CRESCENT/SEAS Benchmark Problems BP9-QD

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The problem set-up for benchmark BP9-QD is that for a planar, thrust fault (with dip angle ψ) intersecting a free surface, in both 2D and 3D (when differentiating, these will be referred to as BP9-QD-2D and BP9-QD-3D, respectively), with depth-varying background stresses. Radiation damping is used to approximate the inertia effects. The 3D problem is outlined in the first few sections, with details of the 2D problem (based on the 3D) given in a subsequent section.

1 3D Problem Setup

The medium is assumed to be a homogeneous, isotropic, linear elastic half-space defined by

$$\mathbf{x} = (x_1, x_2, x_3) \in (-\infty,\ \infty) \times (-\infty,\ \infty) \times (0,\ \infty),$$

with a free surface at $x_3 = 0$ and x_3 as positive downward. We assume 3D motion, letting $u_i = u_i(\mathbf{x}, t), i = 1, 2, 3$ denote the displacement in the positive x_i-direction, with u_1, u_2 in the (horizontal) x_1- and x_2-directions, respectively, and u_3 in the (vertical) x_3-direction (note that positive values of u_3 are downward). A planar fault is embedded in the material, dipping at ψ degrees from horizontal, see Fig. 1(a), with a 2D cross section (at $x_2 = 0$) shown in Fig. 1(b). We assume $0 \leq \psi \leq 90°$. The fault plane is given by $x_1 = x_3 \cot(\psi)$ and partitions the domain into two sub-domains defined by superscripts "+" and "−", namely, $\Omega^+ = \{(x_1, x_2, x_3) : \quad x_1 \geq x_3 \cot(\psi)\}$ (the hanging wall) and $\Omega^- = \{(x_1, x_2, x_3) : \quad x_1 \leq x_3 \cot(\psi)\}$ (the foot wall).

We also introduce unit vectors: $\hat{s} = (-\cos\psi, 0, -\sin\psi)$ is the tangent vector to the fault pointing up-dip and $\hat{n} = (\sin\psi, 0, -\cos\psi)$ is the normal vector pointing from the − to + side of the fault. We also define $\hat{e} = \mathbf{e}_2 = (0, 1, 0)$, the unit vector pointing along-strike.

The displacements and strains are defined with respect to a prestressed, equilibrium reference state that exists at $t = 0$, as explained below. For this benchmark we approximate inertial effects with radiation damping and quasi-static stress changes are calculated using the equilibrium equation

$$\mathbf{0} = \nabla \cdot \boldsymbol{\sigma}. \tag{1}$$

Hooke's law relates stresses to strains by

$$\sigma_{ij} = K\epsilon_{kk}\delta_{ij} + 2\mu\left(\epsilon_{ij} - \frac{1}{3}\epsilon_{kk}\delta_{ij}\right), \tag{2}$$

for bulk modulus K and shear modulus μ. The strain-displacement relations are given by

$$\epsilon_{ij} = \frac{1}{2}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right]. \tag{3}$$

The solution to 1 can be expressed as the superposition of the following three solutions:

1. A rigid body translation with zero associated stress changes, denoted u_i^{rigid}, $i = 1, 2, 3$. This rigid body translation is different for the two sub-domains, and the discontinuity in that translational motion across the fault is the long-term slip.
2. An equilibrium, prestressed reference configuration with initial stress tensor given by

$$\boldsymbol{\sigma}^0 = \begin{bmatrix} \sigma_{11}^0 & \sigma_{12}^0 & \sigma_{13}^0 \\ \sigma_{21}^0 & \sigma_{22}^0 & \sigma_{23}^0 \\ \sigma_{13}^0 & \sigma_{23}^0 & \sigma_{33}^0 \end{bmatrix}. \tag{4}$$

The assumption of linear elastic response means that $\boldsymbol{\sigma}^0$ does not directly influence the medium response. However, the fault tractions associated with $\boldsymbol{\sigma}^0$ do influence fault slip through the friction law. For this reason, only those fault tractions are specified in this benchmark.
3. Displacements, strains, and stress changes due to fault slip differing from the steady slip provided by the rigid body translation.

2 3D Boundary and Interface Conditions

The semi-infinite domain problem requires conditions at infinity. We require that stress and displacement changes (from rigid body translation), vanish at infinity, namely

$$u_i - u_i^{\text{rigid}}, i = 1, 2, 3 \to 0, \quad x_1, x_2 \to \pm\infty, x_3 \to \infty \tag{5a}$$

$$\Delta\sigma_{ij} \to 0 \quad x_1, x_2 \to \pm\infty, x_3 \to \infty. \tag{5b}$$

The rigid body translation we specify as

$$u_1^{\pm,\text{rigid}}(t) = \mp\frac{V_p t}{2}\cos\psi, \tag{6a}$$

$$u_2^{\pm,\text{rigid}}(t) = 0, \tag{6b}$$

$$u_3^{\pm,\text{rigid}}(t) = \mp\frac{V_p t}{2}\sin\psi, \tag{6c}$$

where V_p is the plate rate. Note that $\hat{s}_j(u_j^{+,\text{rigid}} - u_j^{-,\text{rigid}}) = V_p t$ and $\hat{n}_j(u_j^{+,\text{rigid}} - u_j^{-,\text{rigid}}) = 0$, showing that the rigid body translation produces thrust-sense slip at the plate rate, but no opening or interpenetration.

A free surface lies at $x_3 = 0$, where all components of the traction vector equal 0. Mathematically, this generates the following boundary condition:

$$\sigma_{j3}(x_1, x_2, 0, t) = 0, \quad j = 1, 2, 3. \tag{7}$$

In addition to boundary conditions, we require six interface conditions. Letting $X_1(x_3) = \cot(\psi)x_3$ be the distance down-dip from the surface, we define the 2D slip vector $\mathbf{s} = [s_d, s_h]$

