Introduction to Displacement Modeling

Last updated:
4 February 2020

Introduction

- Deformation on the Earth surface informs us about processes and material properties below surface
- Observation tools:
  - GPS (static-dynamic)
  - InSAR (static)
  - Tiltmeters (static)
  - Seismometers (dynamic)

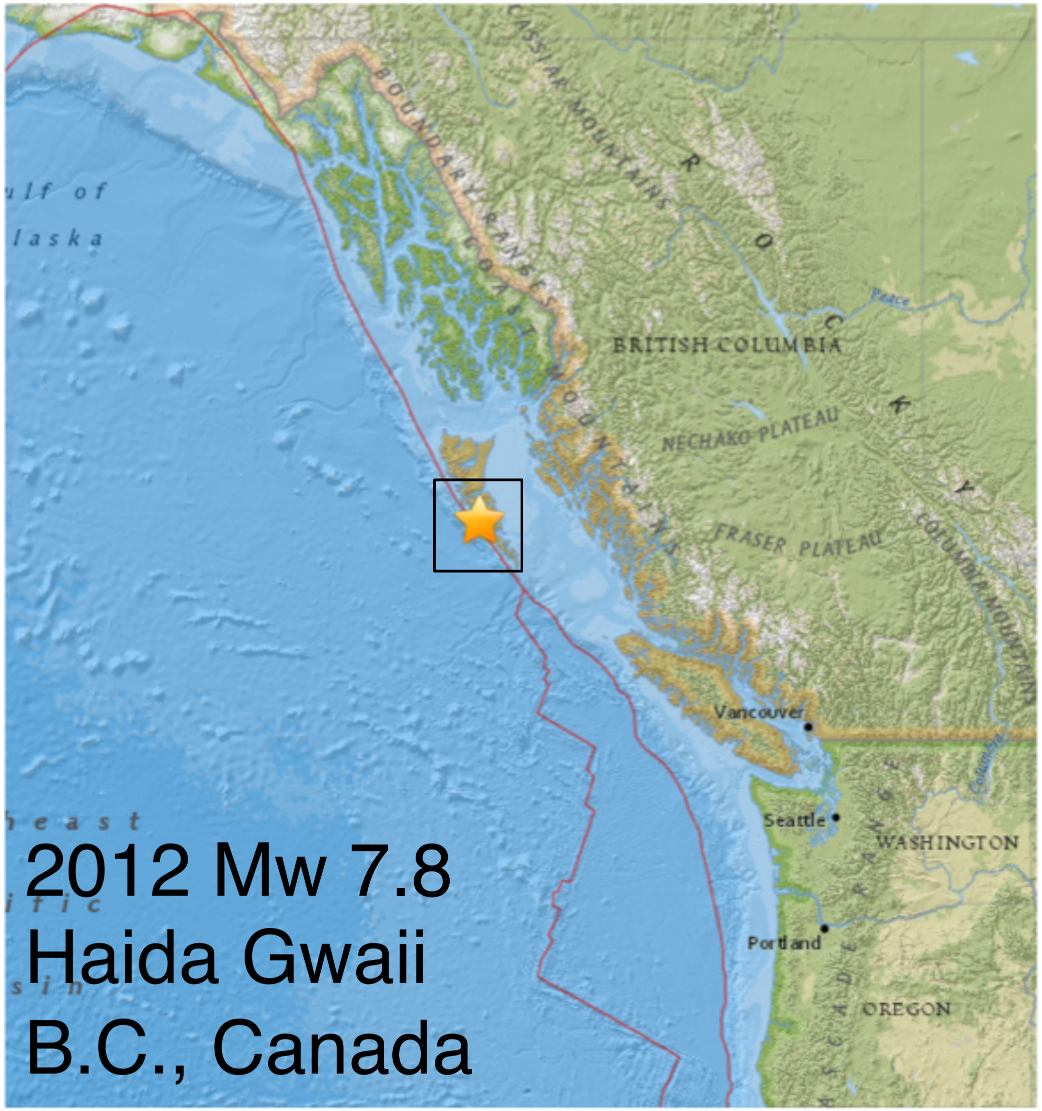
In this tutorial, we will focus on point observations.

GPS Observations

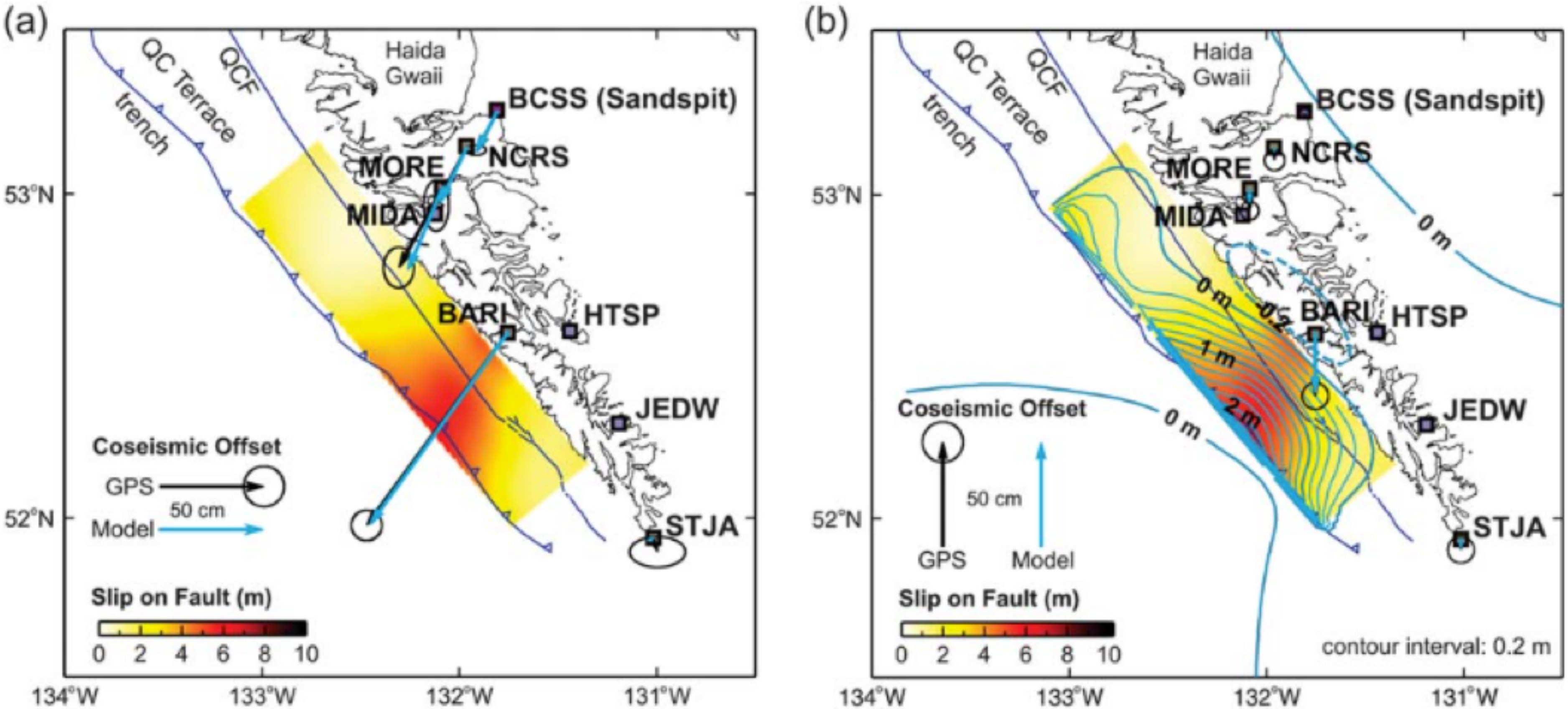
GPS Observations

- Directly measure motion of Earth surface
- In some locations, can resolve millimeter displacements at rate of 1 sample per second
- Applications:
  - Near-field earthquake displacements
  - Plate motions
  - Slow or aseismic slip
  - Intraplate deformation
  - Volcanic deformation

GPS Observations

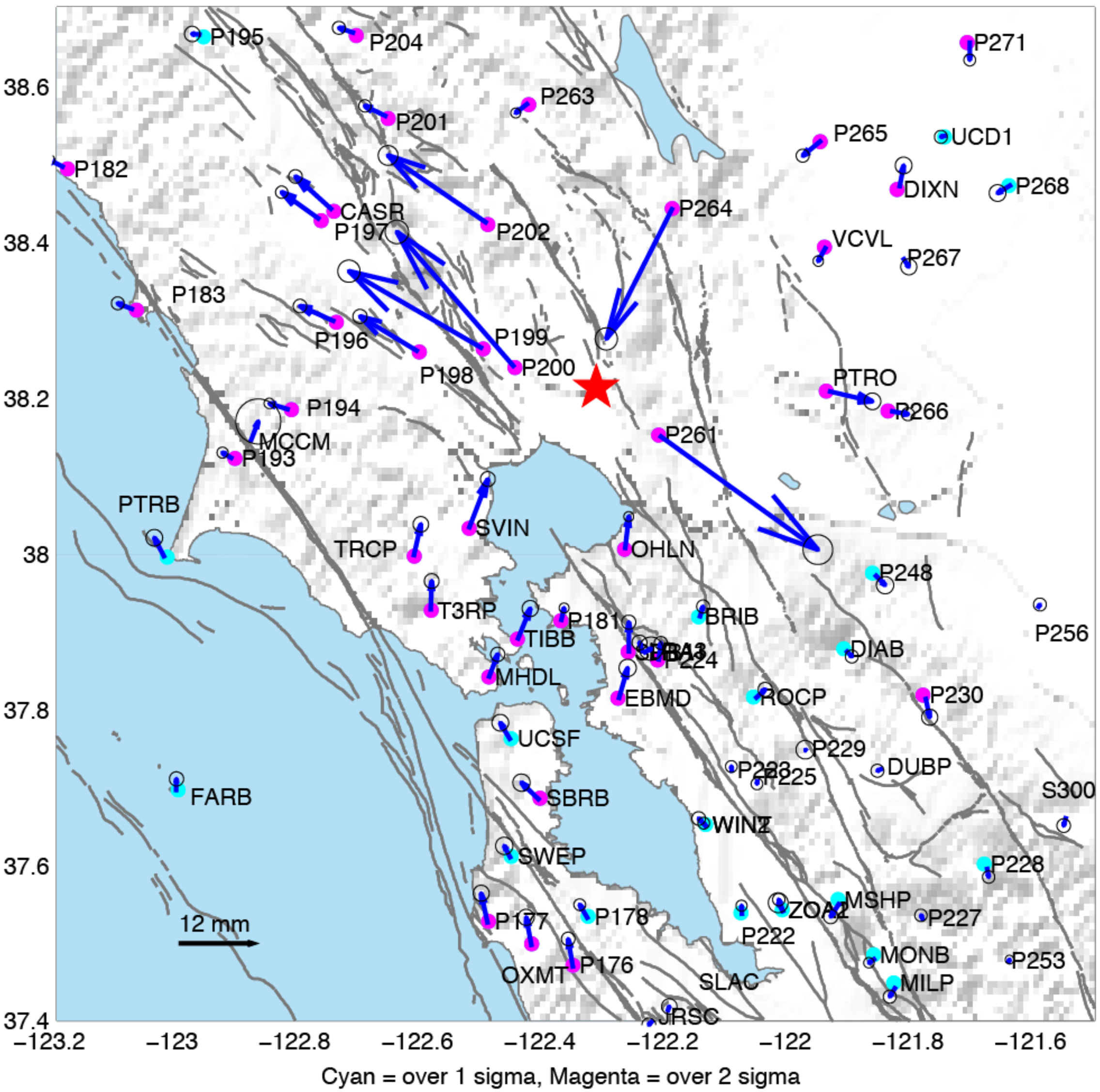


2012 Mw 7.8 GPS Observations
Haida Gwaii
B.C., Canada



Nykolaishen et al., BSSA (2015)

GPS Observations

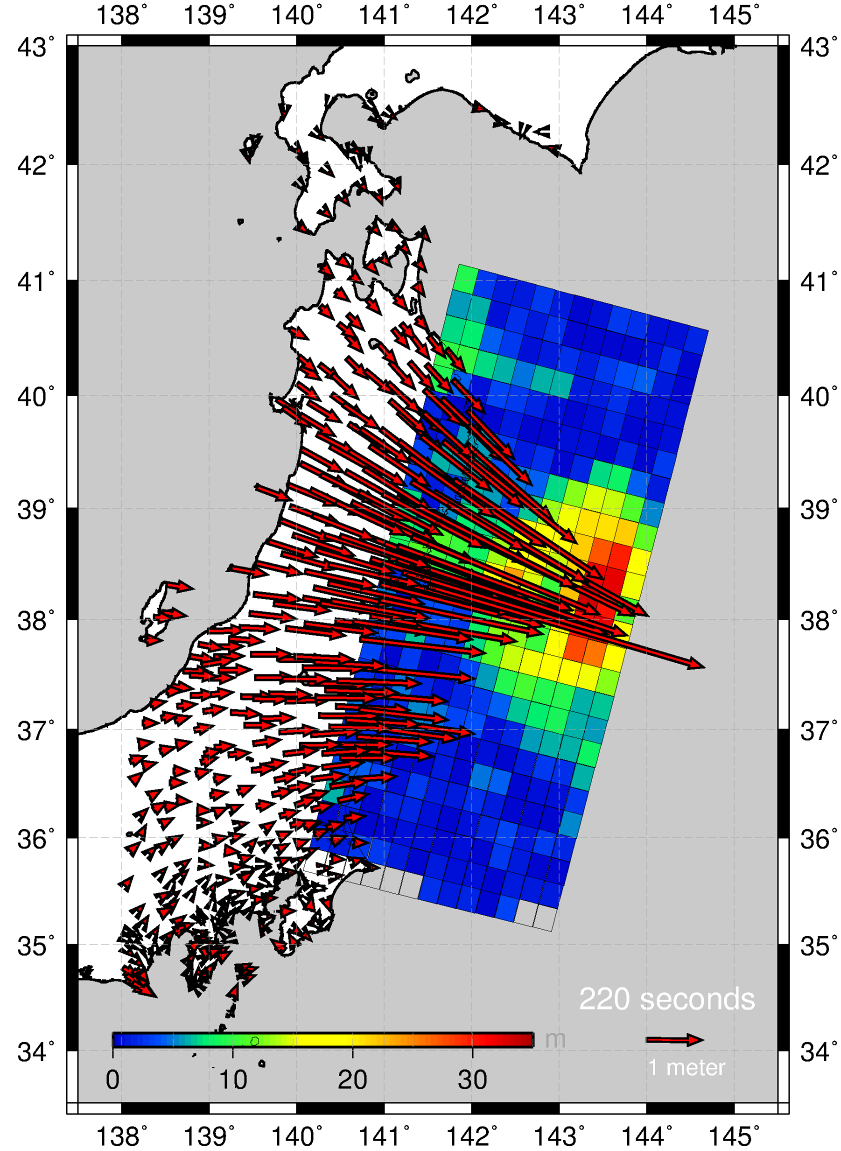


2014 Mw 6.0 Napa, California, USA

Nevada Geodetic Laboratory
geodesy.unr.edu
(a GREAT resource for finding global GPS positions)

GPS Observations

- 2011 Mw 9.0 Tohoku, Japan
- Eastern Japan moved 5-6 meters to the east!



Modeling Overview

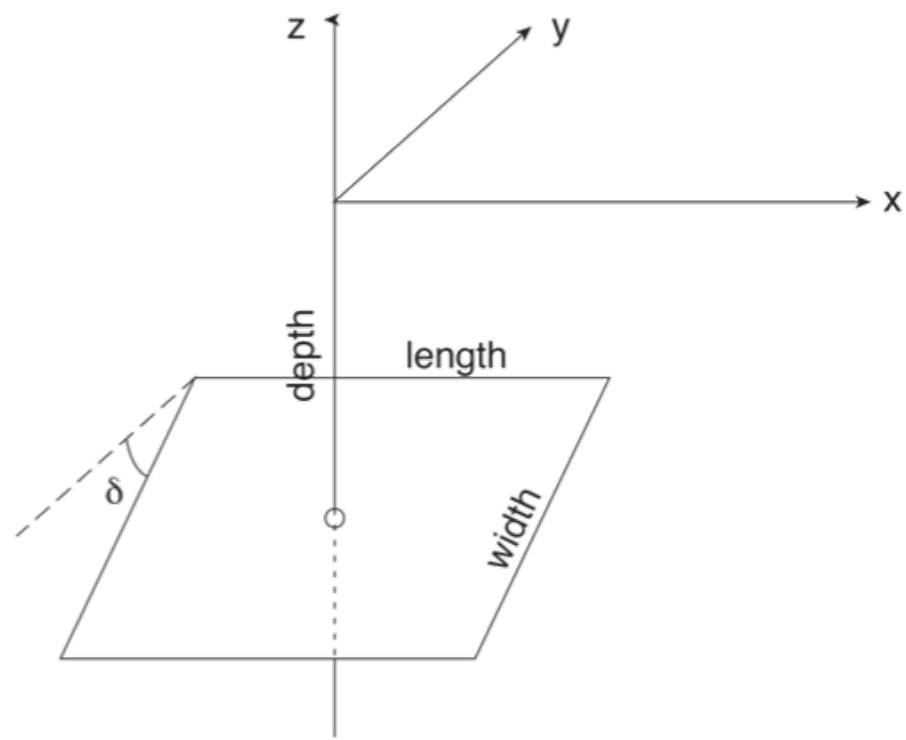
- To understand how GPS displacements are generated, we have to come up with a mental picture (i.e., a model) of how the Earth works.
- The model used in these codes is among the simplest physical descriptions for the Earth: an elastic half-space.

