TPV14 & TPV15 — Branched Fault Benchmarks

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Part 1:

Benchmark Description
These are our first benchmarks that do not use a planar fault.

This is a vertical strike-slip main fault, with a vertical strike-slip branch fault at an angle of 30 degrees.
TPV14 & TPV15 — Main Fault

The main fault has the same conditions as TPV5.

| Initial Stress                  | Normal stress = 120 MPa  
|                                | TPV14 shear stress = 70 MPa (right-lateral)  
|                                | TPV15 shear stress = -70 MPa (left-lateral)  |
| Friction Parameters            | $\mu_s = 0.677$  
| Linear Slip-Weakening          | $\mu_d = 0.525$  
|                                | $d_0 = 0.40$ m  |
| Rock Properties                | $\rho = 2670$ kg/m³  
|                                | $V_S = 3464$ m/s  
|                                | $V_P = 6000$ m/s  |
| Nucleation Zone                | Size = 3 km × 3 km  
|                                | TPV14 shear stress = 81.6 MPa (right-lateral)  
|                                | TPV15 shear stress = -81.6 MPa (left-lateral)  |
TPV14 & TPV15 — Branch Fault

The branch fault also has the same conditions as TPV5, except for initial shear stress.

| Initial Stress | Normal stress = 120 MPa  
|               | TPV14 shear stress = 70 MPa (right-lateral)  
|               | TPV15 shear stress = -78 MPa (left-lateral)  
| Friction Parameters Linear Slip-Weakening | \( \mu_s = 0.677 \)  
|               | \( \mu_d = 0.525 \)  
|               | \( d_0 = 0.40 \text{ m} \)  

The cases we consider differ only in:

• Initial shear stress on the branch fault.
• Right-lateral versus left-lateral (equivalent to switching the branch between the right and left sides of the main fault).
On-Fault Stations

Modelers are asked to submit slip, slip rate, and stress as a function of time, for 8 stations on the main fault (top) and 6 stations on the branch fault (bottom).

In addition, modelers are asked to submit the time at which each point on the fault begins to slip, from which we construct rupture contour plots.
Off-Fault Stations

Modelers are asked to submit displacement and velocity as a function of time, for 11 stations on the earth’s surface.
The main fault passes continuously through the junction point.

The branch fault approaches the junction point, to within one element-size, but does not reach the junction point. (Boundary condition is that slip on the branch fault is zero at the junction point.)

The junction point behaves as an ordinary split-node on the main fault.
Could we let the branch fault reach the junction point?

Challenges of defining a friction law for a triple split node:

• What strike-slip motions are permitted?
• Five possible states of dip-slip motion.
• Inability to calculate shear and normal stresses from nodal forces.

Because of these challenges, we did not use a triple split node in TPV14 & TPV15.
Joe Andrews proposed that at a branch, slip on all three legs is possible and would open a triangular void. But this requires the three legs to all point in different directions.

In our case, two legs are collinear, so the triangle disappears. We are left with no strike-slip motion on the branch fault at the junction point.
There is no geometric obstacle to dip-slip motion, but there are five possible states:

- No sliding, all three blocks are locked.
- One block sliding relative to the other two, which are locked.
- All three blocks sliding relative to each other.

Software would have to implement these states, and state-to-state transitions.
Traction-at-split-nodes does not work for a triple split node

Traction-at-split-nodes (Joe Andrews): Nodal forces (blue) are the forces exerted on each node by elastic deformation and acceleration. Given the nodal forces, the shear and normal stress on the fault can be computed by finding the relative force (red) that reduces the relative acceleration of the two nodes to zero. (Summing the red and blue vectors on each node produces the same total vector, hence the same acceleration assuming the two nodes have equal mass.)

For a triple split node, given the nodal forces it is not possible to compute shear and normal stress for each of the three legs of the fault. There is only enough information to compute two relative forces, not three.
Part 2:

Possible Outcomes of the Branched Fault
Six Cases to Examine

<table>
<thead>
<tr>
<th>Left-Lateral Cases</th>
<th>Right-Lateral Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{\text{branch}} = -70 \text{ MPa}$</td>
<td>$\tau_{\text{branch}} = +70 \text{ MPa}$ [TPV14]</td>
</tr>
<tr>
<td>$\tau_{\text{branch}} = -74 \text{ MPa}$</td>
<td>$\tau_{\text{branch}} = +74 \text{ MPa}$</td>
</tr>
<tr>
<td>$\tau_{\text{branch}} = -78 \text{ MPa}$ [TPV15]</td>
<td>$\tau_{\text{branch}} = +78 \text{ MPa}$</td>
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</tbody>
</table>

The cases differ *only* in initial shear stress on the branch fault, and left-lateral versus right-lateral.

