Presentation for March 20, 2013
SWUS GMC SSHAC Workshop #1

# The SCEC/USGS Rupture Dynamics Code Comparison Exercise

Ruth A. Harris
(U.S. Geological Survey)

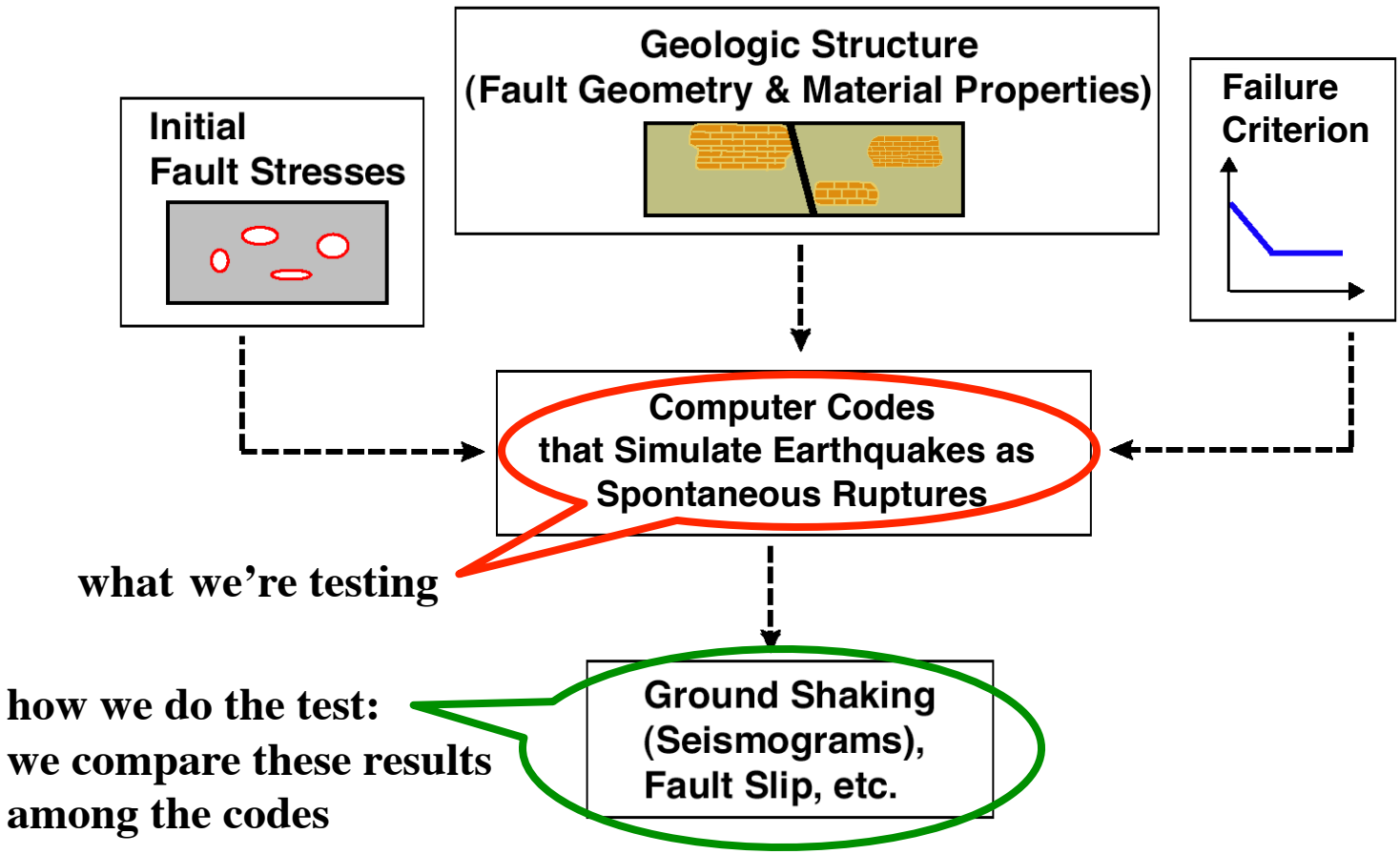
# Acknowledgments

*Thank you to the members of the SCEC Dynamic Rupture Code Verification Group:*

Ralph Archuleta (UCSB), Brad Aagaard (USGS), Pablo Ampuero (Caltech), Victor Cruz-Atienza (UNAM, Mexico), Luis Dalguer (ETH, Switzerland), Steve Day (SDSU), Ben Duan (TAMU), Eric Dunham (Stanford), Alice Gabriel (LMU, Germany), Percy Galvez (ETH, Switzerland), Yoshi Kaneko (GNS, New Zealand), Yuko Kase (AIST, Japan), Jeremy Kozdon (NPS), Nadia Lapusta (Caltech), Shuo Ma (SDSU), David Oglesby (UCR), Kim Olsen (SDSU), Ryan Payne (TAMU), Christian Pelties (LMU, Germany), Surendra Somala (Caltech),

and most especially, Michael Barall (Invisible Software)

## *What our Group Does: We Test Computer Codes Used to Simulate Earthquakes*




Please see our website http://scecdata.usc.edu/cvws

# Overall Goal of our Code Verification Group

Compare the computational methods
currently being used by SCEC and USGS scientists to
simulate (spontaneous) earthquake rupture dynamics

# Some Specific Objectives

Understand if our methods are producing the same results when using
the same assumptions about friction, crustal structure, fault geometry, etc.

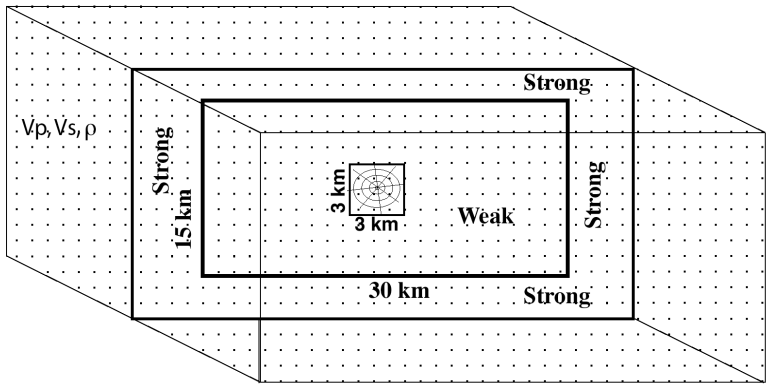
# Funding

This project has been funded by the Southern California Earthquake Center,
the U.S. Geological Survey, the U.S. Dept. of Energy, and the PG&E Company

# Code Comparison Strategy

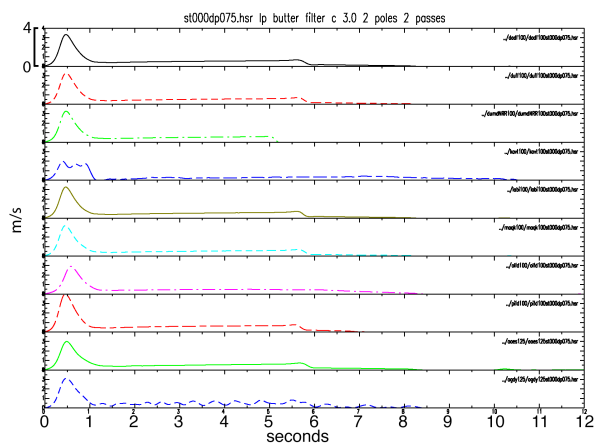
## Start simply

Spontaneous rupture on a **vertical strike-slip fault set in a homogeneous (materials) elastic Fullspace**

