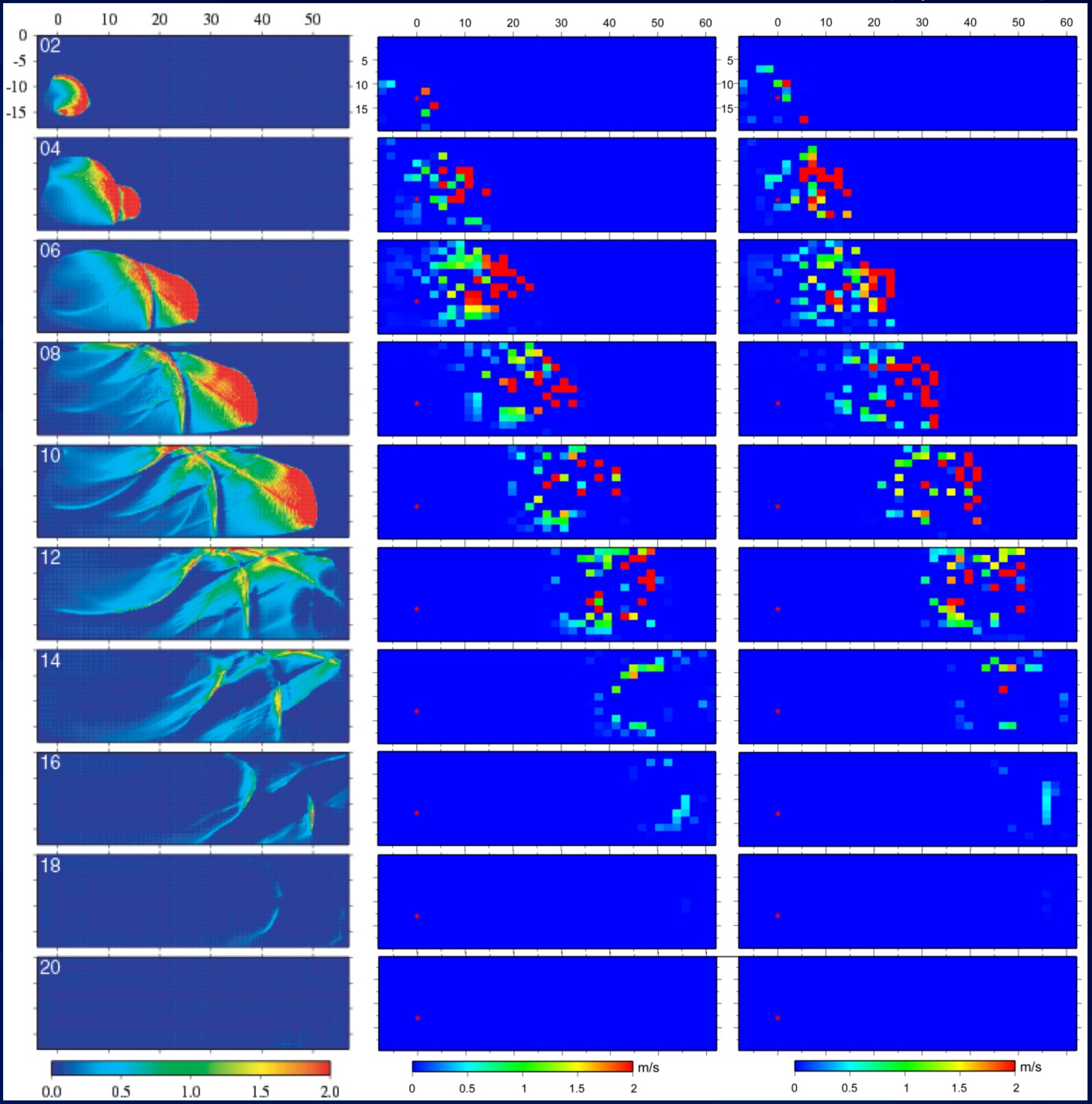

N004 N008 N012 N016 N020 N024 N028 N032 N036
41.25°
N003 N007 N011 N015 N019 N023 N027 N031 N035
N002 N006 N010 N014 N018 N022 N026 N030 N034
N001 N005 N009 N013 N017 N021 N025 N029 N033
41°
S001 S005 S009 S013 S017 S021 S025 S029 S033
S002 S006 S010 S014 S018 S022 S026 S030 S034
S003 S007 S011 S015 S019 S023 S027 S031 S035
40.75°
S004 S008 S012 S016 S020 S024 S028 S032 S036
50cm
30.5°
31°
31.5°


