

3D-DEF: A TUTORIAL

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1 3D-DEF Definitions

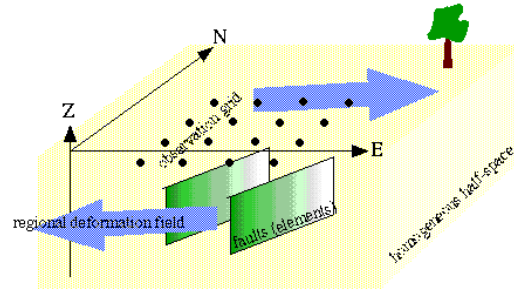


Figure 1:

Element - an element is a planar dislocation that may be used as a fault plane, a dike, a boundary of displacement, or almost anything that is planar.

Subelement - an element may be (and usually is) divided into smaller elements, or subelements. The numbering or ordering system is as shown below, looking down the positive z-axis (planar coordinates) or from the hangingwall if that's clearer.

Ordering of subelements on a single element

1,3	2,3	3,3
1,2	2,2	3,2
1,1	2,1	3,1

🧠 Bear in mind that this ordering is not the same as that which is output in vector format.

Inspection plane - is the plane of coordinates to which output results are referred. For example, it is common to want displacements of the Earth's surface, so the inspection plane might be defined like this:

-10 10 0 90 0 20 20

where the first three numbers refer to the origin of the plane (in either global or in-plane coordinates, in this case, global), which is therefore at 10 km west and 10 km north of the coordinate origin and at the surface. The next two numbers are the strike (90) and dip (0) of the plane, and the last two refer to the along-strike and along-dip distances. Thus, this plane is flat and runs 20 km to the east and 20 km to the south of its origin. You can see that the specification of the inspection plane is the same as it is for any element.

Coordinate systems: we use three different coordinate systems in *3d-def*, each right-handed and shown in the table and figure below. The local system is used only inside the program, so the casual user can ignore it.

Coordinate systems used in *3d-def* with reference to positive directions

System	X	Y	Z
Global	east	north	up
Planar (in-plane)	along strike	up-dip	plane-normal into hangingwall
Local	along strike	horizontal, normal to strike and into footwall	up

Footwalls, hangingwalls, and relative displacements: the footwall lies under the hangingwall, so that a hangingwall moves up and over the footwall across a reverse fault, and it slides down and to a level below the footwall across a normal fault. If you use the right-handed convention (which we do in *3d-def*), then the hangingwall lies to the right of the strike direction.

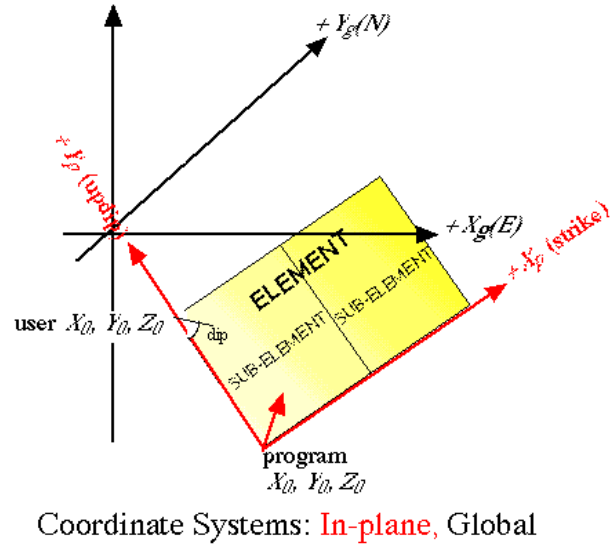


Figure 2:

Relative displacements across elements always refer to the motion of the hangingwall (HW) with respect to the footwall (FW). Thus, a negative shear displacement means that the HW has moved opposite to the strike direction (since the strike is the positive axis), which yields a right-lateral sense of motion. Likewise, a positive displacement in the dip direction indicates a reverse sense of motion. Here are some figures to make it all clear.

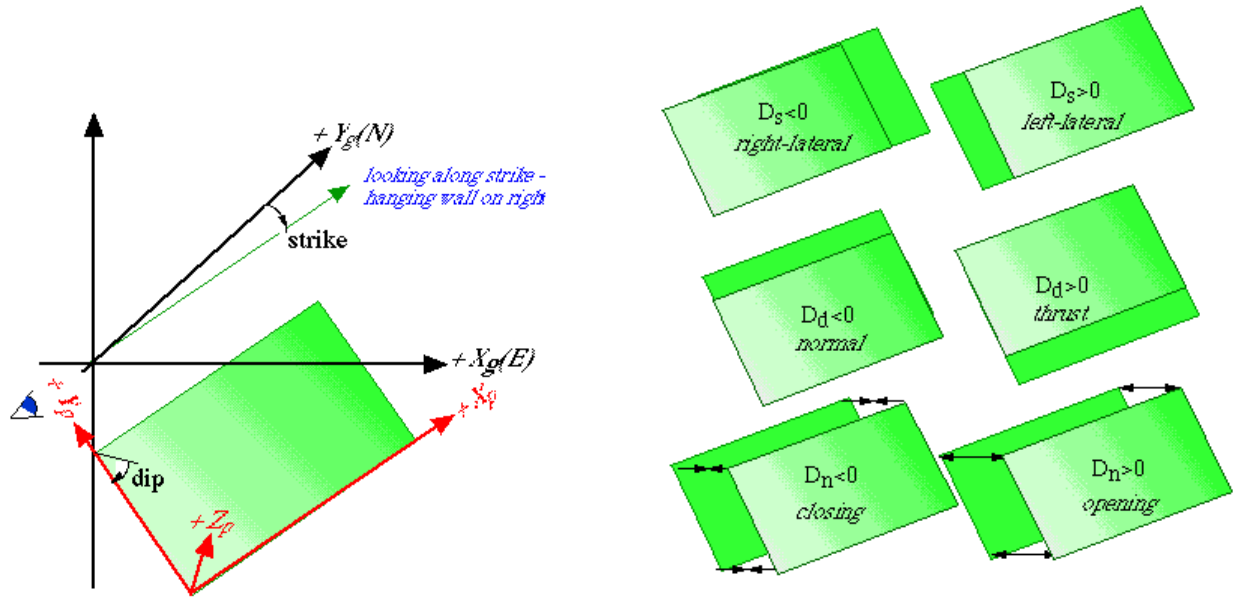


Figure 3:

Units are given in the table below:

Feature	Units
Element dimension	km
Element displacements	cm
Output displacements	cm
Stress	Same as Young's modulus
Strain	none (adimensional)

Boundary conditions: these are the conditions applied to the central points of elements in the model input. They may be specified in terms of relative displacement, shear or normal stress, orientation of that stress, and absolute displacement. "code" numbers in the input file indicate which combination of conditions are being used. Because boundary conditions are applied to a plane, they are divided into components along the planar coordinates (strike, dip, and normal).

Boundary Condition type by component			
<u>Code</u>	<u>strike</u>	<u>dip</u>	<u>normal</u>
1	u_s^-	u_d^-	u_n^-
2	τ_s	τ_d	σ_n
3	τ_s	u_d^-	σ_n
4	u_s^-	τ_d	σ_n
5	τ_s	τ_d	u_n^-
10	D_s	D_d	D_n
11	ϕ°	$\tau(\phi^\circ)$	D_n
12	τ_s	τ_d	D_n
13	τ_s	D_d	D_n
14	D_s	τ_d	D_n

Figure 4:

See driving the deformation, 3, for examples and details.

2 3D-DEF Introduction

3d-def is a three-dimensional boundary-element model that allows the calculation of stresses, strains, and displacements within and on the surface of an elastic half-space; there is no bottom to the model. The power of the model comes from the ability to a) solve for a variety of deformation quantities on a variety of faults and planes simultaneously, and b) to drive the deformation in relatively realistic (and therefore potentially complex) ways.

The principal difference between boundary-element models and standard dislocation models is that in the former the slip values, or the magnitudes of the dislocation components, are treated as unknowns that are solved for in order to minimize the strain energy in the medium while satisfying stress or displacement boundary conditions on each dislocation surface.

The minimization of strain energy is physically reasonable assuming that fault slip is the primary means of relaxing strains in the upper crust. Boundary-element models explicitly account for the interaction among faults whereas dislocation models generally ignore both fault interaction and the minimization of strain energy.

Boundary-element = constant slip surface

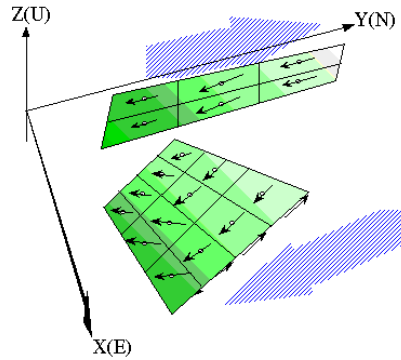



Figure 5:

Minimize the global shear-strain energy

Rectangular, planar dislocations in a uniform elastic half-space are referred to as elements. Not all planar dislocations need be faults; e.g., they may also be used as displacement boundaries or as the surface of a magma chamber.

