TPV33
Planar Vertical Fault with Fault Zone Guided Waves

November 23, 2015

This 3D benchmark uses a right-lateral, planar, vertical, strike-slip fault set in the center of a low-velocity fault zone. The benchmark demonstrates the production of fault zone guided waves.

Benchmarks					
Benchmark	*Dimension*	*Rupture Type*	*Material Properties*	*Velocity Structure*	*Minimum V_S*
TPV33	3D	Strike-slip	Linear elastic	Low-velocity fault zone	2165 m/s

For TPV33, we request that you select a resolution on the fault plane in the range of 12.5 meters to 25 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 16 km long and 10 km deep.

- The fault is centered within a low-velocity zone. The total thickness of the low-velocity zone is 1.6 km. Inside the low-velocity zone, V_S is 2165 m/s. Outside the low-velocity zone, V_S is 3464 m/s on one side of the fault and 3248 m/s on the other side.

- Initial normal stress on the fault is constant. Initial shear stress is tapered, so that the rupture stops spontaneously before it reaches any border of the fault, and before it reaches the earth’s surface. There is no gravity in the model.

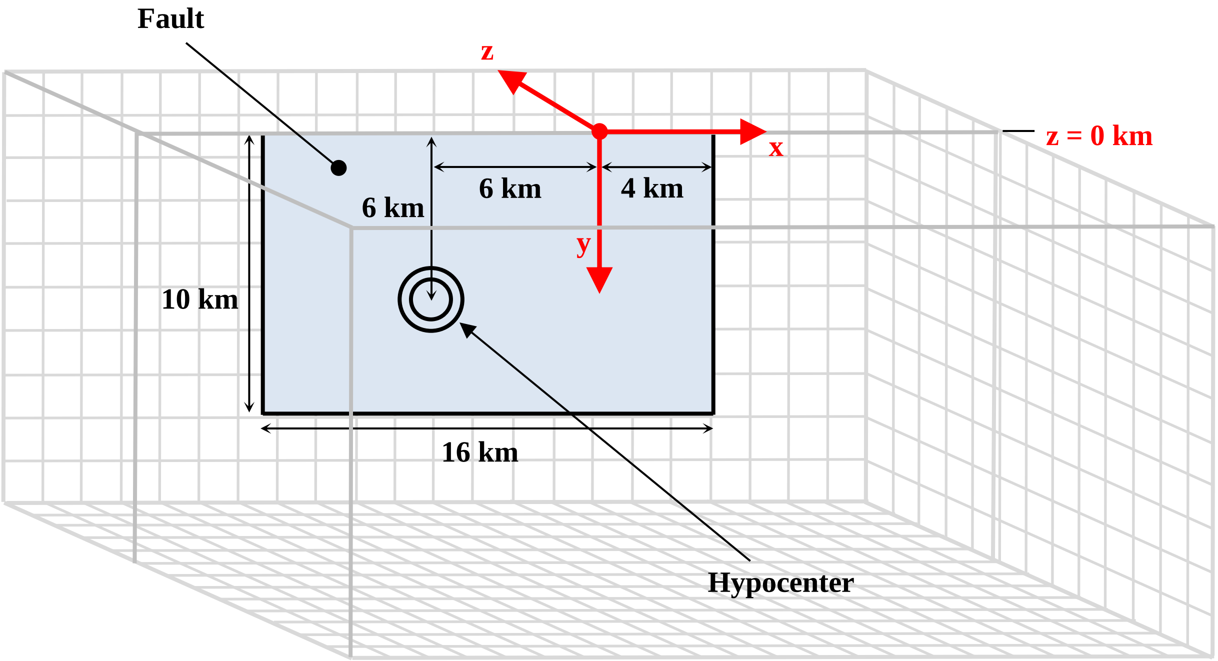
- The benchmark uses linear slip-weakening friction.

- 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. (However, the boundary condition plays no role because rupture does not reach the border.)

- Nucleation is done by applying an additional shear stress in a zone surrounding the hypocenter. Within a circle of radius 550 m surrounding the hypocenter, the resulting initial shear stress is slightly higher than the yield stress. Between 550 m and 800 m from the hypocenter, the initial shear stress tapers down to its background level.

Contents

Part 1: Fault Geometry for TPV33



The model volume is a half-space.

The fault is a vertical plane measuring 16000 m along-strike and 10000 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, 12000 m from the left edge of the fault. In this coordinate system, the fault is:

$$\begin{aligned} -12000\text{ m} \le x &\le 4000\text{ m} \\ 0\text{ m} \le y &\le 10000\text{ m} \\ z &= 0\text{ m} \end{aligned}$$

The hypocenter is located 6000 m from the left edge of the fault, and 6000 m deep, at coordinates $(x, y, z) = (-6000\text{ m},\ 6000\text{ m},\ 0\text{ m})$.

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 Benchmark

Material Properties

In TPV33, the entire model volume is a linear elastic material, with the following parameters.