E-W
N-S
U-D
N034 87.5 cm/s 55.3 cm/s 35.9 cm/s
N033 48.3 cm/s 81.3 cm/s 70.0 cm/s
N030 143.2 cm/s 42.5 cm/s 42.1 cm/s
N029 223.2 cm/s 107.3 cm/s 76.0 cm/s
N026 110.8 cm/s 41.3 cm/s 49.8 cm/s
N025 175.5 cm/s 106.6 cm/s 96.3 cm/s
N022 95.0 cm/s 80.6 cm/s 45.5 cm/s
N021 150.8 cm/s 97.3 cm/s 87.9 cm/s
N018 69.9 cm/s 66.8 cm/s 34.9 cm/s
N017 133.9 cm/s 147.4 cm/s 84.5 cm/s
N014 52.1 cm/s 38.1 cm/s 15.4 cm/s
N013 90.0 cm/s 55.9 cm/s 73.3 cm/s
N010 35.3 cm/s 19.0 cm/s 7.6 cm/s
N009 49.7 cm/s 16.2 cm/s 20.8 cm/s
N006 20.1 cm/s 10.2 cm/s 4.9 cm/s
N005 14.6 cm/s 10.8 cm/s 7.2 cm/s
N002 7.0 cm/s 4.4 cm/s 3.1 cm/s
N001 4.7 cm/s 10.3 cm/s 2.4 cm/s
0 20 0 20 0 20
time (seconds)
data
1-parameter slip rate
2-parameter slip rate

Snapshots

Dynamic simulation Kinematic (symmetric) Kinematic (asymmetric)

