TPV28
Non-Planar Vertical Fault with Two Hills Benchmark

January 8, 2014

This 3D benchmark uses a single strike-slip fault in a half-space. The fault geometry is a vertical plane, except for two hills.

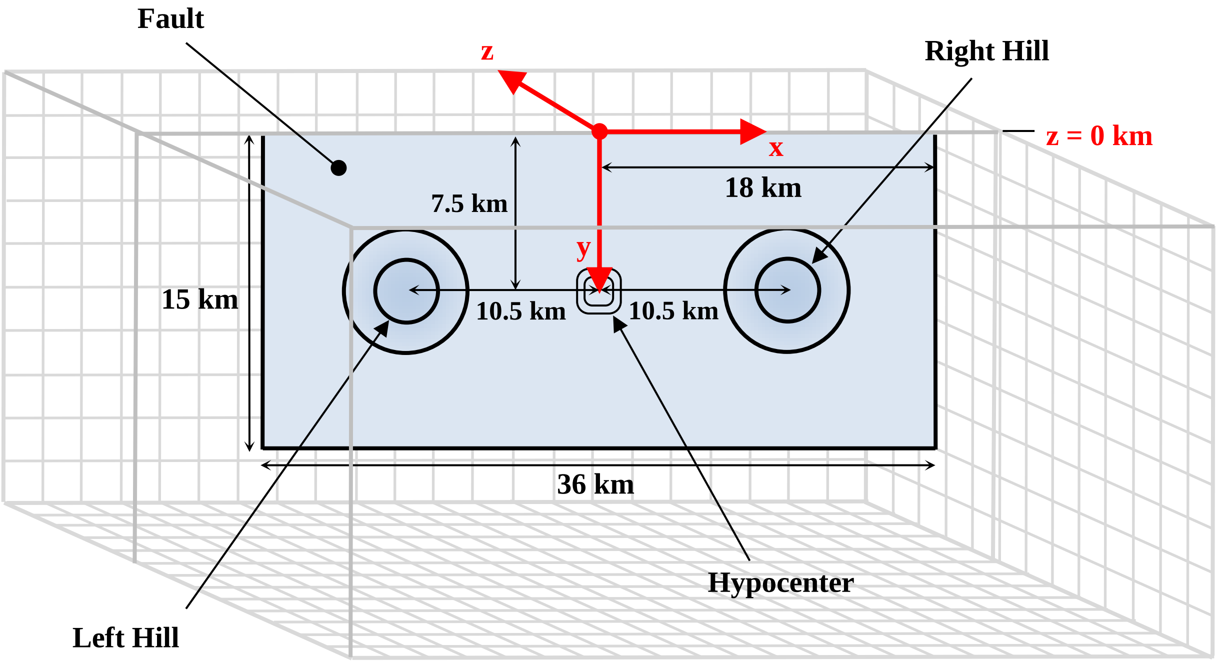
We request that you run the benchmark using 50 meter resolution. If possible, we encourage you to also run the benchmark at 25 meter resolution.

Benchmark Summary

- The geometry is a single strike-slip fault in a half-space. The fault is 36 km long and 15 km deep.
- The fault is a vertical plane, except for two hills. Each hill is circular, with a radius of 3000 m, and a height of 600 m.
- Material properties are uniform throughout the model volume.
- Initial shear and normal stresses on the fault are obtained by resolving a regional stress tensor onto the fault surface. The regional stress tensor is uniform throughout the model volume. There is no gravity in the model.
- The benchmark uses linear slip-weakening friction. Friction parameters are uniform over the fault surface.
- 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.

Contents

Part 1: Fault Geometry for TPV28



The model volume is a half-space.

The fault is a rectangle measuring 36000 m along-strike and 15000 m deep. The fault is a strike-slip, right-lateral fault. The fault reaches the earth's surface.

The hypocenter is located in the center of the fault, 18 km from either edge of the fault, at a depth of 7.5 km.