Modeling Overview

- Slip on a fault generates displacements throughout the host medium
- Source can be represented as:
  - Point source
  - Rectangle — Start simple
  - Circle
  - Triangle
  - More complex.... — Build to complex

Modeling Overview

- Okada (1992) derived solutions for displacements around rectangular faults
- Isotropic, elastic half-space
  - Free surface, infinite in other directions



Modified from Okada (1992)

Modeling Overview

- O92UTIL (written by Matt Herman) is a Fortran implementation of the Okada (1992) solutions
- Designed for a variety of applications related to faulting in a half-space

Modeling Overview

INPUTS
Faults
Receivers
Elastic properties
Target faults*

OUTPUTS
Displacement
Strain tensor
Stress tensor
Normal stress*
Shear stress*
Coulomb stress*

**To resolve stresses on planes in the subsurface, must define target fault orientations*

Modeling Overview

INPUTS
Faults
Receivers
Elastic properties
Target faults*

OUTPUTS
Displacement
Strain tensor
Stress tensor
Normal stress*
Shear stress*
Coulomb stress*

We will examine most of these outputs

**To resolve stresses on planes in the subsurface, must define target fault orientations*

Modeling Overview

INPUTS
Faults
Receivers
Elastic properties
Target faults*

OUTPUTS
Displacement
Strain
Stress
Normal stress*
Shear stress*
Coulomb stress*

First, focus on displacements

**To resolve stresses on planes in the subsurface, must define target fault orientations*

Modeling Overview

<u>INPUTS</u>

Faults
Receivers
Elastic properties
Target faults*

Earthquakes
Slow slip
Back-slip

<u>OUTPUTS</u>

splacement
rain tensor
Stress tensor
Normal stress*
Shear stress*
Coulomb stress*

**To resolve stresses on planes in the subsurface, must define target fault orientations*

Modeling Overview

INPUTS

Faults

Receivers

Elastic prop

Target faults*

> *Locations where we want (or have) displacement information*

OUTPUTS

nt

r

or

Normal stress*

Shear stress*

Coulomb stress*

**To resolve stresses on planes in the subsurface, must define target fault orientations*

Modeling Overview

<u>INPUTS</u>
Faults
Receivers
Elastic properties
Target faults*

*To resolve stresse
define target fault c

<u>OUTPUTS</u>
Displacement
Strain tensor
Stress tensor

Many ways to parameterize elastic properties: seismic velocities, Lame parameters, Young's modulus and Poisson ratio, etc.

O92UTIL can accept several different types of elastic inputs.

Modeling Overview

<u>INPUTS</u>

Faults

Receivers

Elastic properties

Target faults*

<u>OUTPUTS</u>

Displacement

Displacement components in Cartesian coordinates

Normal stress*

Shear stress*

Coulomb stress*

**To resolve stresses on planes in the subsurface, must define target fault orientations*

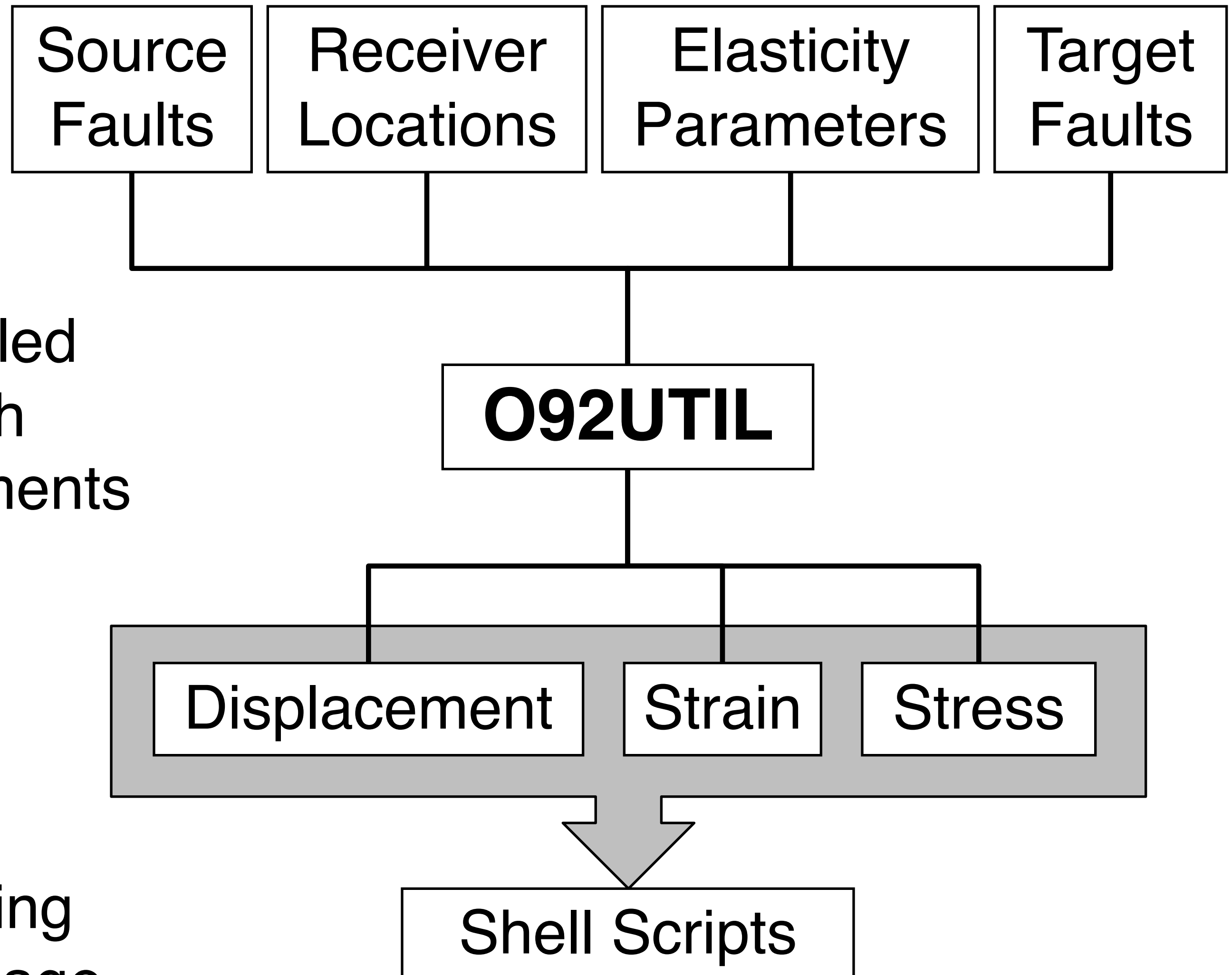
Modeling Overview

Input Files
(Text Files)

Compiled code called
from a terminal with
sequence of arguments

Output Files
(Text Files)

Plot output files using
GMT or other package



Modeling Overview

mherman — bash — 85×18

bash

```
mherman: ~ $ o92util -flt fault.in -sta station.in -haf hafspace.in -disp disp.out
```

Modeling Overview

Modeling Overview

Activity 1: Strike-Slip EQ

- Surface deformation around a <u>hypothetical</u> Mw 7.0 right lateral strike-slip earthquake (e.g. an event on the Sagaing Fault)

Activity 1: Strike-Slip EQ

Input fault file (fault.dat)

location of center

All O92UTIL input files are free-format: values are separated by spaces

```
96     21     15
```

Event Longitude → 96

Event Latitude → 21

Depth (km) → 15

Activity 1: Strike-Slip EQ

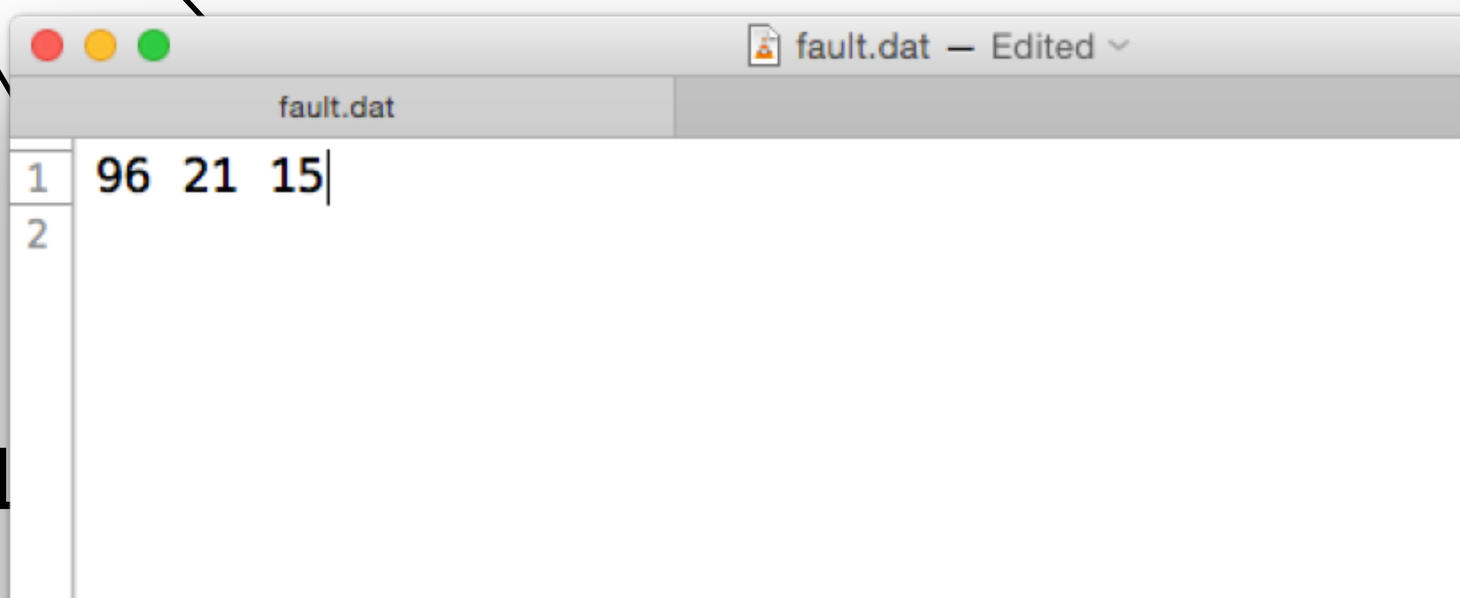
Input fault file (fault.dat)

location of center

Input files are free-format; Values are separated by spaces

96 21 15

Event Longitude



Activity 1: Strike-Slip EQ

<u>Input fault file (fault.dat)</u>

location of center, kinematics

```
96      21      15      0      90    180
```

Strike Dip Rake

Activity 1: Strike-Slip EQ

<u>Input fault file (fault.dat)</u>

location of center, kinematics

96 21 15 0 90 180

Activity 1: Strike-Slip EQ

<u>Input fault file (fault.dat)</u>

location of center, kinematics, slip

```
96    21    15    0    90  180    2
```

Slip (m)

Activity 1: Strike-Slip EQ

<u>Input fault file (fault.dat)</u>

location of center, kinematics, slip

96 21 15 0 90 180 2

Activity 1: Strike-Slip EQ

Input fault file (fault.dat)

location of center, kinematics, slip, dimensions

```
96      21      15      0     90   180      2   15     30
```

Along-dip width (km)

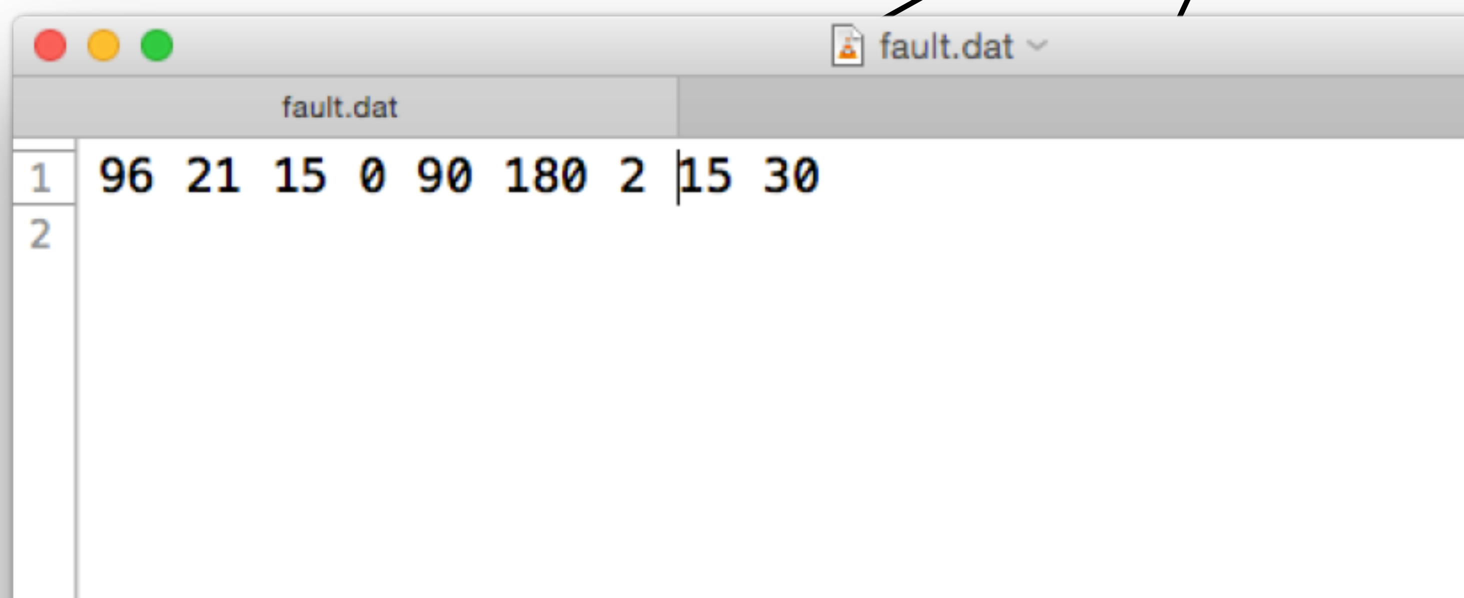
Along-strike length (km)

Activity 1: Strike-Slip EQ

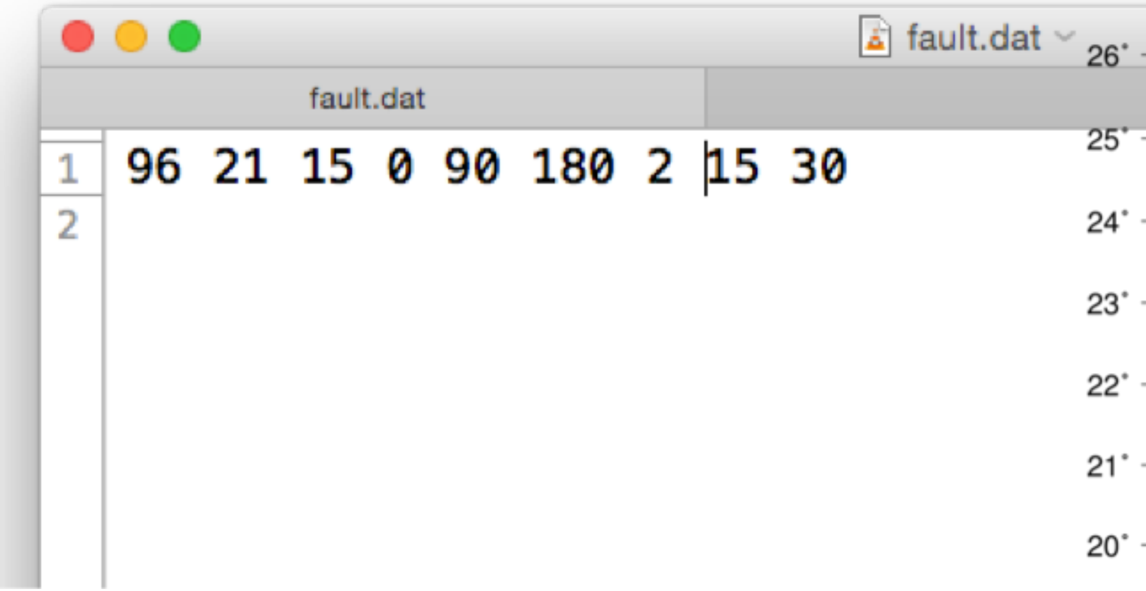
Input fault file (fault.dat)