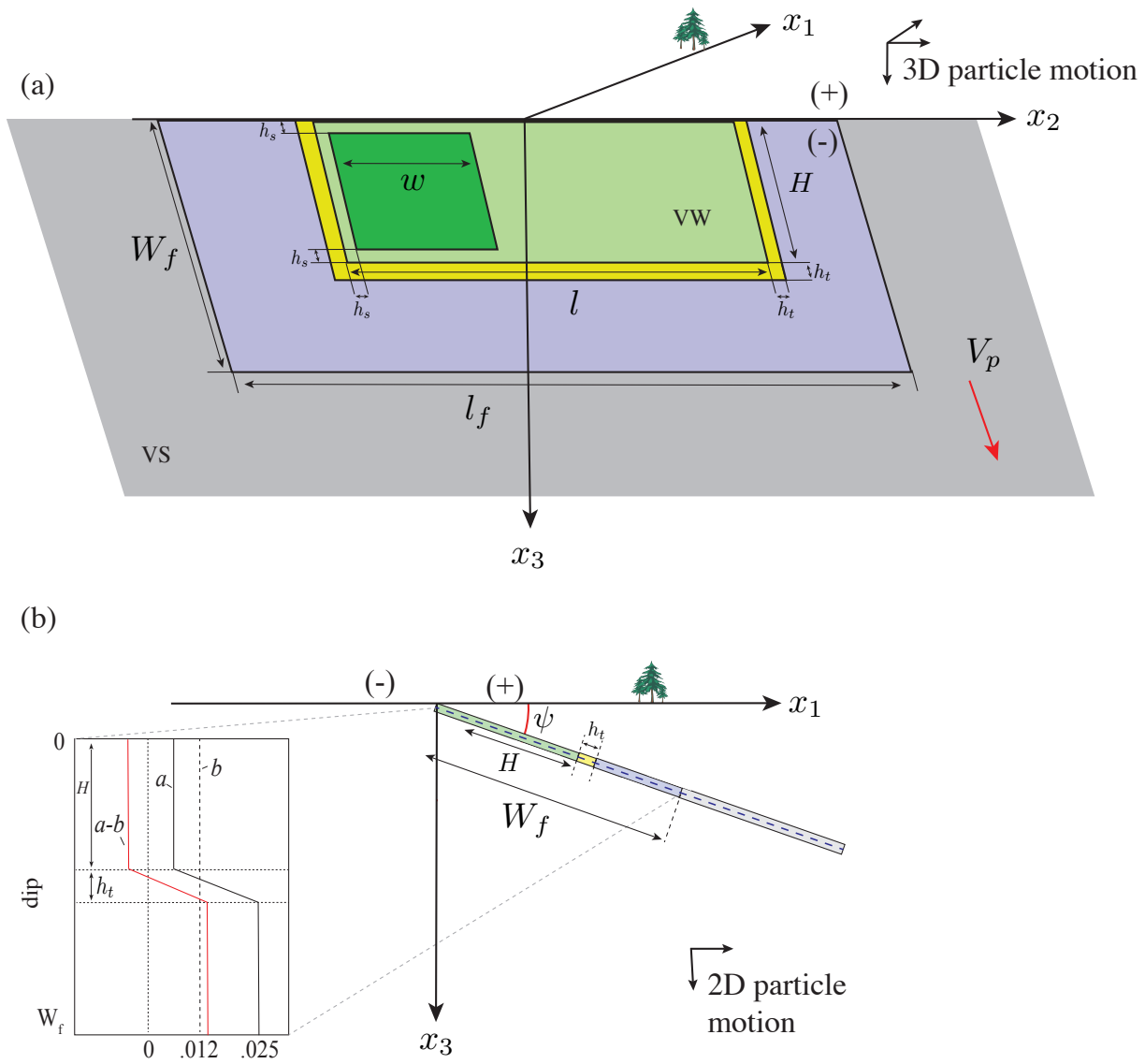


Figure 1: BP9-QD considers a planar thrust fault dipping at angle ψ embedded in a homogeneous, linear elastic half-space with a free surface in (a) 3D and at a (b) 2D cross-section at $x_2 = 0$ where motion is plane-strain. The fault is governed by rate-and-state friction down dip to a distance W_f and creeps at an imposed constant rate V_p down to the infinite dip distance. The simulations will include the nucleation, propagation, and arrest of quasi-dynamic earthquakes, and aseismic slip in the post- and inter-seismic periods. The two sides of the fault are labeled with "(-)" (the foot wall) and "(+)" (the hanging wall).

(jump in tangential displacement across the fault) where $s_d(x_2, x_3, t) = (u_j^+ - u_j^-)\hat{s}_j$ and $s_h(x_2, x_3, t) = (u_j^+ - u_j^-)\hat{e}_j$ are the down-dip and horizontal (along-strike) components, respectively. Note that these are defined such that positive values of s_d correspond to thrust faulting (considered in this benchmark) and that right-lateral motion yields positive values of s_h. We also define the jump in the normal component of displacement across the fault, positive in opening, given by $s_n = (u_j^+ - u_j^-)\hat{n}_j$. The first interface condition we require is a "no-opening" condition, namely

$$s_n = 0. \tag{8}$$

In the rest of this section, we refer to traction by omitting its evaluation at the fault for notational ease. The traction vector on each side of the fault is denoted with a superscript corresponding to the side of the fault and given by $T^\pm = T_0^\pm + \Delta T^\pm$ where

$$T_0^\pm = [\mp\sin(\psi)\sigma_{11}^{0,\pm} \pm \cos(\psi)\sigma_{13}^{0,\pm},\ \mp\sin(\psi)\sigma_{12}^{0,\pm} \pm \cos(\psi)\sigma_{23}^{0,\pm},\ \mp\sin(\psi)\sigma_{13}^{0,\pm} \pm \cos(\psi)\sigma_{33}^{0,\pm}], \tag{9}$$

$$\Delta T^\pm = [\mp\sin(\psi)\Delta\sigma_{11}^{\pm} \pm \cos(\psi)\Delta\sigma_{13}^{\pm},\ \mp\sin(\psi)\Delta\sigma_{12}^{\pm} \pm \cos(\psi)\Delta\sigma_{23}^{\pm},\ \mp\sin(\psi)\Delta\sigma_{13}^{\pm} \pm \cos(\psi)\Delta\sigma_{33}^{\pm}], \tag{10}$$

i.e. $T_0^\pm$ are the background tractions (prestress $\boldsymbol{\sigma}^0$ resolved on the fault) and $\Delta T^\pm$ are the changes in fault tractions associated with the displacement field. We require that components of the traction vector on either side of the fault be equal and opposite, namely, $-T^+ = T^-$ (the common value we denote T). Note that $T_j = \hat{n}_i\sigma_{ij}$. Since the background tractions satisfy $-T_0^+ = T_0^-$ (the common value we denote T^0), we require $-\Delta T^+ = \Delta T^-$ (the common value we denote ΔT), i.e. the fault tractions should satisfy the three interface conditions

$$\sin(\psi)\left(\Delta\sigma_{11}^+ - \Delta\sigma_{11}^-\right) - \cos(\psi)\left(\Delta\sigma_{13}^+ - \Delta\sigma_{13}^-\right) = 0, \tag{11a}$$

$$\sin(\psi)\left(\Delta\sigma_{12}^+ - \Delta\sigma_{12}^-\right) - \cos(\psi)\left(\Delta\sigma_{23}^+ - \Delta\sigma_{23}^-\right) = 0, \tag{11b}$$

$$\sin(\psi)\left(\Delta\sigma_{13}^+ - \Delta\sigma_{13}^-\right) - \cos(\psi)\left(\Delta\sigma_{33}^+ - \Delta\sigma_{33}^-\right) = 0. \tag{11c}$$

We note that T can be further decomposed into shear components $\tau_d = \tau_d^0 + \Delta\tau_d, \tau_h = \tau_h^0 + \Delta\tau_h$, and normal component $\sigma = \sigma^0 + \Delta\sigma$, which must be continuous across the fault. These common values are defined by $\tau_d = T_j\hat{s}_j$, $\tau_h = T_j\hat{e}_j$ and $\sigma = -T_j\hat{n}_j$, or equivalently,

$$\Delta\tau_d = -\sin(\psi)\cos(\psi)[\Delta\sigma_{11} - \Delta\sigma_{33}] + (\cos^2(\psi) - \sin^2(\psi))\Delta\sigma_{13}, \tag{12a}$$

$$\Delta\tau_h = \sin(\psi)\Delta\sigma_{12} + \cos(\psi)\Delta\sigma_{23}, \tag{12b}$$

$$\Delta\sigma = -\sin^2(\psi)\Delta\sigma_{11} + 2\sin(\psi)\cos(\psi)\Delta\sigma_{13} - \cos^2(\psi)\Delta\sigma_{33}, \tag{12c}$$

with normal stress positive in compression. Background values $\tau_d^0, \tau_h^0, \sigma^0$ are specified in the next section. Positive values of τ_d and τ_h promote thrust-sense and right-lateral slip, respectively.

The last two interface conditions are domain dependent. We define the slip velocity vector $\mathbf{V}$ in terms of the components

$$V_j = \dot{s}_j, \quad j = d, h, \tag{13}$$

letting $V = ||\mathbf{V}||$ denote the norm of the vector. For $(x_2, x_3) \in \Omega_f = (-l_\mathrm{f}/2, l_\mathrm{f}/2) \times (0, W_\mathrm{f}\sin(\phi))$ we impose rate-and-state friction, where shear stress on the fault is equal to fault strength $\mathbf{F}$, namely

$$\boldsymbol{\tau} = \mathbf{F}(\mathbf{V}, \theta). \tag{14}$$

Here, $\boldsymbol{\tau} = \boldsymbol{\tau}^0 + \boldsymbol{\Delta}\tau - \eta\mathbf{V}$ is the sum of the prestress, the shear stress transfer due to (quasi-static) deformation, and the radiation-damping stress change; it has components

$$\begin{bmatrix} \tau_d^0 + \Delta\tau_d - \eta V_d \\ \tau_h^0 + \Delta\tau_h - \eta V_h \end{bmatrix}. \tag{15}$$

Here we have applied the radiation damping approximation to inertia, where $\eta = \mu/2c_\mathrm{s}$ is half the shear-wave impedance for shear wave speed $c_\mathrm{s} = \sqrt{\mu/\rho}$ and density ρ.