The fault is a vertical plane, except for the two hills. Each hill has a radius of 3000 m, and a height of 600 m. The centers of the hills are located 10.5 km on either side of the hypocenter, at a depth of 7.5 km. **The hills protrude toward the front side of the fault.**

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, 18000 m from either edge of the fault. In this coordinate system, the fault is:

$$\begin{aligned} -18000\text{ m} \le x &\le 18000\text{ m} \\ 0\text{ m} \le y &\le 15000\text{ m} \\ z &= f(x, y) \end{aligned}$$

The function $f(x, y)$ defines the three-dimensional shape of the fault. Let r_1 and r_2 represent the two-dimensional distance from the centers of the left and right hills, respectively:

$$r_1 = \sqrt{(x + 10500\ \text{m})^2 + (y - 7500\ \text{m})^2}$$

$$r_2 = \sqrt{(x - 10500\ \text{m})^2 + (y - 7500\ \text{m})^2}$$

Then the three-dimensional shape of the fault is:

$$f(x, y) = \begin{cases} -(300\ \text{m})\big(1 + \cos\big(\pi r_1/(3000\ \text{m})\big)\big), & \text{if } r_1 < 3000\ \text{m} \\ -(300\ \text{m})\big(1 + \cos\big(\pi r_2/(3000\ \text{m})\big)\big), & \text{if } r_2 < 3000\ \text{m} \\ 0, & \text{otherwise} \end{cases}$$

Notice that $f(x, y) = -600\ \text{m}$ when $r_1 = 0$ or $r_2 = 0$, that is, at the center of either hill. The minus sign indicates that the hills protrude in front of the fault. Also notice that $f(x, y)$ is smooth, that is, it has a continuous first derivative.

The hypocenter is 18000 m from either edge of the fault, and 7500 m deep, at location $(x, y, z) = (0\ \text{m}, 7500\ \text{m}, 0\ \text{m})$.

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 Benchmark

Material Properties

In TPV28, the entire model volume is a linear elastic material, with the following parameters.

Density $\rho = 2670\ \mathrm{kg/m^3}$
Shear-wave velocity $V_s = 3464\ \mathrm{m/s}$
Pressure-wave velocity $V_p = 6000\ \mathrm{m/s}$

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 3D fault surface. To nucleate the rupture, an additional shear stress is added near the hypocenter, as explained below. For TPV28, the initial stress tensor is uniform. The components of the stress tensor are defined in the following table.

Stress Tensor Components

Component	*Definition*
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:

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

$$\sigma_{11} = -60.00 \text{ MPa}$$

$$\sigma_{33} = -60.00 \text{ MPa}$$

$$\sigma_{13} = 29.38 \text{ MPa}$$

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

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

On the planar part of the fault, the resulting initial shear stress is pure right-lateral, that is, it has no along-dip component. On the hills, the initial shear stress has a non-zero along-dip component.

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:

$$\tau_{\text{nuke}}(x, y) = \begin{cases} 11.60 \text{ MPa}, & \text{if } r \leq 1400 \text{ m} \\ (5.80 \text{ MPa})\big(1 + \cos\big(\pi(r - 1400 \text{ m})/(600 \text{ m})\big)\big), & \text{if } 1400 \text{ m} \leq r \leq 2000 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

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

Notice that the initial shear stress on the fault is smooth, that is, it has a continuous first derivative. Also note that as a result of the nucleation shear stress, the total initial shear stress at the hypocenter is 40.98 MPa. By comparison, the initial yield stress at the hypocenter is 40.62 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:

$\mu_s = 0.677$

$\mu_d = 0.373$

$d_0 = 0.40$ m

$C_0 = 0$

Running Time, Node Spacing, and Results

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

Please submit results for two resolutions:

- Using **50 m node spacing** on the fault plane.
- Using **25 m node spacing** on the fault plane.

When we refer to "50 meter node spacing" we are referring to the two-dimensional spacing of the nodes, that is, the spacing between node locations projected onto the xy-plane. Within the hills, the three-dimensional spacing between nodes will be somewhat larger than 50 meters due to the three-dimensional fault geometry.

If you are unable to run the simulation with 25 m node spacing, then it is OK to omit the 25 m case. However, we suggest that you run the simulation with 25 m resolution if at all possible.

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

Benchmark TPV28 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 TPV28.

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 TPV28, we specify the initial normal and shear stresses on the non-planar 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 3D 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 TPV28 is a linear elastic benchmark, 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.