Displacements of elements may be driven by a variety of ways, including the specification of a regional stress, strain, or displacement gradient tensor, by specifying far-field boundary conditions, or by specifying displacements or stresses on any other elements. These methods can be combined. For example, we might drive a system of fault-elements by a regional strain tensor and by imposing slip on one of the model faults, leaving the remainder to slip as they will, constrained only by the requirement that the shear-strain energy is minimized. Go [here](#),³ for details on driving the models, and [here](#) to check some of the pitfalls ⁶.

 During any deformation, lines and planes will be rotated. Such rotations are properly modeled here only for the symmetric (pure shear) part of the displacement gradient tensor. But, if you are modeling long-term deformation, where there is an implicit repeat of the elastic deformation, then bear in mind that the faults specified in the input file are not rotating as they should be.

2.1 Some general definitions:

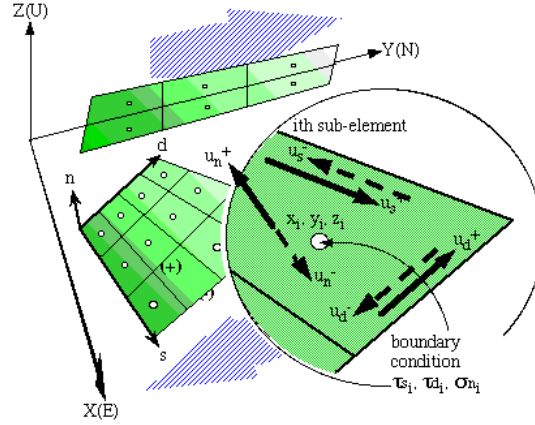


Figure 6:

Deformation at any observation point (x,y,z) is the superposition of the deformation due to slip on each of a set of planar dislocations plus some uniform deformation field. The complete deformation field is fully described by the displacement vector,

$$\vec{u} = u_x \hat{x} + u_y \hat{y} + u_z \hat{z} = u_d \hat{d} + u_s \hat{s} + u_n \hat{n}$$

the displacement gradient tensor,

$$\begin{vmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_y}{\partial x} & \frac{\partial u_z}{\partial x} \\ \frac{\partial u_x}{\partial y} & \frac{\partial u_y}{\partial y} & \frac{\partial u_z}{\partial y} \\ \frac{\partial u_x}{\partial z} & \frac{\partial u_y}{\partial z} & \frac{\partial u_z}{\partial z} \end{vmatrix}$$

and the material constants, Poisson's ratio and Young's modulus. The stress, strain, and rigid body rotation tensors can all be derived from the displacement gradient tensor and the material constants.

The components of relative displacement (fault slip) in the strike, dip, and normal directions respectively, on each element are

$$\begin{aligned} D_s &= u_s^- - u_s^+ \\ D_d &= u_d^- - u_d^+ \\ D_n &= u_n^- - u_n^+ \end{aligned}$$

Negative superscripts refer to the absolute displacement of the footwall, positive to the absolute displacement of the hangingwall.

2.2 Solving the numerical problem:

The interaction of one element (a dislocation or fault segment) with other elements and with the background deformation is modeled by solving a set of linear equations formulated as follows.

1) For each element, a set of displacement and/or stress boundary conditions is specified at a point at the center of the element. The figure below illustrates this for stress boundary conditions and two elements:

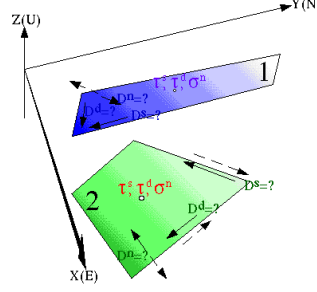



Figure 7:

 Note that boundary conditions are specified only at the center point of each element; they do not apply to the entire surface of the element. More accurate results will be obtained by sub-dividing elements, but at the price of computational time and memory requirements.

2) We write a set of linear equations like this,

$$\begin{bmatrix} \tau_1^s \\ \tau_1^d \\ \sigma_1^n \\ \tau_2^s \\ \tau_2^d \\ \sigma_2^n \end{bmatrix} = \begin{bmatrix} A_{11}^{ss} & A_{11}^{sd} & A_{11}^{sn} & A_{12}^{ss} & A_{12}^{sd} & A_{12}^{sn} \\ A_{11}^{ds} & A_{11}^{dd} & A_{11}^{dn} & A_{12}^{ds} & A_{12}^{dd} & A_{12}^{dn} \\ A_{11}^{ns} & A_{11}^{nd} & A_{11}^{nn} & A_{12}^{ns} & A_{12}^{nd} & A_{12}^{nn} \\ A_{21}^{ss} & A_{21}^{sd} & A_{21}^{sn} & A_{22}^{ss} & A_{22}^{sd} & A_{22}^{sn} \\ A_{21}^{ds} & A_{21}^{dd} & A_{21}^{dn} & A_{22}^{ds} & A_{22}^{dd} & A_{22}^{dn} \\ A_{21}^{ns} & A_{21}^{nd} & A_{21}^{nn} & A_{22}^{ns} & A_{22}^{nd} & A_{22}^{nn} \end{bmatrix} \begin{bmatrix} D_1^s \\ D_1^d \\ D_1^n \\ D_2^s \\ D_2^d \\ D_2^n \end{bmatrix}$$

τ_s , τ_d , σ_n are the tractions on each element in the strike and dip directions and the tensile (normal) stress, respectively. The so-called influence coefficients (Green's functions) (the A's above) are calculated using routines provided by *Okada* [1992]. Displacement boundary conditions may be written in an analogous fashion using the appropriate Green's functions.

3) The unknown relative displacement components (the D's) are solved for using a simple matrix inversion.

4) Once the relative displacements are found, the deformation field at any point in the medium (e.g., yellow star below) is calculated analytically.

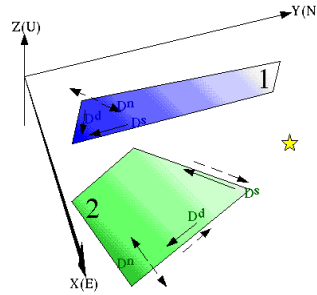


Figure 8:

3 Driving the deformation

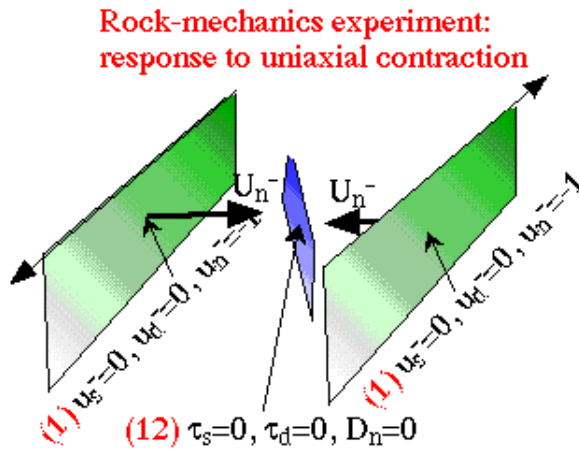
Deformation may be driven in many different ways that fall into three basic categories:


- conditions specified on internal elements (e.g., displacements on fault-elements)
- conditions specified on far-field elements (e.g., boundary displacements)
- a uniform regional field (e.g., a homogeneous strain field).


The choice depends very much on the problem at hand.

3.1 Example 1: Simulating a rock mechanics experiment in uniaxial contraction.

Here the deformation is driven by specifying code 1 conditions (absolute displacements of the footwall along each component of the element) on elements in the far-field relative to the internal fault-element (see figure below). The conditions below state that the footwall (or 'minus' side) of each far-field boundary element will move 1 cm along the negative plane-normal axis and 0 cm along other component axes (planar coordinates, 1). Inside and about to be squeezed by the far-field boundaries is a single fault-element whose boundary conditions are code 12 (shear stress along strike, down dip, and normal stress normal to the element), all set to zero. Code 12 is a commonly used condition for allowing the element to slip freely in shear but to disallow its opening.

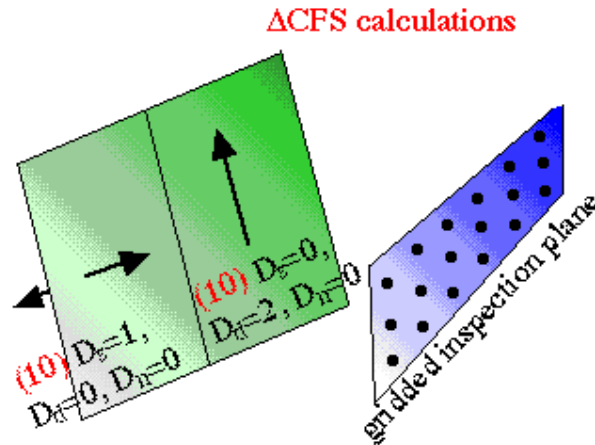


 We recommend that you always check that you've correctly oriented the strike directions and corresponding 'minus' sides for the absolute displacements specified by placing a small inspection plane very close to and parallel to each driving element; the displacements on this inspection plane should equal the displacement value you specified. Note that there can be some numerical error for absolute displacement boundary conditions because the Green's functions are not single-valued on an element and the normal distance goes to zero (see Okada, 1992). Thus, another reason to check each driving element separately is to be sure it is numerically doing what you think it should be.

