

TPV31 and TPV32

Planar Vertical Fault in a 1D Velocity Structure Benchmark

January 21, 2015

These 3D benchmarks use a right-lateral, planar, vertical, strike-slip fault set in a half-space with a 1D velocity structure. We are doing two benchmarks, as shown in the following table.

Benchmarks					
<i>Benchmark</i>	<i>Dimension</i>	<i>Rupture Type</i>	<i>Material Properties</i>	<i>Velocity Structure</i>	<i>Minimum V_S</i>
TPV31	3D	Strike-slip	Linear elastic	Discontinuous 1D	2250 m/s
TPV32	3D	Strike-slip	Linear elastic	Continuous 1D	1050 m/s

For TPV31, we request that you run the benchmark using 50 meter resolution. For TPV32, we request that you select a resolution in the range of 25 meters to 50 meters. See part 2 for a discussion.

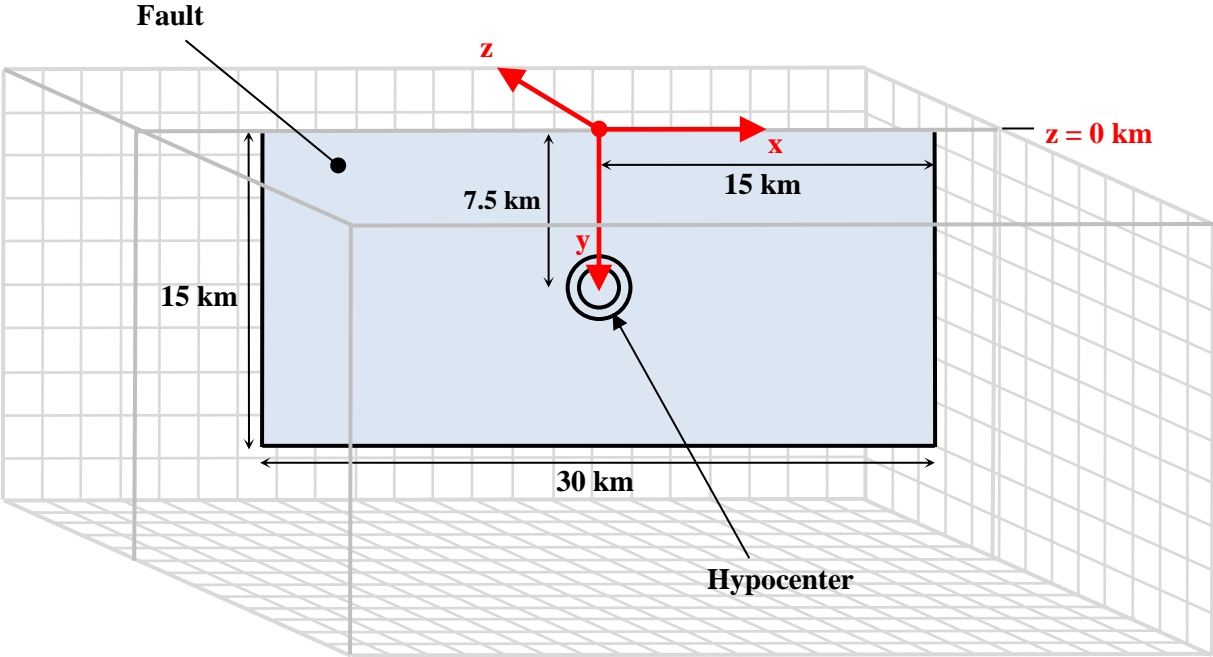
Benchmark Summary

- The geometry is a single, planar, vertical, right-lateral strike-slip fault in a half-space. The fault is 30 km long and 15 km deep.
- Material properties are determined from a 1D velocity structure.
- Initial shear and normal stresses on the fault are obtained by resolving a regional stress tensor onto the fault surface. The initial stress tensor components are proportional to the shear modulus, and so the initial stress tensor also has a 1D structure. There is no gravity in the model.
- The benchmark uses linear slip-weakening friction..
- The fault boundary condition is that slip goes to zero at the border of the fault. So, a node which lies precisely on the border of a fault should *not* be permitted to slip. The free surface is not considered to be a border of the fault.
- Nucleation is done by applying an additional shear stress in a zone surrounding the hypocenter, which is added to the stress imposed by the regional stress tensor. Within a circle of radius 1400 m surrounding the hypocenter, the resulting initial shear stress is slightly higher than the yield stress. Between 1400 m and 2000 m from the hypocenter, the initial shear stress tapers down to its background level. The nucleation stress is also proportional to the shear modulus.

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Part 1: Fault Geometry for TPV31 and TPV32



The model volume is a half-space.

The fault is a vertical plane measuring 30000 m along-strike and 15000 m deep. The fault is a strike-slip, right-lateral fault. The fault reaches the earth’s surface.

Introduce an (x, y, z) coordinate system, where x increases from left to right, y increases from top to bottom, and z increases from front to back. The origin is on the earth’s surface, 15000 m from either edge of the fault. In this coordinate system, the fault is:

$$\begin{aligned}
 -15000 \text{ m} &\leq x \leq 15000 \text{ m} \\
 0 \text{ m} &\leq y \leq 15000 \text{ m} \\
 z &= 0 \text{ m}
 \end{aligned}$$

The hypocenter is located in the center of the fault, 15000 m from either edge of the fault, and 7500 m deep, at coordinates $(x, y, z) = (0 \text{ m}, 7500 \text{ m}, 0 \text{ m})$.

Slip goes to zero at the border of the fault. So, a node which lies precisely on the border of the fault should not be permitted to slip. The free surface is not considered to be a border of the fault.