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.

To apply the second method, you must have formulas for the initial normal and shear stresses acting on the fault surface. We present the formulas below. First we present general formulas applicable to any three-dimensional fault surface, and then we specialize the formulas to the particular fault surface used in TPV28.

General Formulas for Resolving the Stress Tensor

We use the coordinate system illustrated in part 1. The three-dimensional fault surface is described by a function f as follows:

$$z = f(x, y)$$

Let f_x and f_y be the partial derivatives of f with respect to x and y respectively. For convenience in writing formulas, define h_1 and h_2 as:

$$h_1 = \frac{1}{\sqrt{1 + f_x^2}}$$

$$h_2 = \frac{1}{\sqrt{1 + f_x^2 + f_y^2}}$$

The stress tensor components are $\sigma_{11}, \sigma_{12}, \ldots$, as defined in part 2. We number the tensor components $1 = x, 2 = y, 3 = z$, so that $\sigma_{11} = \sigma_{xx}$, and $\sigma_{12} = \sigma_{xy}$, and so on. So the stress tensor is:

$$\text{stress tensor} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{pmatrix}$$

Let σ_n be the normal stress acting on the three-dimensional fault surface. We adopt the sign convention that a positive value of σ_n indicates compression. Then:

$$\sigma_n = h_2^2 \left[-f_x^2\, \sigma_{11} - 2\, f_x\, f_y\, \sigma_{12} + 2\, f_x\, \sigma_{13} - f_y^2\, \sigma_{22} + 2\, f_y\, \sigma_{23} - \sigma_{33} \right]$$

Let τ_{strike} be the shear stress along-strike acting on the three-dimensional fault surface. We adopt the sign convention that a positive value of τ_{strike} indicates right-lateral stress. Then:

$$\tau_{\text{strike}} = h_1\, h_2 \left[-f_x\, \sigma_{11} - f_y\, \sigma_{12} + (1 - f_x^2)\sigma_{13} - f_x\, f_y\, \sigma_{23} + f_x\, \sigma_{33} \right]$$

Let τ_{dip} be the shear stress along-dip acting on the three-dimensional fault surface. We adopt the sign convention that a positive value of τ_{dip} indicates downward stress. Downward stress is stress that causes the far side of the fault to move downward relative to the near side of the fault. As illustrated in part 1, the far side of the fault is the $+z$ side, and the near side of the fault is the $-z$ side. Then:

$$\begin{aligned} \tau_{\text{dip}} = h_1\, h_2^2 \Big[& f_x^2\, f_y\, \sigma_{11} - \left(1 + f_x^2 - f_y^2\right) f_x\, \sigma_{12} - 2\, f_x\, f_y\, \sigma_{13} - (1 + f_x^2) f_y\, \sigma_{22} \\ & + \left(1 + f_x^2 - f_y^2\right)\sigma_{23} + f_y\, \sigma_{33} \Big] \end{aligned}$$

Formulas for TPV28

In order to apply the above formulas to TPV28, we need formulas for the partial derivatives f_x and f_y. For convenience in writing the formulas, introduce the following definitions:

$$A_1 = A_2 = -300\text{ m}$$

$$R_1 = R_2 = 3000\text{ m}$$

$$x_1 = x + 10500\text{ m}$$

$$x_2 = x - 10500\text{ m}$$

$$y_1 = y_2 = y - 7500\text{ m}$$

$$r_1 = \sqrt{x_1^2 + y_1^2}$$

$$r_2 = \sqrt{x_2^2 + y_2^2}$$

Then the three-dimensional shape of the fault in TPV28 can be written as:

$$f(x,y) = \begin{cases} A_1(1 + \cos(\pi r_1/R_1)), & \text{if } r_1 < R_1 \\ A_2(1 + \cos(\pi r_2/R_2)), & \text{if } r_2 < R_2 \\ 0, & \text{otherwise} \end{cases}$$