Density $\rho = 2670\ \mathrm{kg/m^3}$

$$\text{Shear-wave velocity } V_S = \begin{cases} 3248\ \mathrm{m/s}, & \text{if } z < -800\ \mathrm{m} \\ 2165\ \mathrm{m/s}, & \text{if } -800\ \mathrm{m} < z < 800\ \mathrm{m} \\ 3464\ \mathrm{m/s}, & \text{if } 800\ \mathrm{m} < z \end{cases}$$

$$\text{Pressure-wave velocity } V_P = \begin{cases} 5626\ \mathrm{m/s}, & \text{if } z < -800\ \mathrm{m} \\ 3750\ \mathrm{m/s}, & \text{if } -800\ \mathrm{m} < z < 800\ \mathrm{m} \\ 6000\ \mathrm{m/s}, & \text{if } 800\ \mathrm{m} < z \end{cases}$$

Initial Stress

The initial normal stress is constant. Its value is:

$$\sigma_0(x, y) = 60 \text{ MPa}$$

The initial shear stress is pure right-lateral. It varies over the fault surface, so that the rupture stops spontaneously before it reaches the border of the fault, and before it reaches the earth's surface. It also includes extra stress surrounding the hypocenter, to nucleate the rupture. The initial shear stress is given by the formula

$$\tau_0(x, y) = (30 \text{ MPa})(1 - R_\tau) + \tau_{\text{nuke}}(x, y)$$

The stress tapering term R_τ is calculated as follows. First, define

$$R_x = \begin{cases} (-x - 9800 \text{ m})/(10000 \text{ m}), & \text{if } x < -9800 \text{ m} \\ (x - 1100 \text{ m})/(10000 \text{ m}), & \text{if } x > 1100 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

$$R_y = \begin{cases} (-y + 2300 \text{ m})/(10000 \text{ m}), & \text{if } y < 2300 \text{ m} \\ (y - 8000 \text{ m})/(10000 \text{ m}), & \text{if } y > 8000 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

Then the stress tapering term is

$$R_\tau = \min\left(1, \sqrt{R_x^2 + R_y^2}\right)$$

In order to nucleate the rupture, we apply an additional shear stress in a circular zone surrounding the hypocenter. Let r denote the two-dimensional distance to the hypocenter:

$$r = \sqrt{(x + 6000 \text{ m})^2 + (y - 6000 \text{ m})^2}$$

Then the nucleation shear stress is:

$$\tau_{\text{nuke}}(x, y) = \begin{cases} 3.150 \text{ MPa}, & \text{if } r \leq 550 \text{ m} \\ (1.575 \text{ MPa})\big(1 + \cos\big(\pi(r - 550 \text{ m})/(250 \text{ m})\big)\big), & \text{if } 550 \text{ m} \leq r \leq 800 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

Notice that the initial shear stress on the fault is continuous. Also note that as a result of the nucleation shear stress, the total initial shear stress at the hypocenter is 33.15 MPa. By comparison, the initial yield stress at the hypocenter is 33.00 MPa.

Friction Parameters

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

Friction Parameters		
Symbol	*Parameter*	*Unit*
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:

$\mu_s = 0.550$

$\mu_d = 0.450$

$d_0 = 0.18$ m

$C_0 = 0$ MPa

Running Time, Node Spacing, and Results

Run the model for times from **0.0 to 13.0 seconds after nucleation**.

The recommended resolution for TPV33 is:

- **A resolution in the range of 12.5 meters to 25 meters on the fault plane.**
- **50 meters throughout the low-velocity zone.**
- **100 meters outside the low-velocity zone.**

Some codes may be able to get good results using 25 meter resolution on the fault plane, while others may need 12.5 meter resolution on the fault plane, so use your judgment to select an appropriate resolution. We suggest using 12.5 meter resolution if you are able to do so.

TPV33 requires twice the resolution of any earlier benchmark. To avoid makingTPV33 too computationally intensive, we are using a smaller fault than usual, and we have placed the most-distant off-fault stations closer to the fault than usual.

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 4.
- **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 5.
- **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 6.

Part 3: Linear Slip-Weakening Friction

Benchmark TPV33 uses linear slip-weakening friction. This friction law has the following parameters and variables:

Friction Parameters		
Symbol	*Parameter*	*Unit*
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		
Symbol	*Parameter*	*Unit*
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 TPV33.