Part 2: Description of the 3D Benchmarks

Material Properties for TPV31

TPV31 uses a discontinuous 1D velocity structure. There are three discontinuities, at depths of 2400, 5000, and 10000 meters, as shown in the following table.

TPV31 Velocity Structure			
<i>Depth = y (meters)</i>	<i>V_P (meter/second)</i>	<i>V_S (meter/second)</i>	<i>Density= ρ (kg/m³)</i>
0	4050	2250	2580
2400–	4050	2250	2580
2400+	4450	2550	2600
5000–	5200	3050	2620
5000+	5750	3450	2720
10000–	5750	3450	2720
10000+	6500	3800	3000
15000	6500	3800	3000
All depths $y > 15000$	6500	3800	3000

The notation “2400–” means depths y that are slightly less than 2400 m. The notation “2400+” means depths y that are slightly greater than 2400 m. These could also be written in the notations “2400 – ϵ ” and “2400 + ϵ ”.

In-between the listed depths, the values of V_P , V_S , and ρ are linearly interpolated. For example, when the depth y is between 2400 m and 5000 m, the value of V_S is:

$$V_S = 2550 \text{ m/s} + (500 \text{ m/s})(y - 2400 \text{ m})/(2600 \text{ m}) \quad \text{assuming } 2400 \text{ m} < y < 5000 \text{ m}$$

Note that V_P , V_S , and ρ each have a constant value for depths between 0 m and 2400 m, a different constant value for depths between 5000 m and 10000 m, and a third constant value for depths greater than 10000 m. For depths between 2400 m and 5000 m, each of V_P , V_S , and ρ are linearly increasing.

For depths y exceeding 15000 m, the material properties are the same as for $y = 15000$ m, so that the values in the last line of the table apply.

Material Properties for TPV32

TPV32 uses a continuous 1D velocity structure. The material properties are continuous and piecewise-linear, as shown in the following table.

TPV32 Velocity Structure			
<i>Depth = y (meters)</i>	<i>V_P (meter/second)</i>	<i>V_S (meter/second)</i>	<i>Density= ρ (kg/m³)</i>
0	2200	1050	2200
500	3000	1400	2450
1000	3600	1950	2550
1600	4400	2500	2600
2400	4800	2800	2600
3600	5250	3100	2620
5000	5500	3250	2650
9000	5750	3450	2720
11000	6100	3600	2750
15000	6300	3700	2900
All depths <i>y</i> > 15000	6300	3700	2900

In-between the listed depths, the values of V_P , V_S , and ρ are linearly interpolated. For example, when the depth y is between 500 m and 1000 m, the value of V_S is:

$$V_S = 1400 \text{ m/s} + (550 \text{ m/s})(y - 500 \text{ m})/(500 \text{ m}) \quad \text{assuming } 500 \text{ m} < y < 1000 \text{ m}$$

For depths y exceeding 15000 m, the material properties are the same as for $y = 15000$ m, so that the values in the last line of the table apply.

Initial Stress Tensor

To specify initial normal and shear stresses on the fault, we define an initial stress tensor. Then, the initial normal and shear stresses on the fault are obtained by resolving the initial stress tensor onto the fault surface. To nucleate the rupture, an additional shear stress is added near the hypocenter, as explained below.

For TPV31 and TPV32, the initial stress tensor has a 1D structure that parallels the velocity structure. For TPV31, the stress tensor is discontinuous. All the components of the initial stress tensor are proportional to the shear modulus. The components of the stress tensor are defined in the following table.

Stress Tensor Components	
<i>Component</i>	<i>Definition</i>
σ_{22}	Compressive stress in the vertical direction (the y -direction). Negative values denote compression.
σ_{11}	Compressive stress in the direction parallel to the fault (the x -direction). Negative values denote compression.
σ_{33}	Compressive stress in the direction perpendicular to the fault (the z -direction). Negative values denote compression. This equals the negative of the normal stress on the planar part of the fault.
σ_{13}	Shear stress in the horizontal plane (the xz -plane). Positive values denote right-lateral shear stress on the fault. This equals the horizontal shear stress on planar part of the fault.
σ_{23}	Shear stress in a vertical plane perpendicular to the fault (the yz -plane).
σ_{12}	Shear stress in a vertical plane parallel to the fault (the xy -plane).

The stress tensor components can vary with time during the simulation.

For this 3D benchmark, the initial values of the stress tensor are:

$$\sigma_{22} = 0 \text{ MPa}$$

$$\sigma_{11} = (-60.00 \text{ MPa})(\mu/\mu_0)$$

$$\sigma_{33} = (-60.00 \text{ MPa})(\mu/\mu_0)$$

$$\sigma_{13} = (30.00 \text{ MPa})(\mu/\mu_0)$$

$$\sigma_{23} = 0 \text{ MPa}$$

$$\sigma_{12} = 0 \text{ MPa}$$

In the above formulas:

$$\mu = \text{shear modulus}$$

$$\mu_0 = 32.03812032 \text{ GPa}$$

Remark: μ_0 is the value of the shear modulus in benchmark TPV5 and many other benchmarks.

Nucleation Shear Stress

In order to nucleate the rupture, we apply an additional shear stress in a circular zone surrounding the hypocenter. **The nucleation shear stress is added to the shear stress obtained by resolving the stress tensor onto the fault surface.** Let r denote the two-dimensional distance to the hypocenter:

$$r = \sqrt{x^2 + (y - 7500 \text{ m})^2}$$

Then the nucleation shear stress is:

$$\tau_{\text{nuke}}(x, y) = \begin{cases} (4.95 \text{ MPa})(\mu/\mu_0), & \text{if } r \leq 1400 \text{ m} \\ (2.475 \text{ MPa})(1 + \cos(\pi(r - 1400 \text{ m})/(600 \text{ m}))) (\mu/\mu_0), & \text{if } 1400 \text{ m} \leq r \leq 2000 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

In the above formula:

$$\mu = \text{shear modulus}$$

$$\mu_0 = 32.03812032 \text{ GPa}$$

The nucleation shear stress is pure right-lateral. It has no along-dip component.