The partial derivatives are:

$$f_x(x,y) = \begin{cases} -\pi \dfrac{A_1\, x_1}{r_1\, R_1} \sin(\pi r_1/R_1), & \text{if } 0 < r_1 < R_1 \\ -\pi \dfrac{A_2\, x_2}{r_2\, R_2} \sin(\pi r_2/R_2), & \text{if } 0 < r_2 < R_2 \\ 0, & \text{otherwise} \end{cases}$$

$$f_y(x,y) = \begin{cases} -\pi \dfrac{A_1\, y_1}{r_1\, R_1} \sin(\pi r_1/R_1), & \text{if } 0 < r_1 < R_1 \\ -\pi \dfrac{A_2\, y_2}{r_2\, R_2} \sin(\pi r_2/R_2), & \text{if } 0 < r_2 < R_2 \\ 0, & \text{otherwise} \end{cases}$$

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

The benchmark uses 20 stations on the fault, which are listed in the table on the next page. A diagram of station locations is given following the table. You need to supply one time-series file for each station.

Because the fault is non-planar, care is needed in specifying both the station locations, and the components of slip, slip-rate, and stress.

Station locations are given relative to the xy-plane. A station's location along-strike is the station's x-coordinate. A station's location down-dip is the station's y-coordinate. Then, the station's z-coordinate is given by the function $z = f(x, y)$ which defines the three-dimensional shape of the fault surface.

For example, a station which is described as "−10.5 km along strike, 7.5 km down-dip" would be located at coordinates $(x, y, z) = (-10500 \text{ m},\ 7500 \text{ m},\ -600 \text{ m})$. The z-coordinate comes from evaluating the function $z = f(x, y)$; specifically, $f(-10500 \text{ m},\ 7500 \text{ m}) = -600 \text{ m}$ using the formula for f given in part 1.

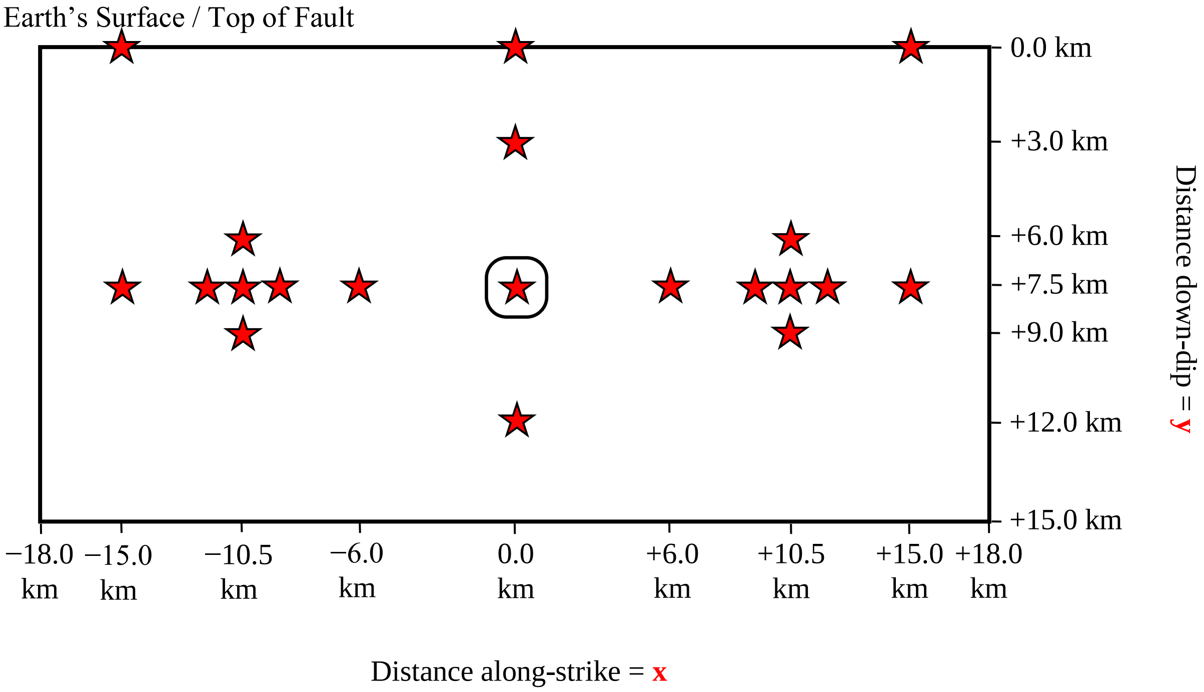
Components of slip, slip-rate, and stress are given relative to the curved three-dimensional fault surface. The "normal" direction is the direction perpendicular to the curved fault surface. The "horizontal" direction is the direction that is perpendicular to the y-axis and tangent to the curved fault surface. The "vertical" direction is the direction that is perpendicular to both the "normal" and "horizontal" directions. (The "vertical" direction is also tangent to the curved fault surface.)