 Note that the stress boundary conditions placed on the central element via code 12 are **ending** conditions. That is, the stresses take the zero values at the end of the model run, and displacements that occur across the element do so in order to preserve the zero stress conditions. In other words, the element behaves like a frictionless fault. To simulate **friction** on the element, you would need to impose a non-zero level of shear stress opposite in sign to that imposed by the driving stresses. This leads to complications of having to assume *a priori* slip directions, which we will discuss elsewhere.

3.2 Example 2: Change in Coulomb Failure Stress calculations.

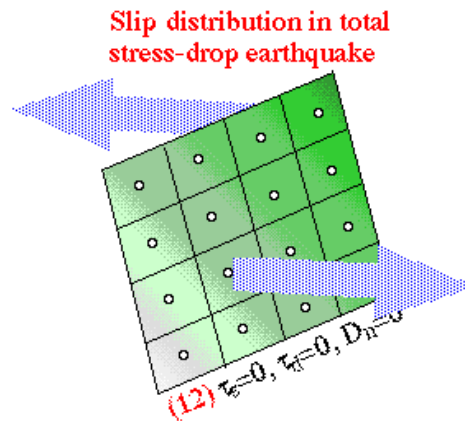
A powerful application of boundary-element codes is the calculation of the change in the so-called Coulomb failure function. In the simple example shown below, the slip of a fault-element (in green) is driven by the specification of relative displacements along each component axis. For illustrative purposes, the fault slips 1 cm only along the strike on the left side and 2 cm only along the dip on the right side. A gridded inspection plane might mark the location of another fault on which you want to calculate the change in Coulomb stress due to this slip distribution.



Note that this is an example of using 3d def as a dislocation program rather than a boundary-element program. Since all the relative displacements are fixed *a priori* there is nothing to solve for. This slip distribution need not minimize the strain energy (if a regional driving deformation field were added) and the effect of slip on one half of the fault on the other half is not accounted for.

3.3 Example 3: Regional strain field.

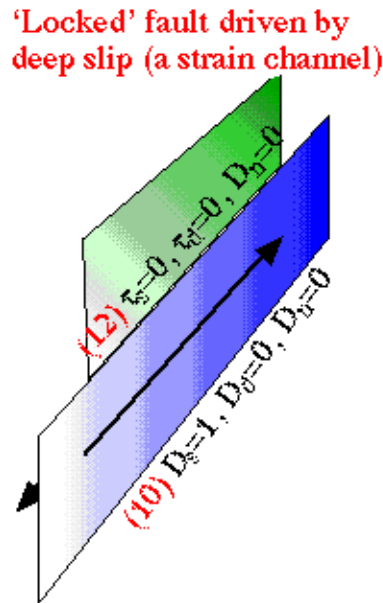
Here the single fault-element has code 12 boundary conditions, each set to zero, and deformation is driven by specifying a far-field regional strain, in this case a simple shear oblique to the fault-element. A simple shear would be specified by a displacement gradient tensor.



🔧 Displacement boundary conditions take precedence over a uniform regional background field, which means that the specification of the latter will not effect displacement on elements for which a displacement boundary condition is specified. You can, however, mix a uniform background field with displacement conditions on some of the elements (e.g., allowing the remaining elements to slip to a stress boundary condition): regional boundary conditions are simply added to other stress boundary conditions on subelements. See the **user's manual** for details.

3.4 Example 4: Strain channels.

Slip on faults in the seismogenic brittle crust may be driven by continuous slip in the ductile layers below. This may be simulated using a 'driving' fault at depth with specified slip beneath a fault that is allowed to slip in response to the deeper slip. The driving fault should be much larger than the shallower fault to avoid any end effects. Here we specify boundary conditions on the shallow fault that will permit a total stress drop earthquake and no fault-opening. Since there is no time-scale, this corresponds to the condition at the end of the seismic cycle just after an earthquake has occurred.



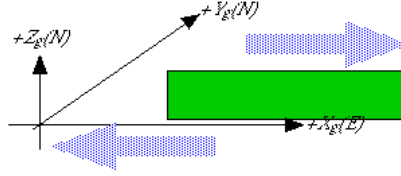
🔧 Note that although a strain-channel or deep slip may occur in a wide zone, in such a model as this, the bottom of the shallower fault must be colinear with the top of the driving fault to insure cancelation of singularities along the element edges.

3.5 Final remark

🔧 Although the user can specify an asymmetric displacement gradient tensor to drive a regional deformation, the asymmetric part (the rigid-body-rotation tensor) does not affect the calculated relative displacements, because of course the rotational part of the tensor does no work.

4 3D-DEF ... input

Let's look first at the whole input file, using an example of a vertical strike-slip fault driven by dextral simple shear:



The input file is reproduced below. The important or relevant pieces are linked to text below the input file; these links provide an annotation of the input file.

```
* POISSONS RATIO YOUNGS MOD #PLANES COEFF INTERNAL FRICTION BACKGROUND DEFORMATION (See manual)

.25          7.E10      2      0.6          displacement gradient
* Background (blank; Exx,Exy,Exz,Eyy,Eyz,Ezz; Sxx,Sxy,Sxz,Syy,Syz,Szz; dUx/dx /dy /dz,dUy/dx /dy /dz,dUz/dx /dy /dz)
-.5e-4 .5e-4 0      -.5e-4 .5e-4 0      0 0 0

for each plane:
ORG:X0 Y0 Z0          WIDTH:STK DIP #SUB-ELEM:STK DIP STK DIP
      10.0 10. 0.0          50. 20.          3 2 45. 90
      38.2843 52.4264 0.0          50. 20.          3 2 45. 90

for each plane (at each fixed distance along strike, going up-dip):
PLN,SUB-ELEM          code BC-shear(STK) BC2-shear(DIP) BC3-normal
1
  1  1      12          0.          0.0          0.0
  1  2      12          0.          0.0          0.0
  1  3      12          0.          0.0          0.0
  2  1      12          0.          0.0          0.0
  2  2      12          0.          0.0          0.0
  2  3      12          0.          0.0          0.0
2
  1  1      12          0.          0.0          0.0
  1  2      12          0.          0.0          0.0
  1  3      12          0.          0.0          0.0
  2  1      12          0.          0.0          0.0
  2  2      12          0.          0.0          0.0
  2  3      12          0.          0.0          0.0

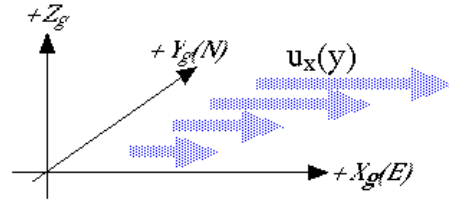
* Run everything else interactively
Non-interactive grid specification
plane
vector
* Coordinate system of output
in-plane
* Output files to create
stress
elements
* Output file suffix
pln
* Xo, Yo, Zo (Ref.corner), strike,dip,length,width:
10.1 10.1 0. 45. 90. 50. 20.
* number of grid points in the strike and dip directions
50 20.
```

Now check the results! 4.6

4.1 Driving the deformation:

```
0 1e-4 0      0 0 0      0 0 0
```

is the row-by-row displacement gradient tensor, and it specifies a dextral or right-lateral simple shear.



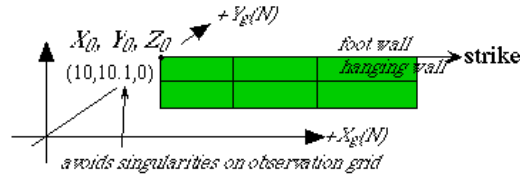
If you wanted to dimensionalize this, you might assume, as an example, that the region being deformed is 100 km across (say 50 km each side of the fault), so that a shear of 1e-04 is generated by a relative displacement of 10m. If you were modeling the San Andreas fault, for example, this would correspond to a time interval between 200 and 300 years.


Go [here](#) for other methods of driving the deformation, 3.

4.2 Specifying the fault plane:

```
ORG:X0  Y0  Z0          WIDTH:STK  DIP  \#SUB-ELEM:STK  DIP  STK  DIP
      10.0 10.1 0.0          100. 20.          3    2   90.   90
```

means that the top left of the plane lies 10 km east and 10.1 km north of the origin, and is at the surface. It is 100 km long, 20 km down-dip, has a subelement every ~ 33 km along strike and every 10 km down-dip. The plane strikes due east, the hangingwall is the southern block, and it's vertical. Like this:



 It is important to offset slightly either the fault-plane or the inspection grid (see below) from each other to avoid the calculation of singularities at the edges of subelements.

4.3 Specifying boundary conditions:

```
1
  1  1      12      0.      0.0      0.0
  1  2      12      0.      0.0      0.0
  1  3      12      0.      0.0      0.0
  2  1      12      0.      0.0      0.0
  2  2      12      0.      0.0      0.0
  2  3      12      0.      0.0      0.0
2
  1  1      12      0.      0.0      0.0
  1  2      12      0.      0.0      0.0
  1  3      12      0.      0.0      0.0
  2  1      12      0.      0.0      0.0
  2  2      12      0.      0.0      0.0
  2  3      12      0.      0.0      0.0
```

The single fault-element in this example has a total of 6 subelements, 3 along strike, 2 down-dip. The first two columns specify the identity of the subelement (col row). Remember that columns start at the left and rows start at the bottom. Thus (1,1) is at the lower left and (3,2) is at the top right.