Note: At the hypocenter, the total initial shear stress is $(34.95 \text{ MPa})(\mu/\mu_0)$, and the yield stress is $(34.80 \text{ MPa})(\mu/\mu_0)$, so the initial shear stress is slightly higher than the yield stress.

Remark: As always, numerical values in the benchmark description should be used exactly as shown, and not approximated or rounded off.

Friction Parameters

We use a linear slip-weakening friction law, which has the following four parameters.

Friction Parameters		
<i>Symbol</i>	<i>Parameter</i>	<i>Unit</i>
μ_s	Static coefficient of friction.	Dimensionless
μ_d	Dynamic coefficient of friction.	Dimensionless
d_0	Slip-weakening critical distance.	Meter
C_0	Frictional cohesion.	Pascal

The operation of the slip-weakening friction law is described in detail later, in part 3.

The friction parameter values are as follows:

$$\mu_s = 0.580$$

$$\mu_d = 0.450$$

$$d_0 = 0.18 \text{ m}$$

$$C_0 = \begin{cases} (0.000425 \text{ MPa/m})(2400 \text{ m} - \text{depth}), & \text{if depth} \leq 2400 \text{ m} \\ 0 \text{ MPa}, & \text{if depth} \geq 2400 \text{ m} \end{cases}$$

The frictional cohesion C_0 is 1.02 MPa at the earth's surface. It is 0 MPa at depths greater than 2400 m, and is linearly tapered in the uppermost 2400 m

Running Time, Node Spacing, and Results

Run the model for times from **0.0 to 15.0 seconds after nucleation**.

For TPV31, please submit results using 50 m node spacing on the fault plane.

For TPV32, please select node spacing on the fault plane in the range of 25 m to 50 m, and submit results for your selected node spacing.

For TPV32, in our preliminary tests we had to use 25 m node spacing to obtain acceptable results in the low-velocity zones near the earth's surface. Some codes may be able to obtain acceptable results using 50 m node spacing, so use your judgment and select a node spacing that is appropriate for your code. Also, if your code can implement variable node spacing on the fault surface, you may consider using 25 m node spacing in the low-velocity zones near the earth's surface, and 50 m spacing at depth.

The requested output files are:

- **On-fault time-series files**, which give slips, slip rates, and stresses for each on-fault station at each time step. These files are described in part 5.
- **Off-fault time-series files**, which give displacements and velocities for each off-fault station at each time step. These files are described in part 6.
- **A contour-plot file** which, for each node on the fault, gives the time at which the slip rate first changes from 0 to greater than 0.001 m/s. This file is described in part 7.

Part 3: Linear Slip-Weakening Friction

Benchmarks TPV31 and TPV32 use linear slip-weakening friction. This friction law has the following parameters and variables:

Friction Parameters		
<i>Symbol</i>	<i>Parameter</i>	<i>Unit</i>
μ_s	Static coefficient of friction.	Dimensionless
μ_d	Dynamic coefficient of friction.	Dimensionless
d_0	Slip-weakening critical distance.	Meter
C_0	Frictional cohesion.	Pascal

Friction Variables		
<i>Symbol</i>	<i>Parameter</i>	<i>Unit</i>
σ_n	Total normal stress acting on the fault, taken to be positive in compression.	Pascal
τ	Shear stress acting on the fault.	Pascal

When the fault is sliding, the shear stress τ at a given point on the fault is given by:

$$\tau = C_0 + \mu \max(0, \sigma_n)$$

The time-varying coefficient of friction μ is given by the following formula, where D is the total distance the node has slipped:

$$\mu = \mu_s + (\mu_d - \mu_s) \min(D/d_0, 1)$$

The distance D that the node has slipped is path-integrated. For example, if the node slips 0.4 m in one direction and then 0.1 m in the opposite direction, the value of D is 0.5 m (and not 0.3 m).

Tension on the fault: If you encounter tension on the fault, you should **treat tension on the fault the same as if the normal stress equals zero**. This is shown in the above formulas by the expression $\max(0, \sigma_n)$. We do not expect tension on the fault to occur in TPV31 and TPV32.

You should **constrain the motion of the node so that the fault cannot open (that is, only permit sliding parallel to the fault), even when the fault is in tension**. During the time the fault is in tension, continue to accumulate the slip distance D as usual.

Part 4: Notes on Implementing the Initial Stress Tensor

In TPV31 and TPV32, we specify the initial normal and shear stresses on the fault by specifying an initial stress tensor throughout the model volume. Then, the initial normal and shear stresses on the fault are the initial stress tensor resolved onto the fault surface, plus the additional shear stress used for nucleation.

We chose to set the vertical component of the initial stress tensor equal to zero. This makes it possible to have a benchmark without gravity or fluid pressure. If the initial stress tensor had a non-zero vertical component, then gravity would be necessary to balance it.

Because TPV31 and TPV32 are linear elastic benchmarks, it is not necessary to specify the initial stress tensor throughout the medium. If the initial normal and shear stress on the fault is known, then the code only needs to track the change in the stress tensor from some unspecified initial state.

So, there are at least two ways to implement the initial stress tensor.

