

# TPV34

## Imperial Fault, Model 1

January 31, 2016

This 3D benchmark uses a right-lateral, planar, vertical, strike-slip fault set in a half-space. The velocity structure is the actual 3D velocity structure surrounding the Imperial Fault, as given by the SCEC Community Velocity Model CVM-H. We are doing one benchmark, as shown in the following table.

| <b>Benchmarks</b> |                  |                     |                            |                           |                                 |
|-------------------|------------------|---------------------|----------------------------|---------------------------|---------------------------------|
| <i>Benchmark</i>  | <i>Dimension</i> | <i>Rupture Type</i> | <i>Material Properties</i> | <i>Velocity Structure</i> | <i>Minimum <math>V_S</math></i> |
| TPV34             | 3D               | Strike-slip         | Linear elastic             | SCEC CVM-H                | 1400 m/s                        |

For TPV34, we request that you select a resolution in the range of 25 meters to 50 meters. See part 3 for a discussion.

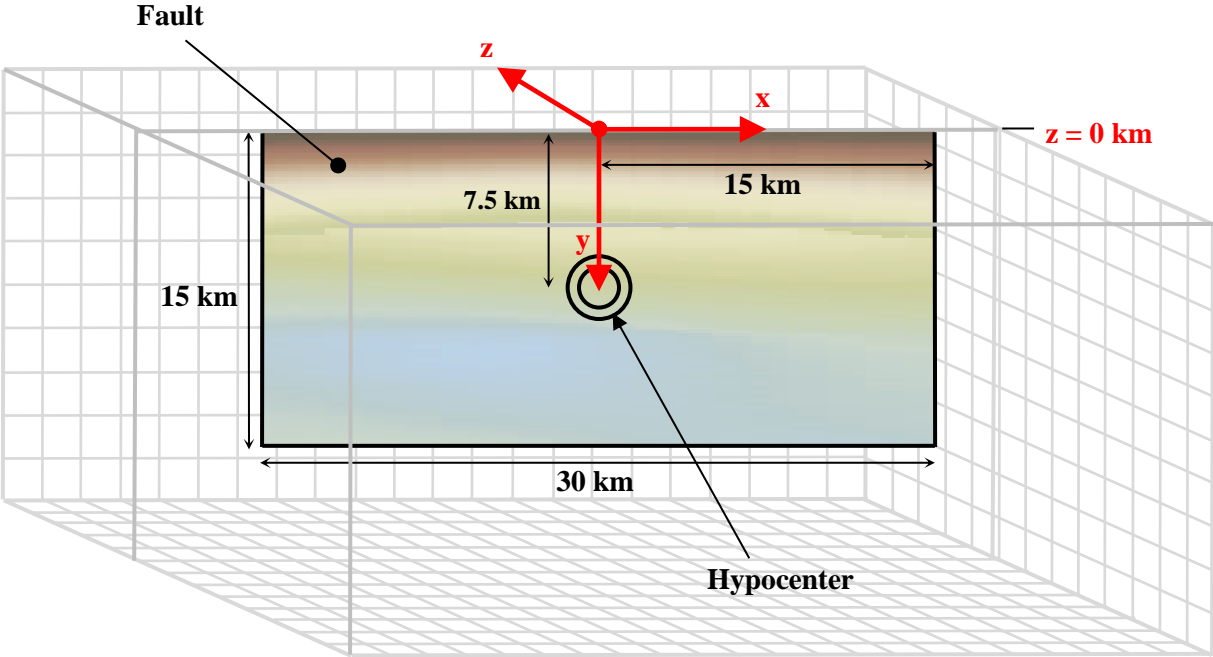
### Benchmark Summary

- 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 obtained from the SCEC Community Velocity Model CVM-H, modified so that the minimum  $V_S$  is 1400 m/s.
- Initial shear and normal stresses on the fault are proportional to the shear modulus. 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 TPV34**



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.

## The Imperial Fault



The red line marks the Imperial Fault. It straddles the California-Mexico border, south of the Salton Sea. The Imperial Fault is approximately 45 km long and 15 km deep, with a dip angle ranging from 81 to 90 degrees (according to the SCEC Community Fault Model CFM-4). In benchmark TPV34, we are using a vertical planar fault surface 30 km long and 15 km deep, which is located in the central 30 km of the red line.

## **Part 2: TPV34 Velocity Structure**

### **The SCEC Community Velocity Model CVM-H**

To obtain the velocity structure, you will need to install and run the SCEC Community Velocity Model CVM-H. For TPV34, we are using CVM-H version 15.1.0, which is the latest version as of this writing.

Instructions for installing and running CVM-H are available on our website at this address:

[http://sceccdata.usc.edu/cvws/download/cvmh/CVM-H\\_for\\_CVWS.pdf](http://sceccdata.usc.edu/cvws/download/cvmh/CVM-H_for_CVWS.pdf)

Additional resources for CVM-H are available on our website download page:

<http://sceccdata.usc.edu/cvws/downloads.html>

We will be obtaining the velocity structure using the program `vx_lite`, which is part of the CVM-H distribution. When running `vx_lite`, you supply an input file containing a list of points, and the program generates an output file containing velocities and densities. The program `vx_lite` is designed to produce sensible values for any underground point, so you don't have to worry about whether your points are located inside some model boundary.