🧑 In most input files that you see from now on, the (col row) identifiers of subelements will be 1s only, because these numbers are not read by the program. The program expects the subelements to be ordered properly, and the numbers are really only for the user.

The boundary conditions shown here correspond to code 12 (strike//stress, dip//stress, normal_relative displacement) and are zero for each component. This means that the strike and dip relative displacement at the center of each subelement will be such that the final state of shear stress is zero, and that there is no normal opening or closing. Code 12 0 0 0 is a common bc for freely slipping fault-elements.

4.4 Results output

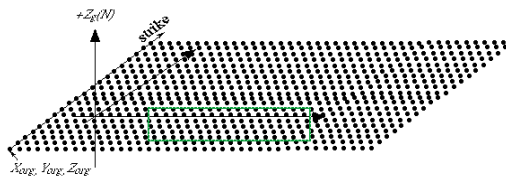
```
planexyz
* Coordinate system of output
global
* Output files to create
displacements
elements
strain
stress
* Output file suffix
out
```

Results are to be output to a plane in only xyz format and in global coordinates. Four types of results will be calculated, displacements on the inspection plane (see below for details of the inspection plane), displacements across each of the subelements, and components of the strain and stress tensor on the inspection plane. Result files will be identified by their suffix .out.

4.5 Inspection plane

```
* Xo, Yo, Zo (Ref.corner), strike,dip,length,width:
-50 -50 0 0 0 200 200
* number of grid intervals in the strike and dip directions
50 50
```

The inspection plane is specified in the same way as an element. This one is horizontal and at the ground surface and is 200 km by 200 km. Each side is divided into 50 even increments, which will yield 51x51 point-calculation results. The inspection plane is defined to be well away from fault edges in order to adequately sample the subtle variations in displacement, strain, etc. away from the fault.



4.6 Checking the results

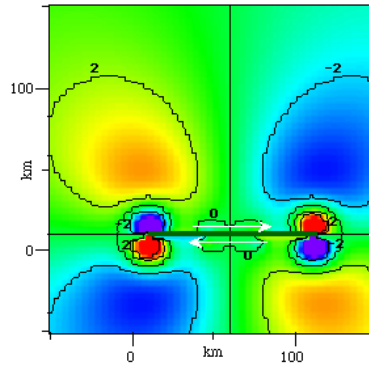
An example of an output file (file: elements.out) showing displacements across the subelements is shown below.

Xg	Yg	Zg	Xp	Yp	Zp	Ds	Dd	Dn
26.667	10.100	-15.000	16.667	5.000	0.000	-281.3	-4.363	0.
26.667	10.100	-5.000	16.667	15.000	0.000	-356.0	-4.013	0.
60.000	10.100	-15.000	50.000	5.000	0.000	-309.0	-0.6585E-07	0.
60.000	10.100	-5.000	50.000	15.000	0.000	-395.9	0.5478E-06	0.
93.333	10.100	-15.000	83.333	5.000	0.000	-281.3	4.363	0.
93.333	10.100	-5.000	83.333	15.000	0.000	-356.0	4.013	0.

(The top header line is not usually part of the output file.)

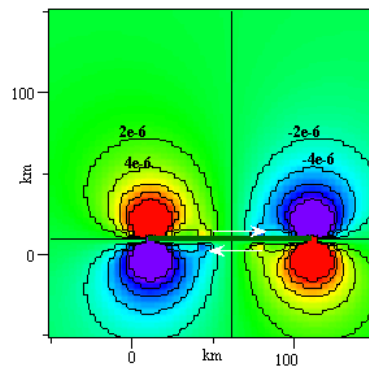
Notice that both strike-parallel and dip-parallel relative displacements are negative, which means that the hangingwall is moving relative to the footwall along $-X_p$ and $-Y_p$, so that the fault is dextral and normal, although the strike-slip component is an order of magnitude larger than the normal component. And as specified in the input file boundary conditions, the fault-normal displacements are zero.

Given this type of fault, the vertical displacements should be as shown below:



Vertical displacements (cm) must be 'up' in contractional quadrants (file displacements.out), as indeed they are here.

And contractional strains (negative = blues) should occupy the contractional quadrants (file strainten.out); see below.



Other examples of both input and output can be found in Examples on the main menu and in Output, 5.

5 3D-DEF Output

5.1 1. Specification of output

The bottom part of the input files describes the types of output requested. Here is an example:

Bottom part of input file	Explanation
* Run everything else interactively	comment
Non-interactive grid specification	specify grid to which output is referred below
plane	let this grid be a plane
vector	request vector output (note: xyz format is always output)
* output coordinate system	specify output coordinate system
global	choose global rather than in-plane
* output files to create	select whichever output is required (there are many choices, read on)
elem	relative displacements on elements
displacements	absolute displacements on inspection grid
rbr	rigid-body rotations on inspection grid
* output file suffix	4 characters or less
t	output file suffix (format allows no more than 4 characters)
* Xo,Yo,Zo (Ref. corner),strike,dip,length,width:	specify inspection plane
0 55 0 90 0 59 59	see below
* number of grid points in strike and dip directions:	actually the number of equal divisions along strike and dip

In this example, results will be written with reference to coordinates that define a horizontal plane at the surface whose origin in global coordinates lies 55 km north of the coordinate origin, and that is 59 km along strike and dip. The plane is then divided into 59 intervals along both strike and dip, so that quantities (in the case, components of displacements and rbr) will be written at 1 km spacings. This will yield 60 results along both strike and dip, for a total of 3,600 x 3 displacement results. Displacements of all subelements will also be written to elem files.

5.2 2. Output files format

Output files formats can be 'xyz' (column) or 'vector' (matrix) format, and they are referenced to either the inspection grid or the elements themselves.

'xyz' format lists each component of the calculated quantity in column format next to its location in either global or in-plane coordinates.

The first three columns are the x, y, and z locations in global coordinates (it's usually better or easier to use global coordinates), the next columns are deformation quantities calculated at this location.

The equivalent vector output comprises three matrices, one for each component of displacement (or whatever quantity is being output): disp1, disp2, and disp3, where 1, 2, and 3 are cryptic mnemonics for x, y, and z. Locations are implicit in the position of the matrix elements. Vector output is useful for plotting purposes (using something like MATLAB or Spyglass) and for quick visual inspection of the results.


🧠 Remember that the vector files elem.. are written in matrix format (with (1,1) at top-left, etc.), in contrast to their order in the input file. There are some applications in which you might want to put the results of one model run back into another model. A few MATLAB commands to do this one elem block at a time are:


```
load elem01...
new_elem = reshape(flipud(elem01), rows x cols, 1)
```

which produces a column of, in this case, elem01 components that can be pasted directly into the input file. A more complete matlab m-file to do this for all elem-files can be found in the m-file directory.

5.3 3. Output filenames and descriptions

A description of some of the output files and the type of output is given below. Global coordinates are referenced if the quantities have x, y, or z as part of their output name (e.g., Exy, Exx, etc.) In-plane coordinates are referenced if s, d, or n (strike, dip, or normal) are part of the output file names (e.g., Esd, Ess, etc.). To avoid a cluttered look, we refer always to the global coordinates in the list below.

 The underlined word or portion of a word is the name of the output file as it should be entered in the input file. For example, if you want the displacement gradient tensor, enter grad, or for rigid-body rotations, enter rbr.

 Each filename, in italics below, whether output in xyz or in vector format carries a suffix (e.g., *strainten.jsuffix_i*). For clarity, this is not indicated below.

Stress tensor:

xyz: *stressten* (x y z sxx txy txz syy tyz szz tmax tmax's rake, tstrike, tdip)

tmax is the max shear stress, tstrike and tdip are shear stresses along strike and dip of the inspection plane

vector: *Sxx, Sxy, Sxz, Syy, Syz, Szz, Syy, tmax, tmaxa, tmx, tmy*

Strain tensor:

xyz: *strainten* (x y z Exx Exy Exz Eyy Eyz Ezz Evol)

Evol is the trace of the tensor and is equal to the volume change.

vector: *Exx Exy Exz Eyy Eyz Ezz Evol*

Although we label these quantities as simple strains, they ARE indeed strain tensor components.

e.g., $E_{xy} = (dU_x/dy + dU_y/dx)/2$, etc.

Absolute displacements:

xyz: *displacements* (x y z Ux Uy Uz)

vector: *disp1, disp2, disp3* (1, 2, and 3 refer to x, y, and z)

Displacement gradients:

xyz: *dgten* (x y z dUx/dx, dUx/dy, dUx/dz, dUy/dx, dUy/dy, dUy/dz, dUz/dx, dUz/dy, dUz/dz)

vector: *dU/dx, dU/dy*, etc.

Magnitudes and orientations of principal strains: xyz: *strainorient* (x y z Emax, Pmax, Tmax, Eint, Pint, Tint, Emin, Pmin, Tmin) For each principal strain axis, in descending order, given is the magnitude, trend, and plunge of the strain. vector: *prince_max, plunge_max, trend_max, prince_int, plunge_int, trend_int, prince_min, plunge_min, trend_min*.