Method 1. — The stress tensor that is calculated and stored in the code is the actual stress tensor. In this case, the stress tensor appearing in the code must be initialized with the values given in part 2. Then, the code automatically resolves the initial stress tensor onto the fault, to obtain the initial normal and shear stresses.

A drawback of this method is that the initial stress tensor exerts forces on the boundaries of the mesh. If the code permits the mesh boundaries to move, then you must apply external tractions to the mesh boundary, to balance the tractions caused by the initial stress tensor.

Method 2. — The stress tensor that is calculated and stored in the code is the change of stress from some unspecified initial state. The initial state is assumed to be in static equilibrium. In this case, the stress tensor appearing in the code must be initialized to zero.

To use this method, you must determine the initial normal and shear stresses acting on the fault in a separate calculation, and then apply those stresses to the fault. Because the fault is planar, the initial normal and shear stresses are the initial values of $-\sigma_{33}$ and σ_{13} respectively.

In either method, the nucleation shear stress τ_{nuke} defined in part 2 must be added to the shear stress obtained by resolving the stress tensor onto the fault surface.

Part 5: On-Fault Stations, and Time-Series File Format

The benchmarks use 30 stations on the fault, which are listed below. A diagram of station locations is given following the table. You need to supply one time-series file for each station.

On-Fault Stations, for TPV31 and TPV32	
Station Name	Location
faultst000dp000	On fault, 0 km along strike, 0 km down-dip.
faultst000dp002	On fault, 0 km along strike, 0.2 km down-dip.
faultst000dp005	On fault, 0 km along strike, 0.5 km down-dip.
faultst000dp010	On fault, 0 km along strike, 1.0 km down-dip.
faultst000dp024	On fault, 0 km along strike, 2.4 km down-dip.
faultst000dp030	On fault, 0 km along strike, 3.0 km down-dip.
faultst000dp050	On fault, 0 km along strike, 5.0 km down-dip.
faultst000dp075	On fault, 0 km along strike, 7.5 km down-dip.
faultst000dp100	On fault, 0 km along strike, 10.0 km down-dip.
faultst000dp120	On fault, 0 km along strike, 12.0 km down-dip.
faultst060dp000	On fault, 6.0 km along strike, 0 km down-dip.
faultst060dp002	On fault, 6.0 km along strike, 0.2 km down-dip.
faultst060dp005	On fault, 6.0 km along strike, 0.5 km down-dip.
faultst060dp010	On fault, 6.0 km along strike, 1.0 km down-dip.
faultst060dp024	On fault, 6.0 km along strike, 2.4 km down-dip.
faultst060dp030	On fault, 6.0 km along strike, 3.0 km down-dip.
faultst060dp050	On fault, 6.0 km along strike, 5.0 km down-dip.
faultst060dp075	On fault, 6.0 km along strike, 7.5 km down-dip.
faultst060dp100	On fault, 6.0 km along strike, 10.0 km down-dip.

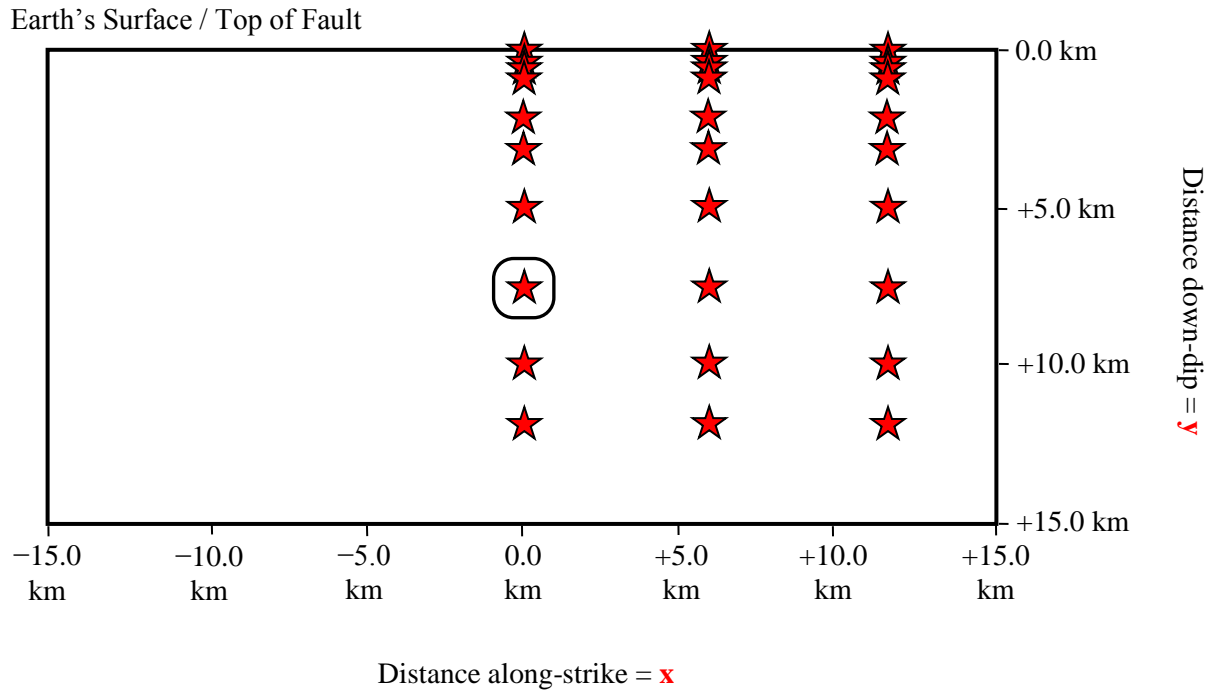
faultst060dp120	On fault, 6.0 km along strike, 12.0 km down-dip.
faultst120dp000	On fault, 12.0 km along strike, 0 km down-dip.
faultst120dp002	On fault, 12.0 km along strike, 0.2 km down-dip.
faultst120dp005	On fault, 12.0 km along strike, 0.5 km down-dip.
faultst120dp010	On fault, 12.0 km along strike, 1.0 km down-dip.
faultst120dp024	On fault, 12.0 km along strike, 2.4 km down-dip.
faultst120dp030	On fault, 12.0 km along strike, 3.0 km down-dip.
faultst120dp050	On fault, 12.0 km along strike, 5.0 km down-dip.
faultst120dp075	On fault, 12.0 km along strike, 7.5 km down-dip.
faultst120dp100	On fault, 12.0 km along strike, 10.0 km down-dip.
faultst120dp120	On fault, 12.0 km along strike, 12.0 km down-dip.