### **Algorithm for Obtaining Velocities and Densities**

Use the following algorithm to obtain velocities and densities.

**Note: You should use the CVM-H velocity model throughout the entire model domain.**

Step 1: Let  $(x, y, z)$  be a point at which you want to obtain material properties, in the coordinate system shown in part 1 of this benchmark description, which is defined as follows:

$x$  = Distance along strike, in meters, positive to the right.

$y$  = Depth in meters, positive underground.

$z$  = Distance perpendicular to the fault, in meters, positive on the far side of the fault.

Step 2: Convert the coordinates into a new coordinate system  $(X, Y, Z)$  which is defined as follows

$X$  = Easting, in UTM coordinates, in meters.

$Y$  = Northing, in UTM coordinates, in meters.

$Z$  = Depth in meters, positive underground.

The UTM (Universal Transverse Mercator) coordinate system used in CVM-H is UTM zone 11, datum NAD 1927, geoid Clarke 1866.

The  $(X, Y, Z)$  coordinates are computed as follows:

$$X = 648446 \text{ m} - 0.5802386 x - 0.8144465 z$$

$$Y = 3625237 \text{ m} + 0.8144465 x - 0.5802386 z$$

$$Z = \max(y, 100 \text{ m})$$

Step 3: Place the  $(X, Y, Z)$  coordinates into an ASCII text file, which has three columns as follows:

Column 1 = Easting  $X$ , in meters.

Column 2 = Northing  $Y$ , in meters.

Column 3 = Depth  $Z$ , in meters (positive underground).

This text file is the input file to `vx_lite`. You can list as many points as you like, one point on each line of the file.

Step 4: Run the `vx_lite` program. Issue the following command:

```
${INSTALL_DIR}/bin/vx_lite -s -z dep -m ${INSTALL_DIR}/model < infile > outfile
```

In the above command, “`${INSTALL_DIR}`” is the directory where you installed CVM-H. You must replace it with the actual directory where CVM-H is installed. For example, if you installed CVM-H in `/usr/local/cvmh`, then you would issue the command like this:

```
/usr/local/cvmh/bin/vx_lite -s -z dep -m /usr/local/cvmh/model < infile > outfile
```

In the command, “infile” is the input file that contains the  $(X, Y, Z)$  coordinates, and “outfile” is the output file that contains the velocities and densities, as described below.

Step 5: Obtain the values of  $V_p$ ,  $V_s$ , and  $\rho$  from the `vx_lite` output file. The output file is an ASCII text file that contains 19 columns. Each line of the file corresponds to one input point. The CVM-H User Guide documents all the columns, but for our purposes we are only concerned with the last three columns:

Column 17: Compressional wave velocity  $V_p$  in m/s.

Column 18: Shear wave velocity  $V_s$  in m/s.

Column 19: Density  $\rho$  in  $\text{kg/m}^3$ .

Step 6: Check for error.

If  $V_p \leq 0$  or  $V_s \leq 0$  or  $\rho \leq 0$ , then an error has occurred. Stop and figure out what's wrong.

Step 7: Enforce minimum velocities.

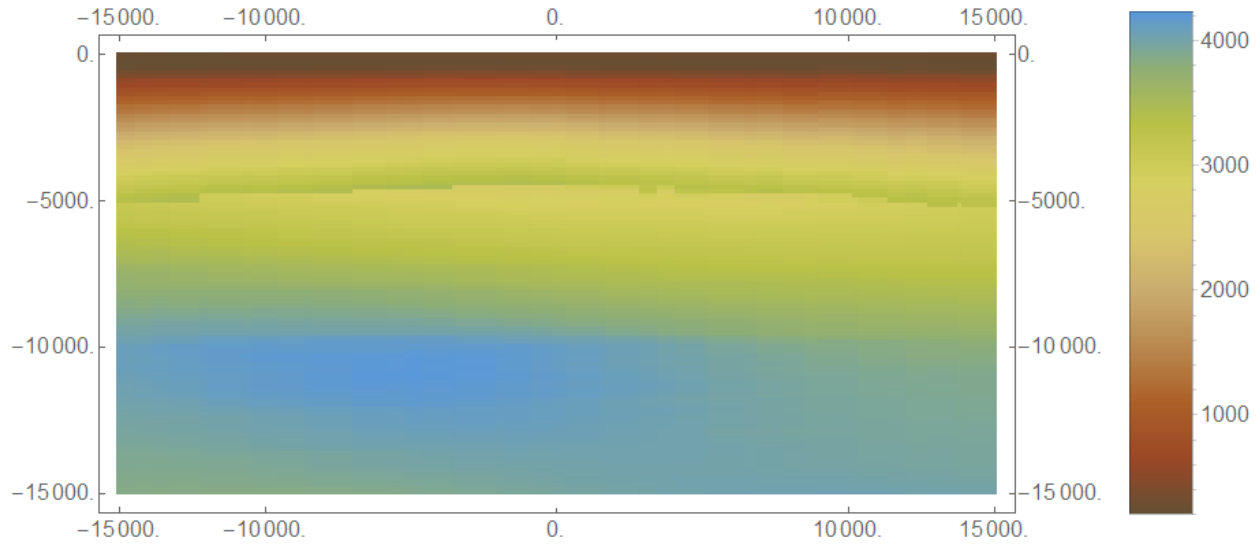
If  $V_p \leq 2984$  m/s or  $V_s \leq 1400$  m/s, then replace the velocity and density values as follows:

$$V_p = 2984 \text{ m/s}$$

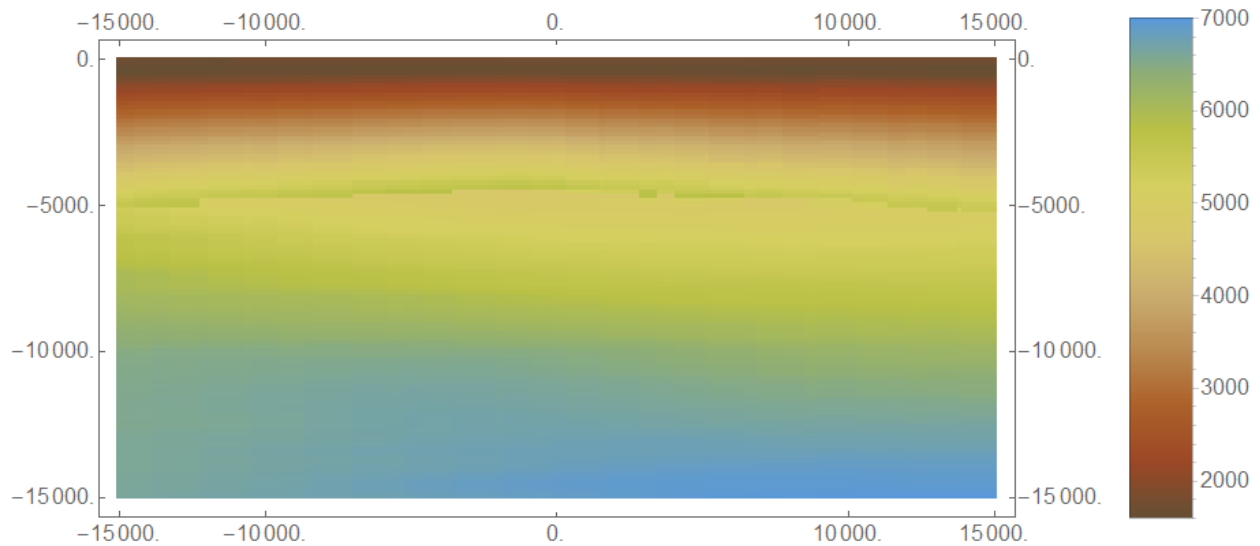
$$V_s = 1400 \text{ m/s}$$

$$\rho = 2220.34 \text{ kg/m}^3$$

## Velocity and Density Figures

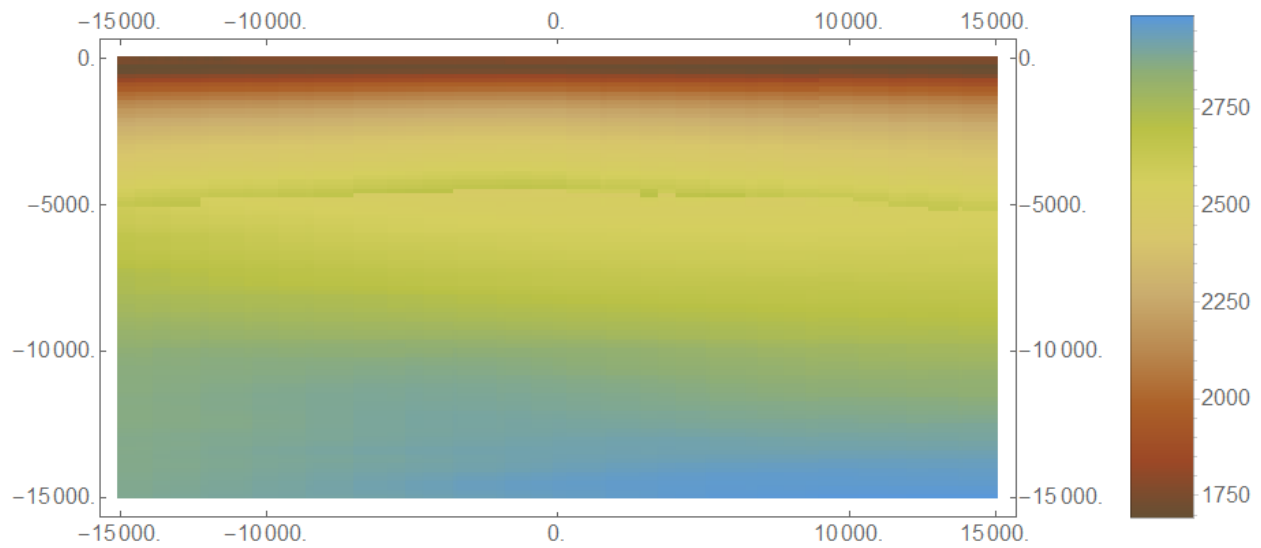


This is the shear-wave velocity  $V_S$  on the TPV34 fault surface, as obtained from the SCEC Community Velocity Model CVM-H. The color scale is shown in m/s. According to CVM-H, the minimum  $V_S$  on the fault surface is 199 m/s (and there are even lower values of  $V_S$  off the fault surface). In benchmark TPV34, we modify the CVM-H velocities so that the minimum  $V_S$  is 1400 m/s.