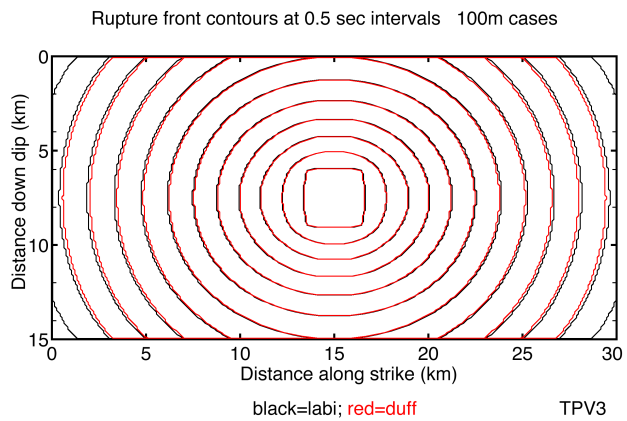



**homogeneous initial stresses**

**slip-weakening friction**

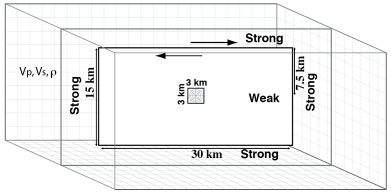



Some Results

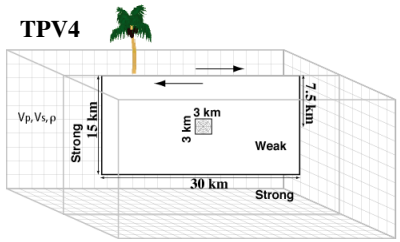


# Code Comparison Benchmarks – Incrementally add complexity

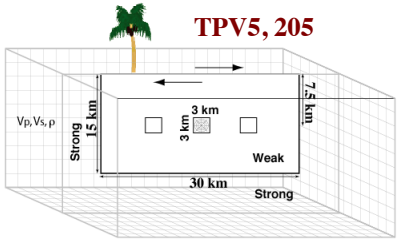
**TPV3**



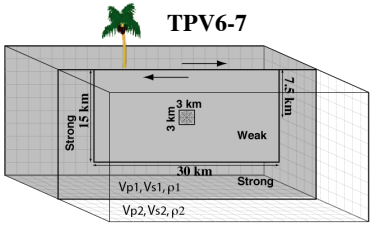

**TPV4**




**TPV5, 205**

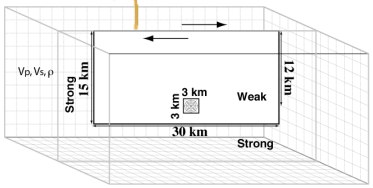



**TPV6-7**

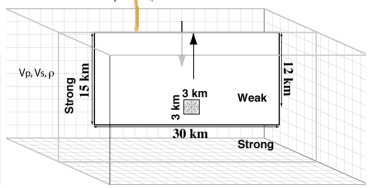



Slip-weakening friction

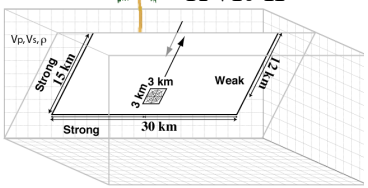
**TPV8**



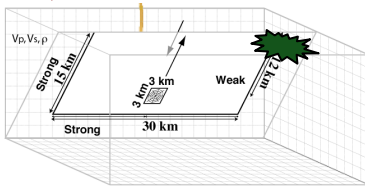

**TPV9**



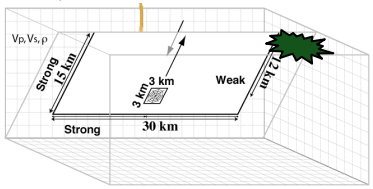

**TPV10-11**




**TPV12**

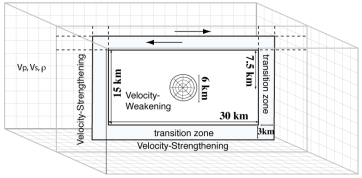



**TPV13**

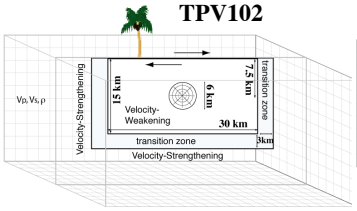



Slip-weakening friction

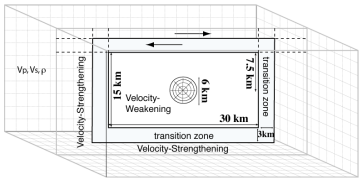
**TPV101**



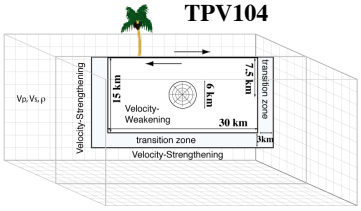

**TPV102**



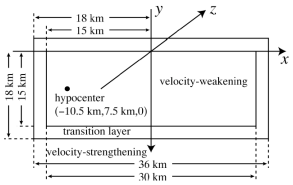

**TPV103**




**TPV104**




**TPV105-2D**

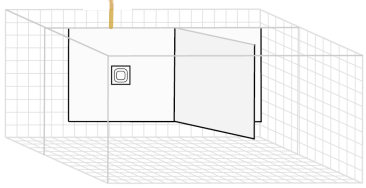



Rate-state friction using an ageing law

Rate-state friction using a slip law with strong rate-weakening

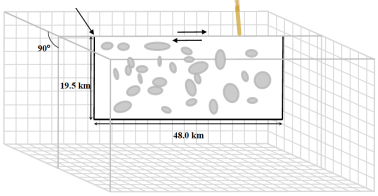
Thermal pressurization, rate-state friction, slip-law, strong rate-weakening

**TPV14-15, 18-21**



Slip-weakening friction

**TPV16-17**




Slip-weakening friction

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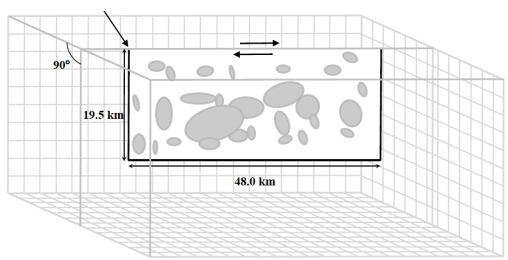
# Code Comparison Strategy

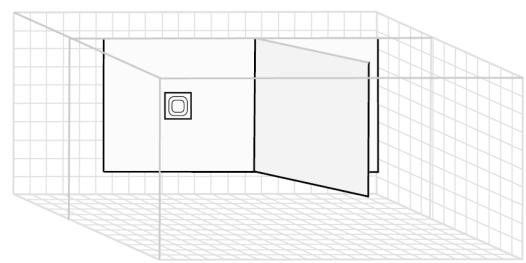
**Incrementally adding complexity: stress, fault geometry**

Rupture on a vertical strike-slip fault set in a homogeneous material elastic halfspace, **Heterogeneous initial Stresses,** Slip-weakening friction




TPV16, 17

Rupture on a **Branching** strike-slip fault set in homogeneous (material) **Plastic yielding**, Slip-weakening friction

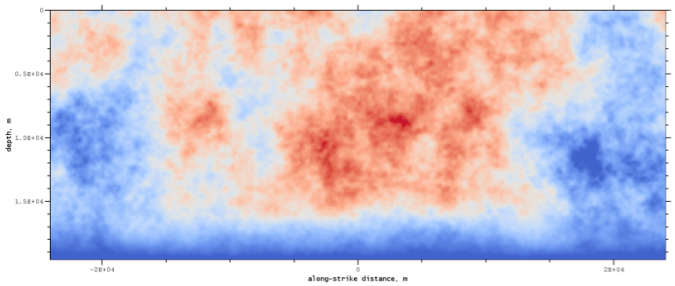


TPV18, 19, 20, 21
elastic, plastic, elastic, plastic

## 2012 BENCHMARKS

# TPV16 (Heterogeneous Initial Stress, SW Friction, Elastic, Vertical Strike-Slip Fault)

## Assumptions




**Contour Plot**

**Benchmark: tpv16 (Vertical strike-slip fault, heterogeneous initial stress)**

**File: cplot (rupture contour plot)**

Back to File List  Logout

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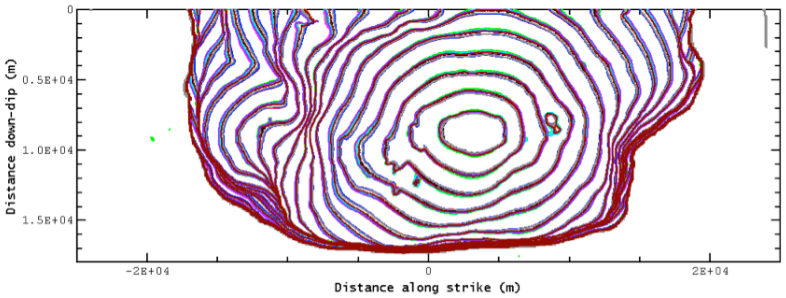
## Results




aagaard.2 (Brad Aagaard - PyLith v1.7.0a - Tet4 75m)
barall.2 (Michael Barall - Finite Element - FaultMod - Denser Mesh)
cruz-atienza (Tago/Cruz-Atienza - 3D Discontinuous Galerkin Code - DGCrack)
dalguer (Luis Dalguer - Finite Difference - DFM)
duan (Benchun Duan - Finite Element - EQdyna)
gabriel (Alice Gabriel - Finite Difference AWP-ODC)
kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D)
kase (Yuko Kase - Finite Difference)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Spectral Element - SESAME)