If you do not have a node at the location of a station, there are two options: (1) you can move the station to the nearest node, or (2) you can interpolate the data values from nodes near the station location.

Note: Location along-strike is measured relative to the origin of the (x, y, z) coordinate system. Positive locations are to the right of the origin.

Note: The filenames and descriptions give the x and y coordinates of the station. For example, station `faultst060dp024` is located at $(x, y, z) = (6000 \text{ m}, 2400 \text{ m}, 0 \text{ m})$.

On-Fault Station Locations



Each time series file is an ASCII file that contains 8 data fields, as follows.

On-Fault Time Series Data Fields for TPV31 and TPV32	
Field Name	Description, Units, and Sign Convention
t	Time (s).
h-slip	Horizontal slip along-strike (m). Sign convention: Positive means right lateral slip.
h-slip-rate	Horizontal slip rate along-strike (m/s). Sign convention: Positive means right lateral motion.
h-shear-stress	Horizontal shear stress along-strike (MPa). Sign convention: Positive means shear stress that tends to cause right-lateral slip.
v-slip	Vertical along-dip slip (m). Sign convention: Positive means downward slip (that is, the far side of the fault moving downward relative to the near side of the fault).
v-slip-rate	Vertical along-dip slip rate (m/s). Sign convention: Positive means downward motion (that is, the far side of the fault moving downward relative to the near side of the fault).
v-shear-stress	Vertical along-dip shear stress (MPa). Sign convention: Positive means shear stress that tends to cause downward slip (that is, the far side of the fault moving downward relative to the near side of the fault).
n-stress	Normal stress (MPa). Sign convention: Positive means extension .

The **near side** of the fault is in the front of the diagram (the $-z$ side of the fault).

The **far side** of the fault is in the back of the diagram (the $+z$ side of the fault).

The on-fault time series file consists of three sections, as follows.

On-Fault Time Series File Format for TPV31 and TPV32	
File Section	Description
File Header	<p>A series of lines, each beginning with a # symbol, that gives the following information:</p> <ul style="list-style-type: none"> • Benchmark problem (TPV31 or TPV32) • Author • Date • Code • Code version • Node spacing or element size • Time step • Number of time steps in file • Station location • Descriptions of data columns (7 lines) • Anything else you think is relevant
Field List	<p>A single line, which lists the names of the 8 data fields, in column order, separated by spaces. It should be:</p> <pre>t h-slip h-slip-rate h-shear-stress v-slip v-slip-rate v-shear-stress n-stress</pre> <p>(all on one line). The server examines this line to check that your file contains the correct data fields.</p>
Time History	<p>A series of lines. Each line contains 8 numbers, which give the data values for a single time step. The lines must appear in order of increasing time.</p> <p>C/C++ users: For all data fields except the time, we recommend using 14.6E or 14.6e floating-point format. For the time field, we recommend using 20.12E or 20.12e format (but see the note on the next page).</p> <p>Fortran users: For all data fields except the time, we recommend using E15.7 or 1PE15.6 floating-point format. For the time field, we recommend using E21.13 or 1PE21.12 format (but see the note on the next page).</p> <p>The server accepts most common numeric formats. If the server cannot understand your file, you will see an error message when you attempt to upload the file.</p>

Note: We recommend higher precision for the time field so the server can tell that your time steps are all equal. (If the server thinks your time steps are not all equal, it will refuse to apply digital filters to your data.) If you use a “simple” time step value like 0.01 seconds or 0.005 seconds, then there is no need for higher precision, and you can write the time using the same precision as all the other data fields. When you upload a file, the server will warn you if it thinks your time steps are not all equal.

Here is an example of an on-fault time-series file. This is an invented file, not real modeling data.

```
# Example on-fault time-series file.
#
# This is the file header:
# problem=TPV31
# author=A.Modeler
# date=2015/01/23
# code=MyCode
# code_version=3.7
# element_size=50 m
# time_step=0.004
# num_time_steps=3750
# location= on fault, 12.0 km along strike, 7.5km down-dip
# Column #1 = Time (s)
# Column #2 = horizontal slip (m)
# Column #3 = horizontal slip rate (m/s)
# Column #4 = horizontal shear stress (MPa)
# Column #5 = vertical slip (m)
# Column #6 = vertical slip rate (m/s)
# Column #7 = vertical shear stress (MPa)
# Column #8 = normal stress (MPa)
#
# The line below lists the names of the data fields:
t h-slip h-slip-rate h-shear-stress v-slip v-slip-rate v-shear-stress n-stress
#
# Here is the time-series data.
# There should be 8 numbers on each line, but this page is not wide enough
# to show 8 numbers on a line, so we only show the first five.
0.000000E+00 0.000000E+00 0.000000E+00 7.000000E+01 0.000000E+00 ...
5.000000E-03 0.000000E+00 0.000000E+00 7.104040E+01 0.000000E+00 ...
1.000000E-02 0.000000E+00 0.000000E+00 7.239080E+01 0.000000E+00 ...
1.500000E-02 0.000000E+00 0.000000E+00 7.349000E+01 0.000000E+00 ...
2.000000E-02 0.000000E+00 0.000000E+00 7.440870E+01 0.000000E+00 ...
2.500000E-02 0.000000E+00 0.000000E+00 7.598240E+01 0.000000E+00 ...
# ... and so on.
```

Part 6: Off-Fault Stations, and Time-Series File Format

The benchmarks use the 18 off-fault stations listed below. There is a diagram of station locations following the table. You need to supply one time-series file for each station.