Invariants:

xyz: *invariants* (x y z Evol, failure stresses, octahedral shear stress, strain energy density)

vector: *delv, aftershocks, oss, work*

Rigid body rotations (rbr):

xyz: *rbr* (x y z rbr_x rbr_y rbr_z) vector: *rbr_deg_x, rbr_deg_y, rbr_deg_z*

Optimal failure planes:

xyz: *failure* (x y z strike dip sv_east, sv_north, sv_up)

sv_east, etc. are direction cosines of the slip vector w/r to east (global x-axis), etc.

vector: *strike1, strike2, ce1, cn1, cz1, ce2, cn2, cz2*

ce1, etc. are the direction cosines of the slip vector for plane 1w/r to east (global x-axis), etc.

Relative sub-element displacements:

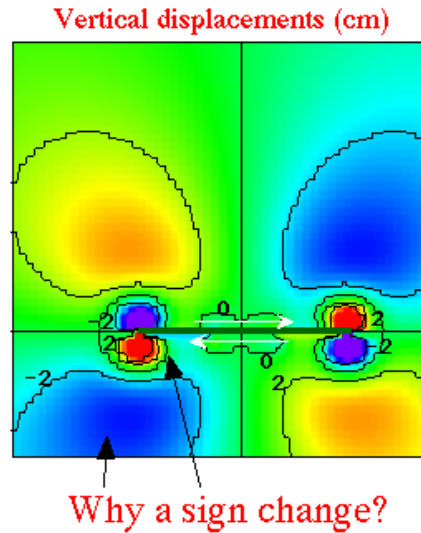
xyz: *elements*

vector: *elemds01, elemdd01, elemdn01*, etc. ds, dd, and dn refer to displacements of the hanging wall relative to the footwall in the strike, dip, and normal directions, respectively. Thus, negative values of elemds, for example, mean that the displacement is dextral or right-lateral; negative values of elemdd refers to a normal fault, etc. The numeral 01 refers to the first element specified in the input file; 02 would refer to the second, and so on.

6 Pitfalls, Advice

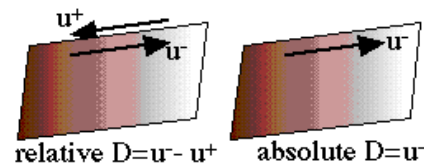
6.1 Start simple!

Even the simplest models can generate deformation fields that are very counter-intuitive; it's best to understand these before daring to try complex models. For example,



6.2 ABSOLUTE and RELATIVE displacements.

Remember the difference between ABSOLUTE and RELATIVE displacements.



6.3 Avoid observation points at element edges.

Avoid observation points at element edges because the stresses are singular there. This may happen inadvertently when generating output on a gridded plane or volume.

6.4 Discretize with care.

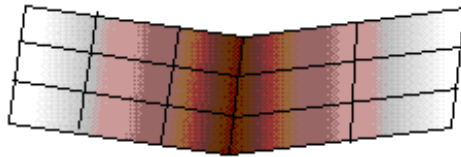
The numerical approximation in boundary-element modeling comes from the fact that one approximates boundary conditions on a surface by specifying them only at a finite number of discrete points. We know of no rigorous way to determine the optimal discretization. One approach is simply to start with a coarse, but intuitively reasonable discretization and to sub-divide it until the deformation no longer changes significantly. This process and the meaning of 'significantly' depends highly on the problem being solved.

6.5 Modeling a single surface using several planes.

When modeling a single surface using several planes be sure the edges of adjacent planes are shared exactly by both planes. The stress singularities along the edges of each plane will cancel, but only if they're truly the same edge.



Cancellation will not be exact if the sub-element corners along the shared edges aren't also co-located.



7 Getting and running 3D-DEF

7.1 Getting 3D-DEF, version 2.1 November 2004.

The standard source code may be downloaded [here](#). You should receive a tar file that you can untar manually (tar -xvf 3ddef.tar) or use a commercial package such as Stuffit or Winzip.

The files within the 3ddefcodes are:

```
3dmain.f
okada_sub.f
vector_output.f
xyz_output.f
allocatable_arrays.f
parameters.f
plus all the object and mod files derived from a compile on a Solaris unix box..
input - this is an example input file that works.
makefile - this is a makefile (!) that also works and set up for F90.
3d* - this is the executable.
```

manual - in some form(s) or another (and remember too that the manual is available via the online guide to 3D-DEF).

7.2 Running 3D-DEF

Make an input file (see the tutorial and manual), type 3d and you will be prompted for the name of the input file. The rest should be history.

Note that in an older version of 3ddef, you were required to limit the array size with parameter settings inside sizes.inc. This is no longer required; Joan Gomberg has since made the array allocation dynamic and you are limited now only by the size of your memory and problem. To compile on most standard unix systems, simply type 'make' and the object and executable files will be created in the same directory as the source codes. If you have any problems, please let one of us know, Mike Ellis or Joan Gomberg.

You're ready to go!

NOTE: Pablo J. Gonzalez (May, 2013)

A version that can be compiled using gfortran can be downloaded from [here](#). To compile, this version just:

```
chmod +x compile.me
```

, and then run in the same folder:

```
./compile.me
```

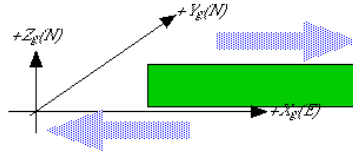
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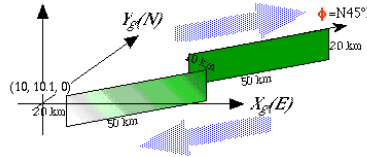
A More examples

A.1 Example #2: En-echelon strike-slip faults

We extend example #1 (below) by rotating the earlier deformation field and placing another fault en echelon to the first, giving a right-step in a right-lateral strike-slip system, which should yield a region of uplift in the step (think New Madrid).



Example 1 (above), which can be viewed in more detail here, 4.6.



Example 2 (above) which has both the deformation field and the faults striking at 45-degrees.

To rotate the deformation field counter-clockwise, as shown above, we rotate the coordinate axes clockwise, which is a negative rotation (using the convention described here).

Thus: $\mathbf{Dn} = \mathbf{R.D.R'}$

where \mathbf{D} is the previous displacement gradient tensor (dgt), \mathbf{Dn} the new, rotated dgt, and \mathbf{R} is the rotation matrix ($\mathbf{R'}$ is its transpose).

$$\text{Rotation } \mathbf{R} = \begin{vmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

Example #2: The input file

```
* POISSONS RATIO      YOUNGS MOD      #PLANES      COEFF INTERNAL FRICTION      BACKGROUND DEFORMATION (See manual)
.25                    7.E10          2              0.6                          displacement gradient
* Background (blank; Exx,Exy,Exz,Eyy,Eyz,Ezz; Sxx,Sxy,Sxz,Syy,Syz,Szz; dUx/dx /dy /dz,dUy/dx /dy /dz,dUz/dx /dy /dz)
-.5e-4 .5e-4 0        -.5e-4 .5e-4 0        0 0 0
```

for each plane:

```
ORG:X0 Y0 Z0          WIDTH:STK DIP #SUB-ELEM:STK DIP STK DIP
10.0 10.0 0.0         50. 20.      3 2 45. 90
38.2843 52.4264 0.0   50. 20.      3 2 45. 90
```

for each plane (at each fixed distance along strike, going up-dip):

```
PLN,SUB-ELEM      code   BC-shear(STK)  BC2-shear(DIP)  BC3-normal
1
1 1 12            0.      0.0            0.0
1 2 12            0.      0.0            0.0
1 3 12            0.      0.0            0.0
2 1 12            0.      0.0            0.0
```

```

      2  2      12      0.      0.0      0.0
      2  3      12      0.      0.0      0.0
2
      1  1      12      0.      0.0      0.0
      1  2      12      0.      0.0      0.0
      1  3      12      0.      0.0      0.0
      2  1      12      0.      0.0      0.0
      2  2      12      0.      0.0      0.0
      2  3      12      0.      0.0      0.0

```

```

* Run everything else interactively
Non-interactive grid specification
plane
vector
* Coordinate system of output
in-plane
* Output files to create
stress
elements
* Output file suffix
pln
* Xo, Yo, Zo (Ref.corner), strike,dip,length,width:
10.1 10.1 0. 45. 90. 50. 20.
* number of grid points in the strike and dip directions
50 20.

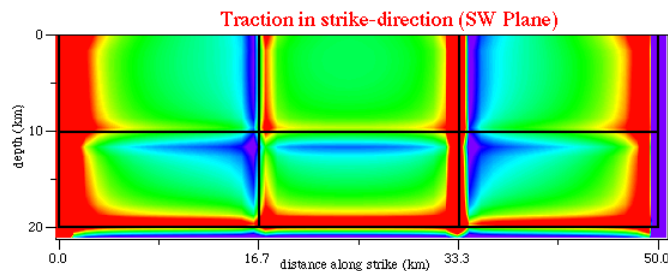
```

Highlights of this input file are:

- each fault is discretized into 6 subelements
- fault (elements) are free to slip
- results are calculated in the in-plane coordinate system
- results are output in both xyz and vector (matrix) format
- stresses are to be calculated at grid points on the inspection plane that is essentially coincident with the SW fault plane
- the inspection plane is slightly offset from the SW fault-element to avoid singularities.

Look at the traction in the strike direction (tsn).

🚧 Remember that the boundary conditions set this to zero - but only at the center point!



Green corresponds to zero shear stress; $tsn=0$ is only satisfied in the centers!