## Results

**Time-Series File**

**Benchmark: tpv16 (Vertical strike-slip fault, heterogeneous initial stress)**

**File: faultst000dp000 (strike 0.0 km, dip 0.0 km)**

**Field: h-slip-rate (Horizontal slip rate (m/s))**

Back to Field List  Logout

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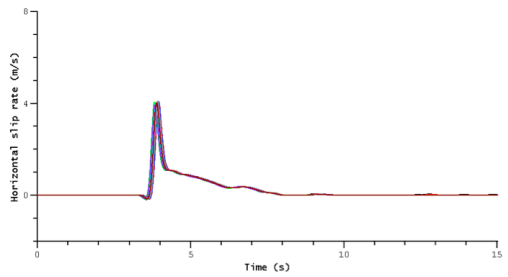


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kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D)
kase (Yuko Kase - Finite Difference)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Spectral Element - SESAME)

## 2012 Benchmark Success

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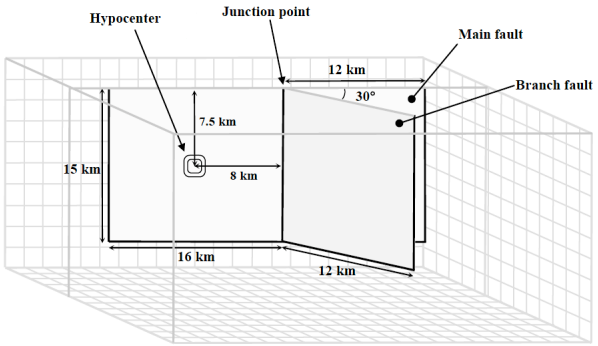
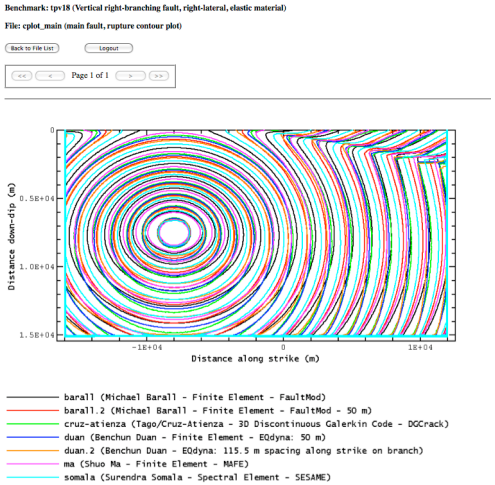
# TPV18 (SW Friction, Elastic, Branched Vertical Strike-Slip Fault)

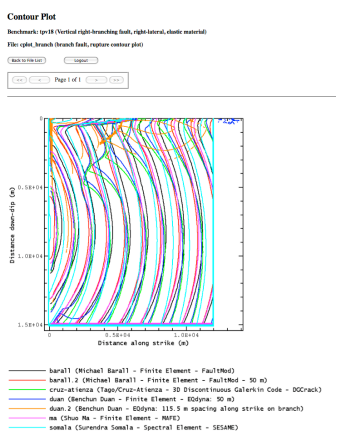
## Schematic




## Results

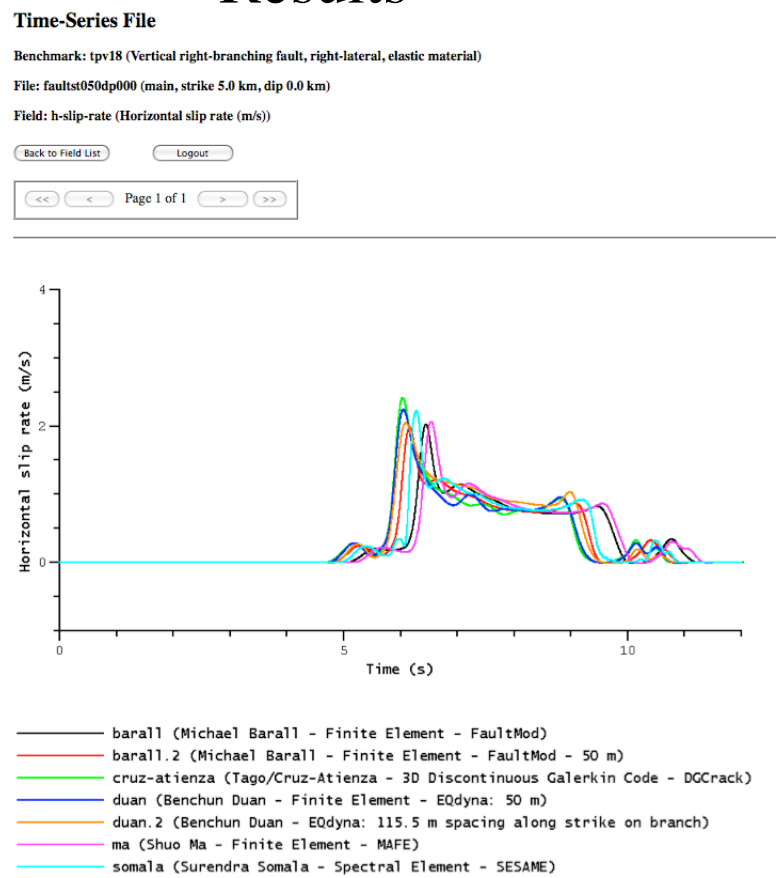



Main Fault




Branch

## Results




## 2012 Benchmark Challenge

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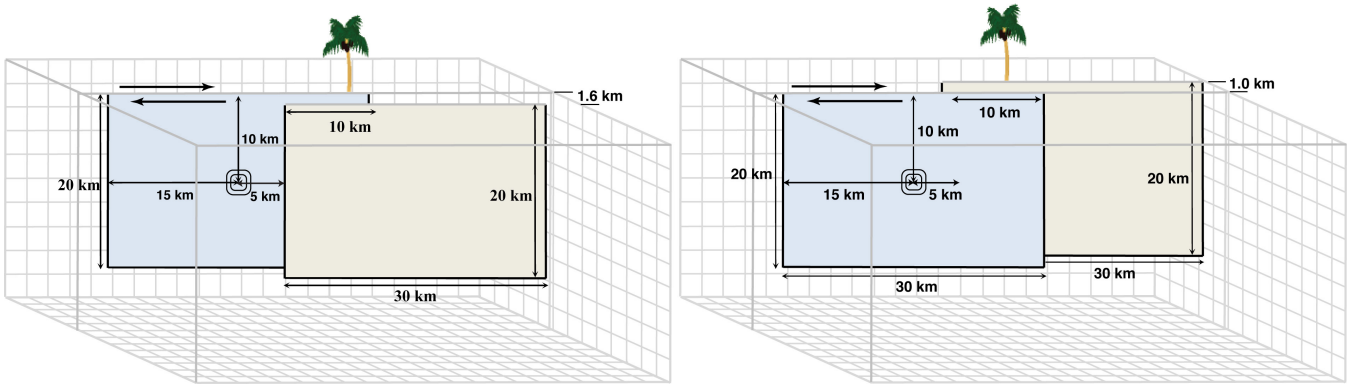
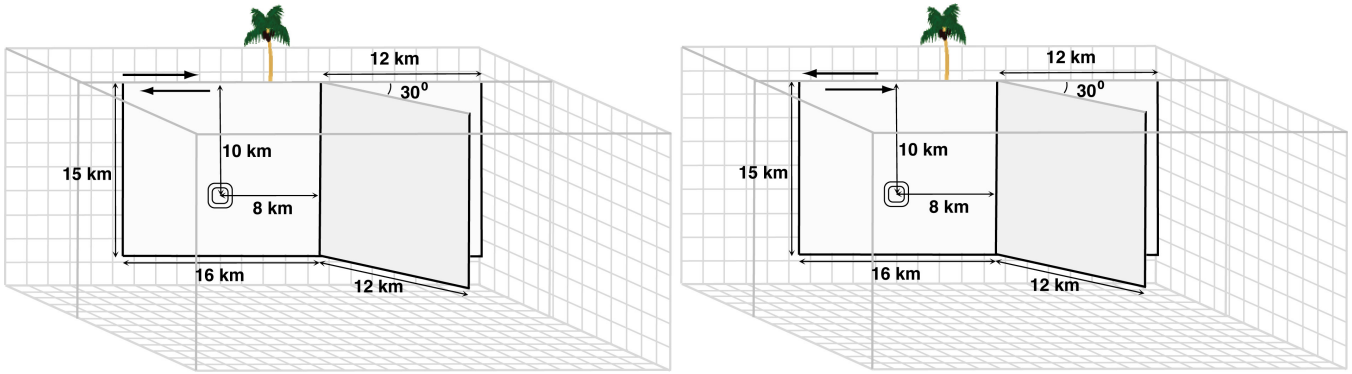
# 2012-2013 Benchmarks: Two-Fault Stepovers
# TPV22 and 23 (SW Friction, Elastic, Stepover in Vertical Strike-Slip Faults)