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

The benchmark uses 28 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 TPV33	
Station Name	**Location**
`faultst-100dp020`	On fault, −10.0 km along strike, 2.0 km down-dip.
`faultst-100dp040`	On fault, −10.0 km along strike, 4.0 km down-dip.
`faultst-100dp060`	On fault, −10.0 km along strike, 6.0 km down-dip.
`faultst-100dp080`	On fault, −10.0 km along strike, 8.0 km down-dip.
`faultst-080dp020`	On fault, −8.0 km along strike, 2.0 km down-dip.
`faultst-080dp040`	On fault, −8.0 km along strike, 4.0 km down-dip.
`faultst-080dp060`	On fault, −8.0 km along strike, 6.0 km down-dip.
`faultst-080dp080`	On fault, −8.0 km along strike, 8.0 km down-dip.
`faultst-060dp020`	On fault, −6.0 km along strike, 2.0 km down-dip.
`faultst-060dp040`	On fault, −6.0 km along strike, 4.0 km down-dip.
`faultst-060dp060`	On fault, −6.0 km along strike, 6.0 km down-dip.
`faultst-060dp080`	On fault, −6.0 km along strike, 8.0 km down-dip.
`faultst-040dp020`	On fault, −4.0 km along strike, 2.0 km down-dip.
`faultst-040dp040`	On fault, −4.0 km along strike, 4.0 km down-dip.
`faultst-040dp060`	On fault, −4.0 km along strike, 6.0 km down-dip.
`faultst-040dp080`	On fault, −4.0 km along strike, 8.0 km down-dip.
`faultst-020dp020`	On fault, −2.0 km along strike, 2.0 km down-dip.
`faultst-020dp040`	On fault, −2.0 km along strike, 4.0 km down-dip.
`faultst-020dp060`	On fault, −2.0 km along strike, 6.0 km down-dip.

`faultst-020dp080`	On fault, −2.0 km along strike, 8.0 km down-dip.
`faultst000dp020`	On fault, 0 km along strike, 2.0 km down-dip.
`faultst000dp040`	On fault, 0 km along strike, 4.0 km down-dip.
`faultst000dp060`	On fault, 0 km along strike, 6.0 km down-dip.
`faultst000dp080`	On fault, 0 km along strike, 8.0 km down-dip.
`faultst020dp020`	On fault, 2.0 km along strike, 2.0 km down-dip.
`faultst020dp040`	On fault, 2.0 km along strike, 4.0 km down-dip.
`faultst020dp060`	On fault, 2.0 km along strike, 6.0 km down-dip.
`faultst020dp080`	On fault, 2.0 km along strike, 8.0 km down-dip.

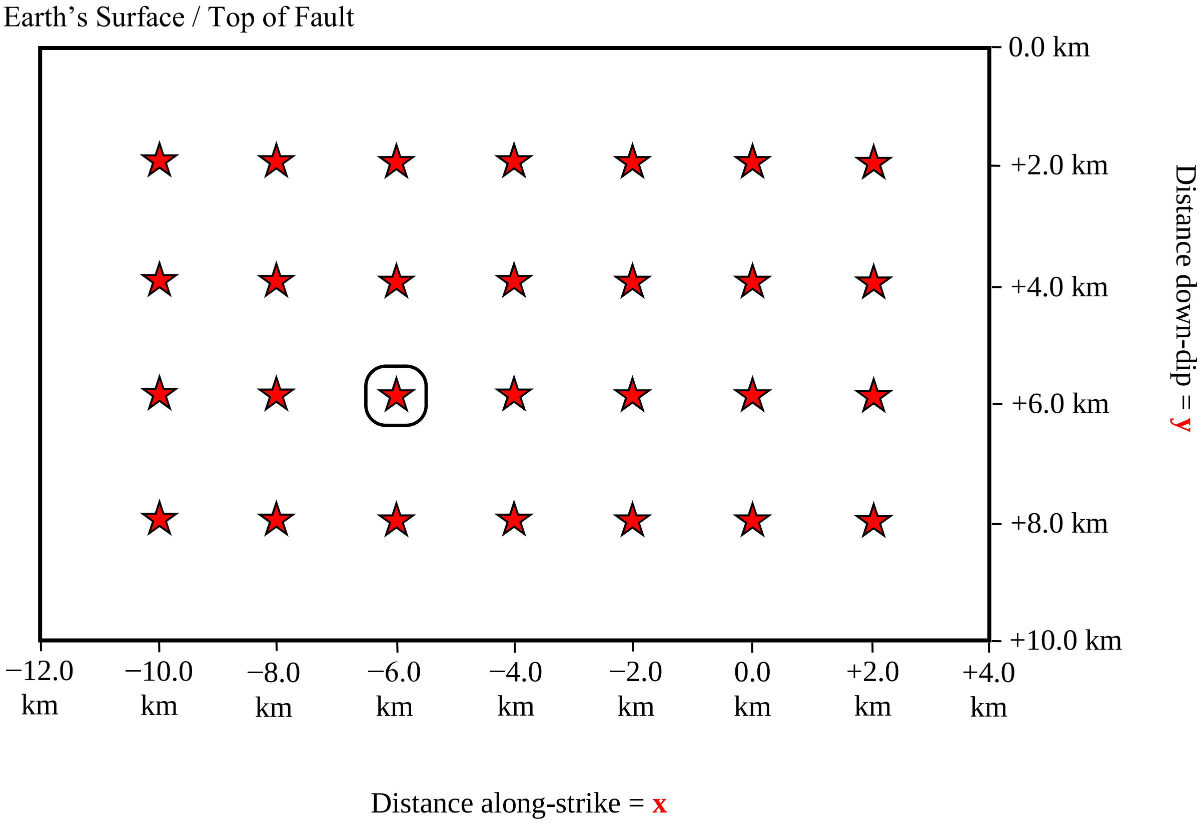
If you do not have a node at the location of a station, there are two options: (1) you can move the station to the nearest node, or (2) you can interpolate the data values from nodes near the station location.