The effective normal stress (which takes into account changes in normal stress induced by slip on the fault) is given by

$$\bar{\sigma}_\mathrm{n} = (\sigma^0 - p^0) + \Delta\sigma, \tag{16}$$

where $\bar{\sigma}_\mathrm{n}^0 = \sigma^0 - p^0$ (for pore pressure p^0, also specified in the next section) is the initial effective normal stress; changes in pressure are neglected. In this benchmark we assume $\bar{\sigma}_\mathrm{n}^0$ linearly increases with depth up to a maximum value; details are provided in the next section. The fault strength

$$\mathbf{F} = \max(\bar{\sigma}_{min}, \bar{\sigma}_\mathrm{n}) f(V,\theta)\frac{\mathbf{V}}{V}, \tag{17}$$

where θ is the state variable and we use parameter $\bar{\sigma}_{min} > 0$ so that shear strength remains nonzero and governed by rate-state friction even when $\bar{\sigma}_\mathrm{n}$ becomes small or tensile.

The state variable θ evolves according to the aging law

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_{RS}}, \tag{18}$$

where D_{RS} (denoted L or D_c in previous benchmarks) is the critical slip distance. The friction coefficient f is given by a regularized formulation

$$f(V,\theta) = a \sinh^{-1}\left[\frac{V}{2V_0}\exp\left(\frac{f_0 + b\ln(V_0\theta/D_{RS})}{a}\right)\right] \tag{19}$$

for reference friction coefficient f_0, reference slip rate V_0, and rate-and-state parameters a and b. For this benchmark, b is constant as b_0 and a varies throughout the frictional subdomain $\Omega_f = (0 \le X_1 \le W_f) \cap (|x_2| \le l_f/2)$ in order to define the velocity-weakening/strengthening regions (see Figure 1):

$$\begin{aligned} \Omega_{VW} &= (0 \le X_1 \le H) \cap (|x_2| \le l/2) \\ \Omega_{transition} &= \Omega_1 \backslash \Omega_{VW} \\ \Omega_{VS} &= \Omega_f \backslash \Omega_1 \end{aligned}$$

where $\Omega_1 = (0 \le X_1 \le h_\mathrm{t} + H) \cap (|x_2| \le (l + h_t)/2)$. a is thus defined by

$$a(x_2, x_3) = \begin{cases} a_0 & \text{on } \Omega_{VW} \\ a_\mathrm{max} & \text{on } \Omega_{VS} \\ a_0 + r(a_\mathrm{max} - a_0), & \text{on } \Omega_{transition} \end{cases} \tag{20}$$

where $r = \max(|x_3/\sin(\psi) - h_t - H/2| - H/2, |x_2| - l/2)/h_\mathrm{t}$.

Outside the domain Ω_f (i.e. $|X_1| > W_\mathrm{f}$ or $|x_2| > l_\mathrm{f}/2$) the fault creeps at an imposed constant rate, given by the interface conditions

$$V_d(x_2, x_3, t) = V_\mathrm{p}, \tag{21a}$$

$$V_h(x_2, x_3, t) = 0. \tag{21b}$$

3 3D Background, Initial Conditions and Simulation Time

We assume that pore pressure p^0 is hydrostatic down to a depth z_h, below which it tracks the lithostatic gradient, namely

$$p^0(x_3) = \begin{cases} \rho_w g x_3, & \text{if } x_3 \le z_h \\ \rho_w g z_h + \rho g (x_3 - z_h), & \text{if } x_3 > z_h. \end{cases} \tag{22}$$

We further assume that the background total normal stress is lithostatic, namely $\sigma^0 = \rho g x_3$. These assumptions yield a background effective normal stress given by

$$\bar{\sigma}_n^0 = \begin{cases} (\rho - \rho_w) g x_3, & \text{if } x_3 \le z_h \\ (\rho - \rho_w) g z_h, & \text{if } x_3 > z_h. \end{cases} \tag{23}$$

We further assume the background shear stresses are as follows:

$$\tau_d^0 = c\,\bar{\sigma}_n^0, \tag{24a}$$

$$\tau_h^0 = 0. \tag{24b}$$

The initial state variable is given by

$$\theta(x_2, x_3, 0) = D_{RS}/V_0. \tag{25}$$

Consistent initial slip rate may be obtained by solving (14) for $\mathbf{V}$. If slip rate is zero, please equate to 10^{-20} m/s to avoid infinite log() in data output. We must also specify an initial value for slip, which we take to be zero, namely

$$s_j(x_2, x_3, t) = 0, \quad j = d, h. \tag{26}$$

To break the symmetry of the 3D problem and facilitate comparisons of different simulations, we choose a square region with width, w, at one end of the VW region, as a favorable location for nucleation of the first and subsequent seismic events. For this purpose, we assign a smaller critical slip distance (see Table 1); the initial state variable in this region still follows (25) (and is reduced inside this square region).

Equations (1)–(3), along with boundary conditions (5), (7), interface conditions (8), (11), (14), (21), and initial conditions (23), (24), (25), 26 are solved over the time period $0 \le t \le t_{\mathrm{f}}$, where t_{f} is a specified final simulation time. All necessary parameter values for this benchmark problem are given in Table 1. Because computational efficiency for 3D problems demands a large cell size, we have chosen model parameters in order to resolve relevant physical length scales. At a rupture speed of 0^+, the quasi-static process zone size, Λ_0, is expressed as:

$$\Lambda_0 = C \frac{\mu D_{RS}}{b \max(\bar{\sigma}_{\mathrm{n}}^0)}, \tag{27}$$

where C is a constant on the order of 1. Another important length scale, the nucleation zone size, h^*, is expressed as:

$$h^* = \frac{\pi}{2} \frac{\mu b D_{RS}}{(b-a)^2 \max(\bar{\sigma}_{\mathrm{n}}^0)}. \tag{28}$$

The provided model parameters yield values of $\Lambda_0 \approx 2.6$ km and $h^* \approx 24km$. We suggest using a cell size of $\Delta z = 1000$ m for the simulations (here we let Δz define the cell size in all

Table 1: Parameter values used in BP9-QD.

Parameter	Definition	Value, Units	2D/3D
ψ	dip angle	30°	both
ρ	density	2670 kg/m^3	both
ρ_w	density of water	1000 kg/m^3	both
ν	Poisson's ratio	0.25	3D only
c_s	shear wave speed	3.464 km/s	both
c	constant factor in background stress state	0.53	both
$\bar{\sigma}^0_{min}$	minimum effective normal stress parameter	5 MPa or 0.1 MPa*	both
z_h	depth to which pore pressure hydrostatic	3 km	both
a_0	rate-and-state parameter	0.007	both
a_max	rate-and-state parameter	0.025	both
b_0	rate-and-state parameter	0.012	both
D_{RS}	critical slip distance	0.05/0.045 m†	both
V_p	plate rate	10^{-9} m/s	both
V_L	fault slip rate	10^{-9} m/s	both
V_init	initial slip rate	10^{-9} m/s	both
V_0	reference slip rate	10^{-6} m/s	both
f_0	reference friction coefficient	0.6	both
H	width of uniform VW region	16 km	both
l	length of uniform VW region	60 km	3D only
l_f	length of RS fault	100 km	3D only
w	width of favorable nucleation zone	12 km	3D only
h_s	offset of nucleation zone	2 km	both
h_t	width of VW-VS transition zone	2 km	both
W_f	width of rate-and-state fault	40 km	both
Δz	suggested cell size	1000 m	both
t_f	final simulation time	1000 years	both

† the value of D_{RS} in the favorable nucleation zone (3D problem only).
*simulation results from different values are uploaded separately, see section 7.

three directions); results from simulations using smaller (if feasible) cell sizes are welcome. For a cell size of 1000 m, Λ_0 is resolved at least ∼2 grid points and h^* by at least ∼20 grid points. For methods that use multiple degrees of freedom along cell edges/faces, please take $\Delta z =$ edge length / number of unique degrees of freedom. For instance, for a high-order finite element method, if Δh is the edge length and N the polynomial order then $\Delta z = \Delta h/N$.