This is the compressional-wave velocity  $V_P$  on the TPV34 fault surface, as obtained from the SCEC Community Velocity Model CVM-H. The color scale is shown in m/s. According to CVM-H, the minimum  $V_P$  on the fault surface is 1590 m/s. In benchmark TPV34, we modify the CVM-H velocities so that the minimum  $V_P$  is 2984 m/s.





This is the density  $\rho$  on the TPV34 fault surface, as obtained from the SCEC Community Velocity Model CVM-H. The color scale is shown in  $\text{kg/m}^3$ . According to CVM-H, the minimum  $\rho$  on the fault surface is  $1702 \text{ kg/m}^3$ . In benchmark TPV34, we modify the CVM-H densities so that the minimum  $\rho$  is  $2220.34 \text{ kg/m}^3$ .

In all three of the preceding figures, the north end of the fault is on the right.

## Part 3: Description of the 3D Benchmark

### Initial Stress

The initial shear stress on the fault is pure right-lateral. The initial shear stress is:

$$\tau_0 = (30.00 \text{ MPa})(\mu/\mu_0)$$

The initial normal stress on the fault is:

$$\sigma_0 = (60.00 \text{ MPa})(\mu/\mu_0)$$

In the above formulas:

$\mu$  = shear modulus

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

Remark:  $\mu_0$  is the value of the shear modulus in benchmark TPV5 and many other benchmarks.

Remark: The CVM-H velocity model does not have a sudden change in material properties across the fault surface. So, you can use any reasonable method to obtain the shear modulus at a point on the fault surface. One possibility is to query CVM-H at the location of the point. Another possibility is to compute the average shear modulus for neighboring volume elements adjacent to both sides of the fault.

### 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 initial shear stress given above.** 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.

| <b>Friction Parameters</b> |                                   |               |
|----------------------------|-----------------------------------|---------------|
| <i>Symbol</i>              | <i>Parameter</i>                  | <i>Unit</i>   |
| $\mu_s$                    | Static coefficient of friction.   | Dimensionless |
| $\mu_d$                    | 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 4.

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 20.0 seconds after nucleation**.

**For TPV34, 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.**

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 4: Linear Slip-Weakening Friction

Benchmark TPV34 uses linear slip-weakening friction. This friction law has the following parameters and variables:

| Friction Parameters |                                   |               |
|---------------------|-----------------------------------|---------------|
| <i>Symbol</i>       | <i>Parameter</i>                  | <i>Unit</i>   |
| $\mu_s$             | Static coefficient of friction.   | Dimensionless |
| $\mu_d$             | 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> |
| $\sigma_n$         | Total normal stress acting on the fault, taken to be positive in compression. | Pascal      |
| $\tau$             | Shear stress acting on the fault.   | Pascal      |

When the fault is sliding, the shear stress  $\tau$  at a given point on the fault is given by:

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

The time-varying coefficient of friction  $\mu$  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 TPV34.

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

The benchmarks use 35 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.

| <b>On-Fault Stations, for TPV34</b> |  |
|-------------------------------------|--|
| <b>Station Name</b>                 | <b>Location</b>                                    |
| faultst-120dp000                    | On fault, -12.0 km along strike, 0 km down-dip.    |
| faultst-120dp010                    | On fault, -12.0 km along strike, 1.0 km down-dip.  |
| faultst-120dp024                    | On fault, -12.0 km along strike, 2.4 km down-dip.  |
| faultst-120dp050                    | On fault, -12.0 km along strike, 5.0 km down-dip.  |
| faultst-120dp075                    | On fault, -12.0 km along strike, 7.5 km down-dip.  |
| faultst-120dp100                    | On fault, -12.0 km along strike, 10.0 km down-dip. |
| faultst-120dp120                    | On fault, -12.0 km along strike, 12.0 km down-dip. |
| faultst-060dp000                    | On fault, -6.0 km along strike, 0 km down-dip.     |
| faultst-060dp010                    | On fault, -6.0 km along strike, 1.0 km down-dip.   |
| faultst-060dp024                    | On fault, -6.0 km along strike, 2.4 km down-dip.   |
| faultst-060dp050                    | On fault, -6.0 km along strike, 5.0 km down-dip.   |
| faultst-060dp075                    | On fault, -6.0 km along strike, 7.5 km down-dip.   |
| faultst-060dp100                    | On fault, -6.0 km along strike, 10.0 km down-dip.  |
| faultst-060dp120                    | On fault, -6.0 km along strike, 12.0 km down-dip.  |
| faultst000dp000                     | On fault, 0 km along strike, 0 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.      |
| 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.     |
| 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.   |
| 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.    |
| 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.  |
| 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. |