On the planar part of the fault surface, the "normal" direction is the z-direction, the "horizontal" direction is the x-direction, and the "vertical" direction is the y-direction. But on the sloping sides of the hills, the "normal", "horizontal", and "vertical" directions do not agree with the z-, x-, and y-directions.

On-Fault Stations, for TPV28	
Station Name	**Location**
`faultst-120dp000`	On fault, −12.0 km along strike, 0 km down-dip.
`faultst000dp000`	On fault, 0.0 km along strike, 0 km down-dip.
`faultst120dp000`	On fault, 12.0 km along strike, 0 km down-dip.
`faultst000dp030`	On fault, 0.0 km along strike, 3.0 km down-dip.
`faultst-105dp060`	On fault, −10.5 km along strike, 6.0 km down-dip.
`faultst105dp060`	On fault, 10.5 km along strike, 6.0 km down-dip.
`faultst-150dp075`	On fault, −15.0 km along strike, 7.5 km down-dip.
`faultst-120dp075`	On fault, −12.0 km along strike, 7.5 km down-dip.
`faultst-105dp075`	On fault, −10.5 km along strike, 7.5 km down-dip.
`faultst-090dp075`	On fault, −9.0 km along strike, 7.5 km down-dip.
`faultst-060dp075`	On fault, −6.0 km along strike, 7.5 km down-dip.
`faultst000dp075`	On fault, 0.0 km along strike, 7.5 km down-dip (hypocenter).
`faultst060dp075`	On fault, 6.0 km along strike, 7.5 km down-dip.
`faultst090dp075`	On fault, 9.0 km along strike, 7.5 km down-dip.
`faultst105dp075`	On fault, 10.5 km along strike, 7.5 km down-dip.
`faultst120dp075`	On fault, 12.0 km along strike, 7.5 km down-dip.
`faultst150dp075`	On fault, 15.0 km along strike, 7.5 km down-dip.
`faultst-105dp090`	On fault, −10.5 km along strike, 9.0 km down-dip.
`faultst105dp090`	On fault, 10.5 km along strike, 9.0 km down-dip.
`faultst000dp120`	On fault, 0.0 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.

Station Locations on the Fault



There are 20 stations:

- −12.0 km, 0.0 km, and +12.0 km along-strike, and 0 km down-dip distance.
- 0.0 km along-strike, and 3.0 km down-dip distance.
- −10.5 km and +10.5 km along-strike, and 6.0 km down-dip distance.
- −15.0 km, −12.0 km, −10.5 km, −9.0 km, −6.0 km, 0.0 km, +6.0 km, +9.0 km, +10.5 km, +12.0 km, and +15.0 km along-strike, and 7.5 km down-dip distance.
- −10.5 km and +10.5 km along-strike, and 9.0 km down-dip distance.
- 0.0 km along-strike, and 12.0 km down-dip distance.

Note that 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.

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

On-Fault Time Series Data Fields for TPV28	
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 TPV28

File Section	**Description**
File Header	A series of lines, each beginning with a # symbol, that gives the following information: • Benchmark problem (TPV28) • 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=TPV28
# author=A.Modeler
# date=2014/01/23
# code=MyCode
# code_version=3.7
# element_size=100 m
# time_step=0.008
# num_time_steps=1625
# location= on fault, 10.5 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 6 off-fault stations listed below. All stations are at the earth's surface.