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 `faultst-060dp020` is located at $(x, y, z) = (-6000\text{ m},\ 2000\text{ m},\ 0\text{ m})$.

Remark: There are more stations than usual. When you upload your files to the website, you don't have to upload them one-by-one. You can upload all your files in a single operation, using the Perl script available at: http://scecdata.usc.edu/cvws/downloads.html.

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 TPV33	
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 TPV33

File Section	**Description**
File Header	A series of lines, each beginning with a # symbol, that gives the following information: • Benchmark problem (TPV33) • 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	A **single line**, which lists the names of the 8 data fields, in column order, separated by spaces. It should be: `t h-slip h-slip-rate h-shear-stress v-slip v-slip-rate v-shear-stress n-stress` (all on one line). The server examines this line to check that your file contains the correct data fields.
Time History	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. **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). **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). 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.

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=TPV33
# author=A.Modeler
# date=2016/01/23
# code=MyCode
# code_version=3.7
# element_size=12.5 m
# time_step=0.00125
# num_time_steps=9600
# location= on fault, -6.0 km along strike, 2.0 km 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 5: Off-Fault Stations, and Time-Series File Format

The benchmark uses the 85 off-fault stations listed below. There are two diagrams of station locations following the table. You need to supply one time-series file for each station.

Off-Fault Stations for TPV33	
Station Name	**Location**
Transect at −6.0 km along strike, at the earth's surface	
`body-016st-060dp000`	−1.6 km off xy-plane (near side), −6.0 km along strike, 0 km depth.
`body-012st-060dp000`	−1.2 km off xy-plane (near side), −6.0 km along strike, 0 km depth.
`body-008st-060dp000`	−0.8 km off xy-plane (near side), −6.0 km along strike, 0 km depth.
`body-004st-060dp000`	−0.4 km off xy-plane (near side), −6.0 km along strike, 0 km depth.
`body000st-060dp000`	0 km off xy-plane (on fault trace), −6.0 km along strike, 0 km depth.
`body004st-060dp000`	0.4 km off xy-plane (far side), −6.0 km along strike, 0 km depth.
`body008st-060dp000`	0.8 km off xy-plane (far side), −6.0 km along strike, 0 km depth.
`body012st-060dp000`	1.2 km off xy-plane (far side), −6.0 km along strike, 0 km depth.
`body016st-060dp000`	1.6 km off xy-plane (far side), −6.0 km along strike, 0 km depth.
Transect at 0.0 km along strike, at a depth of 6 km	
`body-016st000dp060`	−1.6 km off xy-plane (near side), 0.0 km along strike, 6.0 km depth.
`body-012st000dp060`	−1.2 km off xy-plane (near side), 0.0 km along strike, 6.0 km depth.
`body-008st000dp060`	−0.8 km off xy-plane (near side), 0.0 km along strike, 6.0 km depth.
`body-004st000dp060`	−0.4 km off xy-plane (near side), 0.0 km along strike, 6.0 km depth.
`body-001st000dp060`	−0.1 km off xy-plane (near side), 0.0 km along strike, 6.0 km depth.
`body001st000dp060`	0.1 km off xy-plane (far side), 0.0 km along strike, 6.0 km depth.
`body004st000dp060`	0.4 km off xy-plane (far side), 0.0 km along strike, 6.0 km depth.
`body008st000dp060`	0.8 km off xy-plane (far side), 0.0 km along strike, 6.0 km depth.