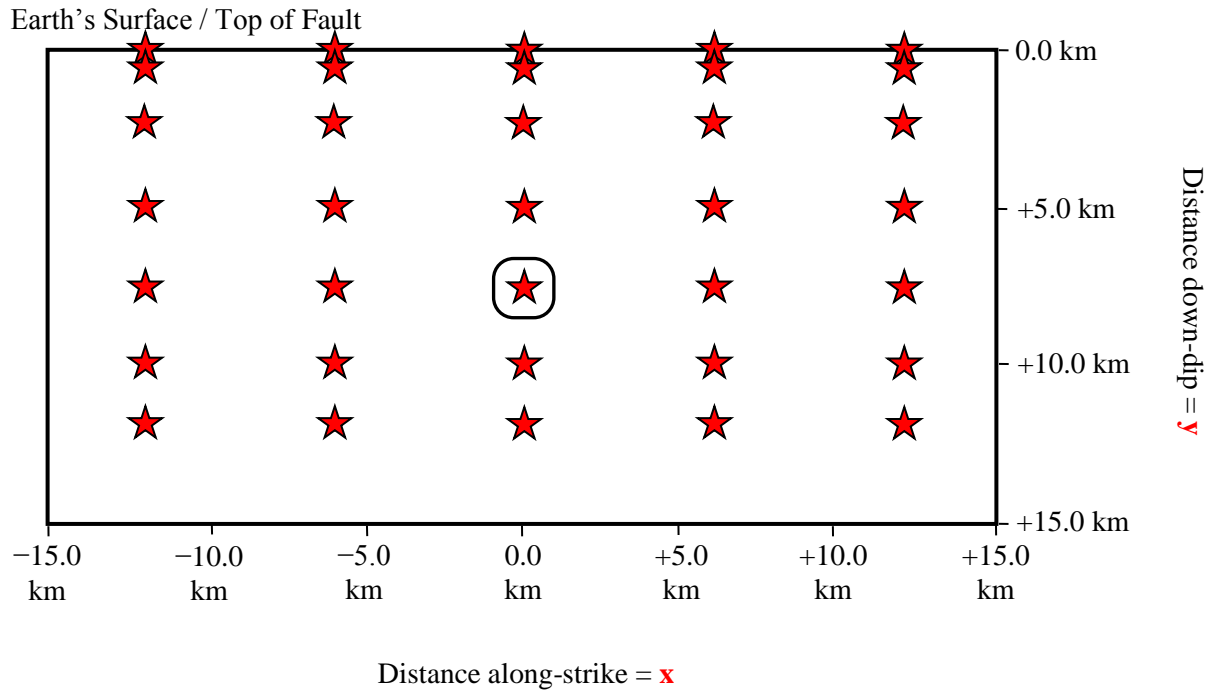
If you do not have a node at the location of a station, there are two options: (1) you can move the station to the nearest node, or (2) you can interpolate the data values from nodes near the station location.

**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  $(x, y, z) = (6000 \text{ m}, 2400 \text{ m}, 0 \text{ m})$ .

**Remark:** 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://scecddata.usc.edu/cvws/downloads.html>.

## On-Fault Station Locations





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

| <b>On-Fault Time Series Data Fields for TPV34</b> |  |
|---|--|
| <b>Field Name</b>                                 | <b>Description, Units, and Sign Convention</b>   |
| t   | Time (s).  |
| h-slip  | Horizontal slip along-strike (m).<br>Sign convention: Positive means <b>right lateral</b> slip.  |
| h-slip-rate                                       | Horizontal slip rate along-strike (m/s).<br>Sign convention: Positive means <b>right lateral</b> motion.   |
| h-shear-stress                                    | Horizontal shear stress along-strike (MPa).<br>Sign convention: Positive means shear stress that tends to cause <b>right-lateral</b> slip.   |
| v-slip  | Vertical along-dip slip (m).<br>Sign convention: Positive means <b>downward slip</b> (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).<br>Sign convention: Positive means <b>downward motion</b> (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).<br>Sign convention: Positive means shear stress that tends to cause <b>downward slip</b> (that is, the far side of the fault moving downward relative to the near side of the fault). |
| n-stress  | Normal stress (MPa).<br>Sign convention: Positive means <b>extension</b> .   |

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.

| <b>On-Fault Time Series File Format for TPV34</b> |  |
|---|--|
| <b>File Section</b>                               | <b>Description</b>   |
| File Header                                       | <p>A series of lines, each beginning with a # symbol, that gives the following information:</p> <ul style="list-style-type: none"> <li>• Benchmark problem (TPV34)</li> <li>• Author</li> <li>• Date</li> <li>• Code</li> <li>• Code version</li> <li>• Node spacing or element size</li> <li>• Time step</li> <li>• Number of time steps in file</li> <li>• Station location</li> <li>• Descriptions of data columns (7 lines)</li> <li>• Anything else you think is relevant</li> </ul>  |
| Field List  | <p>A <b>single line</b>, 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><b>C/C++ users:</b> 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><b>Fortran users:</b> 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=TPV34
# author=A.Modeler
# date=2016/01/23
# 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 56 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-150st-150dp000                    | -15.0 km off <i>xy</i> -plane (near side), -15.0 km along strike, 0 km depth.   |
| body-150st-150dp024                    | -15.0 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-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-150st150dp024                     | -15.0 km off <i>xy</i> -plane (near side), 15.0 km along strike, 2.4 km depth.  |
| body-090st-200dp000                    | -9.0 km off <i>xy</i> -plane (near side), -20.0 km along strike, 0 km depth.    |
| body-090st-200dp024                    | -9.0 km off <i>xy</i> -plane (near side), -20.0 km along strike, 2.4 km depth.  |
| body-090st-100dp000                    | -9.0 km off <i>xy</i> -plane (near side), -10.0 km along strike, 0 km depth.    |
| body-090st-100dp024                    | -9.0 km off <i>xy</i> -plane (near side), -10.0 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-090st000dp024                     | -9.0 km off <i>xy</i> -plane (near side), 0 km along strike, 2.4 km depth.      |
| body-090st100dp000                     | -9.0 km off <i>xy</i> -plane (near side), 10.0 km along strike, 0 km depth.     |
| body-090st100dp024                     | -9.0 km off <i>xy</i> -plane (near side), 10.0 km along strike, 2.4 km depth.   |
| body-090st200dp000                     | -9.0 km off <i>xy</i> -plane (near side), 20.0 km along strike, 0 km depth.     |
| body-090st200dp024                     | -9.0 km off <i>xy</i> -plane (near side), 20.0 km along strike, 2.4 km depth.   |
| body-030st-200dp000                    | -3.0 km off <i>xy</i> -plane (near side), -20.0 km along strike, 0 km depth.    |
| body-030st-200dp024                    | -3.0 km off <i>xy</i> -plane (near side), -20.0 km along strike, 2.4 km depth.  |
| body-030st-100dp000                    | -3.0 km off <i>xy</i> -plane (near side), -10.0 km along strike, 0 km depth.    |