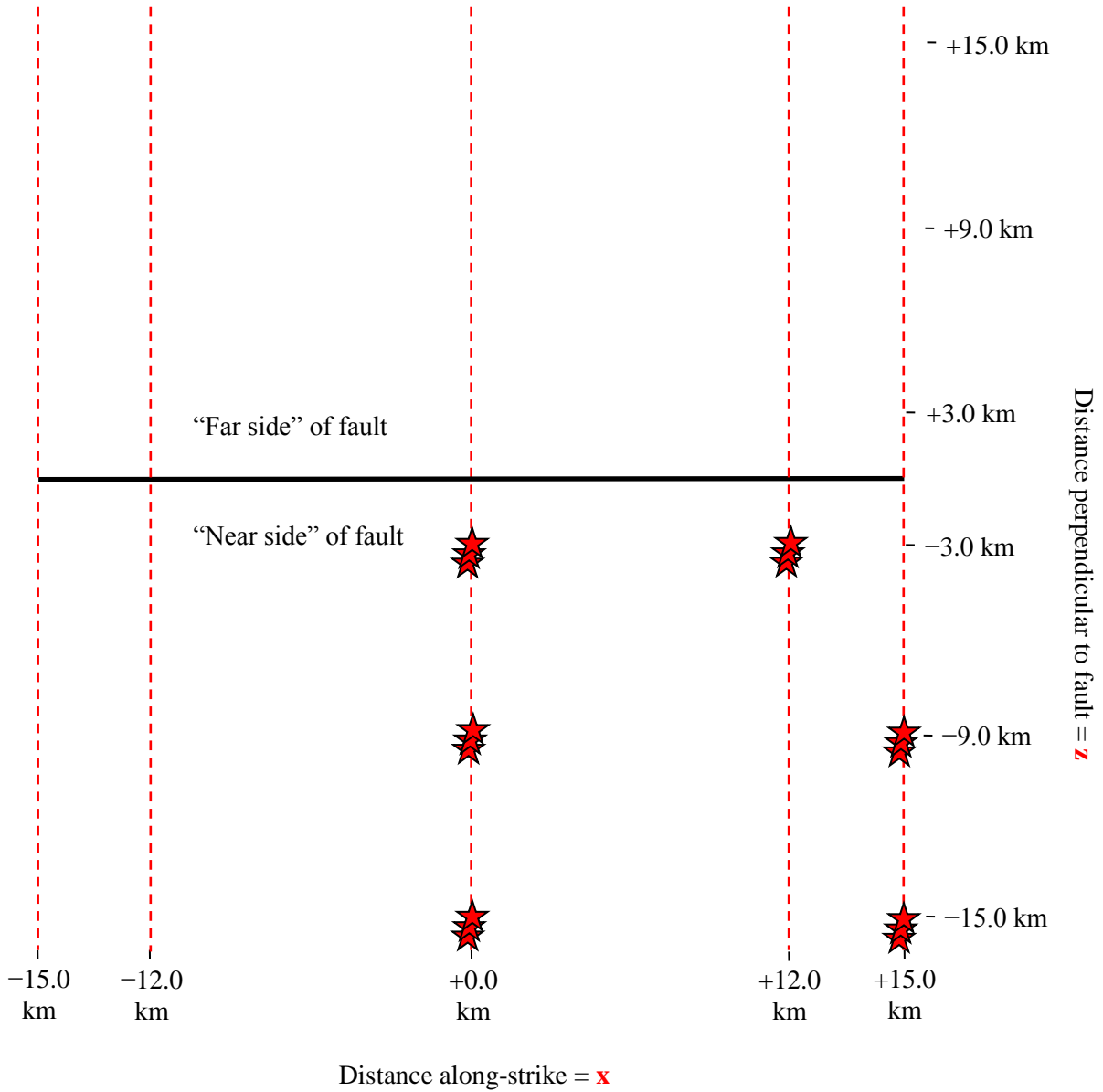
Off-Fault Stations for TPV29 and TPV30	
Station Name	Location
body-030st000dp000	-3.0 km off <i>xy</i> -plane (near side), 0 km along strike, 0 km depth.
body-030st000dp005	-3.0 km off <i>xy</i> -plane (near side), 0 km along strike, 0.5 km depth.
body-030st000dp024	-3.0 km off <i>xy</i> -plane (near side), 0 km along strike, 2.4 km depth.
body-030st120dp000	-3.0 km off <i>xy</i> -plane (near side), 12.0 km along strike, 0 km depth.
body-030st120dp005	-3.0 km off <i>xy</i> -plane (near side), 12.0 km along strike, 0.5 km depth.
body-030st120dp024	-3.0 km off <i>xy</i> -plane (near side), 12.0 km along strike, 2.4 km depth.
body-090st000dp000	-9.0 km off <i>xy</i> -plane (near side), 0 km along strike, 0 km depth.
body-090st000dp005	-9.0 km off <i>xy</i> -plane (near side), 0 km along strike, 0.5 km depth.
body-090st000dp024	-9.0 km off <i>xy</i> -plane (near side), 0 km along strike, 2.4 km depth.
body-090st150dp000	-9.0 km off <i>xy</i> -plane (near side), 15.0 km along strike, 0 km depth.
body-090st150dp005	-9.0 km off <i>xy</i> -plane (near side), 15.0 km along strike, 0.5 km depth.
body-090st150dp024	-9.0 km off <i>xy</i> -plane (near side), 15.0 km along strike, 2.4 km depth.
body-150st000dp000	-15.0 km off <i>xy</i> -plane (near side), 0 km along strike, 0 km depth.
body-150st000dp005	-15.0 km off <i>xy</i> -plane (near side), 0 km along strike, 0.5 km depth.
body-150st000dp024	-15.0 km off <i>xy</i> -plane (near side), 0 km along strike, 2.4 km depth.
body-150st150dp000	-15.0 km off <i>xy</i> -plane (near side), 15.0 km along strike, 0 km depth.
body-150st150dp005	-15.0 km off <i>xy</i> -plane (near side), 15.0 km along strike, 0.5 km depth.
body-150st150dp024	-15.0 km off <i>xy</i> -plane (near side), 15.0 km along strike, 2.4 km depth.