`body012st000dp060`	1.2 km off xy-plane (far side), 0.0 km along strike, 6.0 km depth.
`body016st000dp060`	1.6 km off xy-plane (far side), 0.0 km along strike, 6.0 km depth.
Transect at +4.0 km along strike, at the earth's surface	
`body-016st040dp000`	−1.6 km off xy-plane (near side), 4.0 km along strike, 0 km depth.
`body-012st040dp000`	−1.2 km off xy-plane (near side), 4.0 km along strike, 0 km depth.
`body-008st040dp000`	−0.8 km off xy-plane (near side), 4.0 km along strike, 0 km depth.
`body-004st040dp000`	−0.4 km off xy-plane (near side), 4.0 km along strike, 0 km depth.
`body000st040dp000`	0 km off xy-plane (on fault trace), 4.0 km along strike, 0 km depth.
`body004st040dp000`	0.4 km off xy-plane (far side), 4.0 km along strike, 0 km depth.
`body008st040dp000`	0.8 km off xy-plane (far side), 4.0 km along strike, 0 km depth.
`body012st040dp000`	1.2 km off xy-plane (far side), 4.0 km along strike, 0 km depth.
`body016st040dp000`	1.6 km off xy-plane (far side), 4.0 km along strike, 0 km depth.
Transect at +4.0 km along strike, at a depth of 6 km	
`body-016st040dp060`	−1.6 km off xy-plane (near side), 4.0 km along strike, 6.0 km depth.
`body-012st040dp060`	−1.2 km off xy-plane (near side), 4.0 km along strike, 6.0 km depth.
`body-008st040dp060`	−0.8 km off xy-plane (near side), 4.0 km along strike, 6.0 km depth.
`body-004st040dp060`	−0.4 km off xy-plane (near side), 4.0 km along strike, 6.0 km depth.
`body000st040dp060`	0 km off xy-plane (on fault trace), 4.0 km along strike, 6.0 km depth.
`body004st040dp060`	0.4 km off xy-plane (far side), 4.0 km along strike, 6.0 km depth.
`body008st040dp060`	0.8 km off xy-plane (far side), 4.0 km along strike, 6.0 km depth.
`body012st040dp060`	1.2 km off xy-plane (far side), 4.0 km along strike, 6.0 km depth.
`body016st040dp060`	1.6 km off xy-plane (far side), 4.0 km along strike, 6.0 km depth.
Transect at +8.0 km along strike, at the earth's surface	
`body-016st080dp000`	−1.6 km off xy-plane (near side), 8.0 km along strike, 0 km depth.
`body-012st080dp000`	−1.2 km off xy-plane (near side), 8.0 km along strike, 0 km depth.

`body-008st080dp000`	−0.8 km off xy-plane (near side), 8.0 km along strike, 0 km depth.
`body-004st080dp000`	−0.4 km off xy-plane (near side), 8.0 km along strike, 0 km depth.
`body000st080dp000`	0 km off xy-plane, 8.0 km along strike, 0 km depth.
`body004st080dp000`	0.4 km off xy-plane (far side), 8.0 km along strike, 0 km depth.
`body008st080dp000`	0.8 km off xy-plane (far side), 8.0 km along strike, 0 km depth.
`body012st080dp000`	1.2 km off xy-plane (far side), 8.0 km along strike, 0 km depth.
`body016st080dp000`	1.6 km off xy-plane (far side), 8.0 km along strike, 0 km depth.
Transect at +8.0 km along strike, at a depth of 6 km	
`body-016st080dp060`	−1.6 km off xy-plane (near side), 8.0 km along strike, 6.0 km depth.
`body-012st080dp060`	−1.2 km off xy-plane (near side), 8.0 km along strike, 6.0 km depth.
`body-008st080dp060`	−0.8 km off xy-plane (near side), 8.0 km along strike, 6.0 km depth.
`body-004st080dp060`	−0.4 km off xy-plane (near side), 8.0 km along strike, 6.0 km depth.
`body000st080dp060`	0 km off xy-plane, 8.0 km along strike, 6.0 km depth.
`body004st080dp060`	0.4 km off xy-plane (far side), 8.0 km along strike, 6.0 km depth.
`body008st080dp060`	0.8 km off xy-plane (far side), 8.0 km along strike, 6.0 km depth.
`body012st080dp060`	1.2 km off xy-plane (far side), 8.0 km along strike, 6.0 km depth.
`body016st080dp060`	1.6 km off xy-plane (far side), 8.0 km along strike, 6.0 km depth.
Transect at +12.0 km along strike, at the earth's surface	
`body-016st120dp000`	−1.6 km off xy-plane (near side), 12.0 km along strike, 0 km depth.
`body-012st120dp000`	−1.2 km off xy-plane (near side), 12.0 km along strike, 0 km depth.
`body-008st120dp000`	−0.8 km off xy-plane (near side), 12.0 km along strike, 0 km depth.
`body-004st120dp000`	−0.4 km off xy-plane (near side), 12.0 km along strike, 0 km depth.
`body000st120dp000`	0 km off xy-plane, 12.0 km along strike, 0 km depth.
`body004st120dp000`	0.4 km off xy-plane (far side), 12.0 km along strike, 0 km depth.