4 2D Problem Setup

The 2D version of BP9-QD (referred to as BP9-QD-2D) is a vertical cross-section of BP9-QD-3D (at $x_2 = 0$, outside the favorable nucleation zone), where plane strain motion is assumed. We provide the problem specifics here for completeness. We assume 2D motion, where the only non-zero components of displacement are $u_1(x_1, x_3, t)$ and $u_3(x_1, x_3, t)$. Equations (1)-(3) are solved whose solution is expressed as a superposition as in section 1, with rigid body translation given by (6a) and (6c). The free surface boundary condition (7) reduces to

$$\sigma_{j3}(x1, 0, t) = 0, j = 1, 3. \tag{29}$$

The unit vectors defined for the 3D problem reduce to $\hat{s} = (-\cos\psi, -\sin\psi)$ and $\hat{n} = (\sin\psi, -\cos\psi)$. The down-dip component) is given by $s_d(x_3, t) = (u_j^+ - u_j^-)\hat{s}_j$ and the normal component is given by $s_n = (u_j^+ - u_j^-)\hat{n}_j$. Four interface conditions are required. The first is the no-opening condition (8). Two additional interface conditions stem from (11) (tractions are equal and opposite across the fault), which reduce to (11a) and (11c).

The traction vector is decomposed into shear and normal components τ_d and σ_n, given by (**??**), (**??**), (12a) and (12c). The slip velocity is a scalar given by $V_d = \dot{s}_d$. The last (fourth) interface condition is depth-dependent. In the frictional domain, condition (14) reduces to the scalar equation $\tau = F(V, \theta)$, where $V = |V_d|$, and $\tau = \tau_d^0 + \Delta\tau_d - \eta V_d$. Here $F = \max(\bar{\sigma}_{min}, \bar{\sigma}_n) f(V, \theta) \mathrm{sign}(V_d)$.

Because we take a cross-section at $x_2 = 0$, a varies with depth (see insert in Figure 1), namely:

$$a(x_3) = \begin{cases} a_0, & 0 \le x_3/\sin(\psi) < H \\ a_0 + (a_{\max} - a_0)(x_3/\sin(\psi) - H)/h_t, & H \le x_3/\sin(\psi) < H + h_t \\ a_{\max}, & H + h_t \le x_3/\sin(\psi) < W_{\mathrm{f}} \end{cases} \tag{30}$$

Below down-dip distance W_{f}, the fault creeps at an imposed constant rate, where the fourth interface condition requires

$$V(x_3, t) = V_{\mathrm{p}}, \quad x_3/\sin(\psi) \ge W_{\mathrm{f}}. \tag{31}$$

5 BP9-QD-3D Benchmark Output

We request five types of data output, if available, for the 3D version of this benchmark:

(1) On-fault time series (section 5.1)

(2) Off-fault time series (section 5.2)

(3) Source parameter time series (section 5.3)

(4) Earthquake catalog (section 5.4)

(5) Slip and stress evolution profile (section 5.5)

The location information relevant to these outputs are shown in Fig. 2. Data are uploaded to the CRESCENT code verification web server (section 7).

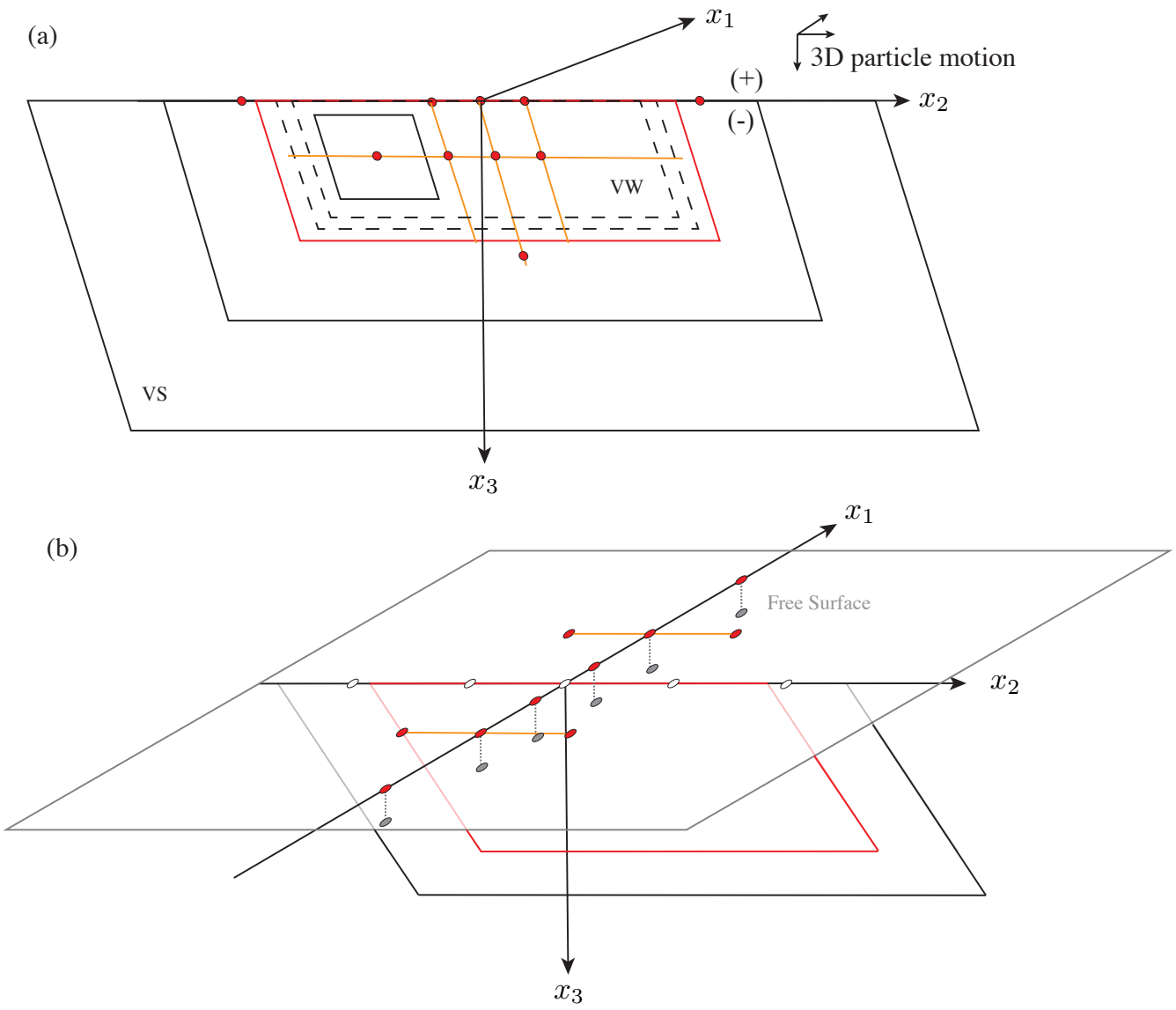


Figure 2: Observation points, lines, and region for model outputs. Local time series is output at (top) on-fault and (bottom) off-fault points (red). Slip and stress evolution are output along two cross-section lines (orange). The region outlined in red is used for estimating source parameter time series and rupture time contour. Dashed rectangles indicate fault areas with different frictional properties, shown in Figure 1.

5.1 On-fault Time Series Output (3D)

Upload on-fault time series files, which give slip components s_d and s_h, base 10 log of the components of slip rate V_d and V_h, base 10 log of the state variable (i.e. $\log_{10}(\theta)$), shear stress components τ_d and τ_h, and effective normal stress $\bar{\sigma}_n$ for each on-fault station at representative time steps. We define the simulation periods as either aseismic (when $\max(V) < 10^{-3}$ m/s, where $\max(V)$ is the maximum of the norm of the slip velocity vector over the entire fault) or seismic (when $\max(V) \geq 10^{-3}$ m/s). When outputting modeling results, use larger time intervals (e.g., ∼0.1 yr) during aseismic periods and smaller time intervals (e.g., ∼0.1 s) during seismic periods. More variable time steps are OK. Please keep the total number of time steps in the data file on the order of 10^4–10^5.