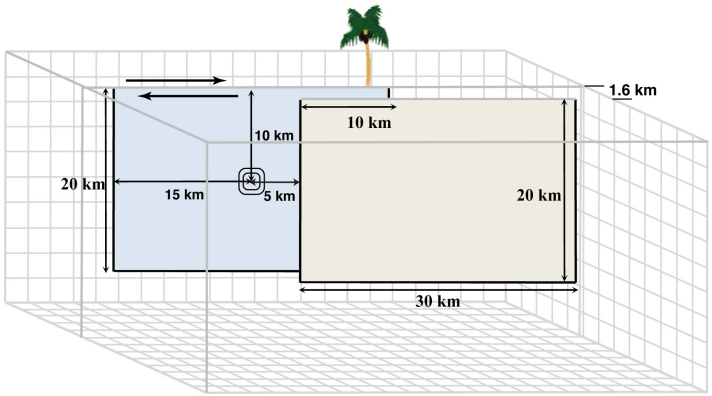


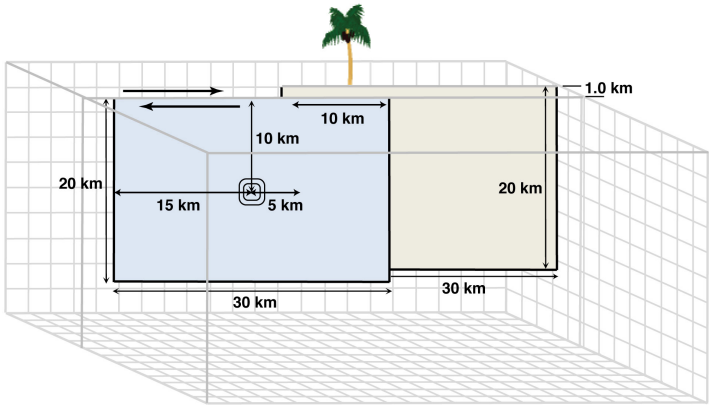

# 2012-2013 Benchmarks: Revisiting the Fault Branch
# TPV24 and 25 (SW Friction, Elastic, Branched Vertical Strike-Slip Fault)



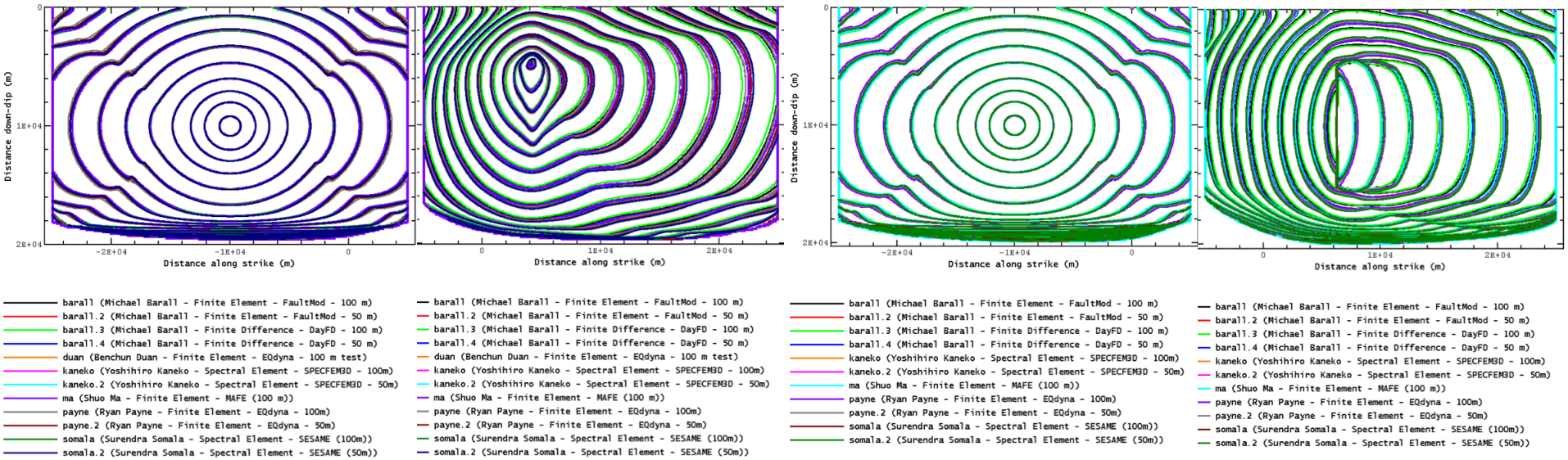
# Results for Benchmarks TPV22 and TPV23 (rupture-front contour plots)

**TPV22**
Dilational stepover




**TPV23**
Compressional stepover




Fault 1 Fault 2 Fault 1 Fault 2

**TPV22** **TPV23**

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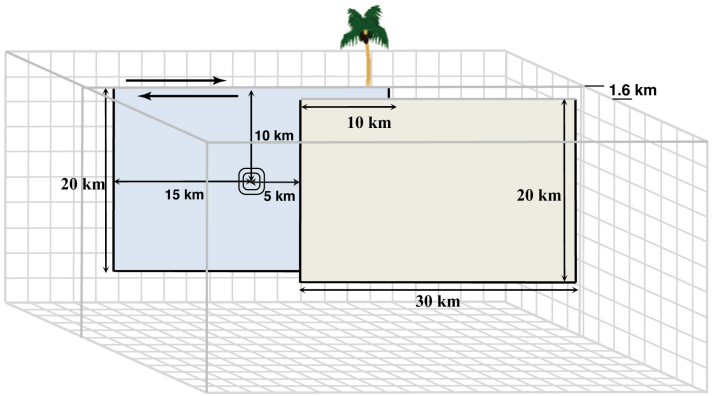
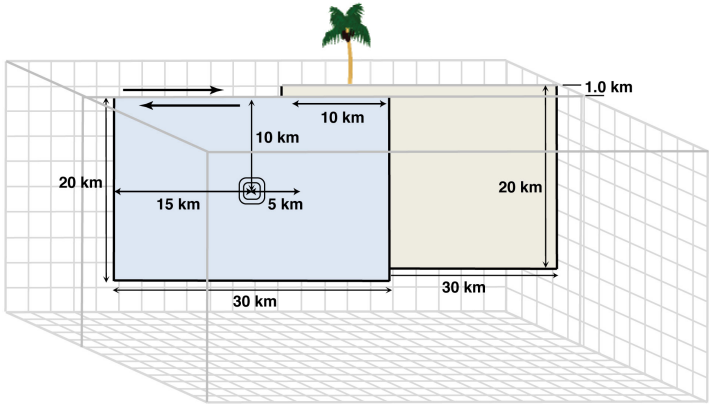
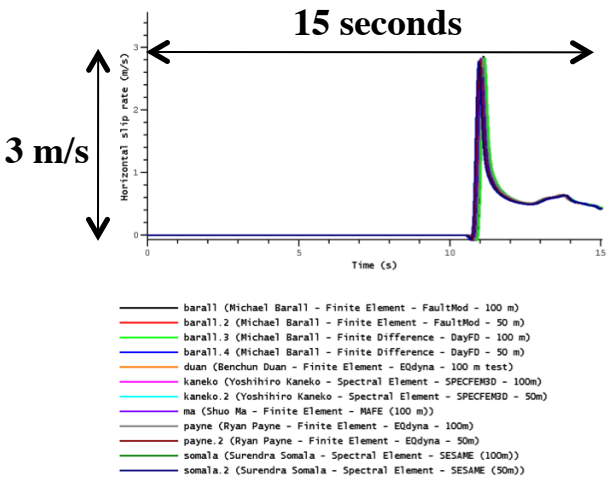
# Results for Benchmarks TPV22 and TPV23 (horizontal slip-rate vs. time)