`body008st120dp000`	0.8 km off xy-plane (far side), 12.0 km along strike, 0 km depth.
`body012st120dp000`	1.2 km off xy-plane (far side), 12.0 km along strike, 0 km depth.
`body016st120dp000`	1.6 km off xy-plane (far side), 12.0 km along strike, 0 km depth.
Transect at +12.0 km along strike, at a depth of 6 km	
`body-016st120dp060`	−1.6 km off xy-plane (near side), 12.0 km along strike, 6.0 km depth.
`body-012st120dp060`	−1.2 km off xy-plane (near side), 12.0 km along strike, 6.0 km depth.
`body-008st120dp060`	−0.8 km off xy-plane (near side), 12.0 km along strike, 6.0 km depth.
`body-004st120dp060`	−0.4 km off xy-plane (near side), 12.0 km along strike, 6.0 km depth.
`body000st120dp060`	0 km off xy-plane, 12.0 km along strike, 6.0 km depth.
`body004st120dp060`	0.4 km off xy-plane (far side), 12.0 km along strike, 6.0 km depth.
`body008st120dp060`	0.8 km off xy-plane (far side), 12.0 km along strike, 6.0 km depth.
`body012st120dp060`	1.2 km off xy-plane (far side), 12.0 km along strike, 6.0 km depth.
`body016st120dp060`	1.6 km off xy-plane (far side), 12.0 km along strike, 6.0 km depth.
Other stations surrounding the fault	
`body-100st-120dp000`	−10.0 km off xy-plane (near side), −12.0 km along strike, 0 km depth.
`body-100st-040dp000`	−10.0 km off xy-plane (near side), −4.0 km along strike, 0 km depth.
`body-100st040dp000`	−10.0 km off xy-plane (near side), 4.0 km along strike, 0 km depth.
`body-050st-120dp000`	−5.0 km off xy-plane (near side), −12.0 km along strike, 0 km depth.
`body-050st-040dp000`	−5.0 km off xy-plane (near side), −4.0 km along strike, 0 km depth.
`body-050st040dp000`	−5.0 km off xy-plane (near side), 4.0 km along strike, 0 km depth.
`body050st-120dp000`	5.0 km off xy-plane (far side), −12.0 km along strike, 0 km depth.
`body050st-040dp000`	5.0 km off xy-plane (far side), −4.0 km along strike, 0 km depth.
`body050st040dp000`	5.0 km off xy-plane (far side), 4.0 km along strike, 0 km depth.
`body100st-120dp000`	10.0 km off xy-plane (far side), −12.0 km along strike, 0 km depth.

`body100st-040dp000`	10.0 km off xy-plane (far side), −4.0 km along strike, 0 km depth.
`body100st040dp000`	10.0 km off xy-plane (far side), 4.0 km along strike, 0 km depth.

Note: The filenames and descriptions give the (x, y, z) coordinates of the station. For example, station `body050st-120dp000` is located at $(x, y, z) = (-12000\text{ m},\ 0\text{ m},\ 5000\text{ m})$.

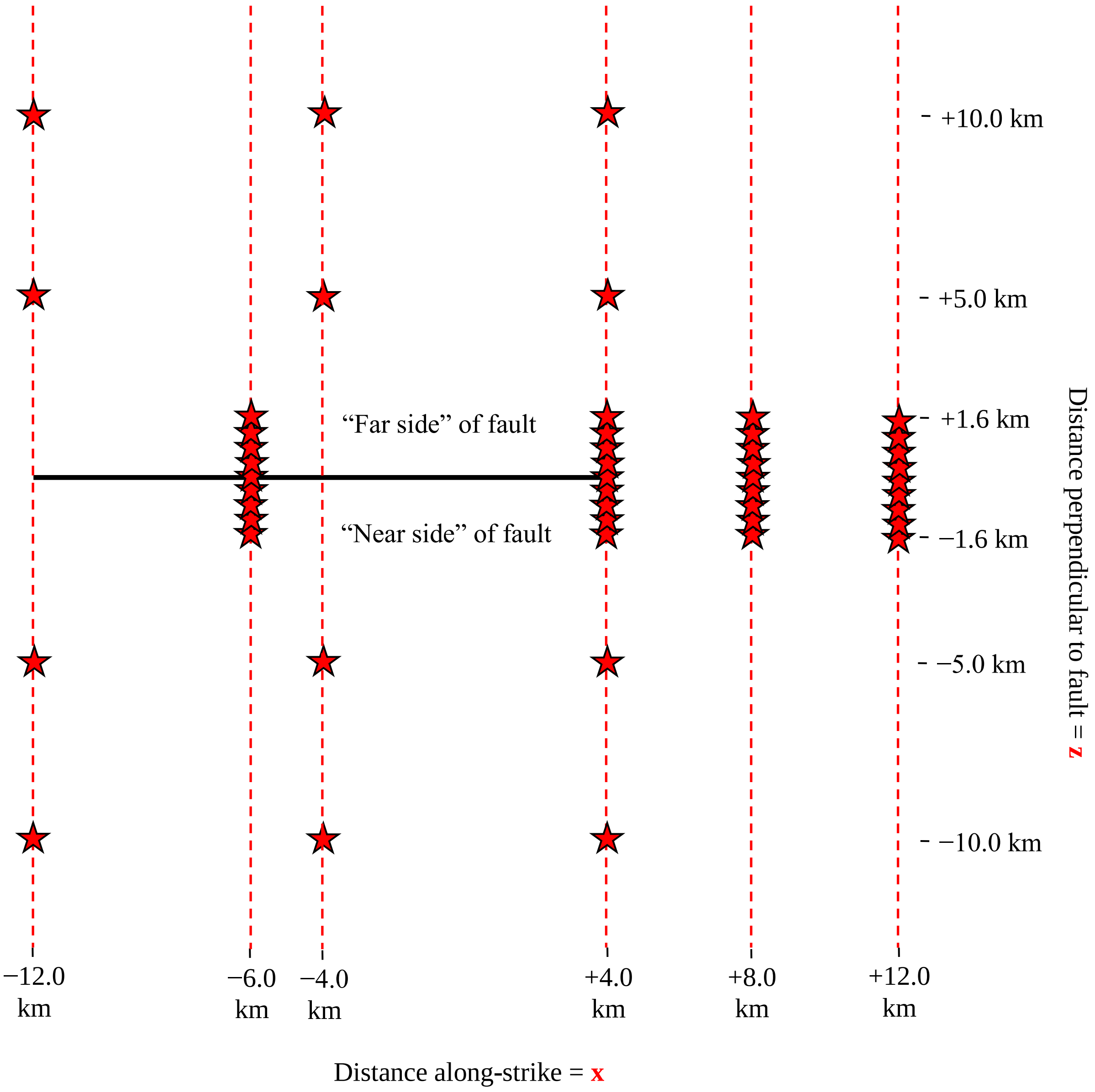
In the station names, the first number is the horizontal perpendicular distance from the station to the xy-plane. A positive number means that the station is located on the **far side**.