Let x_d denote the distance down dip. Time series data are supplied as ASCII files, one file for each station. There are 10 observational points on the fault (including 5 at the surface fault trace), defined by distance down-dip (not depth), with file names:

1. `fltst_strk-36dp+00.dat`: $x_2 = -36$ km, $x_d = 0$ km;
2. `fltst_strk-16dp+00.dat`: $x_2 = -16$ km, $x_d = 0$ km;
3. `fltst_strk+00dp+00.dat`: $x_2 = 0$ km, $x_d = 0$ km;
4. `fltst_strk+16dp+00.dat`: $x_2 = 16$ km, $x_d = 0$ km;
5. `fltst_strk+36dp+00.dat`: $x_2 = 36$ km, $x_d = 0$ km;
6. `fltst_strk-24dp+10.dat`: $x_2 = -24$ km, $x_d = 10$ km;
7. `fltst_strk-16dp+10.dat`: $x_2 = -16$ km, $x_d = 10$ km;
8. `fltst_strk+00dp+10.dat`: $x_2 = 0$ km, $x_d = 10$ km;
9. `fltst_strk+16dp+10.dat`: $x_2 = 16$ km, $x_d = 10$ km;
10. `fltst_strk+00dp+22.dat`: $x_2 = 0$ km, $x_d = 22$ km.

Note that for each of these on-fault stations, the x_1 component is given by $X_1(x_3) = \cot(\psi)x_3$. Each time series has 9 data fields, as follows.

Field Name	Description, Units and Sign Convention
`t`	Time (s)
`slip_d`	Down-dip component of slip (m). Positive for thrust motion.
`slip_h`	Horizontal component of slip (m). Positive for right-lateral motion.
`slip_rate_d`	$\log_{10}$ of the amplitude of the down-dip component of slip-rate ($\log_{10}$ m/s), which is positive for thrust motion.
`slip_rate_h`	$\log_{10}$ of the amplitude of the horizontal component of slip-rate ($\log_{10}$ m/s), which is positive for right-lateral motion.
`shear_stress_d`	Down-dip component of shear stress (MPa), which is positive for shear stress that tends to cause thrust motion.
`shear_stress_h`	Horizontal component of shear stress (MPa), which is positive for shear stress that tends to cause right-lateral motion.
`normal_stress`	Effective normal stress (MPa).
`state`	$\log_{10}$ of state variable ($\log_{10}$ s).

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

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP9-QD) • Code name • Code version (optional) • Modeler • Date • Node spacing or element size • Station location • Minimum time step (optional) • Maximum time step (optional) • Number of time steps in file (optional) • Descriptions of data columns (8 lines) • Anything else you think is relevant
Field List	A single line, which lists the names of the 9 data fields, in column order, separated by spaces. It should be: `t slip_d slip_h slip_rate_d slip_rate_h shear_stress_d shear_stress_h normal_stress state` (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. **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields. 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.

Here is an example of an on-fault time-series file, with invented data.

```
# This is the file header:
# problem=CRESCENT/SEAS Benchmark BP9-QD
# code=MYcode
# version=1.0
# modeler=A.Modeler
# date=2019/12/01
# element_size=1000 m
# location= on fault, 0km along strike, 10km down dip
# minimum_time_step=0.1
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Slip_d (m)
# Column #3 = Slip_h (m)
# Column #4 = Slip_rate_d (log10 m/s)
# Column #5 = Slip_rate_h (log10 m/s)
# Column #6 = Shear_stress_d (MPa)
# Column #7 = Shear_stress_h (MPa)
```

```
# Column #8 = Normal_stress (MPa)
# Column #9 = State (log10 s)
# The line below lists the names of the data fields
t slip_d slip_h slip_rate_d slip_rate_h shear_stress_d shear_stress_h normal_stress state
# Here is the time-series data.
0.000000E+00 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
5.000000E-02 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
1.000000E-01 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
1.500000E-01 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
# ...  and so on.
```

5.2 Off-fault Time Series Output (3D)

You need to upload time series files for off-fault stations, which give three components of displacement u_1, u_2, and u_3, and of velocity v_1, v_2, and v_3 (not base 10 log), for each station at representative time steps. Please use the same time steps for outputting the on-fault and off-fault time series.

Time series data is supplied as ASCII files, one file for each station. There are ten off-fault observational points on the surface ($x_3 = 0$ km), five on each side of the fault, as follows:

1. `blkst_strk-16fn+08dp+00.dat`: $x_2 = -16$ km, $x_1 = 8$ km;
2. `blkst_strk+00fn+08dp+00.dat`: $x_2 = 0$ km, $x_1 = 8$ km;
3. `blkst_strk+16fn+08dp+00.dat`: $x_2 = 16$ km, $x_1 = 8$ km;
4. `blkst_strk+00fn+16dp+00.dat`: $x_2 = 0$ km, $x_1 = 16$ km;
5. `blkst_strk+00fn+32dp+00.dat`: $x_2 = 0$ km, $x_1 = 32$ km;
6. `blkst_strk-16fn-08dp+00.dat`: $x_2 = -16$ km, $x_1 = -8$ km;
7. `blkst_strk+00fn-08dp+00.dat`: $x_2 = 0$ km, $x_1 = -8$ km;
8. `blkst_strk+16fn-08dp+00.dat`: $x_2 = 16$ km, $x_1 = -8$ km;
9. `blkst_strk+00fn-16dp+00.dat`: $x_2 = 0$ km, $x_1 = -16$ km;
10. `blkst_strk+00fn-32dp+00.dat`: $x_2 = 0$ km, $x_1 = -32$ km;

There are six additional off-fault stations at depth (with $x_2 = 0$ km), as follows:

11. `blkst_strk+00fn+08dp+10.dat`: $x_1 = 8$ km, $x_3 = 10$ km;
12. `blkst_strk+00fn+16dp+10.dat`: $x_1 = 16$ km, $x_3 = 10$ km;
13. `blkst_strk+00fn+32dp+10.dat`: $x_1 = 32$ km, $x_3 = 10$ km.
14. `blkst_strk+00fn-08dp+10.dat`: $x_1 = -8$ km, $x_3 = 10$ km;
15. `blkst_strk+00fn-16dp+10.dat`: $x_1 = -16$ km, $x_3 = 10$ km;
16. `blkst_strk+00fn-32dp+10.dat`: $x_1 = -32$ km, $x_3 = 10$ km.

Each time series has 7 data fields, as follows.

Field Name	Description, Units and Sign Convention
`t`	Time (s)
`disp_1`	Horizontal component (x_1) of displacement (m). Positive for motion in x_1 direction.
`disp_2`	Horizontal component (x_2) of displacement (m). Positive for motion in x_2-direction.
`disp_3`	Vertical (x_3) component of displacement (m). Positive for motion in x_3-direction (downward).
`vel_1`	x_1 component of velocity (m/s), which is positive for motion in x_1-direction.
`vel_2`	x_2 component of velocity (m/s), which is positive for motion in x_2-direction.
`vel_3`	x_3 component of velocity (m/s), which is positive for motion in x_3-direction.

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

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP9-QD) • Code name • Code version (optional) • Modeler • Date • Node spacing or element size • Station location • Minimum time step (optional) • Maximum time step (optional) • Number of time steps in file (optional) • Anything else you think is relevant (optional) • 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 disp_1 disp_2 disp_3 vel_1 vel_2 vel_3` (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. **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time and velocity fields, and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time and velocity fields, and E15.7 or 1PE15.6 format for other data fields. 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.