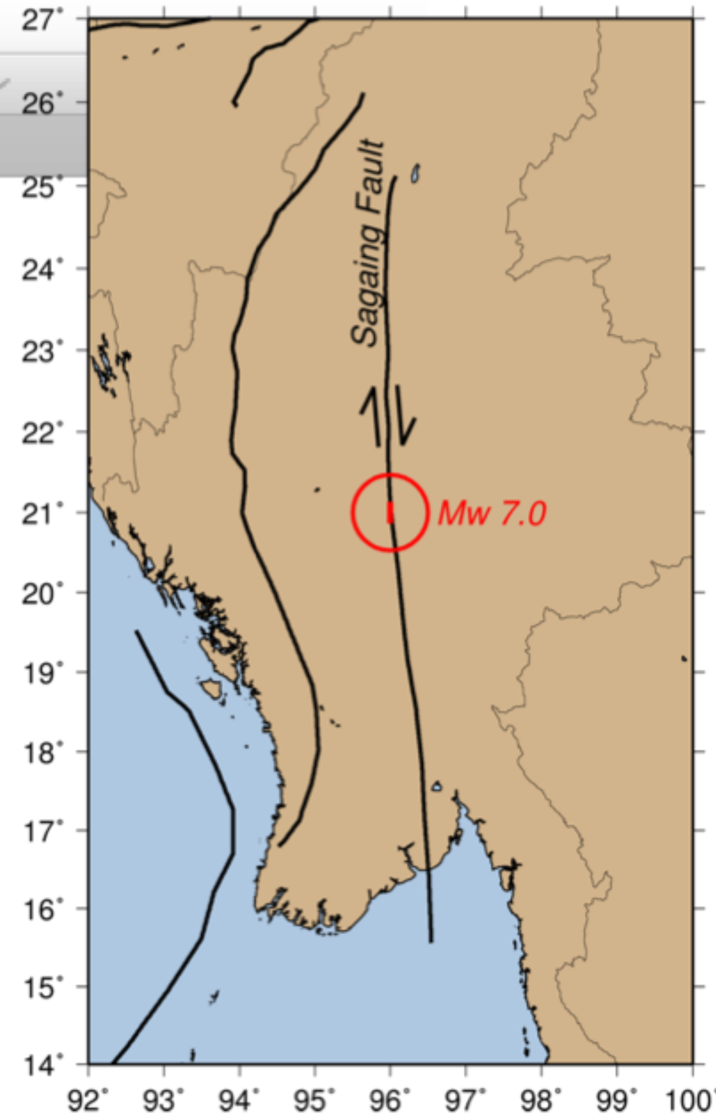
location of center, kinematics, slip, dimensions

96 21 15 0 90 180 2 15 30

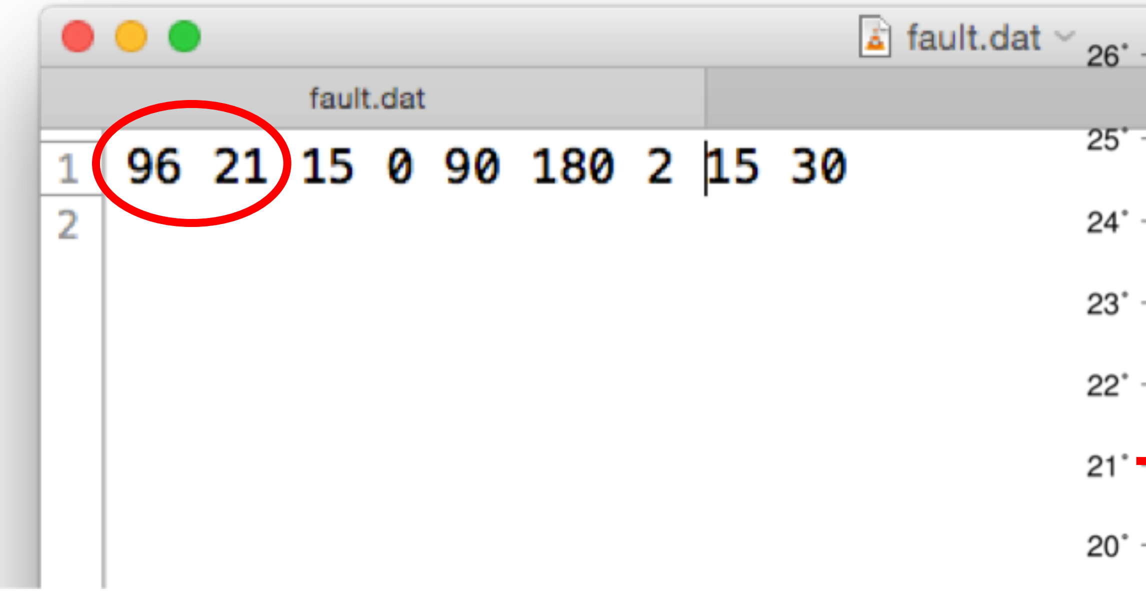


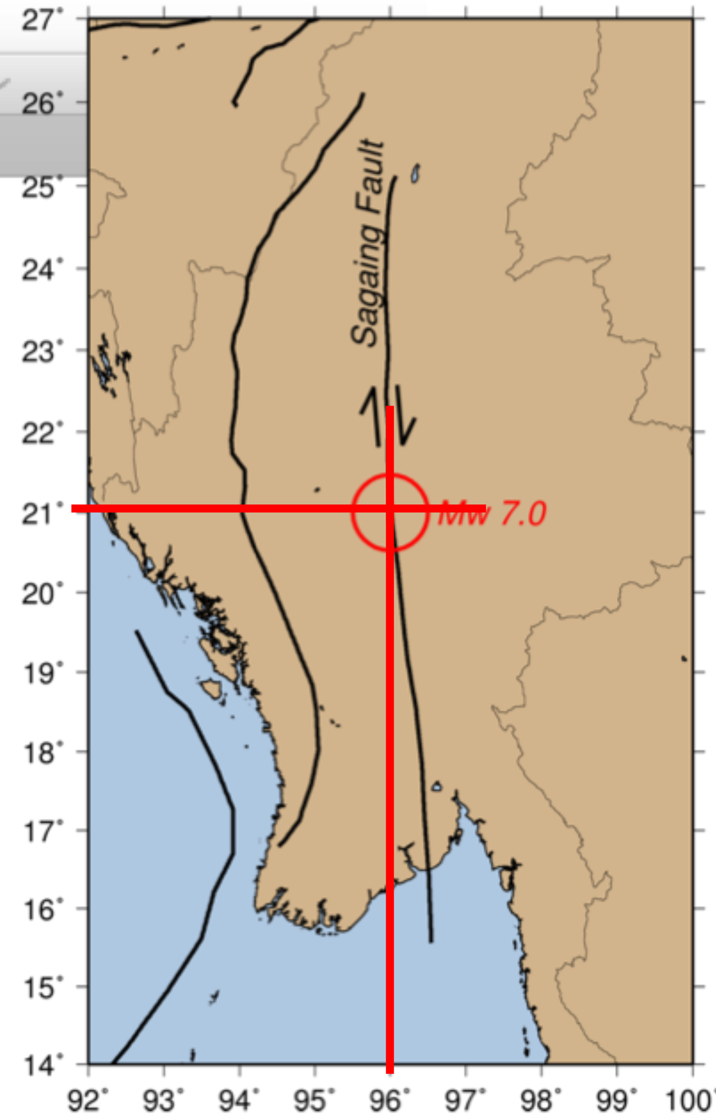
Activity 1: Strike-Slip EQ



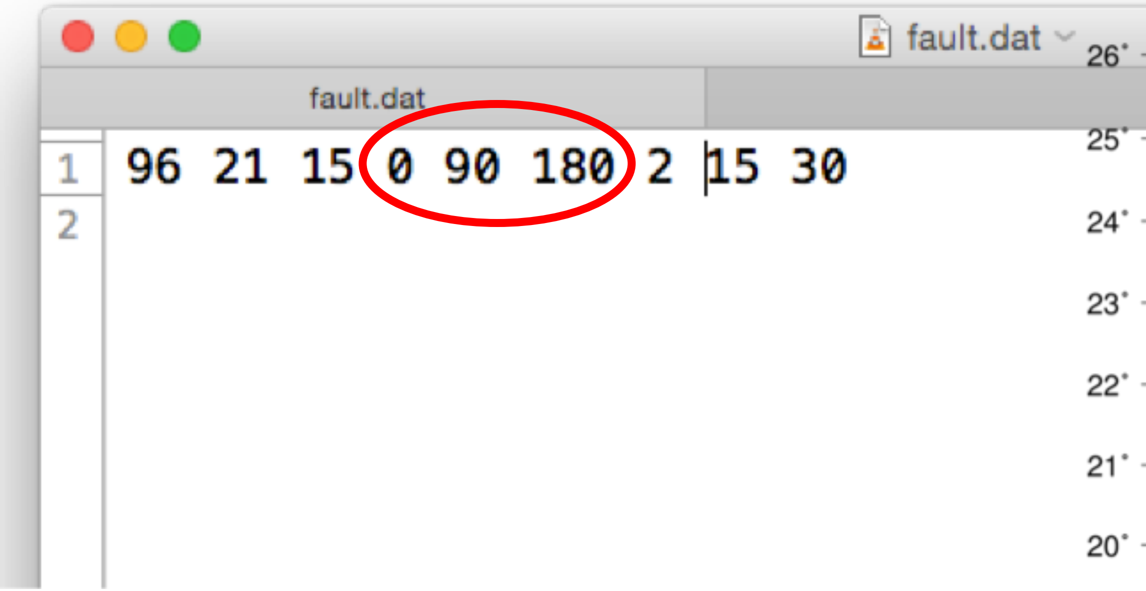


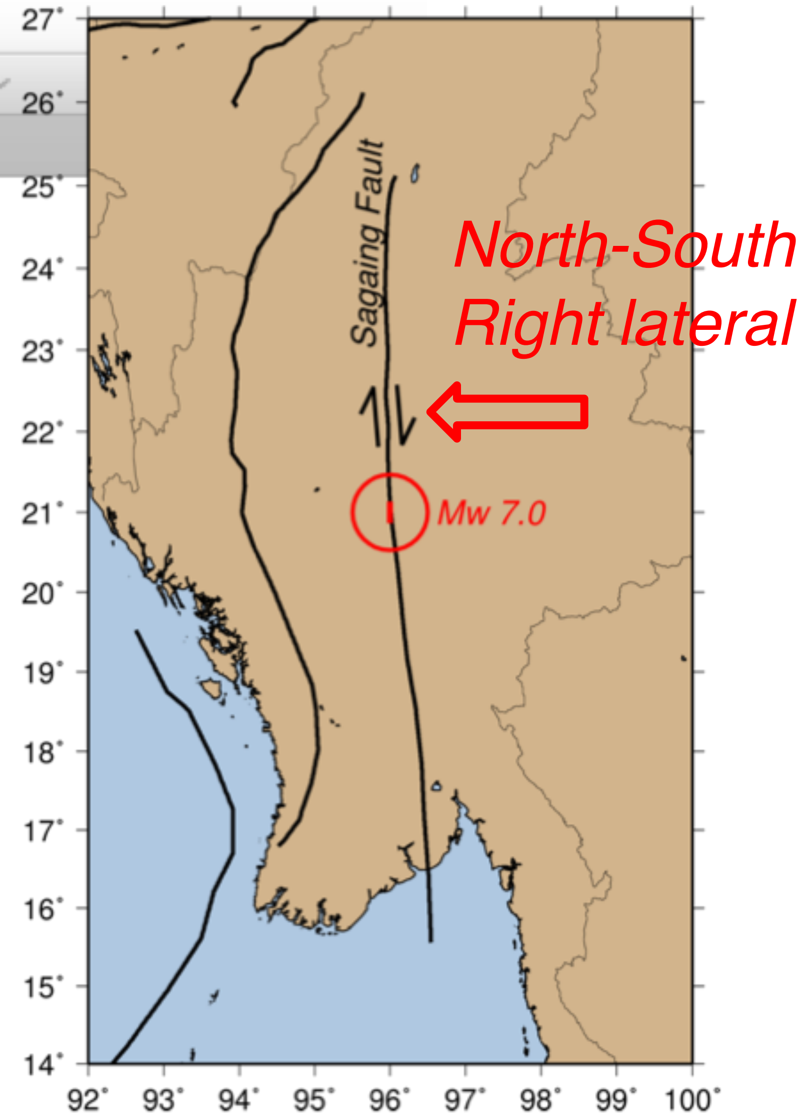
Activity 1: Strike-Slip EQ



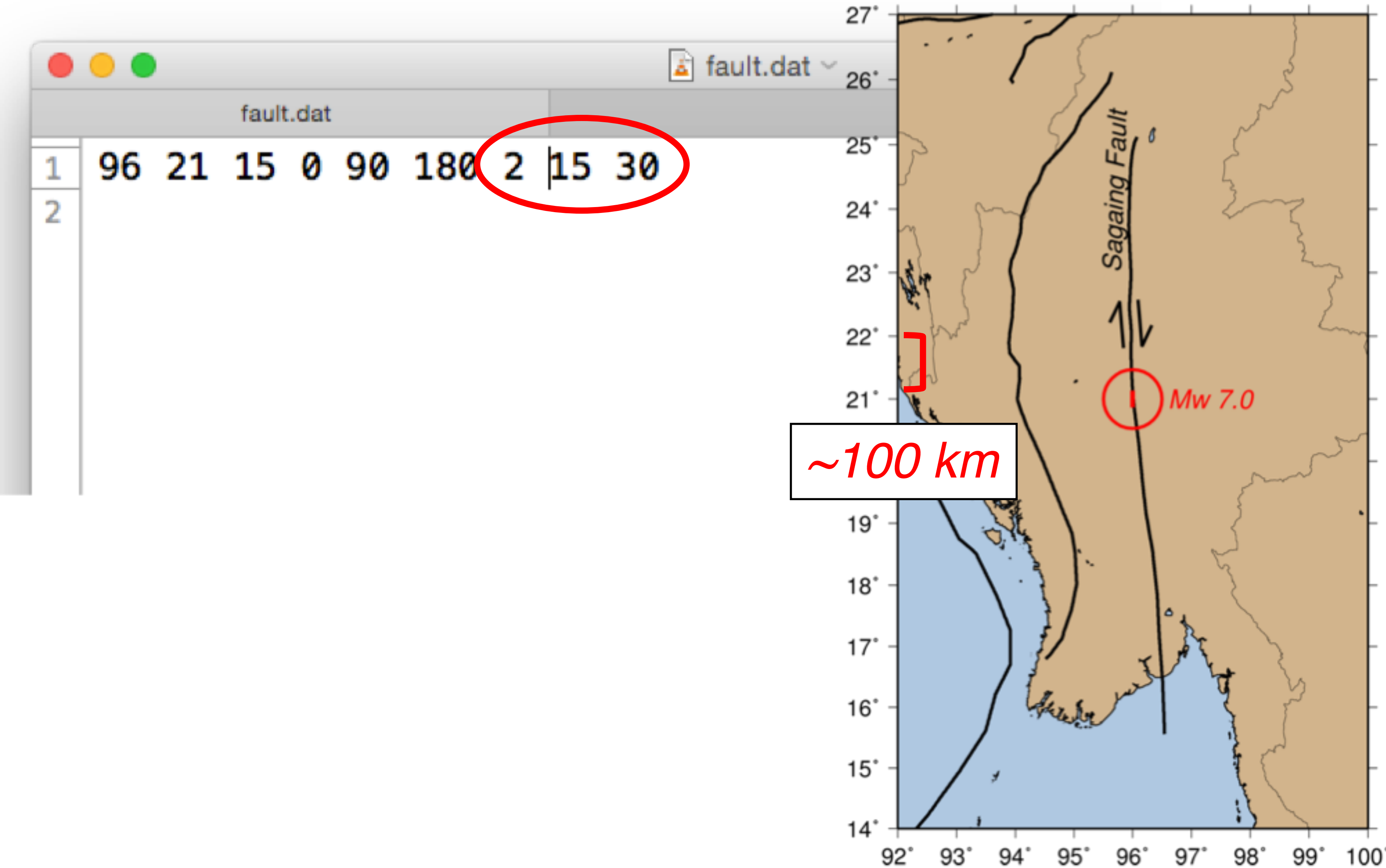


Activity 1: Strike-Slip EQ





Activity 1: Strike-Slip EQ



Activity 1: Strike-Slip EQ

<u>Input fault file (fault.dat)</u>

location of center, kinematics, slip, dimensions

evlo	evla	evdp	str	dip	rak	slip	wid	len
96	21	15	0	90	180	2	15	30

Is this equal to Mw 7.0?

Mo = (shear modulus)(fault area)*(fault slip)*

*Mw = 2/3*log(Mo)-10.7 (Mo in dyne-cm)*

Activity 1: Strike-Slip EQ

Receiver file (station.dat)

location of stations

```
96.1  21.1   0.0
95.9  21.1   0.0
95.9  20.9   0.0
96.1  20.9   0.0
```

Longitude Latitude Depth (km)

You can include multiple stations. O92UTIL will compute displacements at every location in this file. Remember, values are separated by spaces.