**TPV22**
Dilational stepover

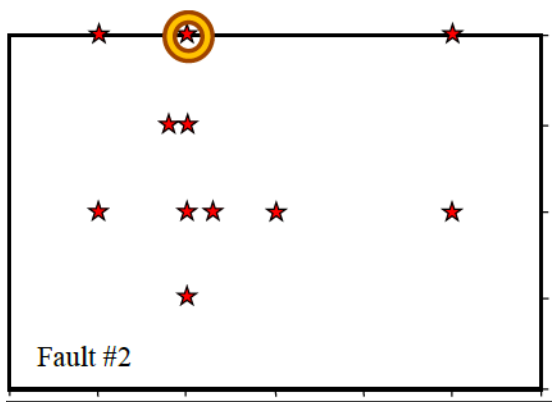


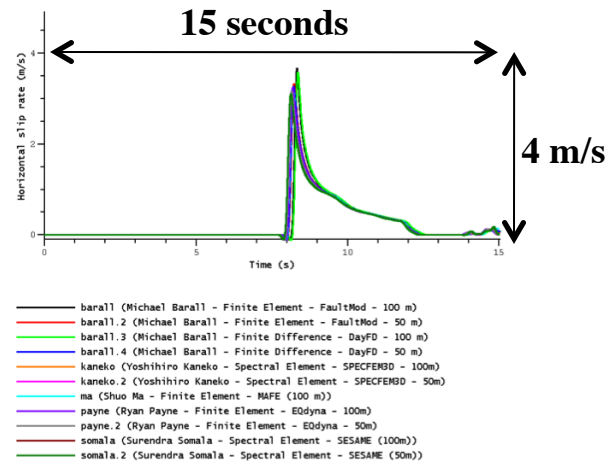

**TPV23**
Compressional stepover




3 hz low-pass Butterworth filter applied




**On-Fault Station Location (5 km along strike at the earth's surface, on fault 2)**




3 hz low-pass Butterworth filter applied

**TPV22** **TPV23**

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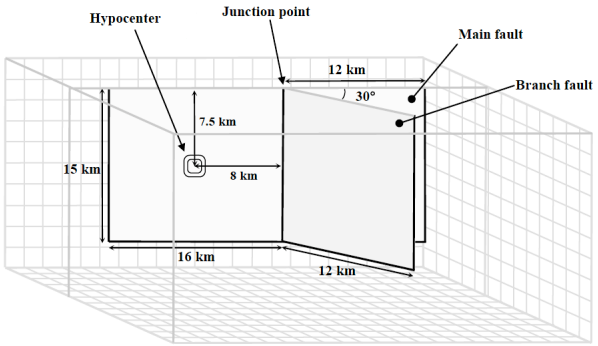
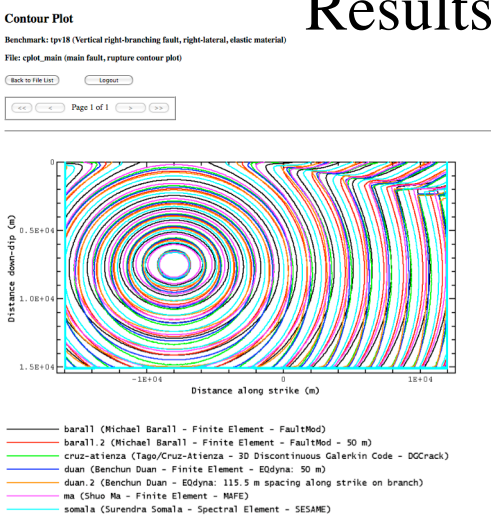
# Older Branch Benchmark: TPV18 (SW Friction, Elastic, Vertical Strike-Slip Faults)

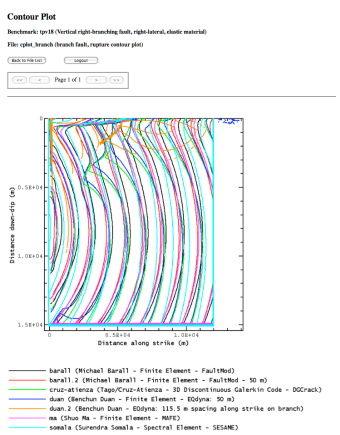
## Schematic




## Results

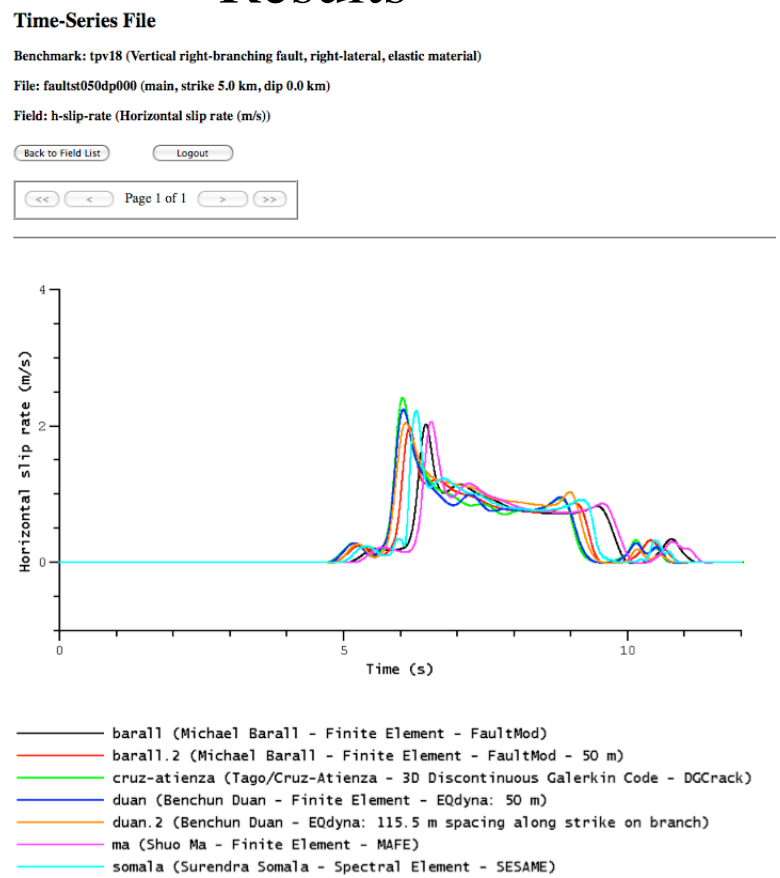



Main Fault




Branch

## Results




## 2012 Benchmark Challenge

# Changes in Branch Fault Benchmarks from 2012 to 2013

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**Branch intersection definition changed, allowing for code-optimized implementations**
2013: slip on the branch goes to zero at the intersection
2012: the branch ends one element away from the main fault