Note: The filenames and descriptions give the (x, y, z) coordinates of the station. For example, station `body-030st120dp005` is located at $(x, y, z) = (-12000 \text{ m}, 500 \text{ m}, -3000 \text{ m})$.

In the station names, the first number is the horizontal perpendicular distance from the station to the xy -plane. A positive number means that the station is located on the **far side**.

If you do not have a node at the location of a station, there are two options: (1) you can move the station to the nearest node, or (2) you can interpolate the data values from nodes near the station location.

Off-Fault Station Locations



The diagram shows the earth's surface, looking downwards.

The 18 stations are organized into 6 "boreholes." Each "borehole" contains 3 stations: one at the earth's surface, one at a depth of 0.5 km, and one at a depth of 2.4 km.

The 6 "boreholes" are at the following locations:

- At +0.0 km along-strike, and -3.0 km perpendicular distance from the x -axis.
- At +12.0 km along-strike, and -3.0 km perpendicular distance from the x -axis.
- At +0.0 km along-strike, and -9.0 km perpendicular distance from the x -axis.
- At +15.0 km along-strike, and -9.0 km perpendicular distance from the x -axis.
- At +0.0 km along-strike, and -15.0 km perpendicular distance from the x -axis.
- At +15.0 km along-strike, and -15.0 km perpendicular distance from the x -axis.

The **near side** of the fault is in the front of the diagram (the $-z$ side of the fault).

The **far side** of the fault is in the back of the diagram (the $+z$ side of the fault).

Positive perpendicular distance from the xy -plane means that the station is on the **far side**.

Each time series file is an ASCII file that contains 7 data fields, as follows.

Off-Fault Time Series Data Fields for TPV31 and TPV32	
Field Name	Description, Units, and Sign Convention
t	Time (s).
h-disp	Horizontal displacement, parallel to the fault strike (m). Sign convention: Positive means displacement to the right relative to the station's initial position (that is, in the $+x$ direction).
h-vel	Horizontal velocity, parallel to the fault strike (m/s). Sign convention: Positive means motion to the right (that is, in the $+x$ direction).
v-disp	Vertical displacement (m). Sign convention: Positive means displacement downward relative to the station's initial position (that is, in the $+y$ direction).
v-vel	Vertical velocity (m/s). Sign convention: Positive means motion downward (that is, in the $+y$ direction).
n-disp	Horizontal displacement, perpendicular to the fault strike (m). Sign convention: Positive means displacement away from the viewer, into the paper (that is, away from near side of the fault and toward the far side of the fault) relative to the station's initial position. In other words, displacement in the $+z$ direction.
n-vel	Horizontal velocity, perpendicular to the fault strike (m/s). Sign convention: Positive means motion away from the viewer, into the paper (that is, away from near side of the fault and toward the far side of the fault). In other words, motion in the $+z$ direction.

The **near side** of the fault is in the front of the diagram (the $-z$ side of the fault)..

The **far side** of the fault is in the back of the diagram (the $+z$ side of the fault).

The off-fault time series file consists of three sections, as follows.

Off-Fault Time Series File Format for TPV31 and TPV32	
File Section	Description
File Header	<p>A series of lines, each beginning with a # symbol, that gives the following information:</p> <ul style="list-style-type: none"> • Benchmark problem (TPV31 or TPV32) • Author • Date • Code • Code version • Node spacing or element size • Time step • Number of time steps in file • Station location • Descriptions of data columns (7 lines) • Anything else you think is relevant
Field List	<p>A single line, which lists the names of the 7 data fields, in column order, separated by spaces. It should be:</p> <pre>t h-disp h-vel v-disp v-vel n-disp n-vel</pre> <p>(all on one line). The server examines this line to check that your file contains the correct data fields.</p>
Time History	<p>A series of lines. Each line contains 7 numbers, which give the data values for a single time step. The lines must appear in order of increasing time.</p> <p>C/C++ users: For all data fields except the time, we recommend using 14.6E or 14.6e floating-point format. For the time field, we recommend using 20.12E or 20.12e format (but see the note on the next page).</p> <p>Fortran users: For all data fields except the time, we recommend using E15.7 or 1PE15.6 floating-point format. For the time field, we recommend using E21.13 or 1PE21.12 format (but see the note on the next page).</p> <p>The server accepts most common numeric formats. If the server cannot understand your file, you will see an error message when you attempt to upload the file.</p>

Note: We recommend higher precision for the time field so the server can tell that your time steps are all equal. (If the server thinks your time steps are not all equal, it will refuse to apply digital filters to your data.) If you use a “simple” time step value like 0.01 seconds or 0.005 seconds, then there is no need for higher precision, and you can write the time using the same precision as all the other data fields. When you upload a file, the server will warn you if it thinks your time steps are not all equal.