Activity 1: Strike-Slip EQ

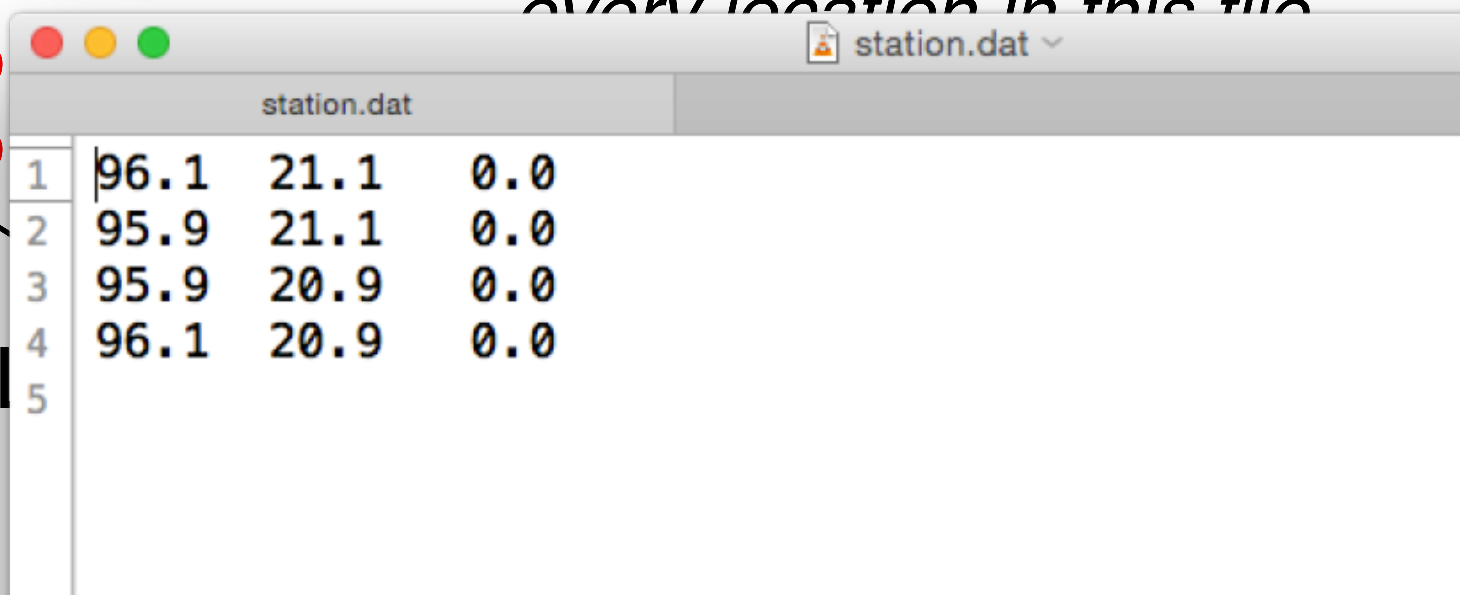
Receiver file (station.dat)

location of stations

You can include multiple stations. O92UTIL will compute displacements at every location in this file

96.1	21.1	0.0
95.9	21.1	0.0
95.9	20.9	
96.1	20.9	

Longitude l

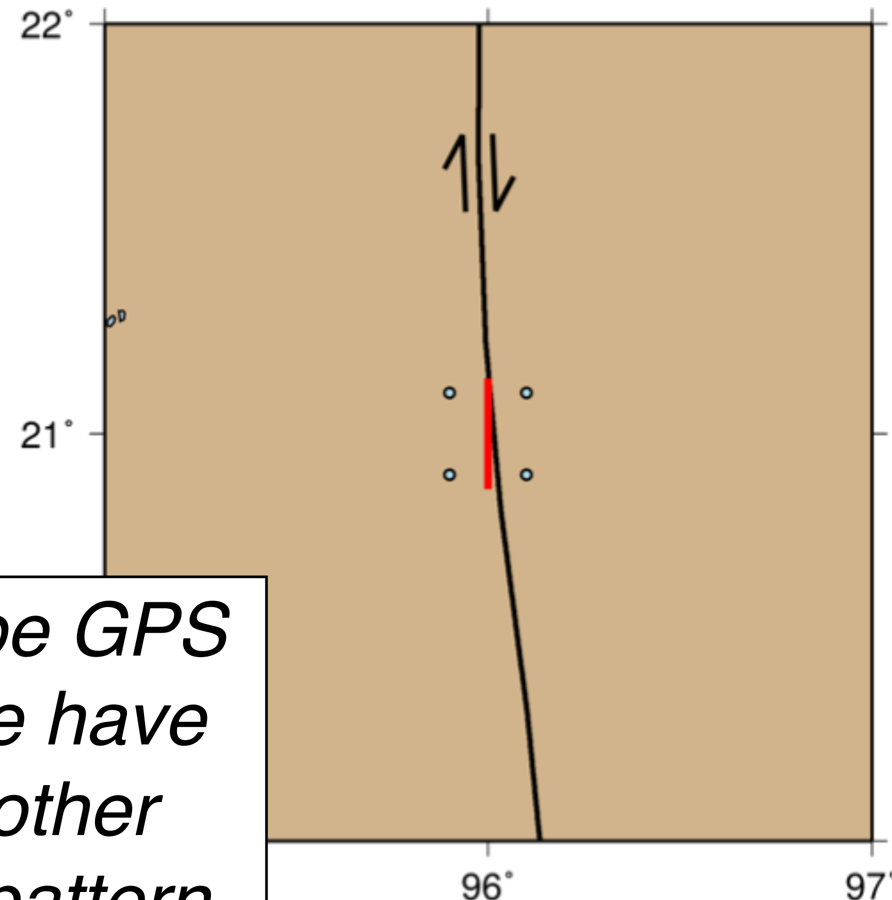


Activity 1: Strike-Slip EQ

Receiver file (station.dat)

location of stations

stlo	stla	stdp
96.1	21.1	0.0
95.9	21.1	0.0
95.9	20.9	0.0
96.1	20.9	0.0



For example, these could be GPS coordinates. Sometimes we have specific locations for data, other times want to see general pattern.

Activity 1: Strike-Slip EQ

<u>Elastic half-space file (halfspace.dat)</u>

seismic velocities, density

```
6800.0      3926.0      3000.0
```

P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m^3)
6800.0	3926.0	3000.0

$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

$$\mu = \rho v_s^2$$

$$\lambda = \rho v_p^2 - 2\mu$$

Activity 1: Strike-Slip EQ

Note that this input format is now deprecated. It still works (for now), but the program will warn you that it is a legacy format and prompt you to use the current format.

The current format is:
vp 6800 vs 3926 dens 3000

Activity 1: Strike-Slip EQ

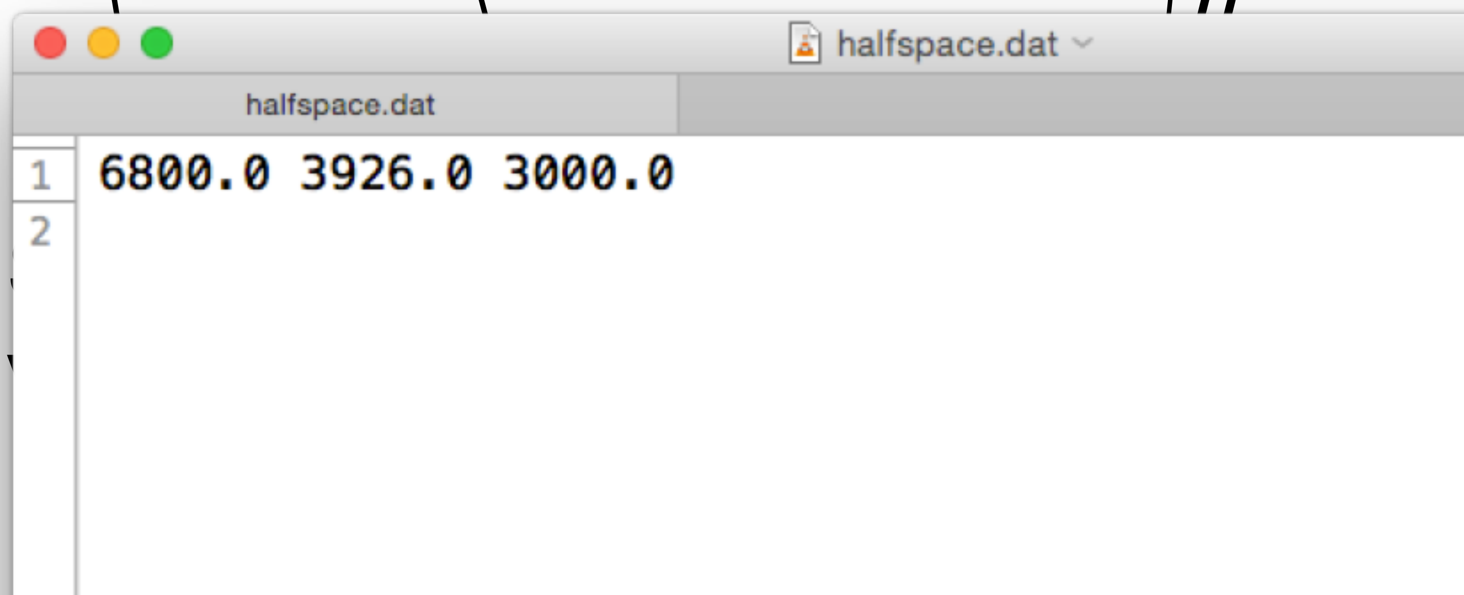
<u>Elastic half-space file (halfspace.dat)</u>

seismic velocities, density

$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

6800.0 3926.0 3000.0

P-wave velocity (m/s)



Activity 1: Strike-Slip EQ

Elastic half-space file (halfspace.dat)

seismic velocities, density

vp	vs	dens
6800.0	3926.0	3000.0

$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

$$\mu = \rho v_s^2$$

$$\lambda = \rho v_p^2 - 2\mu$$

Check that the shear modulus is compatible with the moment-magnitude relation.

Activity 1: Strike-Slip EQ

Compute displacements

input fault

```
o92util -flt fault.dat
```

Activity 1: Strike-Slip EQ

<u>Compute displacements</u>

input fault, input receivers

```
o92util -flt fault.dat -sta station.dat
```

Activity 1: Strike-Slip EQ

Compute displacements

input fault, input receivers,

half-space

```
o92util -flt fault.dat -sta station.dat
    -haf halfspace.dat
```

Activity 1: Strike-Slip EQ

<u>Compute displacements</u>

input fault, input receivers,

half-space, output displacements

```
o92util -flt fault.dat -sta station.dat
    -haf halfspace.dat -disp disp.out
```

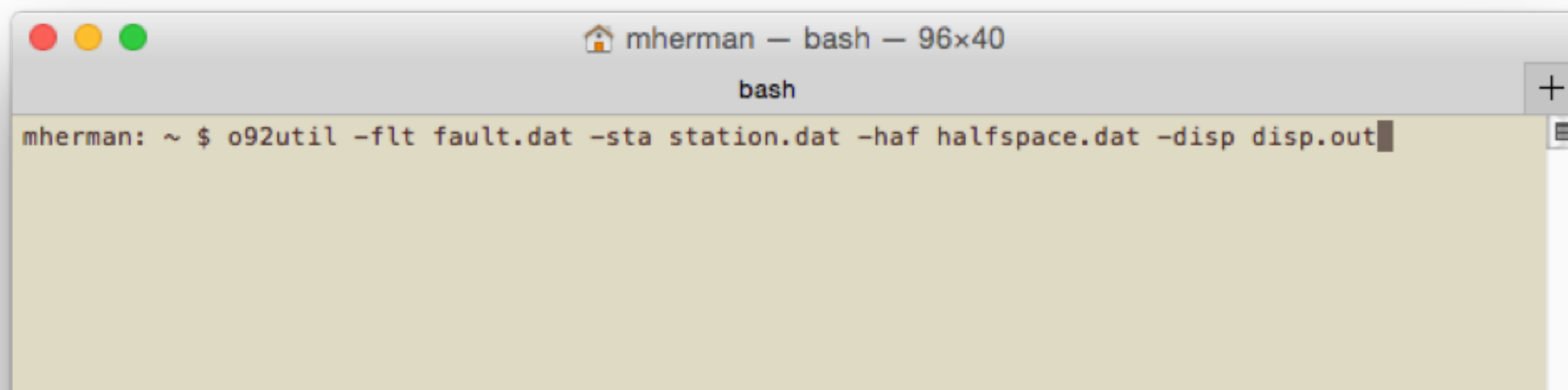
Activity 1: Strike-Slip EQ

<u>Compute displacements</u>

input fault, input receivers,

half-space, output displacements

```
o92util -flt fault.dat -sta station.dat
    -haf halfspace.dat -disp disp.out
```



Activity 1: Strike-Slip EQ

Output displacements (disp.out)

disp.out

96.1000	21.1000	0.0000	-0.0889	-0.1143	-0.0659
95.9000	21.1000	0.0000	-0.0889	0.1143	0.0659
95.9000	20.9000	0.0000	0.0890	0.1143	-0.0659
96.1000	20.9000	0.0000	0.0890	-0.1143	0.0659

Station Longitude | Station Latitude | Station Depth (km)

The outputs correspond to the locations in station.dat

Activity 1: Strike-Slip EQ

Output displacements (disp.out)

disp.out

96.1000	21.1000	0.0000	-0.0889	-0.1143	-0.0659
95.9000	21.1000	0.0000	-0.0889	0.1143	0.0659
95.9000	20.9000	0.0000	0.0890	0.1143	-0.0659
96.1000	20.9000	0.0000	0.0890	-0.1143	0.0659

East-West (m) | North-South (m) | Up-Down (m)

Displacement vectors for each station.
By default, in Cartesian coordinates.

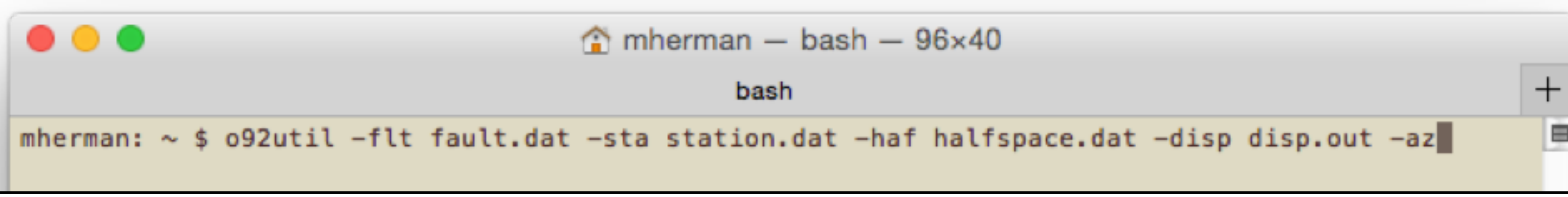
Activity 1: Strike-Slip EQ

<u>Compute displacements</u>

input fault, input receivers,

half-space, output displacements

```
o92util -flt fault.dat -sta station.dat
    -haf halfspace.dat -disp disp.out -az
```



For use with GMT, we want azimuth and magnitude of displacement vectors (not Cartesian components).