A relatively small change in initial conditions can produce a different outcome.
\( \tau_{\text{branch}} = -70 \text{ MPa (left-lateral)} \)

\( \tau_{\text{branch}} = +70 \text{ MPa (right-lateral)} \) [TPV14]
\[ \tau_{\text{branch}} = -74 \text{ MPa (left-lateral)} \]

\[ \tau_{\text{branch}} = +74 \text{ MPa (right-lateral)} \]
\[ \tau_{\text{branch}} = -78 \text{ MPa (left-lateral)} \]

[TPV15]

\[ \tau_{\text{branch}} = +78 \text{ MPa (right-lateral)} \]
Stress on Branch Fault Due to Rupture on Main Fault

We lock the entire branch fault so it cannot slip, so the rupture remains only on the main fault.

We record the stress at two stations on the branch fault as the main fault rupture passes by.
Shear stress on branch fault, due to rupture on main fault

\[ \tau_{\text{branch}} = -70 \text{ MPa (left-lateral)} \]

\[ \tau_{\text{branch}} = +70 \text{ MPa (right-lateral)} \]

[TPV14]

Shear stress on branch fault, due to rupture on main fault
Depth = 0 km

Depth = 7.5 km

[TPV14]
Normal stress on branch fault, due to rupture on main fault

\[ \tau_{\text{branch}} = -70 \text{ MPa (left-lateral)} \]

\[ \tau_{\text{branch}} = +70 \text{ MPa (right-lateral)} \]

[TPV14]

Normal stress on branch fault, due to rupture on main fault

Depth = 0 km

Depth = 7.5 km
Stress ratio (shear/normal) on branch fault, due to rupture on main fault

\[ \tau_{\text{branch}} = -70 \text{ MPa (left-lateral)} \]

\[ \tau_{\text{branch}} = +70 \text{ MPa (right-lateral)} \]

[TPV14] Stress ratio (shear/normal) on branch fault, due to rupture on main fault

Depth = 0 km

Depth = 7.5 km
\( \tau_{\text{branch}} = -74 \text{ MPa (left-lateral)} \)

\( \tau_{\text{branch}} = +74 \text{ MPa (right-lateral)} \)
\( \tau_{\text{branch}} = -70 \text{ MPa (left-lateral)} \)

\( \tau_{\text{branch}} = +70 \text{ MPa (right-lateral)} \) [TPV14]
Stress on Main Fault Due to Rupture on Branch Fault

We lock the main fault to the right of the junction point, so the rupture is forced to divert entirely onto the branch fault.

We record the stress at two stations on the main fault as the rupture passes by on the branch fault.
Stress ratio (shear/normal) on main fault, due to rupture on branch fault

\[ \tau_{\text{branch}} = -78 \text{ MPa (left-lateral)} \]

[TPV15]

\[ \tau_{\text{branch}} = +78 \text{ MPa (right-lateral)} \]
$\tau_{\text{branch}} = -78 \text{ MPa (left-lateral)}$

[TPV15]

$\tau_{\text{branch}} = +78 \text{ MPa (right-lateral)}$
Part 3:

Performance of the Codes
Initial shear stress on branch fault = +70.0 MPa (right-lateral).

Expected outcome:

- Main fault ruptures completely.
- Branch fault ruptures partially.
TPV14 — Main Fault Rupture Contours

- barall (Michael Barall - FaultMod - 100 m)
- galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
- ma (Shuo Ma - Finite Element - MAFE)
- somala (Surendra Somala - Finite Element - PyLith: Tet4 (200m))
TPV14 — Branch Fault Rupture Contours

Distance along strike (m)

Distance down-dip (m)

- barall (Michael Barall - FaultMod - 100 m)
- galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
- ma (Shuo Ma - Finite Element - MAFE)
- somala (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV14 — 100 m vs. 50 m Resolution

- barall (Michael Barall - FaultMod - 100 m)
- barall.2 (Michael Barall - FaultMod - 50 m)
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV14 — Horizontal Slip Rate [faultst020dp075]

Time (s)

Horizontal slip rate (m/s)

- barall (Michael Barall - FaultMod - 100 m)
- galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
- ma (Shuo Ma - Finite Element - MAFE)
- somala (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV14 — Horizontal Slip [faultst020dp075]

Horizontal slip (m)

Time (s)

barall (Michael Barall - FaultMod - 100 m)
galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV14 — Horizontal Shear Stress [branchst050dp075]
TPV14 — Vertical Shear Stress [branchst050dp075]
TPV14 — Normal Stress [branchst050dp075]

![Graph showing normal stress over time with different lines representing different models: barall (Michael Barall - FaultMod - 100 m), galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME), ma (Shuo Ma - Finite Element - MAFE), somala (Surendra Somala - Finite Element - PyLith: Tet4 (200m))]
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV14 — Normal Velocity [body-059st050dp000]

- **barall** (Michael Barall - FaultMod - 100 m)
- **galvez** (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
- **ma** (Shuo Ma - Finite Element - MAFE)
3D Benchmark.