If we discretize more finely

The input file (same as above except that the faults are now discretized into 50 subelements)

```
* POISSONS RATIO      YOUNGS MOD      #PLANES      COEFF INTERNAL FRICTION      BACKGROUND DEFORMATION (See manual)
.25                    7.E10          2              0.6                      displacement gradient
* Background (blank; Exx,Exy,Exz,Eyy,Eyz,Ezz; Sxx,Sxy,Sxz,Syy,Syz,Szz; dUx/dx /dy /dz,dUy/dx /dy /dz,dUz/dx /dy /dz)
-.5e-4 .5e-4 0        -.5e-4 .5e-4 0        0 0 0
```

for each plane:

```
ORG:X0  Y0  Z0          WIDTH:STK  DIP  #SUB-ELEM:STK  DIP  STK  DIP
      10.0 10. 0.0          50.   20.          10   5   45.   90
      38.2843 52.4264 0.0          50.   20.          10   5   45.   90
```

for each plane (at each fixed distance along strike, going up-dip):

```
PLN,SUB-ELEM      code      BC-shear(STK)      BC2-shear(DIP)      BC3-normal
```

```
1
  1  1      12      0.      0.0      0.0
  1  2      12      0.      0.0      0.0
  1  3      12      0.      0.0      0.0
  1  4      12      0.      0.0      0.0
  1  5      12      0.      0.0      0.0
  1  6      12      0.      0.0      0.0
  1  7      12      0.      0.0      0.0
  1  8      12      0.      0.0      0.0
  1  9      12      0.      0.0      0.0
  1 10      12      0.      0.0      0.0
  2  1      12      0.      0.0      0.0
  2  2      12      0.      0.0      0.0
  2  3      12      0.      0.0      0.0
  2  4      12      0.      0.0      0.0
  2  5      12      0.      0.0      0.0
  2  6      12      0.      0.0      0.0
  2  7      12      0.      0.0      0.0
  2  8      12      0.      0.0      0.0
  2  9      12      0.      0.0      0.0
  2 10      12      0.      0.0      0.0
  3  1      12      0.      0.0      0.0
  3  2      12      0.      0.0      0.0
  3  3      12      0.      0.0      0.0
  3  4      12      0.      0.0      0.0
  3  5      12      0.      0.0      0.0
  3  6      12      0.      0.0      0.0
  3  7      12      0.      0.0      0.0
  3  8      12      0.      0.0      0.0
  3  9      12      0.      0.0      0.0
  3 10      12      0.      0.0      0.0
  4  1      12      0.      0.0      0.0
  4  2      12      0.      0.0      0.0
  4  3      12      0.      0.0      0.0
  4  4      12      0.      0.0      0.0
  4  5      12      0.      0.0      0.0
  4  6      12      0.      0.0      0.0
  4  7      12      0.      0.0      0.0
  4  8      12      0.      0.0      0.0
  4  9      12      0.      0.0      0.0
  4 10      12      0.      0.0      0.0
  5  1      12      0.      0.0      0.0
  5  2      12      0.      0.0      0.0
  5  3      12      0.      0.0      0.0
  5  4      12      0.      0.0      0.0
  5  5      12      0.      0.0      0.0
  5  6      12      0.      0.0      0.0
  5  7      12      0.      0.0      0.0
  5  8      12      0.      0.0      0.0
  5  9      12      0.      0.0      0.0
  5 10      12      0.      0.0      0.0
2
  1  1      12      0.      0.0      0.0
  1  2      12      0.      0.0      0.0
  1  3      12      0.      0.0      0.0
  1  4      12      0.      0.0      0.0
  1  5      12      0.      0.0      0.0
  1  6      12      0.      0.0      0.0
```

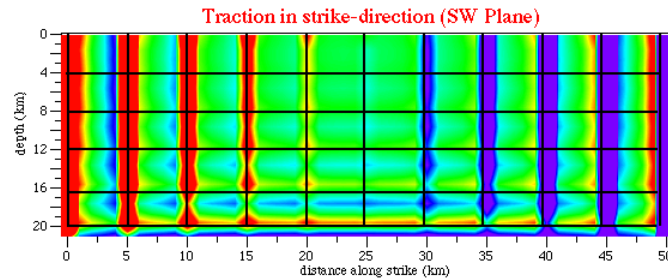

1	7	12	0.	0.0	0.0
1	8	12	0.	0.0	0.0
1	9	12	0.	0.0	0.0
1	10	12	0.	0.0	0.0
2	1	12	0.	0.0	0.0
2	2	12	0.	0.0	0.0
2	3	12	0.	0.0	0.0
2	4	12	0.	0.0	0.0
2	5	12	0.	0.0	0.0
2	6	12	0.	0.0	0.0
2	7	12	0.	0.0	0.0
2	8	12	0.	0.0	0.0
2	9	12	0.	0.0	0.0
2	10	12	0.	0.0	0.0
3	1	12	0.	0.0	0.0
3	2	12	0.	0.0	0.0
3	3	12	0.	0.0	0.0
3	4	12	0.	0.0	0.0
3	5	12	0.	0.0	0.0
3	6	12	0.	0.0	0.0
3	7	12	0.	0.0	0.0
3	8	12	0.	0.0	0.0
3	9	12	0.	0.0	0.0
3	10	12	0.	0.0	0.0
4	1	12	0.	0.0	0.0
4	2	12	0.	0.0	0.0
4	3	12	0.	0.0	0.0
4	4	12	0.	0.0	0.0
4	5	12	0.	0.0	0.0
4	6	12	0.	0.0	0.0
4	7	12	0.	0.0	0.0
4	8	12	0.	0.0	0.0
4	9	12	0.	0.0	0.0
4	10	12	0.	0.0	0.0
5	1	12	0.	0.0	0.0
5	2	12	0.	0.0	0.0
5	3	12	0.	0.0	0.0
5	4	12	0.	0.0	0.0
5	5	12	0.	0.0	0.0
5	6	12	0.	0.0	0.0
5	7	12	0.	0.0	0.0
5	8	12	0.	0.0	0.0
5	9	12	0.	0.0	0.0
5	10	12	0.	0.0	0.0

```

* Run everything else interactively
Non-interactive grid specification
plane
vector
* Coordinate system of output
in-plane
* Output files to create
stress
* Output file suffix
out
* Xo, Yo, Zo (Ref.corner), strike,dip,length,width:
10.1 10.1 0. 45. 90. 50. 20.
* number of grid points in the strike and dip directions
50 20.

```

Now the tractions in the strike direction (t_{sn}) are zero over more of the plane - but not all!



Next look at the surface displacement field.

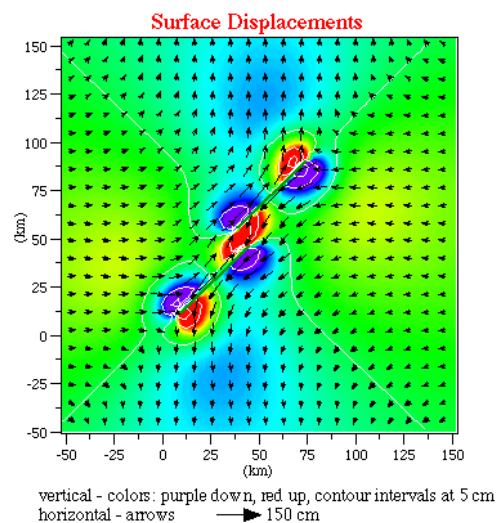
Change only the output portion (2nd half) of the input file:

```
* Run everything else interactively
Non-interactive grid specification
plane
xyz
* Coordinate system of output
global
* Output files to create
displacements
* Output file suffix
out
* Xo, Yo, Zo (Ref.corner), strike,dip,length,width:
-50 -50 0 0 0 200 200
* number of grid points in the strike and dip directions
50 50
```

Highlights of this input file:

- the inspection plane is now a horizontal surface at ground level
- results are output in the global coordinate system

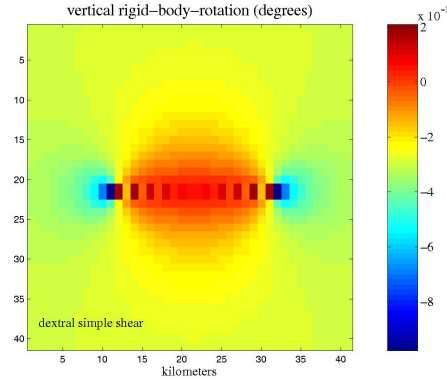
Here are the surface displacements:



A.2 Example #3: Rigid body rotations and horizontal displacements

We return to a simple geometry of a vertical strike-slip fault driven by a dextral simple shear (input file) to illustrate an important aspect of the output of displacements and rigid-body rotations.

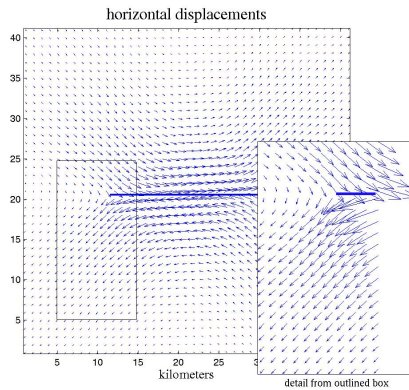
Vertically oriented dextral or right-lateral simple shear involves a clockwise rigid-body rotation about the vertical (z) axis equal to half of the sum of the (1,2) and (2,1) components of the displacement gradient tensor, which in this case is equal to $0.5\text{e-}04$. The plot below (which is linked to a larger and clearer version of the same thing) shows the distribution of rotations about z:



Note that the mean-looking background value is about $3\text{e-}03$ (it's actually $0.2865\text{e-}02$) degrees, which is equal to $0.5\text{e-}04$ radians or the input value. The background value of rbr is added to that which results from slip across the fault.