Activity 1: Strike-Slip EQ

Output displacements (disp.out) with -az

disp.out

1	96.1000	21.1000	0.0000	−142.1273	0.1448	−0.0659
2	95.9000	21.1000	0.0000	−37.8943	0.1448	0.0659
3	95.9000	20.9000	0.0000	37.9305	0.1449	−0.0659
4	96.1000	20.9000	0.0000	142.0992	0.1448	0.0659
5						

Azimuth (CW from N)

Horizontal Displacement (m)

Up-Down (m)

Activity 1: Strike-Slip EQ

<u>Plot results (basic plotting script provided)</u>

plot_disp.sh

```
#!/bin/sh

#####
#	BOURNE SHELL SCRIPT FOR PLOTTING DISPLACEMENT VECTORS
#####

#####
#	INPUT/OUTPUT FILES FROM O92UTIL
#####
# Input source fault file
FLT_FILE="fault.dat" # EVLO EVLA EVDP STR DIP RAK SLIP WID LEN
# Output displacement file
DISP_FILE="disp.out" # STLO STLA STDP AZ UH UZ

#####
#	GMT PLOTTING VARIABLES
#####
# Map projection (use 'man psbasemap' to see options)
PROJ="-JM4i -P"
# Map limits (-RXMIN/XMAX/YMIN/YMAX)
LIMS="-R95/97/20/22"
# Output PostScript file name
PSFILE="displacement.ps"

#####
#	GMT PLOTTING COMMANDS
#####
# Draw coastline (-W) and national boundaries (-N1)
# (-Scolor is water color, -Gcolor is land color)
pscoast $PROJ $LIMS -Dh -W0.75p -N1/0.5p -Slightblue -Gtan -K > $PSFILE

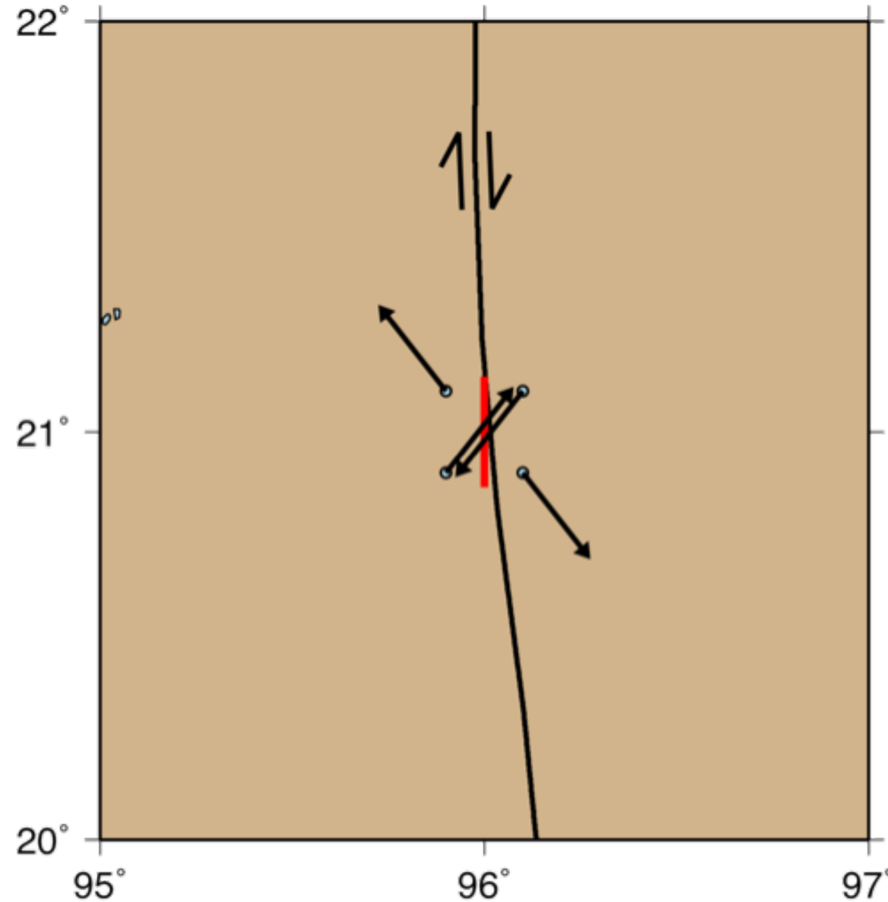
# Plot focal mechanisms of input faults
awk '{print $1,$2,$3,$4,$5,$6,5}' $FLT_FILE |\
    psmeca $PROJ $LIMS -Sa0.5i -W1p -L1p -Ggrey -K -O >> $PSFILE
# Plot horizontal projection of rectangular input faults
# To convert degrees to radians, multiply by pi/180 = 0.01745
awk '{print $1,$2,$4,$9,$8*cos($5*0.017)}' $FLT_FILE |\
    psxy $PROJ $LIMS -SJ -W3p,red -K -O >> $PSFILE

# Plot receiver locations
awk '{print $1,$2}' $DISP_FILE |\
    psxy $PROJ $LIMS -Sc0.05i -W1p -Glightblue -K -O >> $PSFILE
# Plot displacement vectors, with vector amplitudes scaled
# Options after -SV specify arrow tail_width/head_length/head_width
SCALE="10"
awk '{print $1,$2,$4,'"$SCALE"'*$5}' $DISP_FILE |\
    psxy $PROJ $LIMS -SV0.03i/0.08i/0.05i -Gblack -K -O >> $PSFILE

# Draw map outline and label axes
psbasemap $PROJ $LIMS -Ba1WeSn -O >> $PSFILE
```

Activity 1: Strike-Slip EQ

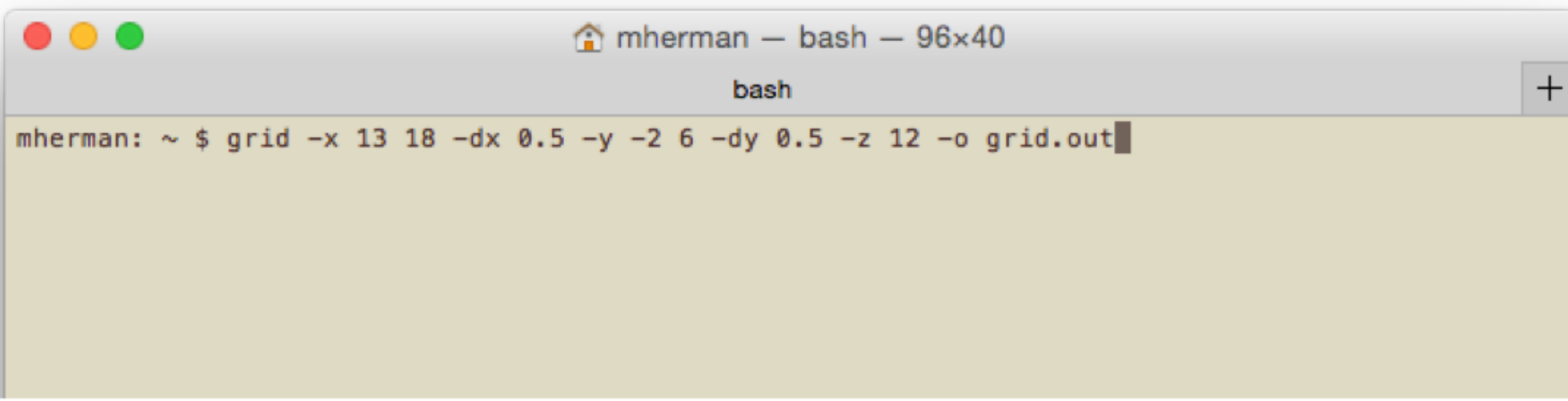
- Not very many points...poor idea of displacement field.
- Similar to sparse GPS dataset.
- Easy to increase density of modeled points



Activity 1: Strike-Slip EQ

<u>Receiver file (station.dat) using GRID</u>

GRID is a Fortran code like O92UTIL, run from a terminal window



Activity 1: Strike-Slip EQ

<u>Receiver file (station.dat) using GRID</u>

x-limits and spacing

Either manually enter station locations, or use a program like GRID to generate many station locations automatically.

```
grid -x 94 98 -dx 0.2
```

Minimum Longitude

Maximum Longitude

Longitude Spacing

Activity 1: Strike-Slip EQ

<u>Receiver file (station.dat) using GRID</u>

x-limits and spacing, y-limits and spacing

```
grid -x 94 98 -dx 0.2 -y 19 23 -dy 0.2
```

- 19 → Minimum Latitude
- 23 → Maximum Latitude
- 0.2 → Latitude Spacing

Activity 1: Strike-Slip EQ

<u>Receiver file (station.dat) using GRID</u>

x-limits and spacing, y-limits and spacing,

z-value

```
grid -x 94 98 -dx 0.2 -y 19 23 -dy 0.2
     -z 0.0
```

Depth (km)

Observations are on the surface

Activity 1: Strike-Slip EQ

<u>Receiver file (station.dat) using GRID</u>

x-limits and spacing, y-limits and spacing, z-value, output file

```
grid -x 94 98 -dx 0.2 -y 19 23 -dy 0.2
    -z 0.0 -o station.dat
```

Output File

In all of these examples, you can choose whatever input/output file names you want.

Activity 1: Strike-Slip EQ

Receiver file (station.dat) using GRID

station.dat

station.dat

```
94.00000000    19.00000000    0.00000000
94.00000000    19.20000000    0.00000000
94.00000000    19.40000000    0.00000000
94.00000000    19.60000000    0.00000000
94.00000000    19.80000000    0.00000000
94.00000000    20.00000000    0.00000000
94.00000000    20.20000000    0.00000000
94.00000000    20.40000000    0.00000000
94.00000000    20.60000000    0.00000000
94.00000000    20.80000000    0.00000000
94.00000000    21.00000000    0.00000000
94.00000000    21.20000000    0.00000000
94.00000000    21.40000000    0.00000000
94.00000000    21.60000000    0.00000000
94.00000000    21.80000000    0.00000000
94.00000000    22.00000000    0.00000000
94.00000000    22.20000000    0.00000000
94.00000000    22.40000000    0.00000000
94.00000000    22.60000000    0.00000000
94.00000000    22.80000000    0.00000000
94.00000000    23.00000000    0.00000000
```

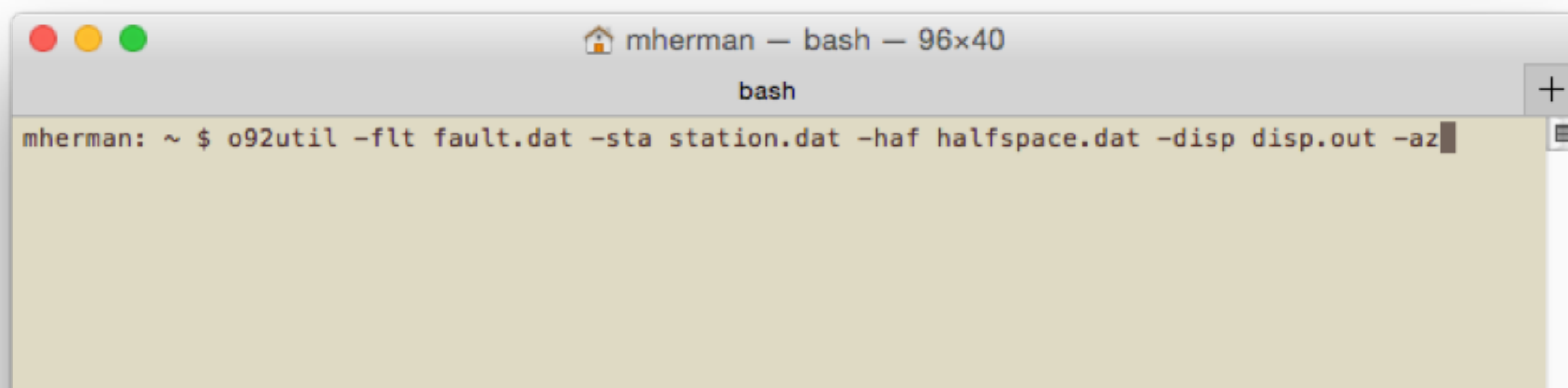
Activity 1: Strike-Slip EQ

<u>Compute displacements (again)</u>

input fault, input receivers,

half-space, output displacements

```
o92util -flt fault.dat -sta station.dat
    -haf halfspace.dat -disp disp.out -az
```



Activity 1: Strike-Slip EQ

<u>Plot results (use same plotting script)</u>

plot_disp.sh

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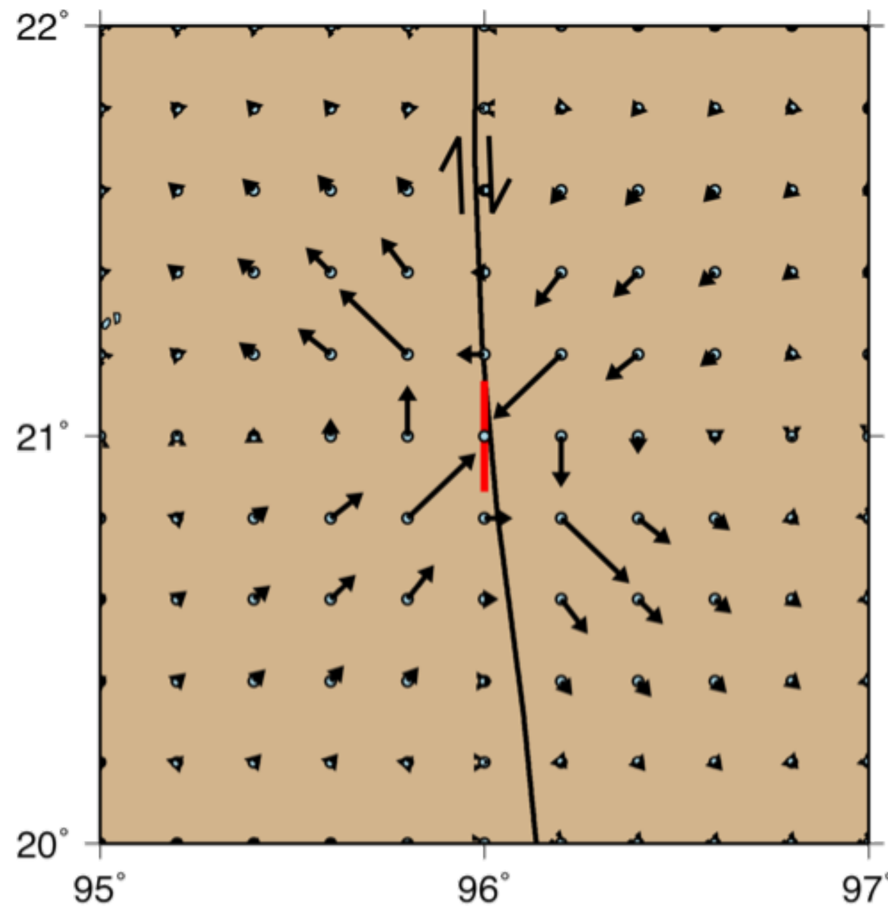
# Plot horizontal projection of rectangular input faults
# To convert degrees to radians, multiply by pi/180 = 0.01745
awk '{print $1,$2,$4,$9,$8*cos($5*0.017)}' $FLT_FILE |\
    psxy $PROJ $LIMS -SJ -W3p,red -K -O >> $PSFILE

# Plot receiver locations
awk '{print $1,$2}' $DISP_FILE |\
    psxy $PROJ $LIMS -Sc0.05i -W1p -Glightblue -K -O >> $PSFILE
# Plot displacement vectors, with vector amplitudes scaled
# Options after -SV specify arrow tail_width/head_length/head_width
SCALE="10"
awk '{print $1,$2,$4,'"$SCALE"'*$5}' $DISP_FILE |\
    psxy $PROJ $LIMS -SV0.03i/0.08i/0.05i -Gblack -K -O >> $PSFILE