Initial shear stress on branch fault = $-78.0$ MPa (left-lateral).

Expected outcome:

- Main fault rupture stops past the junction point.
- Branch fault ruptures completely.
TPV15 — Main Fault Rupture Contours

- **barall** (Michael Barall - FaultMod - 100 m)
- **galvez** (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
- **ma** (Shuo Ma - Finite Element - MAFE)
- **somala** (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV15 — Branch Fault Rupture Contours

Distance down-dip (m)

Distance along strike (m)

- barall (Michael Barall - FaultMod - 100 m)
- galvez (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
- ma (Shuo Ma - Finite Element - MAFE)
- somala (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV15 — 100 m vs. 50 m Resolution

- **barall** (Michael Barall - FaultMod - 100 m)
- **barall.2** (Michael Barall - FaultMod - 50 m)
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV15 — Horizontal Slip Rate [branchst020dp000]

![Graph showing horizontal slip rate over time](image)

- **barall** (Michael Barall - FaultMod - 100 m)
- **ma** (Shuo Ma - Finite Element - MAFE)
- **somala** (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV15 — Vertical Slip Rate [branchst020dp000]
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV15 — Horizontal Shear Stress [faultst050dp075]

![Graph showing horizontal shear stress over time for different simulations.]

- **barall** (Michael Barall - FaultMod - 100 m)
- **ma** (Shuo Ma - Finite Element - MAFE)
- **somala** (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV15 — Vertical Shear Stress [faultst050dp075]

Along-dip shear stress (MPa)

Time (s)

barall (Michael Barall - FaultMod - 100 m)
ma (Shuo Ma - Finite Element - MAFE)
somala (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV15 — Normal Stress [faultst050dp075]

![Graph showing normal stress over time with different lines representing different models.

- **barall** (Michael Barall - FaultMod - 100 m)
- **ma** (Shuo Ma - Finite Element - MAFE)
- **somala** (Surendra Somala - Finite Element - PyLith : Tet4 (200m))

The graph displays the normal stress in MPa over time, with time in seconds on the x-axis and normal stress on the y-axis. The different lines represent different models and their predictions for normal stress, with some showing a peak around the 5-second mark.
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV15 — Horizontal Velocity [body030st080dp000]

- **barall** (Michael Barall - FaultMod - 100 m)
- **galvez** (Percy Galvez - 3D Spectral Element - SPECFEM3D-SESAME)
- **ma** (Shuo Ma - Finite Element - MAFE)
- **somala** (Surendra Somala - Finite Element - PyLith : Tet4 (200m))
TPV15 — Normal Velocity [body030st080dp000]
TPV14-2D

2D Benchmark.

Initial shear stress on branch fault = +70.0 MPa (right-lateral).

Expected outcome:

- Main fault ruptures completely.
- Branch fault ruptures completely.

Note: The expected outcome is different than the 3D case.
TPV14-2D — Main Fault Rupture Contours

Distance along strike (m)

Distance down-dip (m)

- barall (Michael Barall - FaultMod - 100 m)
- dedontney (ABAQUS - 100m)
- dunham4 (Eric Dunham - 2D Finite Difference - fdmap SBP6 100m)
- dunham4.2 (Eric Dunham - 2D Finite Difference - fdmap UPW5 100m)
- ma (MAFE 100m)
- oglesby (David Oglesby - Finite Element - DYNA3D)
- somala (PyLith - 2D : quad4 (100m))
- somala.2 (PyLith - 2D : tri3 (100m))
TPV14-2D — Branch Fault Rupture Contours

Distance along strike (m)

Distance down-dip (m)

- **barall** (Michael Barall - FaultMod - 100 m)
- **dedontney** (ABAQUS - 100m)
- **dunham4** (Eric Dunham - 2D Finite Difference - fdmap SBP6 100m)
- **dunham4.2** (Eric Dunham - 2D Finite Difference - fdmap UPW5 100m)
- **ma** (MAFE 100m)
- **oglesby** (David Oglesby - Finite Element - DYNA3D)
- **somala** (PyLith - 2D : quad4 ( 100m ))
- **somala.2** (PyLith - 2D : tri3 (100m))
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV14-2D — Normal Stress [faultst-020dp075]
TPV14-2D — Horizontal Shear Stress [faultst-020dp075]