|                     |  |
|---------------------|--|
| body-030st-100dp024 | -3.0 km off <i>xy</i> -plane (near side), -10.0 km along strike, 2.4 km depth. |
| body-030st000dp000  | -3.0 km off <i>xy</i> -plane (near side), 0 km along strike, 0 km depth.       |
| body-030st000dp024  | -3.0 km off <i>xy</i> -plane (near side), 0 km along strike, 2.4 km depth.     |
| body-030st100dp000  | -3.0 km off <i>xy</i> -plane (near side), 10.0 km along strike, 0 km depth.    |
| body-030st100dp024  | -3.0 km off <i>xy</i> -plane (near side), 10.0 km along strike, 2.4 km depth.  |
| body-030st200dp000  | -3.0 km off <i>xy</i> -plane (near side), 20.0 km along strike, 0 km depth.    |
| body-030st200dp024  | -3.0 km off <i>xy</i> -plane (near side), 20.0 km along strike, 2.4 km depth.  |
| body000st-200dp000  | 0 km off <i>xy</i> -plane (in the plane), -20.0 km along strike, 0 km depth.   |
| body000st-200dp024  | 0 km off <i>xy</i> -plane (in the plane), -20.0 km along strike, 2.4 km depth. |
| body000st200dp000   | 0 km off <i>xy</i> -plane (in the plane), 20.0 km along strike, 0 km depth.    |
| body000st200dp024   | 0 km off <i>xy</i> -plane (in the plane), 20.0 km along strike, 2.4 km depth.  |
| body030st-200dp000  | 3.0 km off <i>xy</i> -plane (far side), -20.0 km along strike, 0 km depth.     |
| body030st-200dp024  | 3.0 km off <i>xy</i> -plane (far side), -20.0 km along strike, 2.4 km depth.   |
| body030st-100dp000  | 3.0 km off <i>xy</i> -plane (far side), -10.0 km along strike, 0 km depth.     |
| body030st-100dp024  | 3.0 km off <i>xy</i> -plane (far side), -10.0 km along strike, 2.4 km depth.   |
| body030st000dp000   | 3.0 km off <i>xy</i> -plane (far side), 0 km along strike, 0 km depth.         |
| body030st000dp024   | 3.0 km off <i>xy</i> -plane (far side), 0 km along strike, 2.4 km depth.       |
| body030st100dp000   | 3.0 km off <i>xy</i> -plane (far side), 10.0 km along strike, 0 km depth.      |
| body030st100dp024   | 3.0 km off <i>xy</i> -plane (far side), 10.0 km along strike, 2.4 km depth.    |
| body030st200dp000   | 3.0 km off <i>xy</i> -plane (far side), 20.0 km along strike, 0 km depth.      |
| body030st200dp024   | 3.0 km off <i>xy</i> -plane (far side), 20.0 km along strike, 2.4 km depth.    |
| body090st-200dp000  | 9.0 km off <i>xy</i> -plane (far side), -20.0 km along strike, 0 km depth.     |
| body090st-200dp024  | 9.0 km off <i>xy</i> -plane (far side), -20.0 km along strike, 2.4 km depth.   |
| body090st-100dp000  | 9.0 km off <i>xy</i> -plane (far side), -10.0 km along strike, 0 km depth.     |