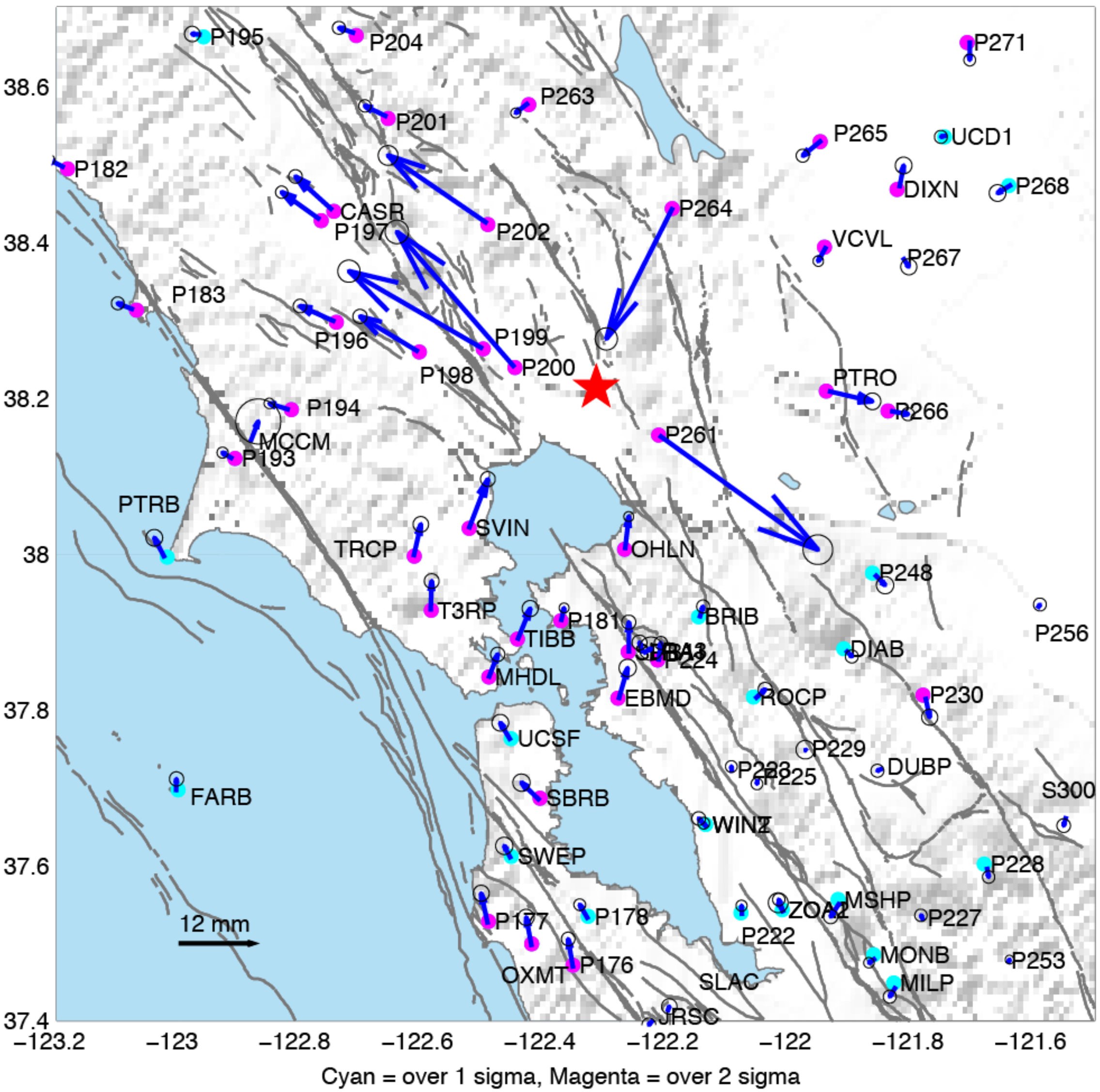
# Draw map outline and label axes
psbasemap $PROJ $LIMS -Ba1WeSn -O >> $PSFILE
```

Activity 1: Strike-Slip EQ

- Better resolution of displacement field around the Mw 7.0 right lateral strike-slip earthquake.
- *Does this displacement field make sense?*



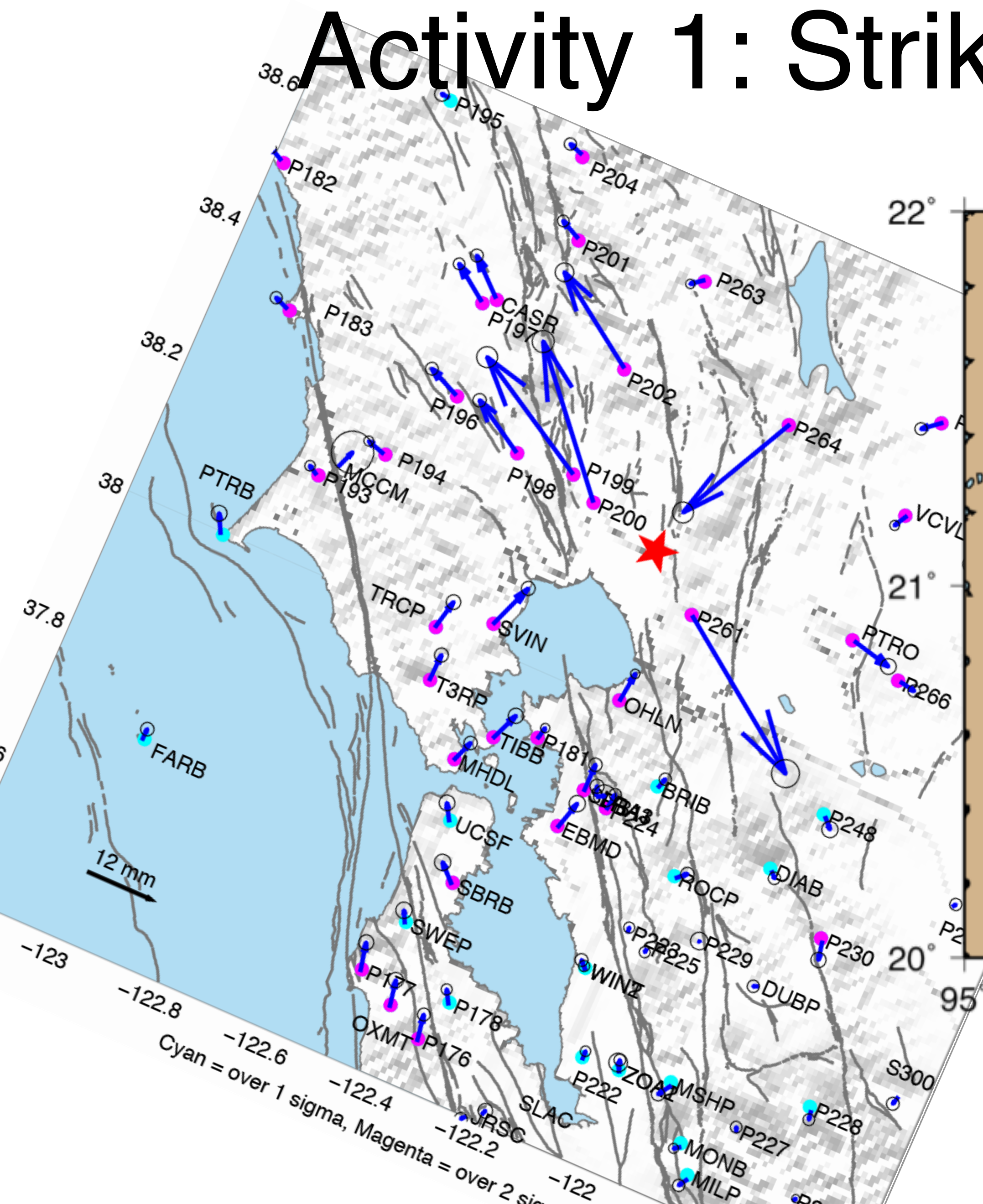
Activity 1: Strike-Slip EQ

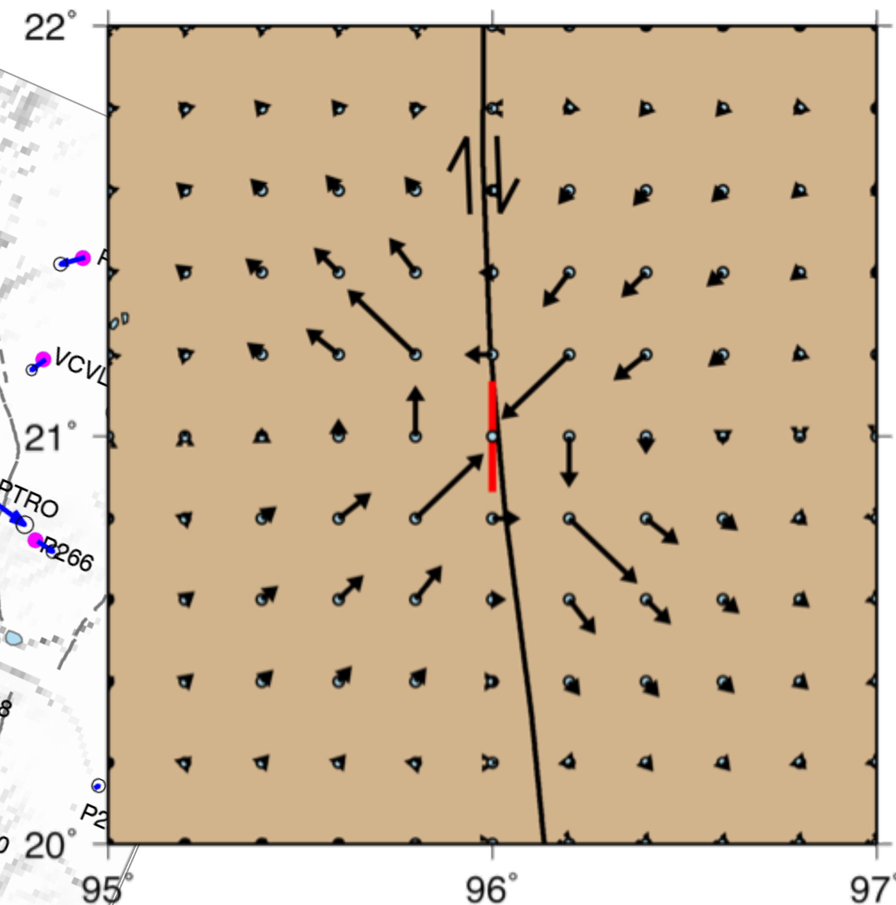


2014 Mw 6.0
Napa,
California, USA

Nevada Geodetic Laboratory
geodesy.unr.edu
(a GREAT resource for finding global GPS positions)

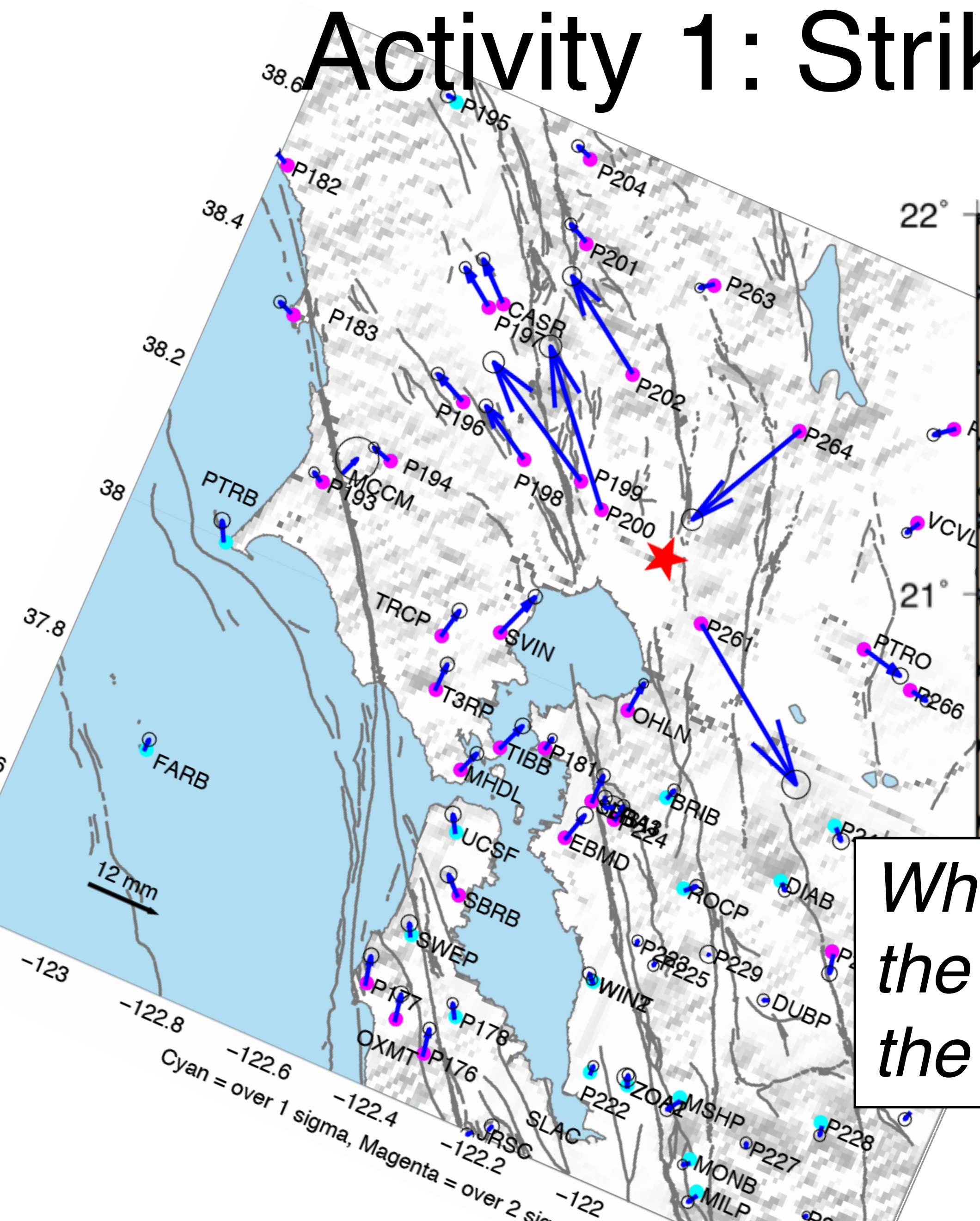
Activity 1: Strike-Slip EQ

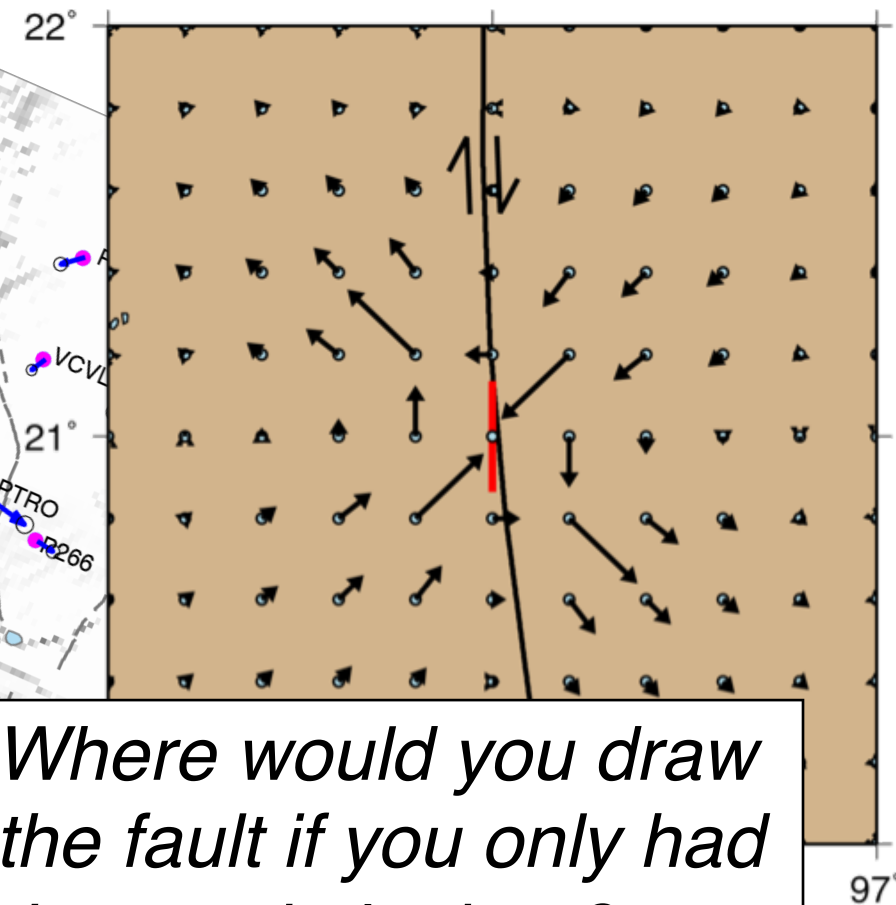




Nevada Geodetic Laboratory

Activity 1: Strike-Slip EQ



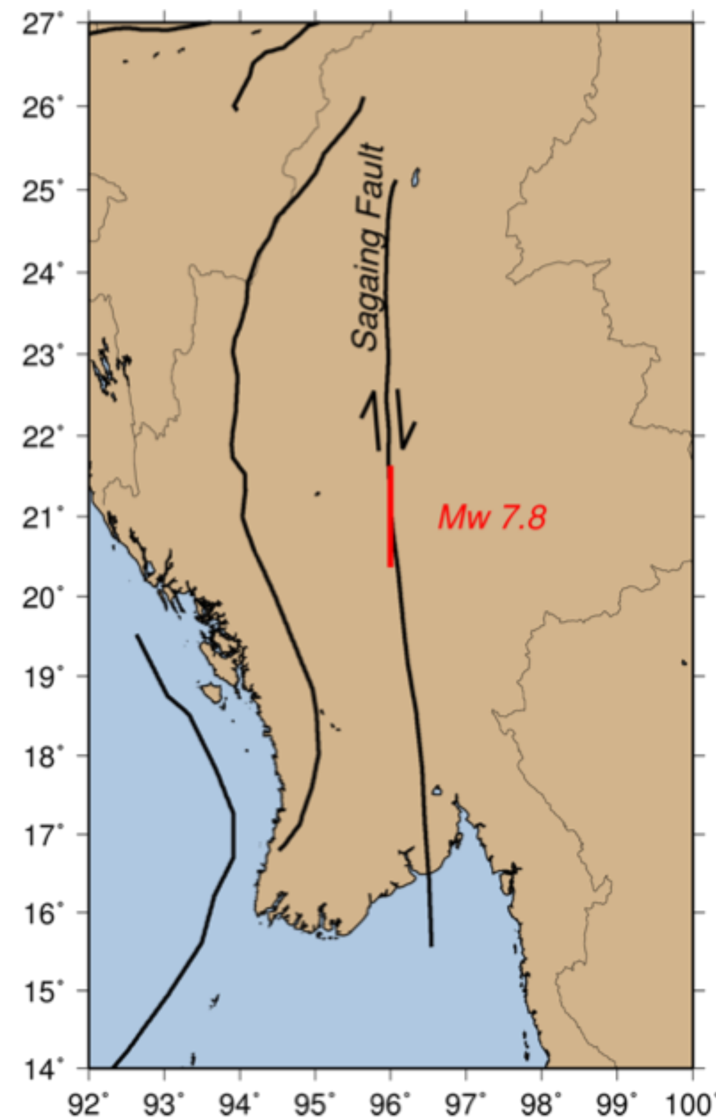


Where would you draw the fault if you only had the geodetic data?

Nevada Geodetic Laboratory

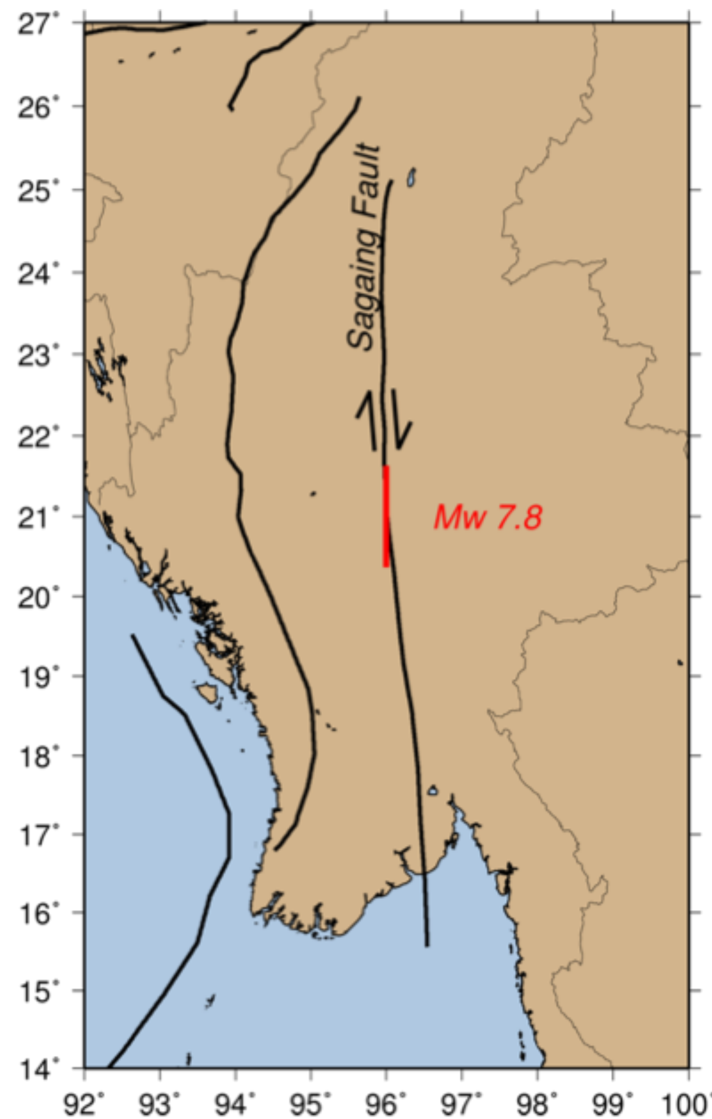
Activity 2: Strike-Slip EQ

- What do the displacements from a larger earthquake look like?



Activity 2: Strike-Slip EQ

- What do displacements from a larger earthquake look like?
- *Exercise: model a hypothetical Mw 7.8 earthquake on the Sagaing fault and compare results to Mw 7.0*



Activity 2: Strike-Slip EQ

Input fault file (fault.dat)

location of center, kinematics, slip, dimensions