Horizontal shear stress (MPa)

Time (s)

- aagaard (Brad Aagaard - PyLith - tri3 - 100m)
- aagaard.4 (Brad Aagaard - PyLith - quad4 - 100m)
- barall (Michael Barall - FaultMod - 100 m)
- dedontney (ABAQUS - 100m)
- dunham4 (Eric Dunham - 2D Finite Difference - fdmap SBP6 100m)
- dunham4.2 (Eric Dunham - 2D Finite Difference - fdmap UPW5 100m)
- ma (MAFE 100m)
- oglesby (David Oglesby - Finite Element - DYNA3D)
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV14-2D — Normal Stress [branchst090dp075]
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV14-2D — Horizontal Velocity [body-006st020dp075]
TPV14-2D — Normal Velocity [body-006st020dp075]
TPV15-2D

2D Benchmark.

Initial shear stress on branch fault = \(-78.0\) MPa (left-lateral).

Expected outcome:
- Main fault rupture stops past the junction point.
- Branch fault ruptures completely.
TPV15-2D — Branch Fault Rupture Contours

![Graph showing branch fault rupture contours]

- **barall** (Michael Barall - FaultMod - 100 m)
- **dedontney** (ABAQUS - 100 m)
- **dunham4** (Eric Dunham - 2D Finite Difference - fdmap SBP6 100m)
- **dunham4.2** (Eric Dunham - 2D Finite Difference - fdmap UPW5 100m)
- **ma** (MAFE 100m)
- **oglesby** (David Oglesby - Finite Element - DYNA3D)
- **somala** (PyLith - 2D : quad4 (100m))
- **somala.2** (PyLith - 2D : tri3 (100m))
TPV15-2D — Main Fault Rupture Contours

Distance along strike (m)

Distance down-dip (m)

- barall (Michael Barall - FaultMod - 100 m)
- dedontney (ABAQUS - 100 m)
- dunham4 (Eric Dunham - 2D Finite Difference - fdmap SBP6 100m)
- dunham4.2 (Eric Dunham - 2D Finite Difference - fdmap UPW5 100m)
- ma (MAFE 100m)
- oglesby (David Oglesby - Finite Element - DYNA3D)
- somala (PyLith - 2D : quad4 ( 100m ))
- somala.2 (PyLith - 2D : tri3 (100m))
TPV15-2D — Main Fault Rupture Contours, 100 m vs. 25 m

Distance along strike (m)

Distance down-dip (m)

-1E+04  0  1E+04

1.0E+04  1.5E+04  0.5E+04

dedontney (ABAQUS - 100 m)
dedontney.2 (ABAQUS - mod - 25 m)
TPV15-2D — Main Fault Rupture Contours, 100 m vs. 25 m

- dunham4 (Eric Dunham - 2D Finite Difference - fdmap SBP6 100m)
- dunham4.3 (Eric Dunham - 2D Finite Difference - fdmap SBP6 25m)
TPV15-2D — Main Fault Rupture Contours, 100 m vs. 25 m

Distance down-dip (m)

Distance along strike (m)

-1E+04

0

1E+04

1.0E+04

0.5E+04

1.5E+04

Legend:
- dunham4.2 (Eric Dunham - 2D Finite Difference - fdmap UPW5 100m)
- dunham4.4 (Eric Dunham - 2D Finite Difference - fdmap UW5 25m)
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV15-2D — Horizontal Slip Rate [branchst020dp075]

![Graph showing horizontal slip rate over time for different models and software packages.](image)

- **barall** (Michael Barall - FaultMod - 100 m)
- **dedontney** (ABAQUS - 100 m)
- **dunham4** (Eric Dunham - 2D Finite Difference - fdmap SBP6 100m)
- **dunham4.2** (Eric Dunham - 2D Finite Difference - fdmap UPW5 100m)
- **ma** (MAFE 100m)
- **oglesby** (David Oglesby - Finite Element - DYNA3D)
- **somala** (PyLith - 2D : quad4 (100m))
- **somala.2** (PyLith - 2D : tri3 (100m))
TPV15-2D — Horizontal Slip [branchst020dp075]
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV15-2D — Horizontal Shear Stress [faultst020dp075]
TPV15-2D — Normal Stress [faultst020dp075]
Time series data is filtered with a 5 Hz low-pass filter (2-pass, 2-pole Butterworth).
TPV15-2D — Horizontal Velocity [body030st050dp075]
TPV15-2D — Normal Velocity [body030st050dp075]