Here is an example of an on-fault time-series file, with invented data.

```
# This is the file header:
# problem=CRESCENT/SEAS Benchmark BP9-QD
# code=MYcode
# version=1.0
```

```
# modeler=A.Modeler
# date=2026/12/01
# element_size=1000 m
# location= off fault, 0km along strike, 8km away from the fault, 0km depth
# minimum_time_step=0.1
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Displacement_1 (m)
# Column #3 = Displacement_2 (m)
# Column #4 = Displacement_3 (m)
# Column #5 = Velocity_1 (m/s)
# Column #6 = Velocity_2 (m/s)
# Column #7 = Velocity_3 (m/s)
# The line below lists the names of the data fields
t disp_1 disp_2 disp_3 vel_1 vel_2 vel_3
# Here is the time-series data.
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 1.000000E-20 1.000000E-9 1.000000E-20
5.000000E-02 0.000000E+00 0.000000E+00 0.000000E+00 1.000000E-20 1.000000E-9 1.000000E-20
1.000000E-01 0.000000E+00 0.000000E+00 0.000000E+00 1.000000E-20 1.000000E-9 1.000000E-20
# ...  and so on.
```

5.3 Source Parameter Time Series Output (3D)

You need to upload a file named `global.dat`, which includes time series of two global source variables, maximum amplitude of slip rates

$$V_{\max} = \max_{(x_2,x_3)\in\Omega_f} V$$

and moment rates

$$M_t = \int_{\Omega_f} \mu\, V d\Omega_f$$

for the frictional domain Ω_f. Upload data corresponding to the same time steps you used for section 5.1.

Here is an example of a source parameter time-series file, with invented data.

```
# This is the file header:
# problem=CRESCENT/SEAS Benchmark BP9-QD
# code=MYcode
# version=1.0
# modeler=A.Modeler
# date=2019/12/01
# element_size=1000 m
# location= frictional domain
# minimum_time_step=0.1
```

```
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Max_slip_rate (log10 m/s)
# Column #3 = Moment_rate (N-m/s)
# The line below lists the names of the data fields
t max_slip_rate moment_rate
# Here is the time-series data.
0.000000E+00 0.000000E+00 -9.000000E+00
5.000000E-02 0.000000E+00 -9.000000E+00
1.000000E-01 0.000000E+00 -9.000000E+00
1.500000E-01 0.000000E+00 -9.000000E+00
# ...  and so on.
```

5.4 Earthquake Catalog Output (3D)

The earthquake catalog output file with a name `catalog.dat` is a single ASCII file that includes characteristics of all seismic events in the simulation. We define an event to start when the maximum slip rate exceeds 10^{-3} m/s, and to be over when maximum slip rate dips below 10^{-3} m/s for a time duration of at least 10 seconds (to avoid inaccurate estimate of event termination in the presence of slip rate fluctuation at the end of rupture). For each earthquake in the entire simulation period, the file contains the event number, the event initiation time, event termination time, the total rupture area R, average stress in the rupture area τ_{avg} at the beginning and end of the event (so stress drops can be computed from the two values), and the average coseismic slip in the rupture area s_{avg}.

We consider the rupture domain Ω_R as those locations on the fault where slip rates have exceeded 10^{-3} m/s at any time during the event, with $R = \left|\Omega_R\right|$ being the total rupture area. We define τ_{avg} as the amplitude of spatially averaged stress vector $\boldsymbol{\tau}$ within the rupture area:

$$\tau_{\text{avg}} = \frac{1}{R} \Big| \int_{\Omega_R} \boldsymbol{\tau}\, d\Omega_R \Big|.$$

Similarly, we define s_{avg} as the amplitude of spatially averaged slip vector $\boldsymbol{s}$ within the rupture domain:

$$s_{\text{avg}} = \frac{1}{R} \Big| \int_{\Omega_R} \mathbf{s}\, d\Omega_R \Big|.$$

The data file has 7 data fields, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP9-QD) • Modeler • Date • Code • Code version (if desired) • Node spacing or element size • Descriptions of data fields (1 line) • Anything else you think is relevant (e.g. computational domain size)
Field List	One line listing the 7 data fields on one line, separated by spaces. It should be: `event_no t_start t_end rup_area avg_stress_start avg_stress_end avg_slip` (all on one line).
Catalog	A series of lines. **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields.

Field Name	Description, Units and Sign Convention
`event_no`	Event number.
`t_start`	Time event starts (s).
`t_end`	Time event ends (s).
`rup_area`	Rupture area (m^2).
`avg_stress_start`	Spatial average of stress within rupture area at `t_start` (MPa).
`avg_stress_end`	Spatial average of stress within rupture area at `t_end` (MPa).
`avg_slip`	Average slip in rupture area (m).

The data output consists of three sections, as follows:

Here is an example of a catalog file, with invented data.

```
# This is the file header:
# problem=CRESCENTSEAS Benchmark BP9-QD
# author=A.Modeler
# date=2019/12/01
# code=MyCode
# code_version=3.7
# element_size=1000 m
# Column #1 = Event number
# Column #2 = Event start time (s)
# Column #3 = Event end time (s)
# Column #6 = Rupture area (m^2)
# Column #7 = Stress avg at start time (MPa)
# Column #8 = Stress avg at end time (MPa)
# Column #9 = Avg slip in rupture area (m)
# Computational domain size:  depth 100 km, distance off fault 100 km
# The line below lists the names of the data fields
event_no  t_start t_end rup_area avg_stress_start avg_stress_end avg_slip
# Here are the data
1 3.15500000E+07 3.15500200E+07 1.800000E+09 ...  5.000000E+00
2 4.70000000E+09 4.70000002E+09 1.800000E+09 ...  4.800000E+00
3 9.45000000E+09 9.45000002E+09 1.800000E+09 ...  4.820000E+00
# ...  and so on.
```

5.5 Slip and Stress Evolution Output (3D)

The slip and stress evolution output files with the names

```
slip_d_dip.dat
slip_d_strike.dat
stress_d_dip.dat
stress_d_strike.dat
slip_h_dip.dat
slip_h_strike.dat
stress_h_dip.dat
stress_h_strike.dat
stress_n_dip.dat
stress_n_strike.dat
```

are 10 ASCII files that record the spatial distribution of slip and stress (both horizontal, vertical, and normal components of fault traction) on a subset of fault nodes at one-dimensional cross sections (either a specified distance along strike OR along dip), at representative time steps during the aseismic and seismic phases of the simulation. Data can be saved using representative time intervals of $\sim$5 yr and $\sim$1 s for results in aseismic and seismic phases, respectively, or with variable time steps. Either way, data will be interpolated to plot slip every 5 yr during the aseismic phase, and every 1 s during the coseismic phase.

The data should include nodes with a spacing of ∼1000 m (or larger for simulations with larger cells) along dip ($0 \leq x_d \leq W_\mathrm{f}$) or along strike ($-l/2 - 8\,\mathrm{km} \leq x_2 \leq l/2 + 8\,\mathrm{km}$). The files should also contain the time series of maximum slip rate amplitude (taken over the entire fault), so that we can precisely differentiate aseismic and seismic phases. We request a total of 10 data files containing slip and stress data at two one-dimensional cross sections: one along-dip profile at $x_2 = 0\,\mathrm{km}$ and one along-strike profile at $x_d = 10\,\mathrm{km}$ (see the orange lines in Figure 2).

Each data file has 4 data fields, as follows:

Field Name	Description, Units and Sign Convention
`x2` OR `xd`	Strike (m) at ∼1000 m increments from −38 km to 38 km OR Dip (m) at ∼1000 m increments from 0 km to 40 km
`t`	Time (s). Nonuniform time steps.
`max_slip_rate`	The $\log_{10}$ of maximum amplitude of slip-rate (taken over the entire fault) ($\log_{10}$ m/s).
`slip_d` OR `slip_h` OR `stress_d` OR `stress_h` OR `stress_n`	Horizontal OR vertical component of slip (m) (positive for right-lateral motion OR for + side moving downward, respectively) OR horizontal OR vertical component of fault traction (in MPa) OR effective normal stress (in MPa).