|                    |   |
|--------------------|---|
| body090st-100dp024 | 9.0 km off <i>xy</i> -plane (far side), -10.0 km along strike, 2.4 km depth.  |
| body090st000dp000  | 9.0 km off <i>xy</i> -plane (far side), 0 km along strike, 0 km depth.        |
| body090st000dp024  | 9.0 km off <i>xy</i> -plane (far side), 0 km along strike, 2.4 km depth.      |
| body090st100dp000  | 9.0 km off <i>xy</i> -plane (far side), 10.0 km along strike, 0 km depth.     |
| body090st100dp024  | 9.0 km off <i>xy</i> -plane (far side), 10.0 km along strike, 2.4 km depth.   |
| body090st200dp000  | 9.0 km off <i>xy</i> -plane (far side), 20.0 km along strike, 0 km depth.     |
| body090st200dp024  | 9.0 km off <i>xy</i> -plane (far side), 20.0 km along strike, 2.4 km depth.   |
| body150st-150dp000 | 15.0 km off <i>xy</i> -plane (far side), -15.0 km along strike, 0 km depth.   |
| body150st-150dp024 | 15.0 km off <i>xy</i> -plane (far side), -15.0 km along strike, 2.4 km depth. |
| body150st000dp000  | 15.0 km off <i>xy</i> -plane (far side), 0 km along strike, 0 km depth.       |
| body150st000dp024  | 15.0 km off <i>xy</i> -plane (far side), 0 km along strike, 2.4 km depth.     |
| body150st150dp000  | 15.0 km off <i>xy</i> -plane (far side), 15.0 km along strike, 0 km depth.    |
| body150st150dp024  | 15.0 km off <i>xy</i> -plane (far 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-030st-200dp024` is located at  $(x, y, z) = (-20000 \text{ m}, 2400 \text{ m}, -3000 \text{ m})$ .

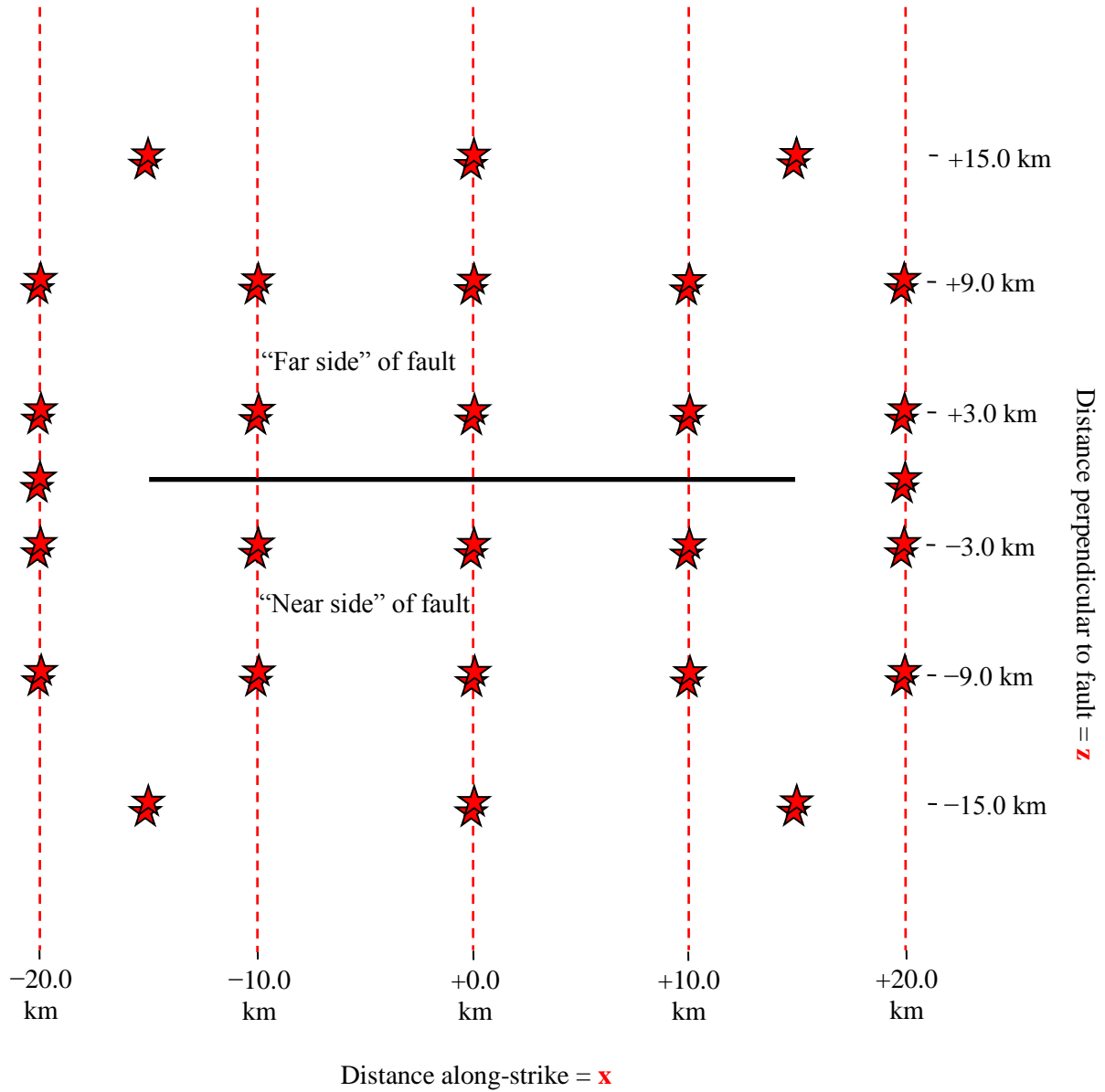
In the station names, the first number is the horizontal perpendicular distance from the station to the *xy*-plane. A positive number means that the station is located on the **far side**.

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.

**Remark:** 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://scecddata.usc.edu/cvws/downloads.html>.

## Off-Fault Station Locations



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

The 56 stations are organized into 28 "boreholes." Each "borehole" contains 2 stations: one at the earth's surface, and one at a depth of 2.4 km.