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.

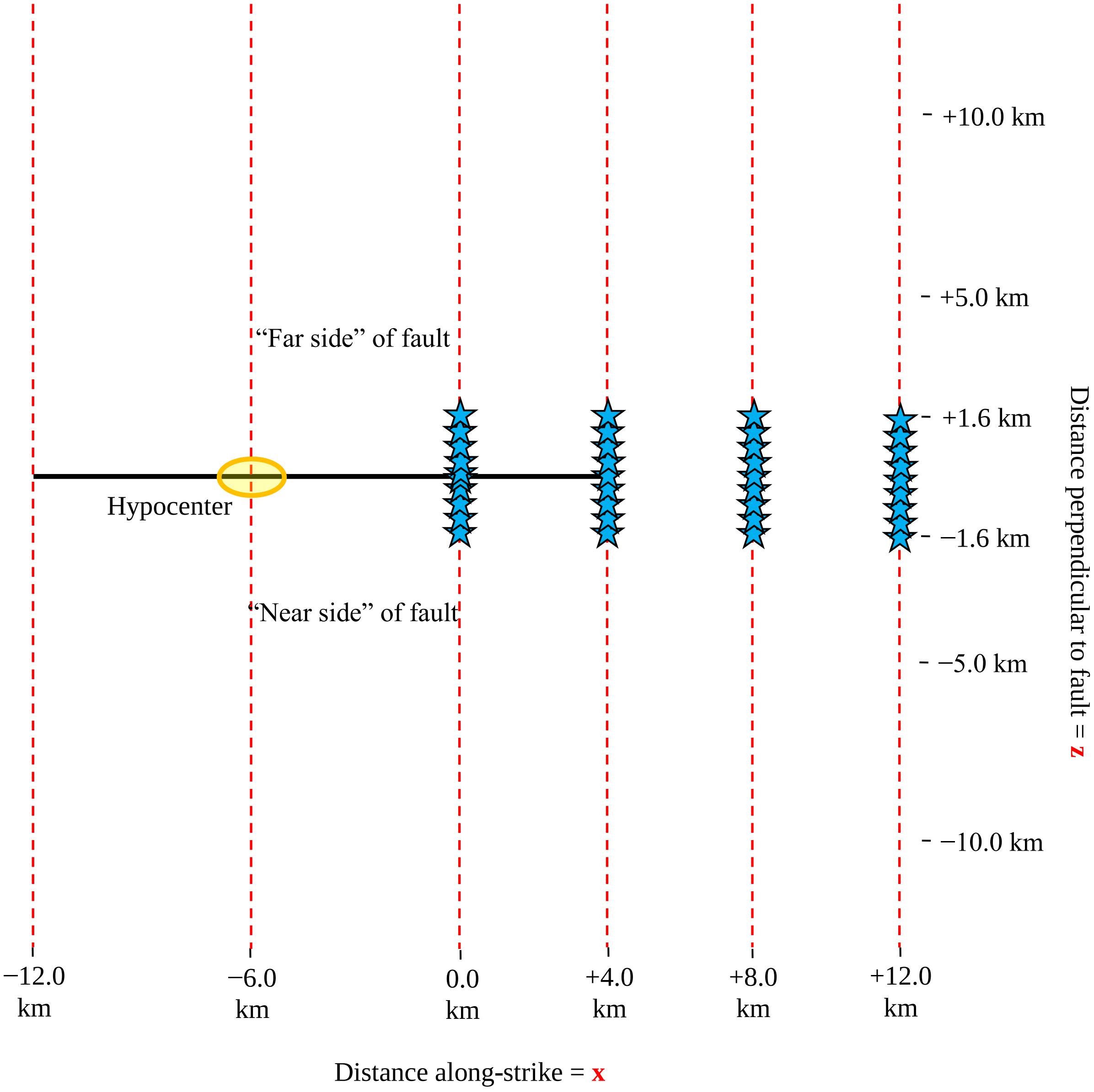
Note: There are two stations located directly on the fault trace, and one located in the right-hand edge of the fault. Because benchmark TPV33 is designed so that the rupture does not reach the earth's surface or any edge of the fault, there is no ambiguity about what values should be reported for those three stations.