Here is an example of an off-fault time-series file. This is an invented file, not real modeling data.

```
# Example off-fault time-series file.
#
# This is the file header:
# problem=TPV31
# author=A.Modeler
# date=2015/01/23
# code=MyCode
# code_version=3.7
# element_size=50 m
# time_step=0.004
# num_time_steps=3750
# location= -3.0 km off fault, 12.0 km along strike, 0.0 km depth
# Column #1 = Time (s)
# Column #2 = horizontal displacement (m)
# Column #3 = horizontal velocity (m/s)
# Column #4 = vertical displacement (m)
# Column #5 = vertical velocity (m/s)
# Column #6 = normal displacement (m)
# Column #7 = normal velocity (m/s)
#
# The line below lists the names of the data fields:
t h-disp h-vel v-disp v-vel n-disp n-vel
#
# Here is the time-series data.
# There should be 7 numbers on each line, but this page is not wide enough
# to show 7 numbers on a line, so we only show the first five.
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 ...
5.000000E-03 -2.077270E-85 -2.575055E-83 -2.922774E-86 -3.623018E-84 ...
1.000000E-02 -1.622118E-82 -2.005817E-80 -1.387778E-83 -1.713249E-81 ...
1.500000E-02 -9.020043E-80 -1.114231E-77 -4.402893E-81 -5.424313E-79 ...
2.000000E-02 -1.201684E-77 -1.467704E-75 -4.549845E-79 -5.533119E-77 ...
2.500000E-02 -1.528953E-75 -1.866265E-73 -4.126064E-77 -5.004886E-75 ...
# ... and so on.
```


Part 7: Contour-Plot File Format

There is one contour-plot file, as shown here:

Contour-plot file for TPV31 and TPV32	
File Name	Description
cplot	Rupture times for the fault.

The contour plot file lists the locations of all the nodes on the fault surface, and the time at which each node ruptures.

The contour plot file is an ASCII file that contains three data fields, as follows.

Contour Plot Data Fields for TPV31 and TPV32	
Field Name	Description, Units, and Sign Convention
j	Distance along strike (m). Sign convention: Positive means a location to the right of the origin. For TPV31 and TPV32, the value of j can range from -15000 to 15000 .
k	Distance down-dip (m). Sign convention: Zero is the earth's surface, and positive means underground . For TPV31 and TPV32, the value of k can range from 0 to 15000 .
t	Rupture time (s). This is the time at which fault slip-rate first changes from 0 to greater than 0.001 m/s. If this node never ruptures, use the value $1.0E+09$.

A pair of numbers (j, k) denotes a point on the fault surface. It is equal to the (x, y) coordinates.

The contour plot file consists of three sections, as follows.

Contour Plot File Format for TPV31 and TPV32	
File Section	Description
File Header	<p>A series of lines, each beginning with a # symbol, that gives the following information:</p> <ul style="list-style-type: none"> • Benchmark problem (TPV31 or TPV32) • Author • Date • Code • Code version • Node spacing or element size • Descriptions of data columns (7 lines) • Anything else you think is relevant
Field List	<p>A single line, which lists the names of the 3 data fields, in column order, separated by spaces. It should be:</p> <p style="text-align: center;">j k t</p> <p>(all on one line). The server examines this line to check that your file contains the correct data fields.</p>
Rupture History	<p>A series of lines. Each line contains three numbers, which give the (j, k) coordinates of a node on the fault surface, and the time t at which that node ruptures.</p> <p>C/C++ users: We recommend using 14.6E or 14.6e floating-point format.</p> <p>Fortran users: We recommend using E15.7 or 1PE15.6 floating-point format.</p> <p>If a node never ruptures, the time should be given as 1.0E+09.</p> <p>Nodes may be listed in any order.</p>

Note: The nodes may appear in any order. The nodes do not have to form a rectangular grid, or any other regular pattern.

Note: When you upload a file, the server constructs the Delaunay triangulation of your nodes. Then, it uses the Delaunay triangulation to interpolate the rupture times over the entire fault surface. Finally, it uses the interpolated rupture times to draw a series of contour curves at intervals of 0.5 seconds.

Here is an example of a contour-plot file. This is an invented file, not real modeling data.

```
# Example contour-plot file.
#
# This is the file header:
# problem=TPV31
# author=A.Modeler
# date=2015/01/23
# code=MyCode
# code_version=3.7
# element_size=50 m
# Column #1 = horizontal coordinate, distance along strike (m)
# Column #2 = vertical coordinate, distance down-dip (m)
# Column #3 = rupture time (s)
#
# The line below lists the names of the data fields.
# It indicates that the first column contains the horizontal
# coordinate (j), the second column contains the vertical
# coordinate (k), and the third column contains the time (t).
j k t
#
# Here is the rupture history
-6.000000E+02 7.000000E+03 3.100000E-02
-6.000000E+02 7.100000E+03 4.900000E-02
-6.000000E+02 7.200000E+03 6.700000E-02
-7.000000E+02 7.000000E+03 1.230000E-01
-7.000000E+02 7.100000E+03 1.350000E-01
-7.000000E+02 7.200000E+03 1.470000E-01
# ... and so on.
```