**Nucleation method changed**
2013: smoother nucleation with fewer unwanted oscillations.

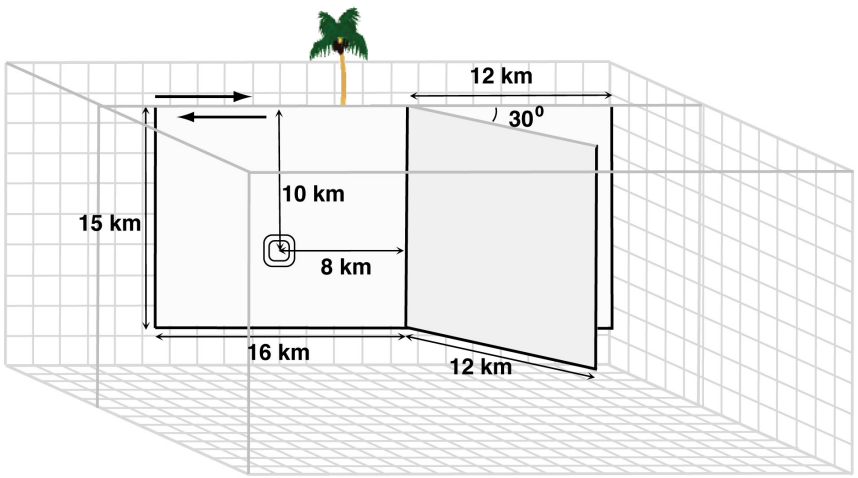
**Regional stress field changed**
2013**:** neutral
2012: strongly extensional

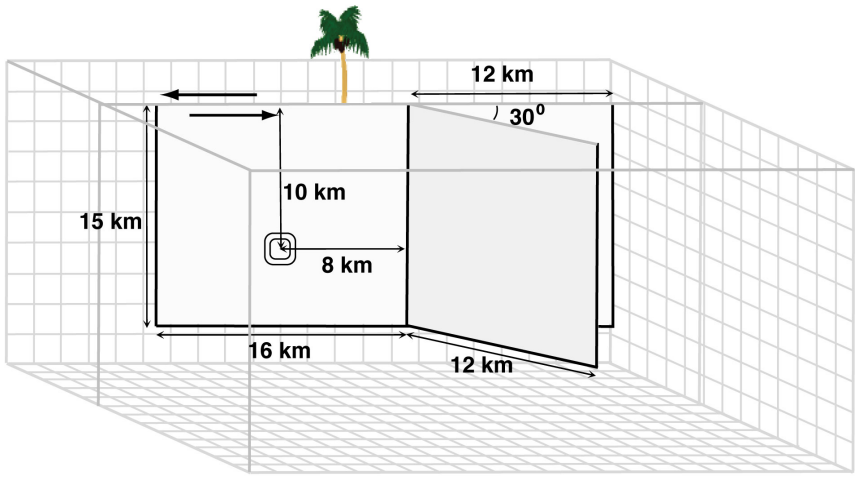
**Difference between static & dynamic friction coefficients reduced, producing an easier to resolve cohesive zone**
2013: $\mu s=0.18$ and $\mu d=0.12$
2012: $\mu s=0.60$ and $\mu d=0.12$

**Slip-weakening critical distance reduced**
2013: 0.30 m
2012: 0.40 m

**2013: Convergence of each benchmark was tested by running 50 m and 100 m cases**

# New Branch Fault Benchmarks: TPV24 and TPV25



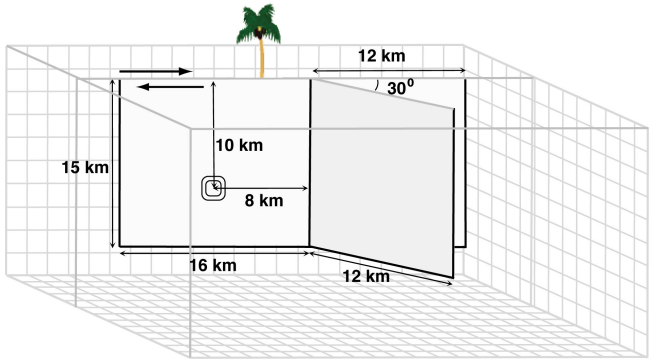



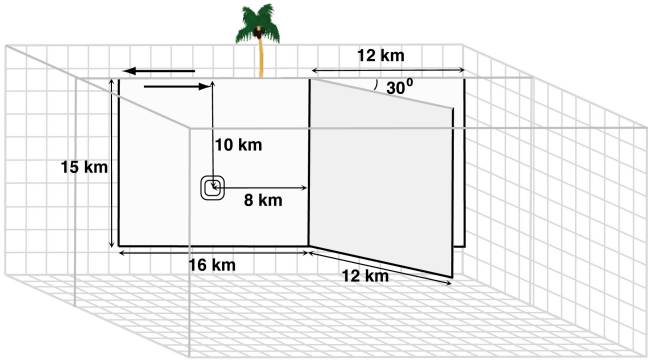

**TPV24**
Releasing
Branch

**TPV25**
Restraining
Branch

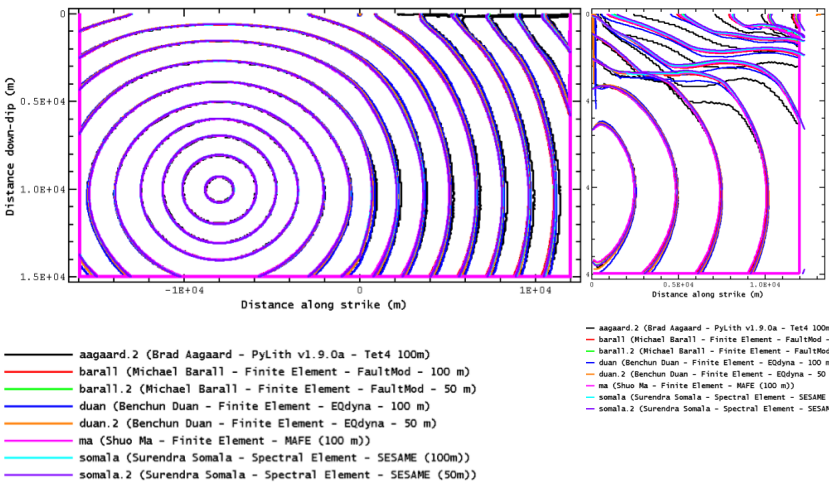
# Results for Benchmarks TPV24 and TPV25 (rupture-front contour plots)