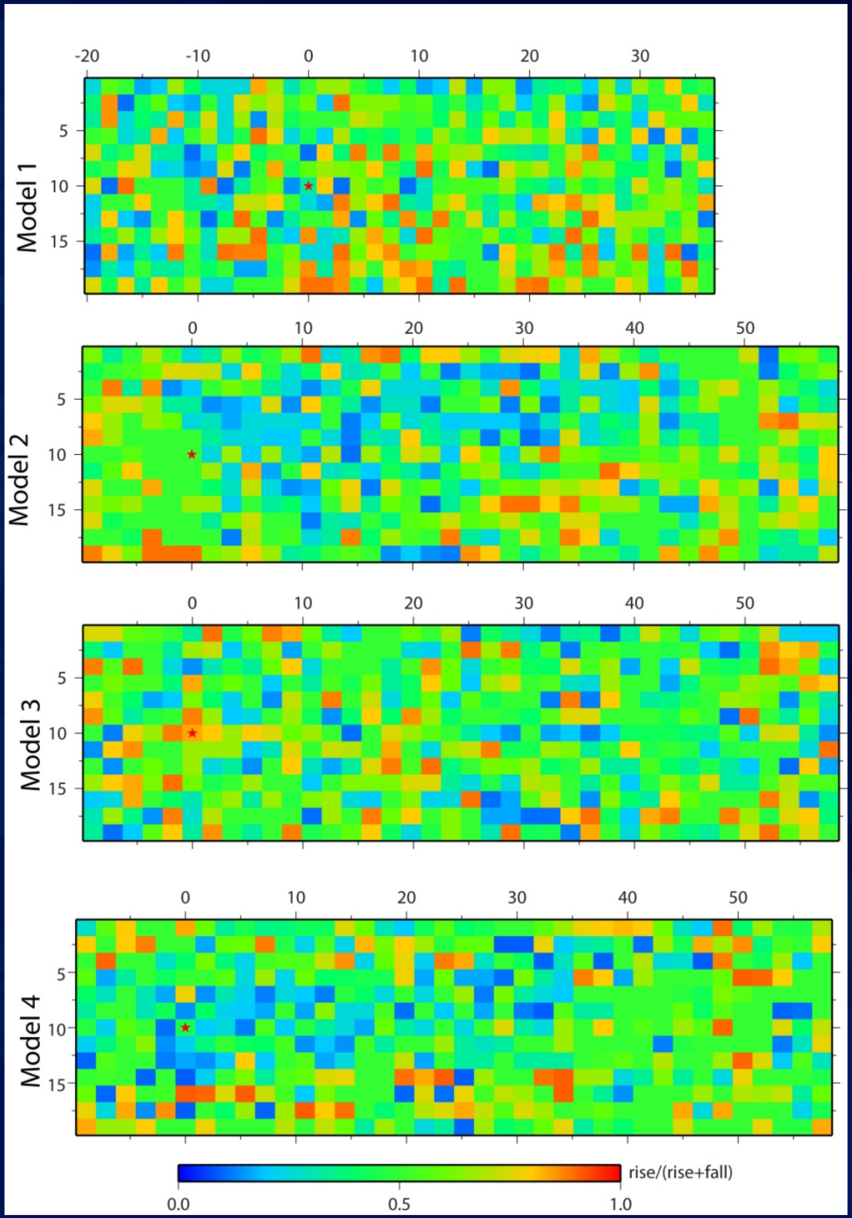




Conclusion

- Regularizations and simplifications of kinematic modeling do not introduce obvious bias.
- Rupture velocity and slip distribution are well-determined in all the models.
- Since we put a priori constraint on slip-time function, both crack-like and pulse-like ruptures appear as pulses in the inverted models, but crack-like ruptures have larger spatial extent at each moment. The difference between the two kinds of ruptures is thus still observable.
- The slip history at a specific point on the fault cannot be obtained accurately due to the assumed shape of the slip time function and low resolution in the frequency band of the inversion (0.75s-50 s).
- The asymmetric slip rate functions are only slightly improving the models.

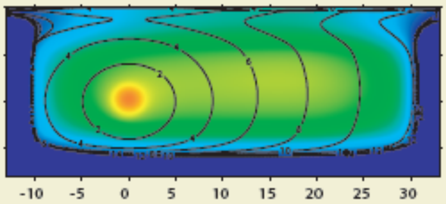
Asymmetric rise and fall functions

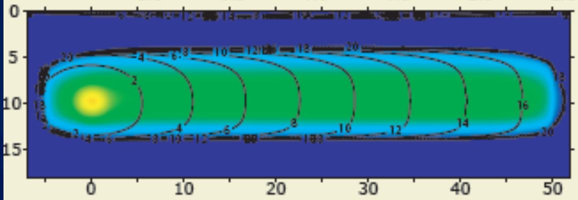


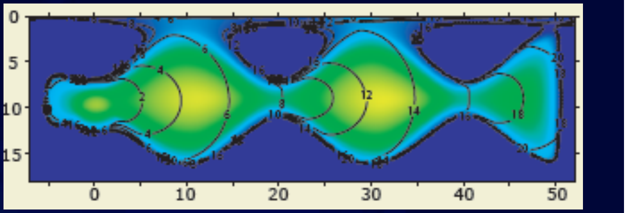
Slip Rate Snapshots

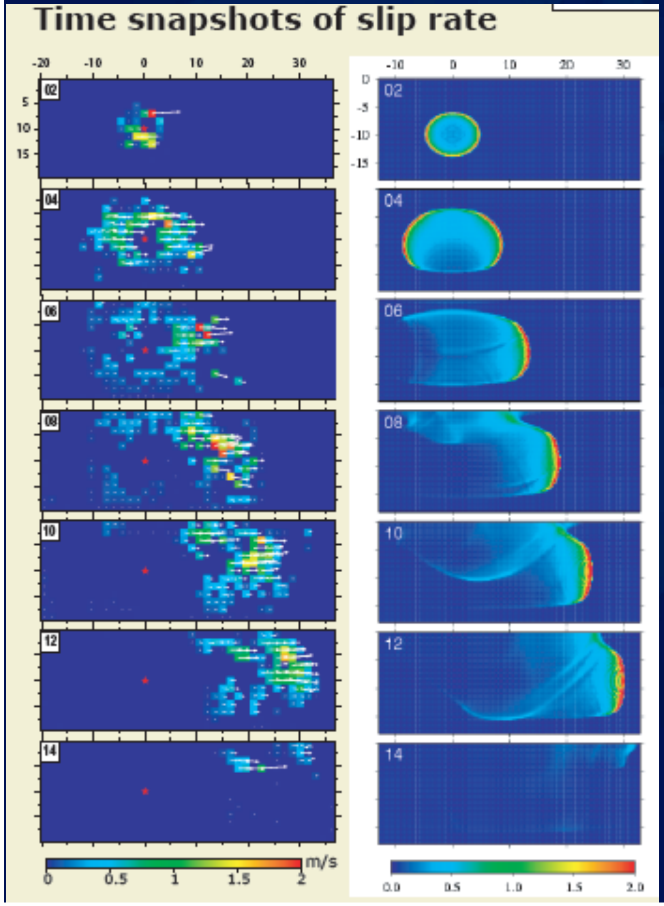
Rupture velocity and pulse width can be obtained from kinematic solutions