Note too that the sign of a clockwise rotation is negative, but that as a consequence of slip across the fault there is a relatively large area of counterclockwise or anticlockwise rotation along the length of the fault as well as significant clockwise rotations in the tip-zones of the fault.

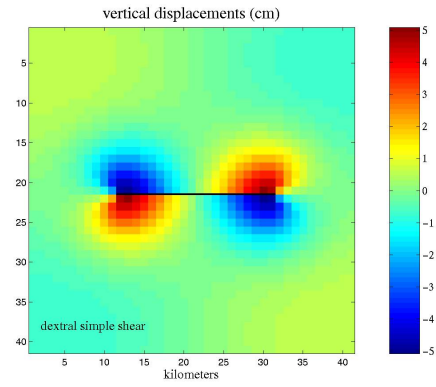
Now take a look at the horizontal displacements. The small figure below may not be very clear, so the image is linked to a larger and clearer one.



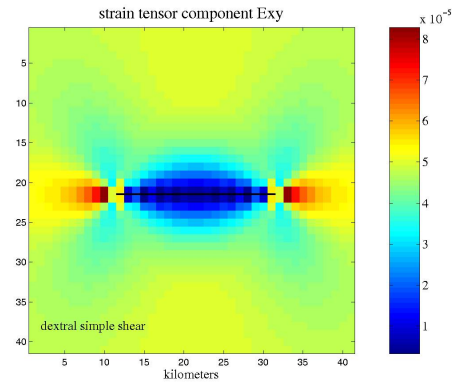
Horizontal displacements show clearly the right-lateral relative displacements across the fault, but note that in contrast to the rbr output above the far-field displacements (that would look like horizontal arrows) are not shown. Displacements resulting only from slip across the fault are shown. We do not add the background displacements because they are functions of distance from an arbitrary origin and so would hide the more interesting displacements that occur as a result of slip across the fault or faults.

Examples of other output from the same input file.

Vertical displacements look like this:



and tensor shear strain across vertical E-W or N-S planes look like this:



Note again that the background (input) value is approximately $0.5e-04$.

A.3 Example #4: Topography and structure as a regional strain markers

The measurement of regional strain can be tricky, mainly because there are very few markers that straddle the entire region over a long enough time to be useful. Geodetic methods measure displacements of points at a time scale approaching a decade, and both the spatial and temporal limitations lead to difficulties in interpretation. One of the best strain markers may be the topography (of both the ground surface and older surfaces).

As with all methods, there are a number of assumptions that must be made and limitations to be acknowledged. In this case, we will assume the following:

1. Topography of both the ground surface and the recent structural topography (e.g., basin floors) is generated to a first order by displacements across crustal scale faults in the upper crust and that the source of energy is uniformly distributed.
2. The regional strain is to first order homogeneous.
3. Long-term patterns of deformation are generated by the "freezing in" of short-term infinitesimal strains, of the sort that 3d def can model.

If these assumptions are satisfactory, then we can use 3d def to calculate the interdependence of and displacements across a series of faults that can be shown to have been active over the last several hundred kyr or My. Obviously, the further back in time we try to apply this method, the worse the approximation gets.

Here we show an example of part of the southwest Basin and Range province, the Saline Valley - Panamint Valley linked fault system. The figure below shows the topography.

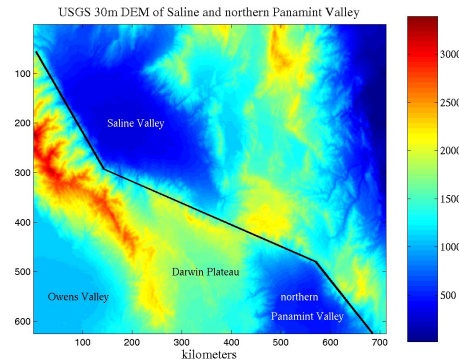
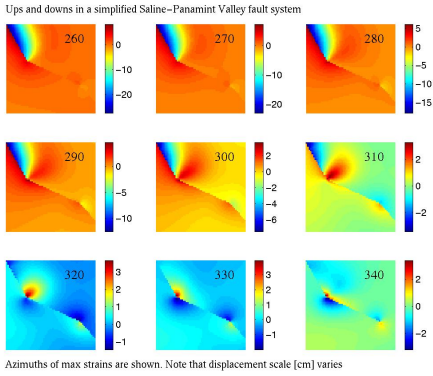


Figure 9: USGS DEM of Saline Valley and northern Panamint Valley

Saline Valley is one of the deepest enclosed holes in the country, and is bordered to the west by the fault bounded Inyo Range and to the south by basalts of the Darwin Plateau and granitoids of Hunter Mountain. A single pass connects Saline Valley to Panamint Valley, and the two valleys are joined by the Hunter Mountain (predominantly) strike-slip fault (HMF). The HMF connects to the eastern side of north Panamint Valley, where the fault continues southeast along the edge of the Panamint block.

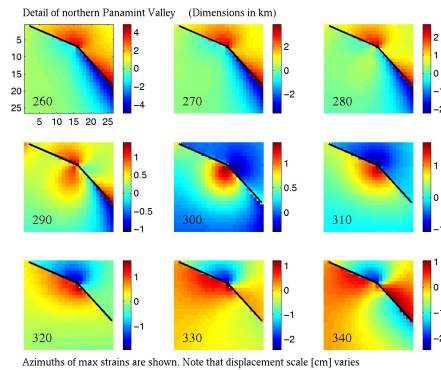
For this example (and it is only an example of the utility of 3D-DEF), we shall ignore the faults within the Darwin Plateau and along the western boundary of the Inyos.

An example of the input file can be obtained [here](#). Click on the thumbnail image below to see more details.



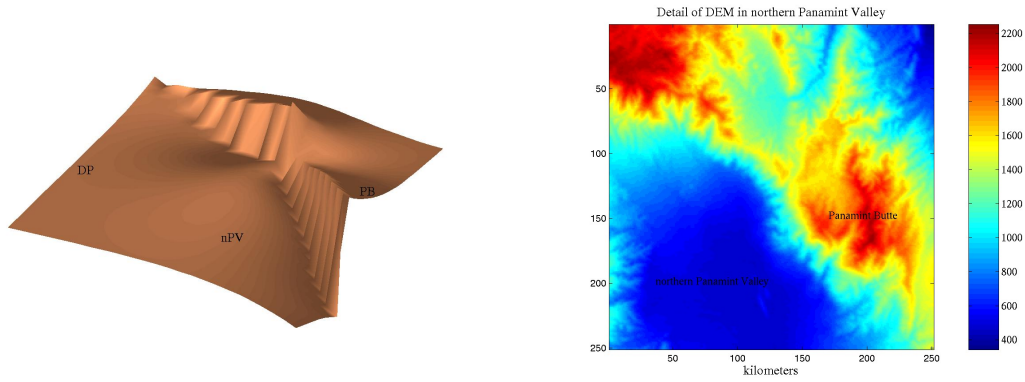
Saline Valley is predicted very well in most of these models, certainly ones in which the maximum strain (or stretch) is toward the west or northwest. This means that Saline Valley is not a good regional strain discriminator. Because Saline Valley is such a dominant feature, both in the models and in reality, it overwhelms the scaling of elevations, which means that we don't get to see much of the detail in northern Panamint Valley. (This is again true in reality, since northern Panamint Valley offers a very different drama to the visitor than does the gaping hole of Saline Valley.)

The figure below shows thumbnail sketches of the southern part of the modeled region, that is, northern Panamint Valley. To see more details, follow the link.



These figures show quite a different picture. If we go with the assumption that northern Panamint Valley is an actively subsiding basin (and there is some reason to doubt that) and that the topography generally reflects the current ups and downs of the region, then the maximum strain must be oriented between 260 - 290 degrees.

The figures below show more detail still from model #3 (max strain toward 280), in which the model successfully predicts a topographic low (i.e. a pass) between Panamint Butte and Hunter Mountain, each to the northeast of the faults. Whether this pass is tectonically controlled (as the model predicts) or not is unknown, as far as I know, at least.



On the left is a perspective view looking toward the north - northeast over the floor of northern Panamint Valley. The model-fault runs from the bottom-right to top-left; its corrugation reflects the discretization of the elements. On the right is the USGS 30m DEM of roughly the same area.