The data output consists of three sections, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP9-QD) • Modeler • Date • Code • Code version (if desired) • Node spacing or element size • Descriptions of data fields (4 lines) • Anything else you think is relevant (e.g. computational domain size)

Field List	Four lines. The first line lists either x_2 OR x_d. The next two lines lists the time steps and max slip rate (respectively). The last line lists which component of slip or stress. It should be:
	`x2` OR `xd`
	`t`
	`max_slip_rate`
	`slip_d` OR `slip_h` OR `stress_d` OR `stress_h` OR `stress_n`

Slip History	A series of lines that form a 2-dimensional array of rows and columns. The first row/line lists the numbers 0, 0 (to maintain a consistent array size), followed by the spatial nodes with increasing distance along strike OR depth as you go across the row. Starting from the second row/line, each row/line contains time, maximum slip rate, and slip OR stress at all nodes at the time. These lines appear in order of increasing time (from top to bottom) and slip OR stress is recorded with increasing distance along strike or dip (from left to right). **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields.

Note that x_2 or x_d should appear in the first row, preceded by two zero numbers, for nodes with a spacing of $\sim$1000 m. Time and maximum slip rate should appear as two single columns that start on the second row, with time increasing as you go down. Slip or stress history (the remaining block) is represented by a two-dimensional array with time increasing as you go down the rows/lines, and either x_2 or x_d increasing as you go across the columns ($\sim$77 and 41 columns, respectively). For example, the output in `slip_d_strike.dat` is a two-dimensional matrix of the form:

$$\begin{bmatrix} 0 & 0 & x_d \\ T & \max(V) & \text{slip} \end{bmatrix}$$

The matrix should be of size $(N_\text{t}+1, \sim 79)$, where N_t is the total number of time steps. This means that you output slip at selected nodes at one time step and move on to the next time step. (To keep the file on the order of 10s of MB, N_t should be on the order of 10,000).

Here is an example of a slip-evolution file for `slip_h_strike.dat`, with invented data.

```
# This is the file header:
# problem=CRESCENT/SEAS Benchmark BP9-QD
```

```
# author=A.Modeler
# date=2019/12/01
# code=MyCode
# code_version=3.7
# element_size=1000 m
# Row #1 = Strike (m) with two zeros first
# Column #1 = Time (s)
# Column #2 = Max slip rate (log10 m/s)
# Columns #3-83 = Horizontal slip along dip (Slip_h) (m)
# Computational domain size:  -100km < x1 < 100km, -100km < x2 < 100km, -100km < x3 < 100km
# The line below lists the names of the data fields
xd
t
max_slip_rate
slip_h
# Here are the data
0.000000E+00  0.000000E+00 -3.80000E+04 -3.70000E+04 ...  3.600000E+04
0.000000E+00 -9.000000E+00 0.000000E+00 0.000000E+00 ...  0.000000E+00
3.140000E+05 -9.000000E+00 1.340000E-05 1.340000E-05 ...  3.140000E-05
1.227000E+07 -9.000000E+00 1.560000E-05 1.560000E-05 ...  1.220000E-02
4.690000E+07 -9.000000E+00 1.580000E-05 1.580000E-05 ...  4.680000E-02
...
9.467078E+10 -4.500000E-01 9.050000E+01 9.050000E+01 ...  9.461000E+01
```

6 BP9-QD-2D Benchmark Output

We request a subset of the five types of data output as BP9-QD-3D, with location information relevant to the $x_2 = 0$ cross-section in Fig. 2. Data files are uploaded in the same manner as for the 3D problem; please follow the same conventions for outputting model results.

6.1 On-fault Time Series Output (2D)

You need to upload on-fault time series files, which give slip component s_d, base 10 log of the component of slip rate V_d, base 10 log of the state variable (i.e. $\log_{10}(\theta)$), shear stress component τ_d, and effective normal stress component $\bar{\sigma}_d$ for each on-fault station at representative time steps (as in 3D problem). Time series data is supplied as ASCII files, one file for each station. Again let $x_d = x_3 \sin(\psi)$. There are 12 observational points on the fault, with file names defined by distance down-dip (not depth) as follows:

1. `fltst_dp000.dat`: $x_d = 0$ km;
2. `fltst_dp025.dat`: $x_d = 2.5$ km;
3. `fltst_dp050.dat`: $x_d = 5$ km;
4. `fltst_dp075.dat`: $x_d = 7.5$ km;
5. `fltst_dp100.dat`: $x_d = 10$ km;
6. `fltst_dp125.dat`: $x_d = 12.5$ km;
7. `fltst_dp150.dat`: $x_d = 15$ km;

8. `fltst_dp175.dat`: $x_d = 17.5$ km;
9. `fltst_dp200.dat`: $x_d = 20$ km;
10. `fltst_dp250.dat`: $x_d = 25$ km;
11. `fltst_dp300.dat`: $x_d = 30$ km;
12. `fltst_dp350.dat`: $x_d = 35$ km.

Each time series has 6 data fields, as follows.

Field Name	Description, Units and Sign Convention
`t`	Time (s)
`slip_d`	Down-dip component of slip (m). Positive for thrust motion.
`slip_rate_d`	$\log_{10}$ of the amplitude of the down-dip component of slip-rate ($\log_{10}$ m/s), which is positive for thrust motion.
`shear_stress_d`	Down-dip component of shear stress (MPa), which is positive for shear stress that tends to cause thrust motion.
`normal_stress`	Effective normal stress.
`state`	$\log_{10}$ of state variable ($\log_{10}$ s).

The on-fault time series file consists of three sections, defined analagously as the 3D problem.

6.2 Off-fault Time Series Output (2D)

You need to upload time series files for off-fault stations, which give two components of displacement u_1 and u_3, and of velocity v_1 and v_3 (not base 10 log), for each station at representative time steps. Please use the same time steps for outputting the on-fault and off-fault time series.

Recall that the 2D problem takes $x_2 = 0$. There are six off-fault observational points on the surface ($x_3 = 0$ km), three on each side of the fault, as follows:
1. `blkst_fn+08dp+00.dat`: $x_1 = 8$ km, $x_3 = 0$ km;
2. `blkst_fn+16dp+00.dat`: $x_1 = 16$ km, $x_3 = 0$ km;
3. `blkst_fn+32dp+00.dat`: $x_1 = 32$ km, $x_3 = 0$ km;
4. `blkst_fn-08dp+00.dat`: $x_1 = -8$ km, $x_3 = 0$ km;
5. `blkst_fn-16dp+00.dat`: $x_1 = -16$ km, $x_3 = 0$ km;
6. `blkst_fn-32dp+00.dat`: $x_1 = -32$ km, $x_3 = 0$ km;

There are six additional off-fault stations at depth, as follows:
7. `blkst_fn+08dp+10.dat`: $x_1 = 8$ km, $x_3 = 10$ km;
8. `blkst_fn+16dp+10.dat`: $x_1 = 16$ km, $x_3 = 10$ km;
9. `blkst_fn+32dp+10.dat`: $x_1 = 32$ km, $x_3 = 10$ km.
10. `blkst_fn-08dp+10.dat`: $x_1 = -8$ km, $x_3 = 10$ km;
11. `blkst_fn-16dp+10.dat`: $x_1 = -16$ km, $x_3 = 10$ km;
12. `blkst_fn-32dp+10.dat`: $x_1 = -32$ km, $x_3 = 10$ km.

Each time series has 5 data fields, with file names as follows.

Field Name	Description, Units and Sign Convention
`t`	Time (s)
`disp_1`	Fault-perpendicular component of displacement (m). Positive for motion in x_1 direction.
`disp_3`	Vertical (x_3) component of displacement (m). Positive for motion in x_3-direction (downward).
`vel_1`	x_1 component of velocity (m/s), which is positive for motion in x_1-direction.
`vel_3`	x_3 component of velocity (m/s), which is positive for motion in x_3-direction.

The off-fault time series file consists of three sections, as in the 3D problem.

6.3 Source Parameter Time Series Output (2D)

You need to upload a file named `global.dat`, which includes time series of two global source variables, maximum amplitude of slip rate

$$V_{\max} = \max_{x_3 \in \omega_f} V$$

and moment rates

$$M_t = \int_{\omega_f} \mu V dA$$

for the 1D cross section ω_f of the frictional domain (i.e. Ω_f, with $x_2 = 0$). Upload data corresponding to the same time steps you used for section 5.1.