Remark: There are more stations than usual. When you upload your files to the website, you don't have to upload them one-by-one. You can upload all your files in a single operation, using the Perl script available at: http://scecdata.usc.edu/cvws/downloads.html.

Off-Fault Station Locations at the Earth’s Surface



Off-Fault Station Locations at a Depth of 6 km (Hypocenter Depth)



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

There are 73 stations organized into 8 "transects." Each transect contains 9 stations, in a line perpendicular to the fault trace, spaced 400 m apart (except for the second transect listed below, which has 10 stations). Each transect extends from −1.6 km perpendicular distance from the x-axis, to +1.6 km perpendicular distance from the x-axis, so that it crosses the low-velocity zone. The 8 transects are located:

- At −6.0 km along strike, at the earth's surface (directly above the hypocenter).
- At 0.0 km along strike, at a depth of 6.0 km. (This transect has 10 stations, because the station at z = 0.0 km, which would lie in the fault surface, is replaced by two stations located at z = +0.1 km and z = −0.1 km).
- At +4.0 km along strike, at the earth's surface (at the right-hand edge of the fault surface).
- At +4.0 km along strike, at a depth of 6.0 km (at the right-hand edge of the fault surface).
- At +8.0 km along strike, at the earth's surface (which is 4 km past the right-hand edge of the fault surface).
- At +8.0 km along strike, at a depth of 6.0 km (which is 4 km past the right-hand edge of the fault surface).
- At +12.0 km along strike, at the earth's surface (which is 8 km past the right-hand edge of the fault surface).
- At +12.0 km along strike, at a depth of 6.0 km (which is 8 km past the right-hand edge of the fault surface).

There are an additional 12 stations distributed around the fault as follows:

- At −12.0 km along strike, −4.0 km along strike, and +4.0 km along strike.
- At −10.0 km perpendicular distance to the x -axis, −5.0 km perpendicular distance to the x -axis, +5.0 km perpendicular distance to the x -axis, and +10.0 km perpendicular distance to 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 TPV33	
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 TPV33	
File Section	**Description**
File Header	A series of lines, each beginning with a # symbol, that gives the following information: • Benchmark problem (TPV33) • 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	A **single line**, which lists the names of the 7 data fields, in column order, separated by spaces. It should be: `t  h-disp  h-vel  v-disp  v-vel  n-disp  n-vel` (all on one line). The server examines this line to check that your file contains the correct data fields.
Time History	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. **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). **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). 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.

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=TPV33
# author=A.Modeler
# date=2016/01/23
# code=MyCode
# code_version=3.7
# element_size=12.5 m
# time_step=0.00125
# num_time_steps=9600
# location= 5.0 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 6: Contour-Plot File Format

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

Contour-plot file for TPV33	
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 TPV33	
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 TPV33, the value of `j` can range from −12000 to 4000.
`k`	Distance down-dip (m). Sign convention: Zero is the earth’s surface, and positive means **underground**. For TPV33, the value of `k` can range from 0 to 10000.
`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 TPV33	
File Section	**Description**
File Header	A series of lines, each beginning with a # symbol, that gives the following information: • Benchmark problem (TPV33) • Author • Date • Code • Code version • Node spacing or element size • Descriptions of data columns (7 lines) • Anything else you think is relevant
Field List	A **single line**, which lists the names of the 3 data fields, in column order, separated by spaces. It should be: `j  k  t` (all on one line). The server examines this line to check that your file contains the correct data fields.
Rupture History	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. **C/C++ users:** We recommend using 14.6E or 14.6e floating-point format. **Fortran users:** We recommend using E15.7 or 1PE15.6 floating-point format. If a node never ruptures, the time should be given as 1.0E+09. Nodes may be listed in any order.

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=TPV33
# author=A.Modeler
# date=2016/01/23
# code=MyCode
# code_version=3.7
# element_size=12.5 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.
```