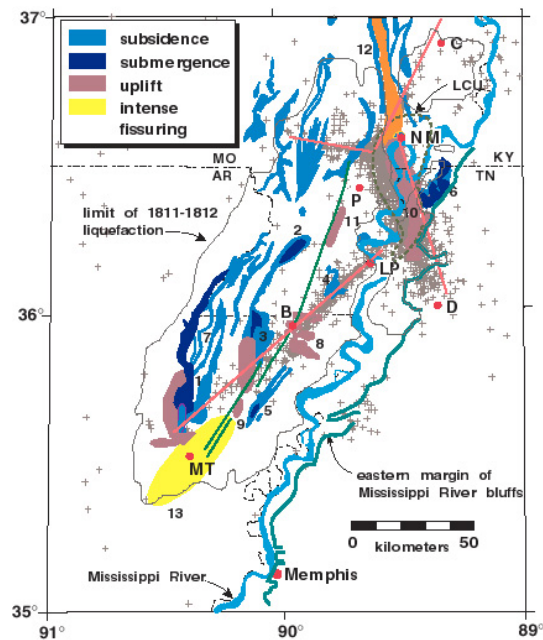
And the lesson to be learned is: the models appear to successfully predict the topography to a first order using relatively few faults. If the assumptions discussed at the beginning are valid, then the numerical experiments (which is how these models should be viewed) provide us with a regionally averaged strain field in which the maximum extension lies somewhere between 260 and 300 degrees. We are also left with the predictions that a) northern Panamint Valley is far less of a sedimentary basin than is Saline Valley (which is by all accounts true), b) that the (Cottonwood) pass, to the northwest of Panamint Butte, is tectonically controlled, and c) that the currently active fault in northern Panamint Valley is predominantly strike-slip (we've not shown evidence for that here, but nonetheless it is predicted).

There is more to the Saline Valley - Panamint Valley story than we've described here, so please don't take these results as gospel. Yet.

A.4 Example #5: Rupture scenarios of the New Madrid earthquakes of 1811-1812

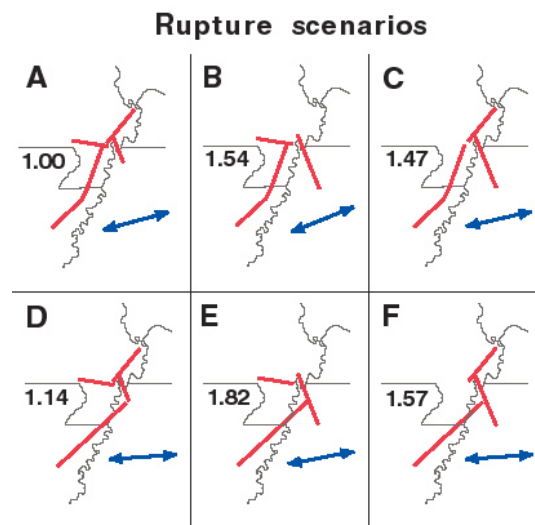
In a continuing effort to understand three of the largest earthquakes to strike the lower 48 in historical times (1811-1812, 3 M 7.8-8.1, New Madrid, central USA), we have set up some numerical experiments using 3D-DEF to examine likely rupture scenarios.

We use as first-order evidence the accumulated historical observations of uplift, subsidence, and fissuring that occurred during and immediately after the three earthquakes. Much of the observational evidence comes from the first official survey by the U.S.G.S., published in 1910, by Fuller. A summary of Fuller's evidence and other geomorphic features is shown below:



Likely faults are shown as straight line segments. The seismicity pattern outlines a classic left-step in a NE-oriented dextral strike-slip system. Within the resultant compressional step is our local "mountain", Lake County Uplift, which has a relief of up to 10 m. In the Mississippi floodplain, 10 m is nothing to be sneezed at.

Likely rupture scenarios are shown below:

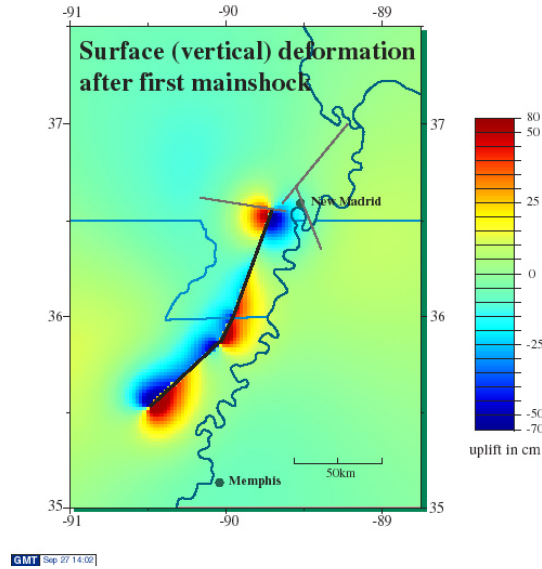


A.4.1 Numerical Procedure.

The models shown below use the abilities of 3D-DEF in a slightly different way than have previous examples. The experimental procedure is this:

1. An initially uniform driving force is derived: The driving force for each scenario was assumed to be regionally uniform and was derived from a moment-tensor summing of the scenario shown in each panel: the arrows show the direction of maximum compression, and the numbers show the relative magnitude of maximum shear strain in each regional strain tensor (normalized to the minimum value in panel A). Thus, all else being equal, we might expect the scenario in A to be preferred, since as strain accumulates, it is this level of shear strain that is reached first.
2. Rupture is permitted only on the first-chosen fault segment, the dimensions of which are enlarged or reduced in order to generate the "correct" magnitude earthquake (assuming $M_0 = r.A.u$, where r is rigidity, A is rupture area, and u is average displacement).
3. The result of step 2 is that the regional strain field is reduced and reduced inhomogeneously. To simulate this for the second earthquake, the result of the first earthquake is placed back into the model and now aids in driving that first fault segment. This then adds and subtracts appropriately from the regional strain field and in sum drives the second and subsequent ruptures.
4. After each earthquake, as well as calculating surface vertical displacements (see figures below), we evaluated if the net strain field was consistent with static stress triggering of subsequent events. In each case, positive triggering appeared consistent, although we do not show the appropriate figures here.

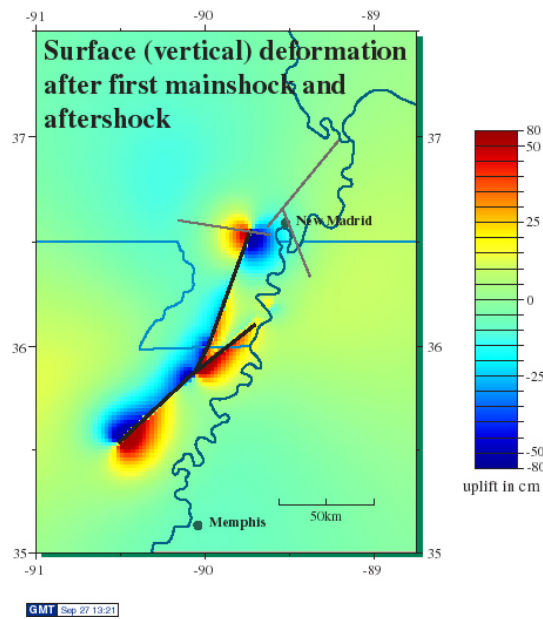
For various other reasons, we placed the first main shock on the southern arm of seismicity, but bent it off of the seismicity and onto the Bootheel lineament. This generates the uplift/subsidence pattern seen below:



(Note that the scale is not linear.)

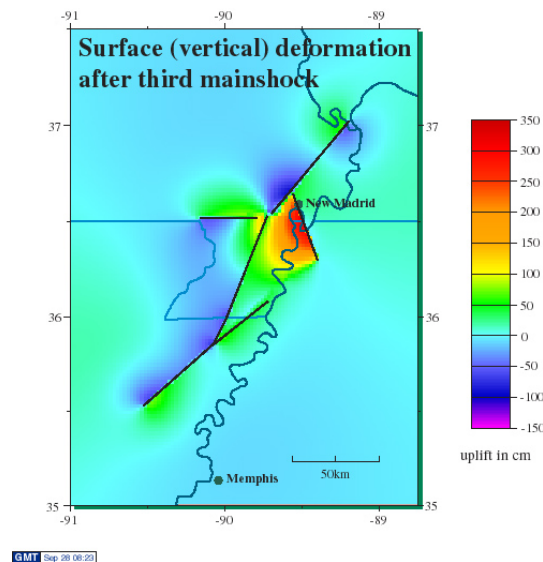
This produces a pattern that is a fairly good fit to the observations, particularly the thin zone of uplift to the east of the Bootheel lineament and in the vicinity of the fault bend.

We next placed the principal aftershock on the remainder of the southern arm of seismicity, which produced this cumulative pattern of vertical deformation:



This highlights the thin zone of uplift to the east of the Bootheel lineament, which is precisely what is observed, and it provides a small region of relative subsidence between the main rupture and the aftershock rupture. It is here that historic lake Cagel (since drained) formed shortly after the two earthquakes.

We next placed the second mainshock on the northern arm of seismicity and the third mainshock on the thrust and vertical fault that extends the thrust to the west. The final pattern of vertical deformation looks like this:



This pattern of uplift and subsidence is remarkably close to the observations in the top figure, although we are currently examining more geomorphic evidence for rupture extension of the central thrust toward the southeast rather than toward the west.

Forward models of this type are of course not unique in any sense of the word, but they do provide impetus for directed field work, and they do allow for a check on realms of possibility, and - as always - tempered with restraint, they are excellent pedagogic tools.

🚧 These figures and text are preliminary. Please respect the rights of the owner (M. Ellis) and do not use for purposes other than teaching the use of 3D-DEF. Thanks.