Follow example format of 3D problem.

6.4 Slip and Stress Evolution Output (2D)

The slip and stress evolution output files with the names

```
slip_d_dip.dat
stress_d_dip.dat
stress_n_dip.dat
```

are 3 ASCII files that record the spatial distribution of slip, fault traction (the down-dip horizontal component) and effective normal stress, respectively, on a subset of fault nodes at representative time steps during the aseismic and seismic phases of the simulation. Data can be saved using representative time intervals of ∼5 yr and ∼1 s for results in aseismic and seismic phases, respectively, or with variable time steps. Either way, data will be interpolated to plot slip every 5 yr during the aseismic phase, and every 1 s during the coseismic phase.

The data should include nodes with a spacing of ∼1000 m (or larger for simulations with larger cells) along dip ($0 \leq x_d \leq W_f$). The files should also contain the time series of maximum slip rate amplitude (taken over the entire fault), so that we can precisely differentiate aseismic and seismic phases.

Each data file has 4 data fields, as follows:

Field Name	Description, Units and Sign Convention
`xd`	(m) at ∼1000 m increments from 0 km to 40 km
`t`	Time (s). Nonuniform time steps.
`max_slip_rate`	The $\log_{10}$ of maximum amplitude of slip-rate (taken over the entire fault) ($\log_{10}$ m/s).
`slip_d` OR `stress_d` OR `stress_n`	Down-dip component of slip (m) (positive for thrust motion) OR down-dip component of stress (in MPa) OR effective normal stress.

The data output consists of three sections, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP9-QD) • Modeler • Date • Code • Code version (if desired) • Node spacing or element size • Descriptions of data fields (4 lines) • Anything else you think is relevant (e.g. computational domain size)

Field List	Four lines. The first line lists x_d. The next two lines lists the time steps and max slip rate (respectively). The last line lists which component of slip or stress. It should be:
	`xd`
	`t`
	`max_slip_rate`
	`slip_d` OR `stress_d` OR `stress_n`

Slip History	A series of lines that form a 2-dimensional array of rows and columns. The first row/line lists the numbers 0, 0 (to maintain a consistent array size), followed by the spatial nodes with increasing distance along dip as you go across the row. Starting from the second row/line, each row/line contains time, maximum slip rate, and slip OR stress at all nodes at the time. These lines appear in order of increasing time (from top to bottom) and slip OR stress is recorded with increasing distance along dip (from left to right). **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields.

Note that x_d should appear in the first row, preceded by two zero numbers, for nodes with a

spacing of ∼1000 m. Time and maximum slip rate should appear as two single columns that start on the second row, with time increasing as you go down. Slip or stress history (the remaining block) is represented by a two-dimensional array with time increasing as you go down the rows/lines, and x_d increasing as you go across the columns (∼77 and 41 columns, respectively). For example, the output in `slip_d.dat` is a two-dimensional matrix of the form:

$$\begin{bmatrix} 0 & 0 & x_d \\ T & \max(V) & \text{slip} \end{bmatrix}$$

The matrix should be of size $(N_\text{t}+1, \sim 79)$, where N_t is the total number of time steps. This means that you output slip at selected nodes at one time step and move on to the next time step. (To keep the file on the order of 10s of MB, N_t should be on the order of 10,000).

Here is an example of a slip-evolution file for `slip_d.dat`, with invented data.

```
# This is the file header:
# problem=CRESCENT/SEAS Benchmark BP9-QD
# author=A.Modeler
# date=2019/12/01
# code=MyCode
# code_version=3.7
# element_size=1000 m
# Row #1 = Dip (m) with two zeros first
# Column #1 = Time (s)
# Column #2 = Max slip rate (log10 m/s)
# Columns #3-83 = Down-dip slip along depth (Slip_d) (m)
# Computational domain size:  -100km < x1 < 100km, -100km < x3 < 100km
# The line below lists the names of the data fields
xd
t
max_slip_rate
slip_d
# Here are the data
0.000000E+00  0.000000E+00 -3.80000E+04 -3.70000E+04 ...  3.600000E+04
0.000000E+00 -9.000000E+00 0.000000E+00 0.000000E+00 ...  0.000000E+00
3.140000E+05 -9.000000E+00 1.340000E-05 1.340000E-05 ...  3.140000E-05
1.227000E+07 -9.000000E+00 1.560000E-05 1.560000E-05 ...  1.220000E-02
4.690000E+07 -9.000000E+00 1.580000E-05 1.580000E-05 ...  4.680000E-02
...
9.467078E+10 -4.500000E-01 9.050000E+01 9.050000E+01 ...  9.461000E+01
```

7 Using the CRESCENT DET Benchmark Uploader

The CRESCENT DET benchmark uploader lets you upload your modeling results (sections 5 and 6). Once uploaded, you and other modelers can view the data in various ways.

7.1 Logging in and Selecting a Problem

To log in, start your web browser and go to the home page at:

`https://det-uploader.cascadiaquakes.org/`

You will be prompted to request access by filling out your name, email, and affiliation. Once the request is approved, you will receive an email to activate the account and access the data sharing platform.

7.2 Uploading Files

Once logged in, you will see the main homepage for the data sharing platform. To upload files, scroll along the drop-down menu for "Select Benchmark ID" and choose either "BP9-QD-2D-5MPa", "BP9-QD-2D-01MPa", "BP9-QD-3D-5MPa" or "BP9-QD-3D-01MPa", depending on whether the 2D or 3D version is being considered, and the specific value of $\bar{\sigma}^0_{min}$ used. Compress all results (from sections 5 or 6) into a single zip folder with the naming convention of nameOfModeler_version.zip. After reviewing the terms and conditions, accept and upload the zip folder. The platform will appropriately organize the contents of the zip folder based on the names of the files (thus, it is important that the file names are according to the conventions set by sections 5 and 6). If there are errors in the filenames, no data will be visualized.

7.3 Graphing and Deleting Files

After uploading a file, additional functions become available. These functions let you graph or delete the uploaded file.

Graphing: To graph a file, find the drop-down menu for "View Benchmark Results" at the bottom of the page. Click "Go to Result" which will take you to the data visualization page. Under "Dataset choice," you may check the boxes for the datasets you would like to visualize.

For time-series files (sections 5.1-5.2 and 6.1-6.2), the different datasets will be plotted on the same graph with different colors. A legend to the right of the graph will indicate which colors correspond to which datasets. You may use the mouse scroll to zoom in and out of the plot or click on the plot to draw a specific region to zoom-in. You can always click the home button at the top right to return to the default plotting window.

For the line profiles (sections 5.3 and 6.3), contour plots in the space-time domain for the different datasets will be plotted separately. Under the "Graph control" tab, you can change the variable that is plotted under the drop-down menu for "variable selection". At the bottom of all contour plots, snapshots at a specified time will be plotted on the same graph for all datasets. This time can be changed with the cross-section slider at the bottom of the "Graph control" tab. In the "Graph control" tab, you can also change the min and max values of the plotted variable.

Deleting: To delete a dataset that you uploaded, first scroll along the "Select Benchmark ID" drop-down menu under the "File Management" tab. Once you select a particular bench-

mark problem, you should see all files you have uploaded with the option to click "Delete" for each dataset.

8 Benchmark Tips

Note that with the parameters specified in this benchmark, the background effective normal stress gradient is $\sim$ 16.3 MPa/km down to depth z_h = 3 km (6 km down-dip), where it reaches a maximum of $\sim$50 MPa. Also, numerical boundary conditions (to truncate the half-space when defining the computational domain) will most likely change results at least quantitatively, or even qualitatively. We suggest extending these boundaries until you see results appear independent of the computational domain size. We prefer participants to use the cell size suggested in Table 1 and welcome results for different spatial resolutions. Each person can submit (at most) results from two different spatial resolutions and two different computational domain sizes for each of the two simulations (i.e. for each of the values of $\bar{\sigma}^0_{min}$).