The 28 "boreholes" are at the following locations:

- At  $-15.0$  km perpendicular distance from the  $x$ -axis, at the following locations along-strike:  $-15.0$  km,  $0$  km, and  $+15$  km.
- At  $-9.0$  km perpendicular distance from the  $x$ -axis, at the following locations along-strike:  $-20.0$  km,  $-10.0$  km,  $0$  km,  $+10.0$  km, and  $+20$  km.
- At  $-3.0$  km perpendicular distance from the  $x$ -axis, at the following locations along-strike:  $-20.0$  km,  $-10.0$  km,  $0$  km,  $+10.0$  km, and  $+20$  km.
- At  $0$  km perpendicular distance from the  $x$ -axis, at the following locations along-strike:  $-20.0$  km and  $+20$  km.
- At  $+3.0$  km perpendicular distance from the  $x$ -axis, at the following locations along-strike:  $-20.0$  km,  $-10.0$  km,  $0$  km,  $+10.0$  km, and  $+20$  km.
- At  $+9.0$  km perpendicular distance from the  $x$ -axis, at the following locations along-strike:  $-20.0$  km,  $-10.0$  km,  $0$  km,  $+10.0$  km, and  $+20$  km.
- At  $+15.0$  km perpendicular distance from the  $x$ -axis, at the following locations along-strike:  $-15.0$  km,  $0$  km, and  $+15$  km.

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**.

**Remark:** The Imperial Fault is located in a deep basin. At the Imperial Fault, a depth of 2.4 km corresponds approximately to a shear wave velocity  $V_S$  equal to 1600 m/s. We have chosen this depth to be representative of the bottom of the basin.



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

| <b>Off-Fault Time Series Data Fields for TPV34</b> |  |
|--|--|
| <b>Field Name</b>                                  | <b>Description, Units, and Sign Convention</b>   |
| t  | Time (s).  |
| h-disp   | Horizontal displacement, parallel to the fault strike (m).<br>Sign convention: Positive means displacement <b>to the right</b> relative to the station's initial position (that is, in the $+x$ direction).  |
| h-vel  | Horizontal velocity, parallel to the fault strike (m/s).<br>Sign convention: Positive means motion <b>to the right</b> (that is, in the $+x$ direction).   |
| v-disp   | Vertical displacement (m).<br>Sign convention: Positive means displacement <b>downward</b> relative to the station's initial position (that is, in the $+y$ direction).  |
| v-vel  | Vertical velocity (m/s).<br>Sign convention: Positive means motion <b>downward</b> (that is, in the $+y$ direction).   |
| n-disp   | Horizontal displacement, perpendicular to the fault strike (m).<br>Sign convention: Positive means displacement <b>away from the viewer, into the paper</b> (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).<br>Sign convention: Positive means motion <b>away from the viewer, into the paper</b> (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.

| <b>Off-Fault Time Series File Format for TPV34</b> |  |
|--|--|
| <b>File Section</b>                                | <b>Description</b>   |
| File Header  | <p>A series of lines, each beginning with a # symbol, that gives the following information:</p> <ul style="list-style-type: none"> <li>• Benchmark problem (TPV34)</li> <li>• Author</li> <li>• Date</li> <li>• Code</li> <li>• Code version</li> <li>• Node spacing or element size</li> <li>• Time step</li> <li>• Number of time steps in file</li> <li>• Station location</li> <li>• Descriptions of data columns (7 lines)</li> <li>• Anything else you think is relevant</li> </ul>  |
| Field List   | <p>A <b>single line</b>, 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><b>C/C++ users:</b> 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><b>Fortran users:</b> 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=TPV34
# author=A.Modeler
# date=2016/01/23
# 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 TPV34 |                              |
|-----------------------------|------------------------------|
| 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 TPV34 |   |
|------------------------------------|---|
| Field Name                         | Description, Units, and Sign Convention   |
| j                                  | Distance along strike (m).<br>Sign convention: Positive means a location <b>to the right</b> of the origin.<br>For TPV34, the value of $j$ can range from $-15000$ to $15000$ . |
| k                                  | Distance down-dip (m).<br>Sign convention: Zero is the earth's surface, and positive means <b>underground</b> .<br>For TPV34, the value of $k$ can range from $0$ to $15000$ .  |
| t                                  | Rupture time (s).<br>This is the time at which fault slip-rate first changes from $0$ to greater than $0.001$ m/s.<br>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.

| <b>Contour Plot File Format for TPV34</b> |  |
|---|--|
| <b>File Section</b>                       | <b>Description</b>   |
| File Header                               | <p>A series of lines, each beginning with a # symbol, that gives the following information:</p> <ul style="list-style-type: none"> <li>• Benchmark problem (TPV34)</li> <li>• Author</li> <li>• Date</li> <li>• Code</li> <li>• Code version</li> <li>• Node spacing or element size</li> <li>• Descriptions of data columns (7 lines)</li> <li>• Anything else you think is relevant</li> </ul>   |
| Field List                                | <p>A <b>single line</b>, 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 <math>(j, k)</math> coordinates of a node on the fault surface, and the time <math>t</math> at which that node ruptures.</p> <p><b>C/C++ users:</b> We recommend using 14.6E or 14.6e floating-point format.</p> <p><b>Fortran users:</b> 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=TPV34
# author=A.Modeler
# date=2016/01/23
# 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.
```