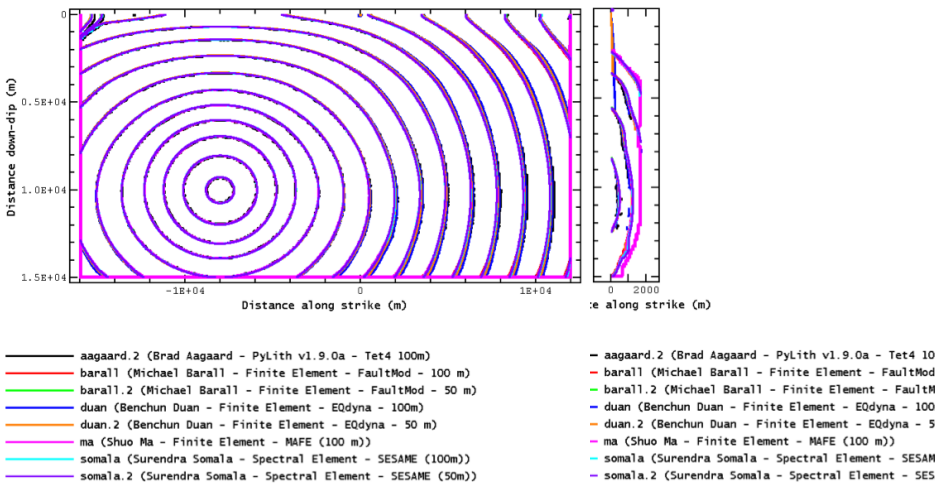
**TPV24**
Releasing
Branch




**TPV25**
Restraining
Branch




Main Fault Branch Fault Main Fault Branch Fault

**TPV24** **TPV25**

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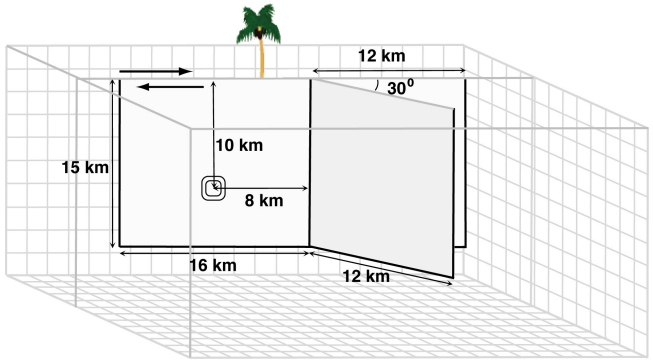
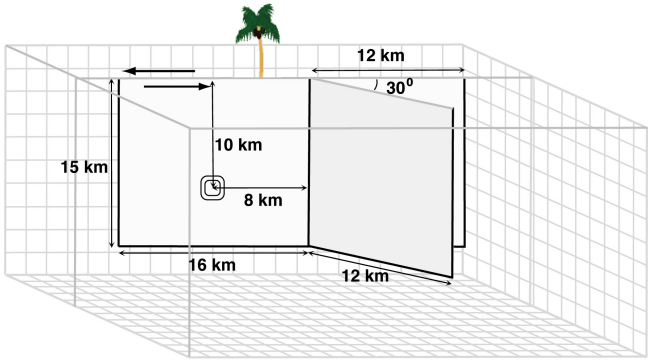
# Results for Benchmarks TPV24 and TPV25 (horizontal velocity vs. time)

**TPV24**
Releasing
Branch

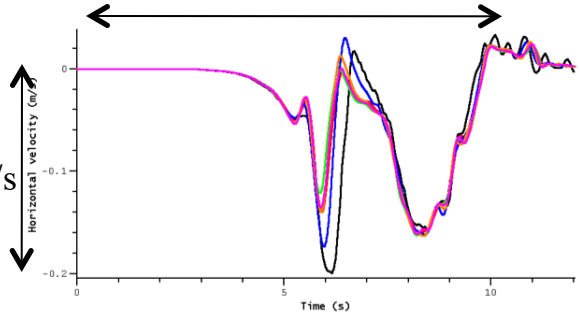



**TPV25**
Restraining
Branch

**10 seconds**

0.2 m/s

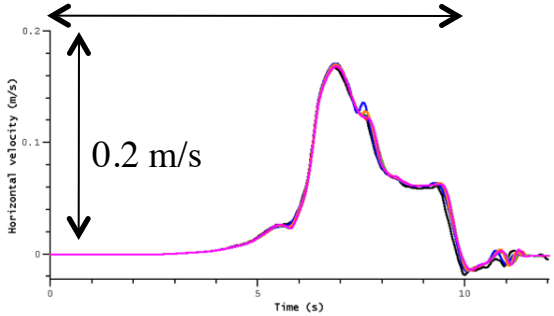



3 hz low-pass Butterworth filter applied

**TPV24**
Releasing Branch

**Off-Fault Station Location at the earth's surface between main fault & branch**

**10 seconds**




3 hz low-pass Butterworth filter applied

**TPV25**
Restraining Branch

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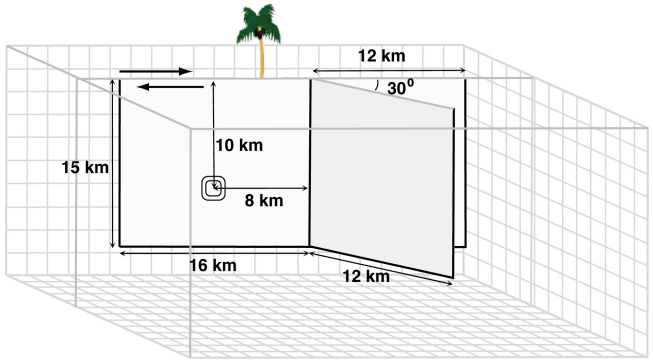
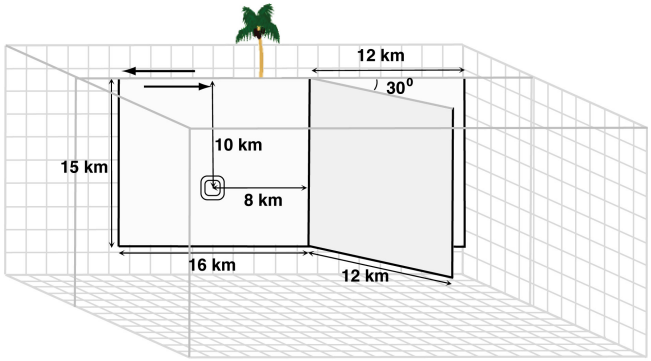
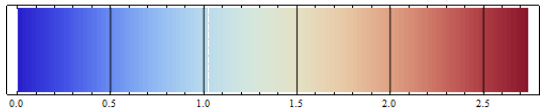
# Results for Benchmarks TPV24 and TPV25 (final fault slip)

**TPV24**
Releasing
Branch



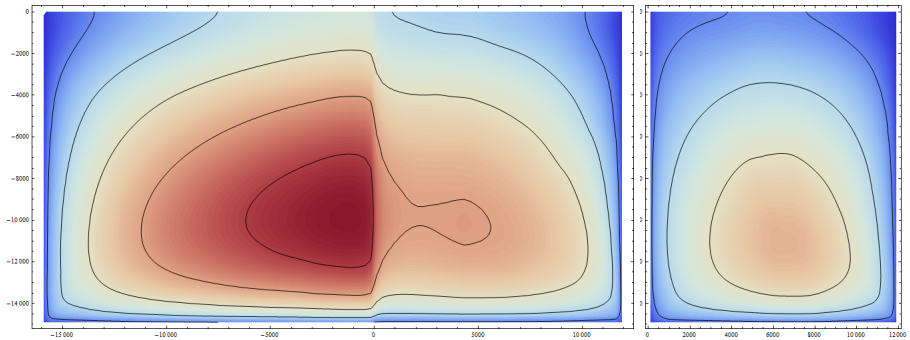




**TPV25**
Restraining
Branch



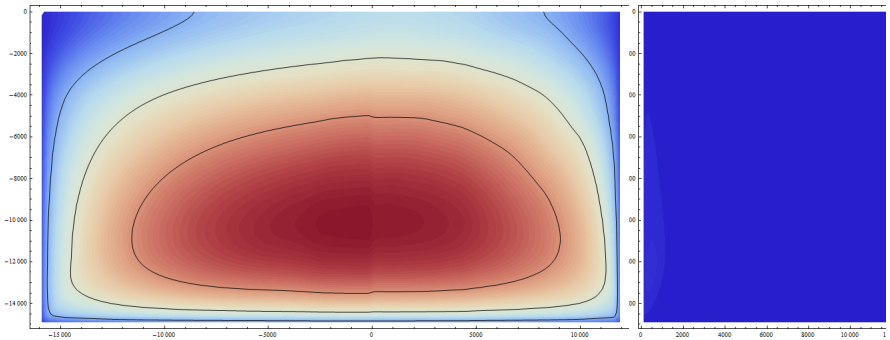

**Final slip**

**0.0 0.5 1.0 1.5 2.0 2.5 m**



Main Fault Branch Fault

**TPV24** Releasing Branch



Main Fault Branch Fault

**TPV25** Restraining Branch

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For More Information about our group's work,
Please see our website **http://scecdata.usc.edu/cvws**

## Our 2011 SRL article

Harris, R.A., M. Barall, D.J. Andrews, B. Duan, S. Ma, E.M. Dunham,
A.-A. Gabriel, Y. Kaneko, Y. Kase, B.T. Aagaard, D.D. Oglesby,
J.-P. Ampuero, T.C. Hanks, N. Abrahamson,
**Verifying a Computational Method for Predicting Extreme Ground Motion**,
Seismological Research Letters, vol. 82, 638-644, 2011.