```
96      21      15      0      90   180      5    20   140
```

Slip (m) | Width (km) | Length (km)

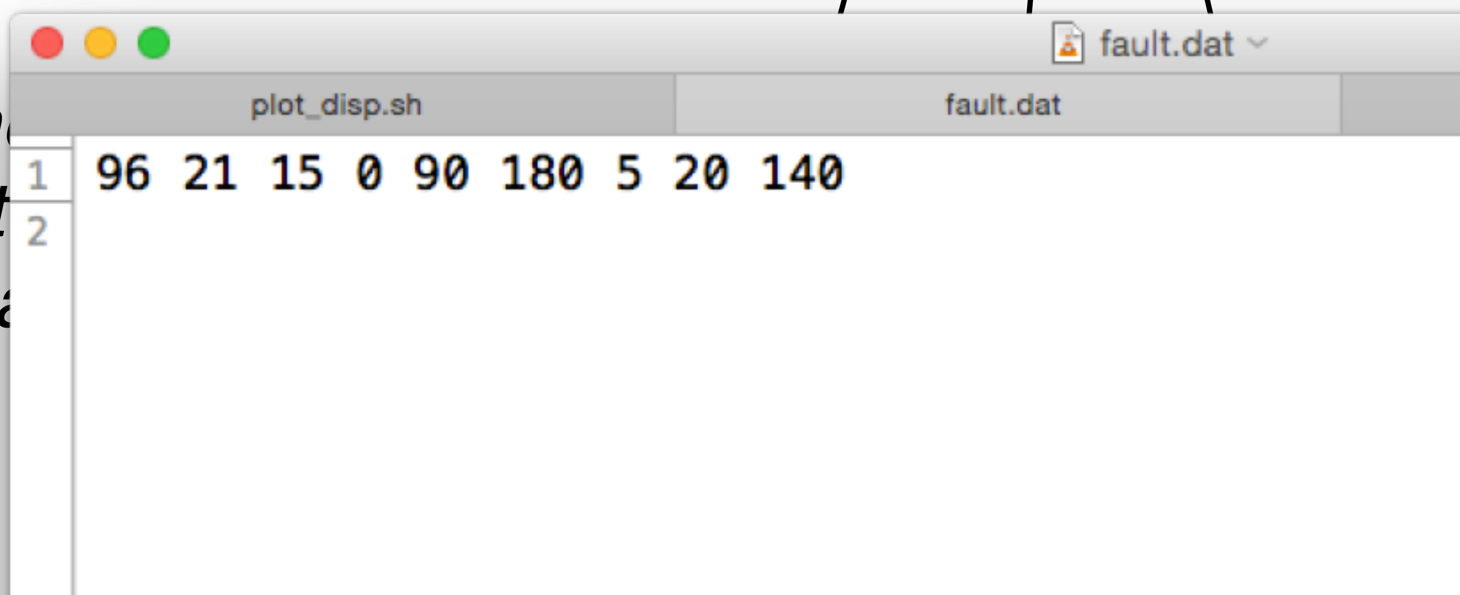
Change the slip and size of the fault. Check that this is equal to Mw 7.8.

Activity 2: Strike-Slip EQ

Input fault file (fault.dat)

location of center, kinematics, slip, dimensions

96 21 15 0 90 180 5 20 140



Change th
of the fault
this is equa

Activity 2: Strike-Slip EQ

<u>Compute displacements</u>

input fault, input receivers,

half-space, output displacements

```
o92util -flt fault.dat -sta station.dat
    -haf halfspace.dat -disp disp.out -az
```

Keep everything else the same.

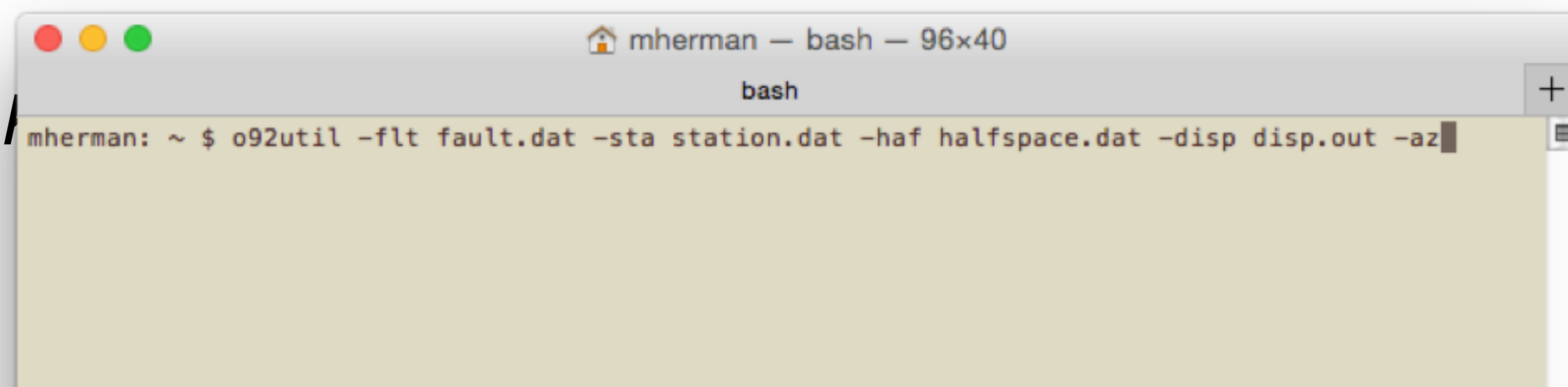
Activity 2: Strike-Slip EQ

<u>Compute displacements</u>

input fault, input receivers,

half-space, output displacements

```
o92util -flt fault.dat -sta station.dat
    -haf halfspace.dat -disp disp.out -az
```



Activity 2: Strike-Slip EQ

Plot results (use same plotting script; change output file name)

plot_disp.sh

```
#!/bin/sh

#####
#       BOURNE SHELL SCRIPT FOR PLOTTING DISPLACEMENT VECTORS
#####

#####
#       INPUT/OUTPUT FILES FROM O92UTIL
#####
# Input source fault file
FLT_FILE="fault.dat" # EVLO EVLA EVDP STR DIP RAK SLIP WID LEN
# Output displacement file
DISP_FILE="disp.out" # STLO STLA STDP AZ UH UZ

#####
#       GMT PLOTTING VARIABLES
#####
# Map projection (use 'man psbasemap' to see options)
PROJ="-JM4i -P"
# Map limits (-RXMIN/XMAX/YMIN/YMAX)
LIMS="-R95/97/20/22"
# Output PostScript file name
PSFILE="displacement_7.8.ps"

#####
#       GMT PLOTTING COMMANDS
#####
# Draw coastline (-W) and national boundaries (-N1)
# (-Scolor is water color, -Gcolor is land color)
pscoast $PROJ $LIMS -Dh -W0.75p -N1/0.5p -Slightblue -Gtan -K > $PSFILE

# Plot focal mechanisms of input faults
awk '{print $1,$2,$3,$4,$5,$6,5}' $FLT_FILE |\
    psmeca $PROJ $LIMS -Sa0.5i -W1p -L1p -Ggrey -K -O >> $PSFILE
# Plot horizontal projection of rectangular input faults
# To convert degrees to radians, multiply by pi/180 = 0.01745
awk '{print $1,$2,$4,$9,$8*cos($5*0.017)}' $FLT_FILE |\
    psxy $PROJ $LIMS -SJ -W3p,red -K -O >> $PSFILE

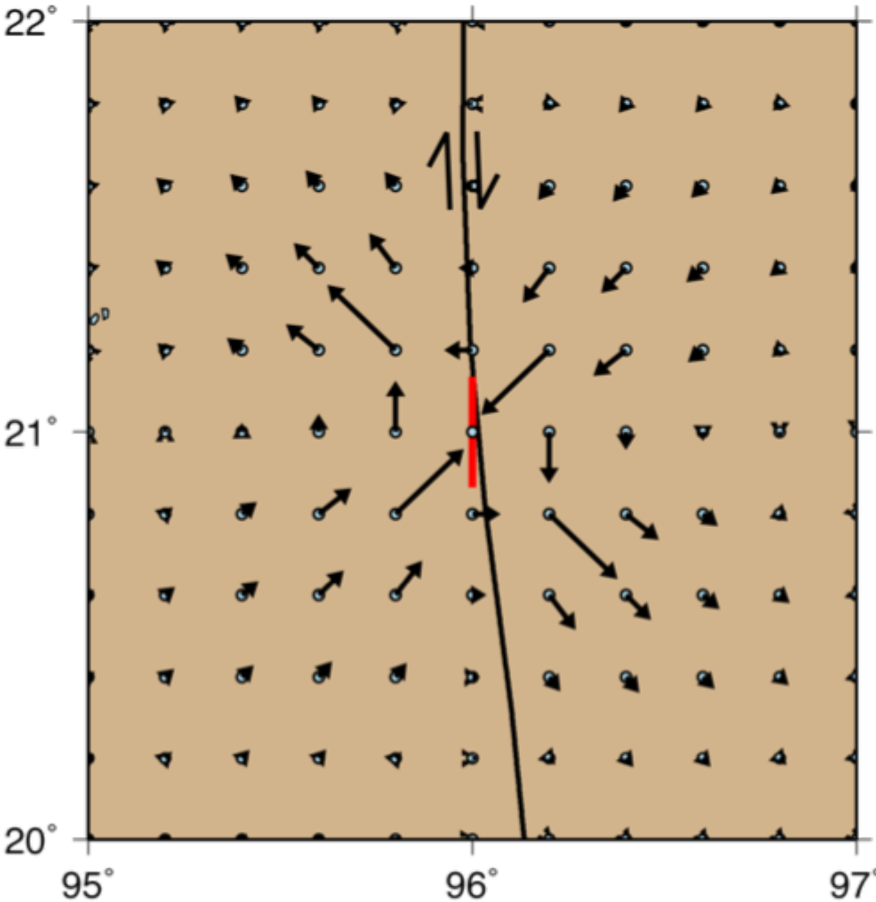
# Plot receiver locations
awk '{print $1,$2}' $DISP_FILE |\
    psxy $PROJ $LIMS -Sc0.05i -W1p -Glightblue -K -O >> $PSFILE
# Plot displacement vectors, with vector amplitudes scaled
# Options after -SV specify arrow tail_width/head_length/head_width
SCALE="10"
awk '{print $1,$2,$4,'"$SCALE"'*$5}' $DISP_FILE |\
    psxy $PROJ $LIMS -SV0.03i/0.08i/0.05i -Gblack -K -O >> $PSFILE

# Draw map outline and label axes
psbasemap $PROJ $LIMS -Ba1WeSn -O >> $PSFILE

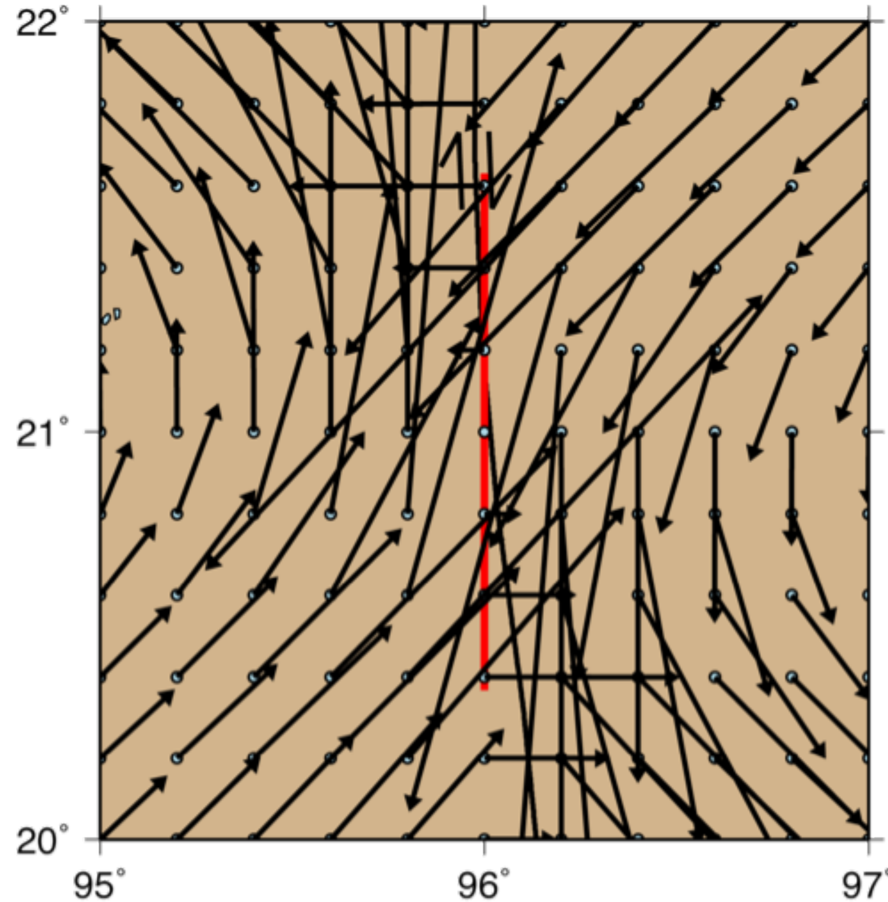
```

Name of output PostScript file

Activity 2: Strike-Slip EQ



Mw 7.0



Mw 7.8

(Plotted on the same scale)

Activity 2: Strike-Slip EQ

- Difficult to see details of larger event
- Zoom out and decrease scale of vectors by factor of 10

plot_disp.sh

```
#!/bin/sh

#####
#       BOURNE SHELL SCRIPT FOR PLOTTING DISPLACEMENT VECTORS
#####

#####
#       INPUT/OUTPUT FILES FROM O92UTIL
#####
# Input source fault file
FLT_FILE="fault.dat" # EVLO EVLA EVDP STR DIP RAK SLIP WID LEN
# Output displacement file
DISP_FILE="disp.out" # STLO STLA STDP AZ UH UZ

#####
#       GMT PLOTTING VARIABLES
#####
# Map projection (use 'man psbasemap' to see options)
PROJ="-JM4i -P"
# Map limits (-RXMIN/XMAX/YMIN/YMAX)
LIMS="-R94/98/19/23"
# Output PostScript file name
PSFILE="displacement_7.8.ps"

#####
#       GMT PLOTTING COMMANDS
#####
# Draw coastline (-W) and national boundaries (-N1)
# (-Scolor is water color, -Gcolor is land color)
pscoast $PROJ $LIMS -Dh -W0.75p -N1/0.5p -Slightblue -Gtan -K > $PSFILE

# Plot focal mechanisms of input faults
awk '{print $1,$2,$3,$4,$5,$6,5}' $FLT_FILE |\
    psmeca $PROJ $LIMS -Sa0.5i -W1p -L1p -Ggrey -K -O >> $PSFILE
# Plot horizontal projection of rectangular input faults
# To convert degrees to radians, multiply by pi/180 = 0.01745
awk '{print $1,$2,$4,$9,$8*cos($5*0.017)}' $FLT_FILE |\
    psxy $PROJ $LIMS -SJ -W3p,red -K -O >> $PSFILE