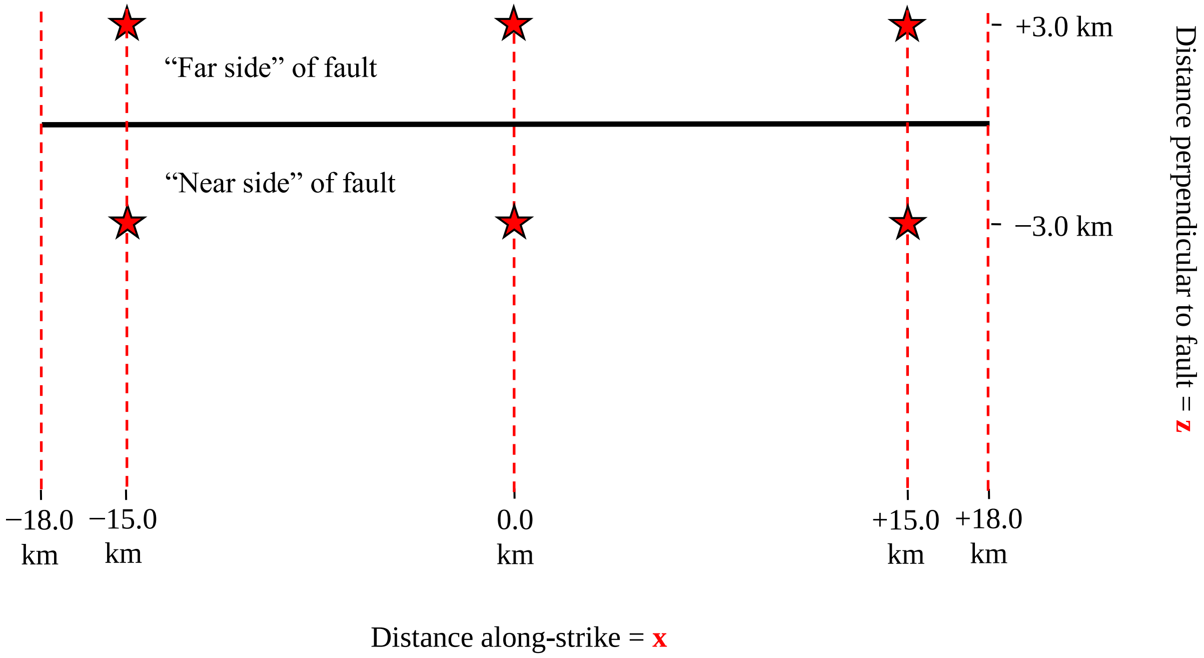
Refer to the next page for a diagram of station locations. You need to supply one time-series file for each station.

Off-Fault Stations for TPV28	
Station Name	**Location**
`body030st-150dp000`	3.0 km off fault (far side), −15.0 km along strike, 0 km depth.
`body-030st-150dp000`	−3.0 km off fault (near side), −15.0 km along strike, 0 km depth.
`body030st000dp000`	3.0 km off fault (far side), 0.0 km along strike, 0 km depth.
`body-030st000dp000`	−3.0 km off fault (near side), 0.0 km along strike, 0 km depth.
`body030st150dp000`	3.0 km off fault (far side), 15.0 km along strike, 0 km depth.
`body-030st150dp000`	−3.0 km off fault (near side), 15.0 km along strike, 0 km depth.

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

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.

There are 6 stations at the earth's surface:

- −15.0 km, 0.0 km, and +15.0 km along-strike, and +3.0 km perpendicular distance from the fault trace.
- −15.0 km, 0.0 km, and +15.0 km along-strike, and −3.0 km perpendicular distance from the fault trace.

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 fault 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 TPV28	
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 TPV28

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that gives the following information: • Benchmark problem (TPV28) • 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=TPV28
# author=A.Modeler
# date=2014/01/23
# code=MyCode
# code_version=3.7
# element_size=100 m
# time_step=0.008
# num_time_steps=1625
# location= 3.0 km off fault, 15.0 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 TPV28	
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 TPV28	
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 TPV28, the value of `j` can range from −18000 to 18000.
`k`	Distance down-dip (m). Sign convention: Zero is the earth's surface, and positive means **underground**. For TPV28, 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 TPV28	
File Section	**Description**
File Header	A series of lines, each beginning with a # symbol, that gives the following information: • Benchmark problem (TPV28) • 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=TPV28
# author=A.Modeler
# date=2014/01/23
# code=MyCode
# code_version=3.7
# element_size=100 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.
```