## Our 2009 SRL article

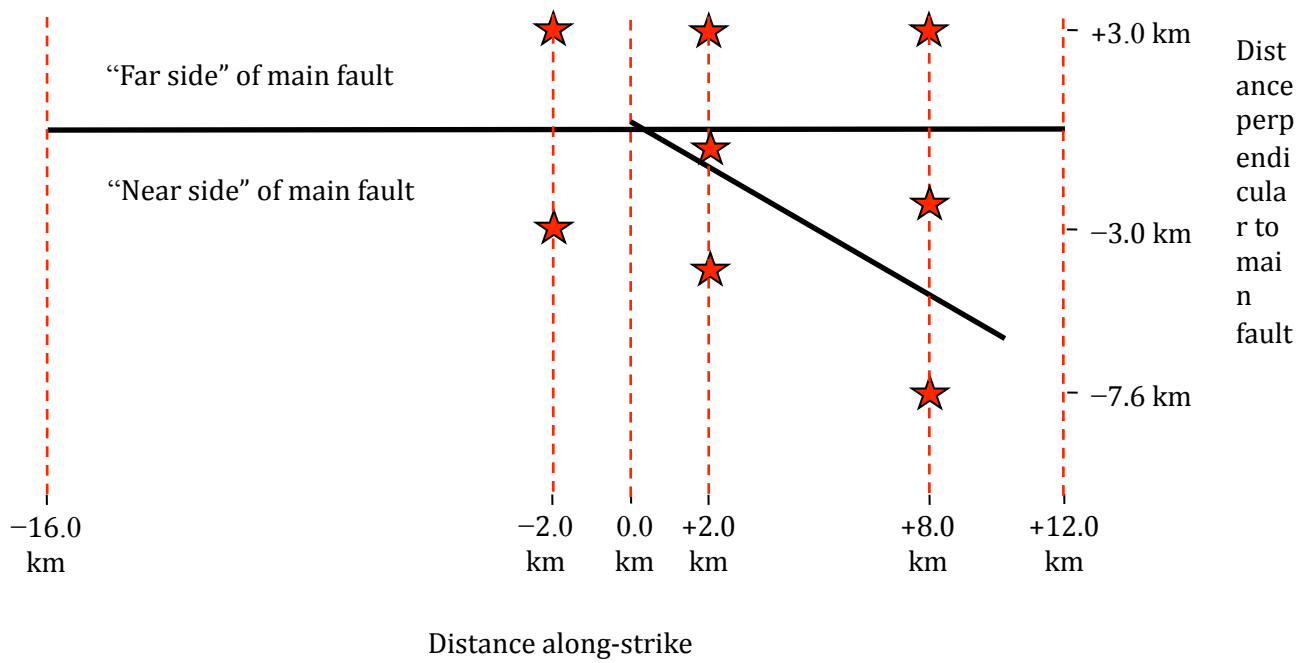
Harris, R.A., M. Barall, R. Archuleta, B. Aagaard, J.-P. Ampuero,
H. Bhat, V. Cruz-Atienza, L. Dalguer, P. Dawson, S. Day,
B. Duan, E. Dunham, G. Ely, Y. Kaneko, Y. Kase, N. Lapusta, Y. Liu,
S. Ma, D. Oglesby, K. Olsen, A. Pitarka, S. Song, and E. Templeton,
**The SCEC/USGS Dynamic Earthquake-Rupture Code Verification Exercise**,
Seismological Research Letters, vol. 80, 119-126, 2009.

# Notes on some of the parameters for the branching faults

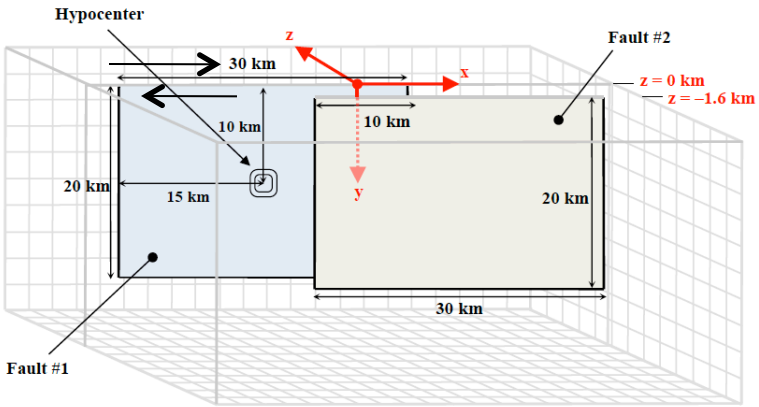
Friction coefficients are low because of the high initial normal stress, which is lithostatic.

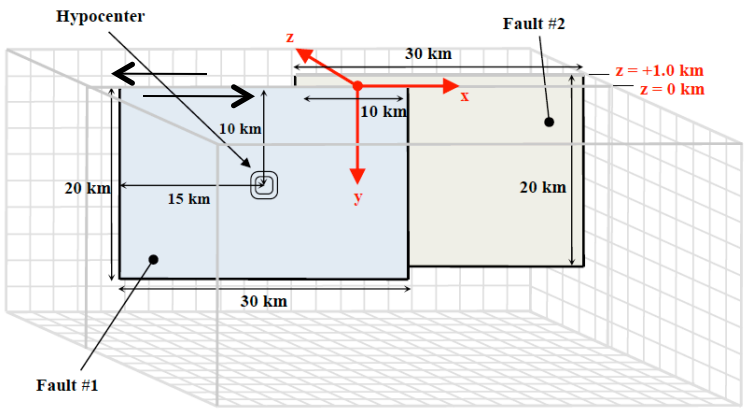
Cohesion tapers from 3.0 MPa at the earth's surface, to 0.3 MPa at depths of 4000 m or greater.

Cohesion in the upper 4 km suppresses free surface effects.

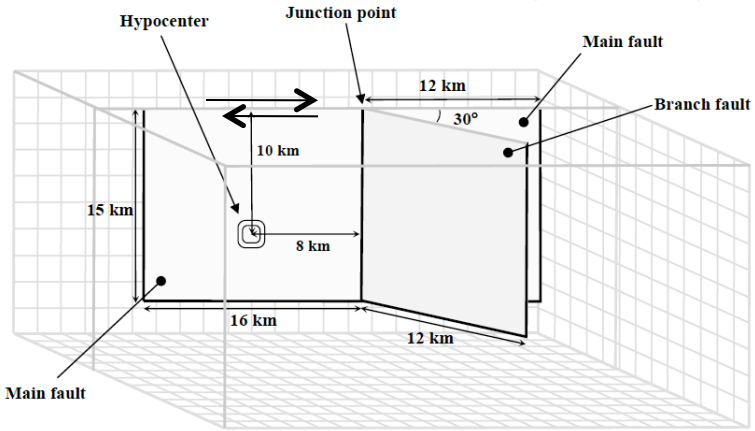

"Far side" of main fault
"Near side" of main fault
+3.0 km
−3.0 km
−7.6 km
Distance perpendicular to main fault
−16.0 km
−2.0 km
0.0 km
+2.0 km
+8.0 km
+12.0 km
Distance along-strike

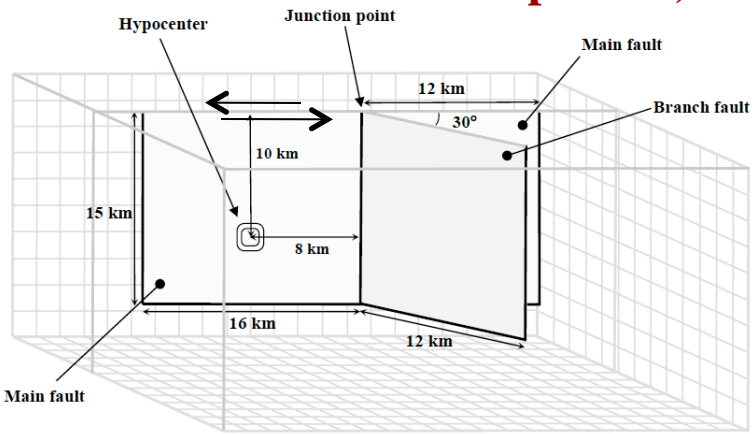
# 2012-2013 Benchmarks: Two-Fault Stepovers
# TPV22-23 (SW Friction, Elastic, Stepover in Vertical Strike-Slip Faults)




# 2012-2013 Benchmarks: Revisiting the Fault Branch
# TPV24-25 (SW Friction, Elastic, Branched Vertical Strike-Slip Fault)

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