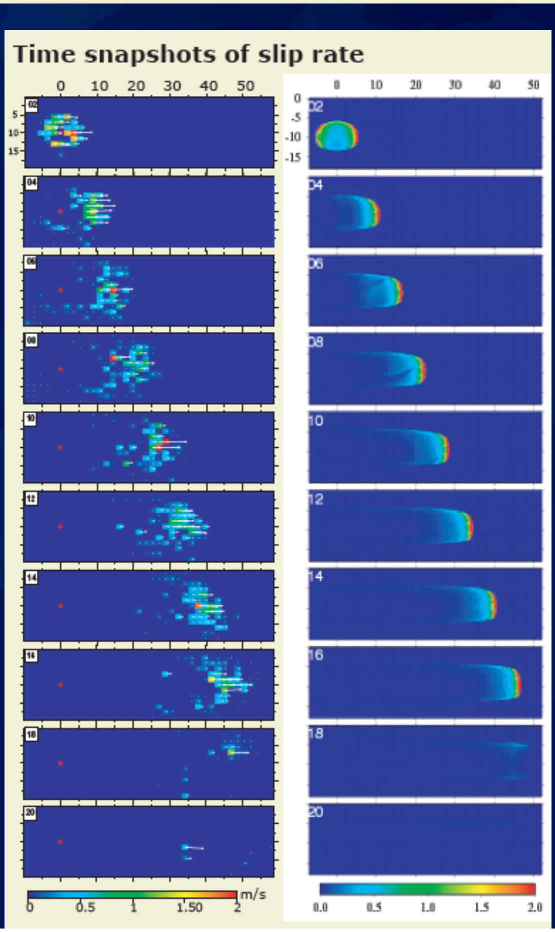
Exact slip history of a point on the fault can not be resolved well

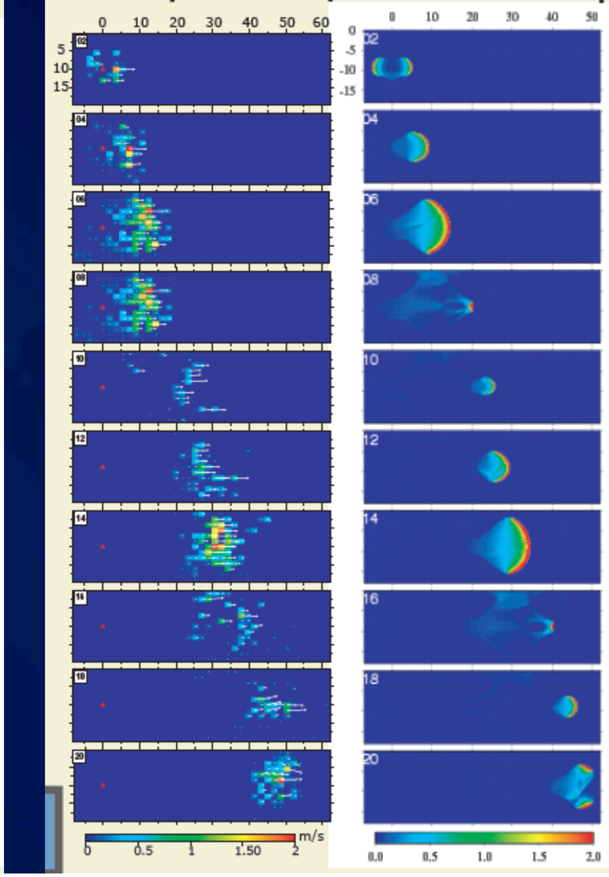












Kinematic Source Modeling