# Plot receiver locations
awk '{print $1,$2}' $DISP_FILE |\
    psxy $PROJ $LIMS -Sc0.05i -W1p -Glightblue -K -O >> $PSFILE
# Plot displacement vectors, with vector amplitudes scaled
# Options after -SV specify arrow tail_width/head_length/head_width
SCALE="1"
awk '{print $1,$2,$4,'"$SCALE"'*$5}' $DISP_FILE |\
    psxy $PROJ $LIMS -SV0.03i/0.08i/0.05i -Gblack -K -O >> $PSFILE

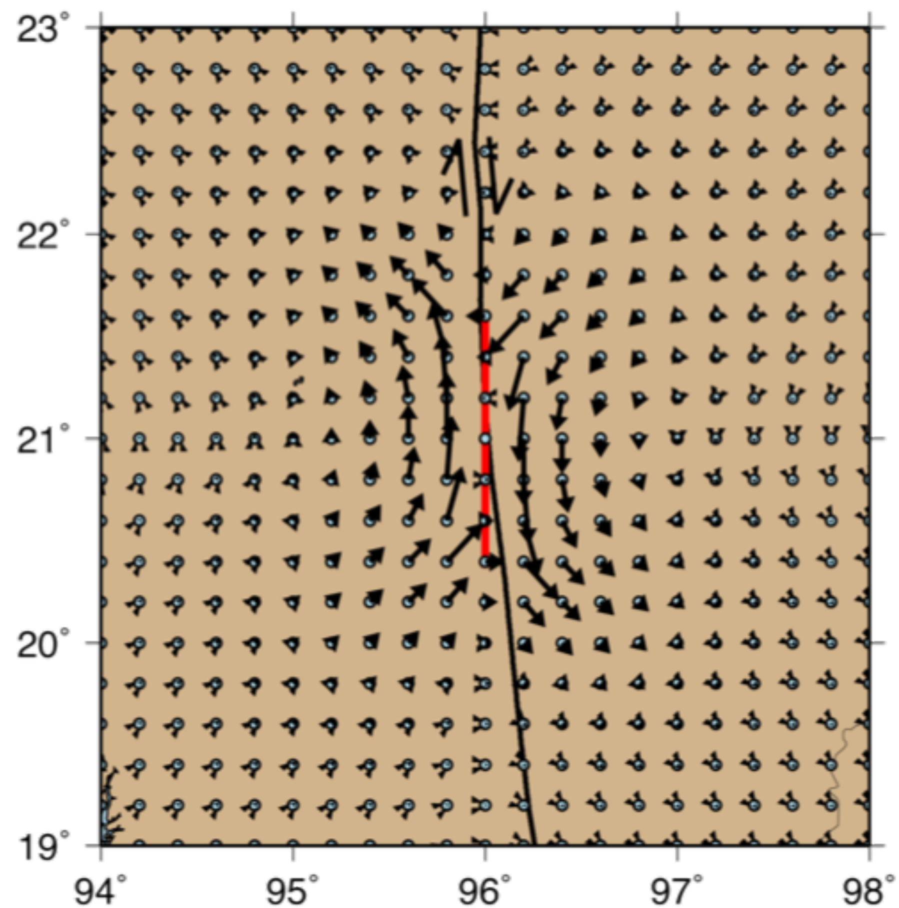
# Draw map outline and label axes
psbasemap $PROJ $LIMS -Ba1WeSn -O >> $PSFILE
```

Larger area

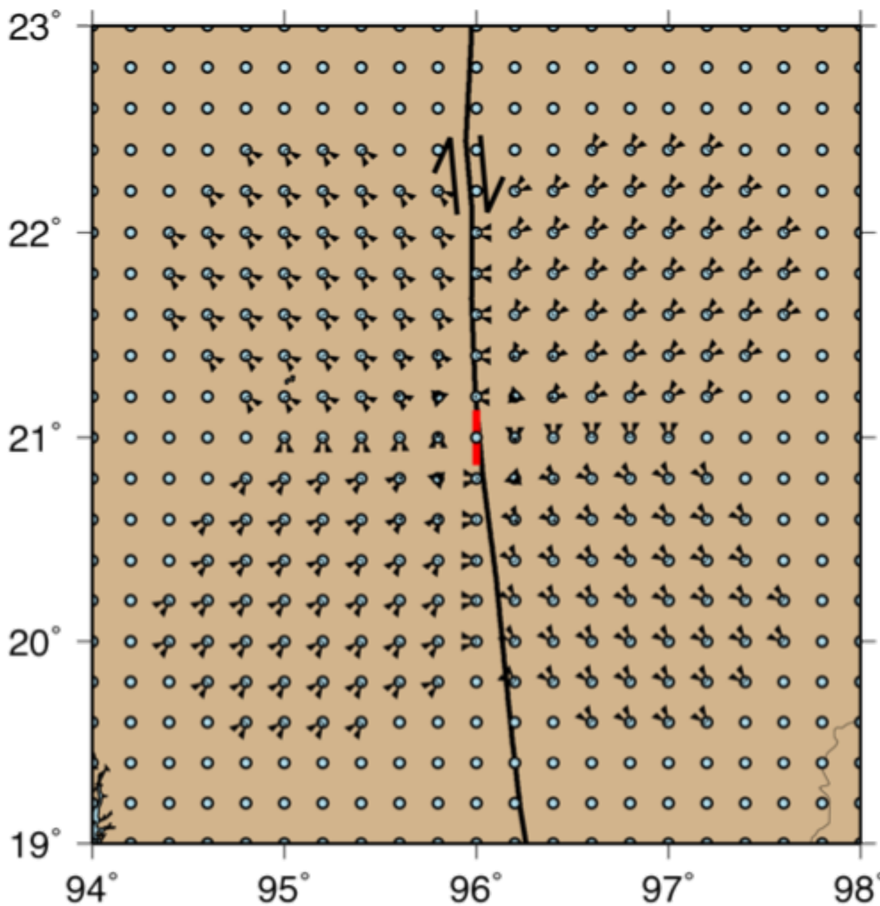
Reduce scale from 10 to 1

Activity 2: Strike-Slip EQ

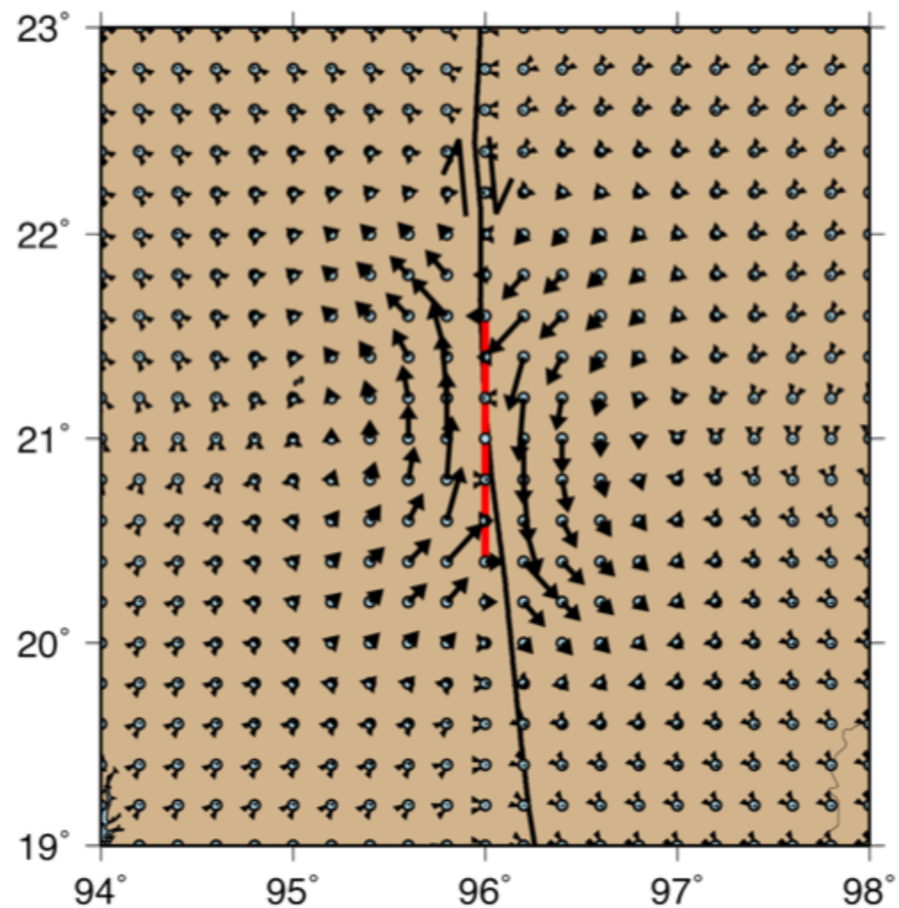
- *Where is displacement parallel to fault?*
- *What happens at ends of fault?*



Activity 2: Strike-Slip EQ



Mw 7.0

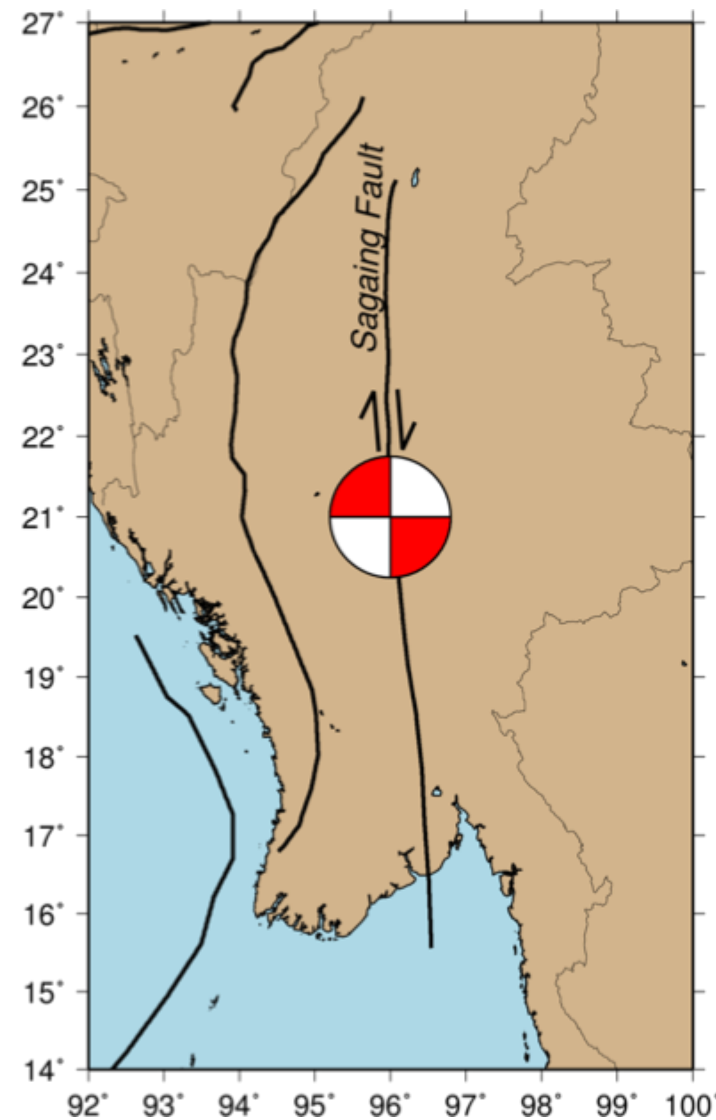


Mw 7.8

(Plotted on the same scale)

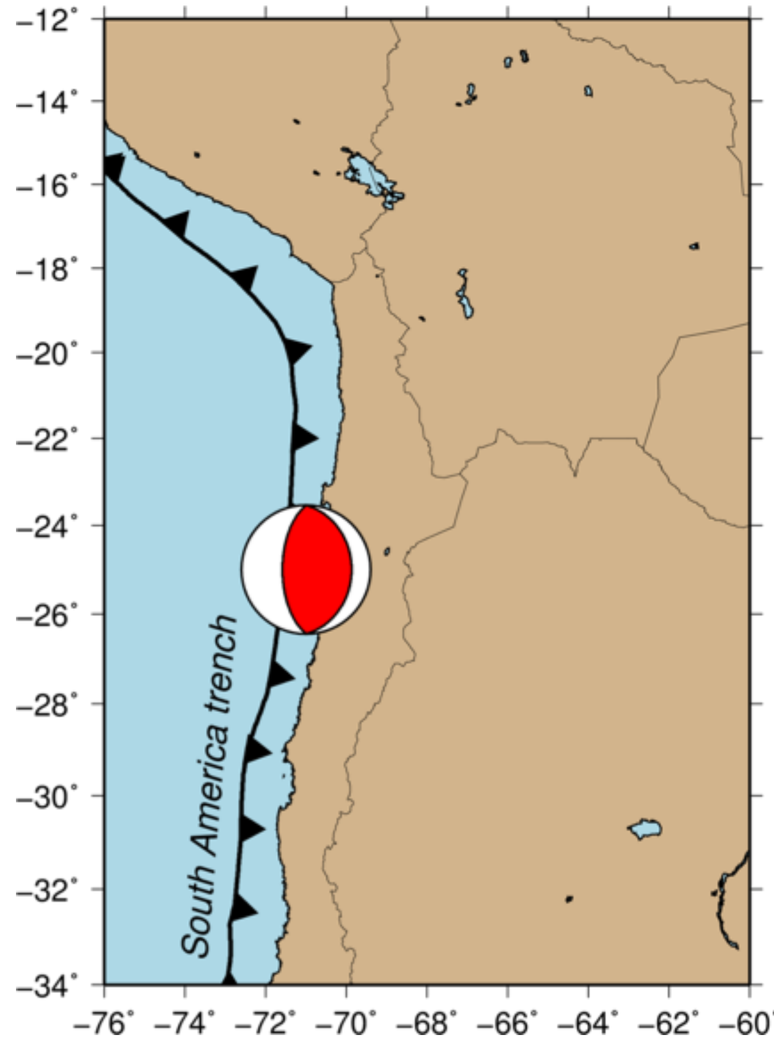
Activity 3: Common Patterns

- Most common types of earthquakes:
  - Strike-slip events on vertical faults



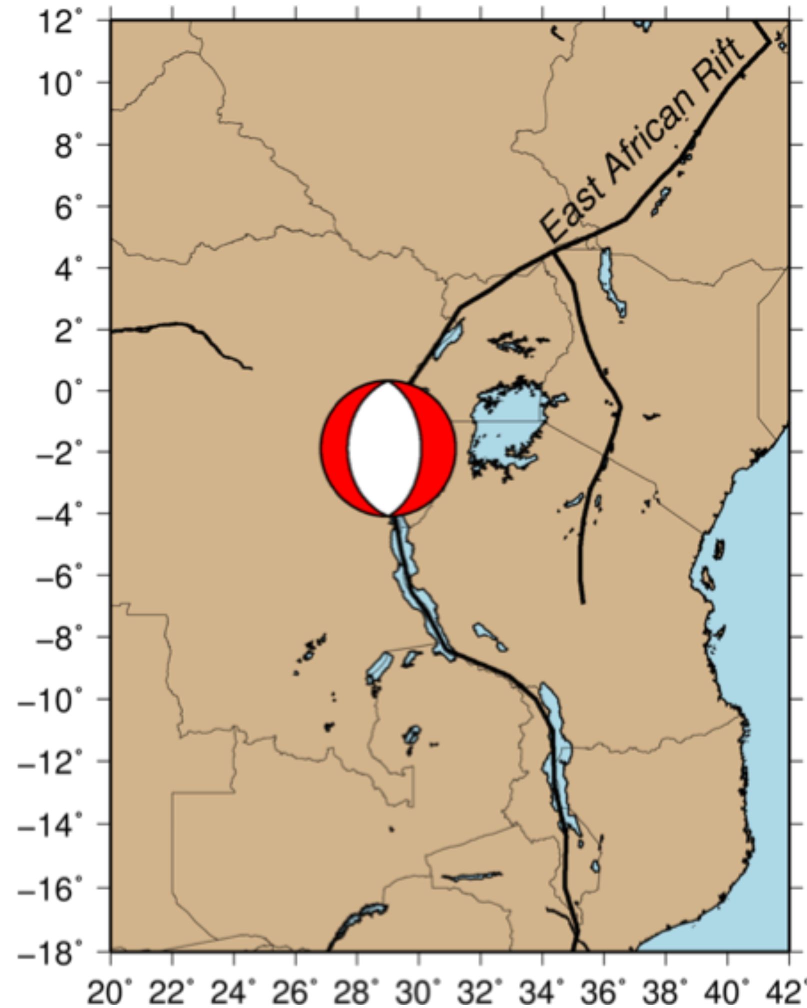
Activity 3: Common Patterns

- Most common types of earthquakes:
  - Strike-slip events on vertical faults
  - Reverse (thrust) events on faults dipping 30º



Activity 3: Common Patterns

- Most common types of earthquakes:
  - Strike-slip events on vertical faults
  - Reverse (thrust) events on faults dipping 30º
  - Normal events on faults dipping 50º



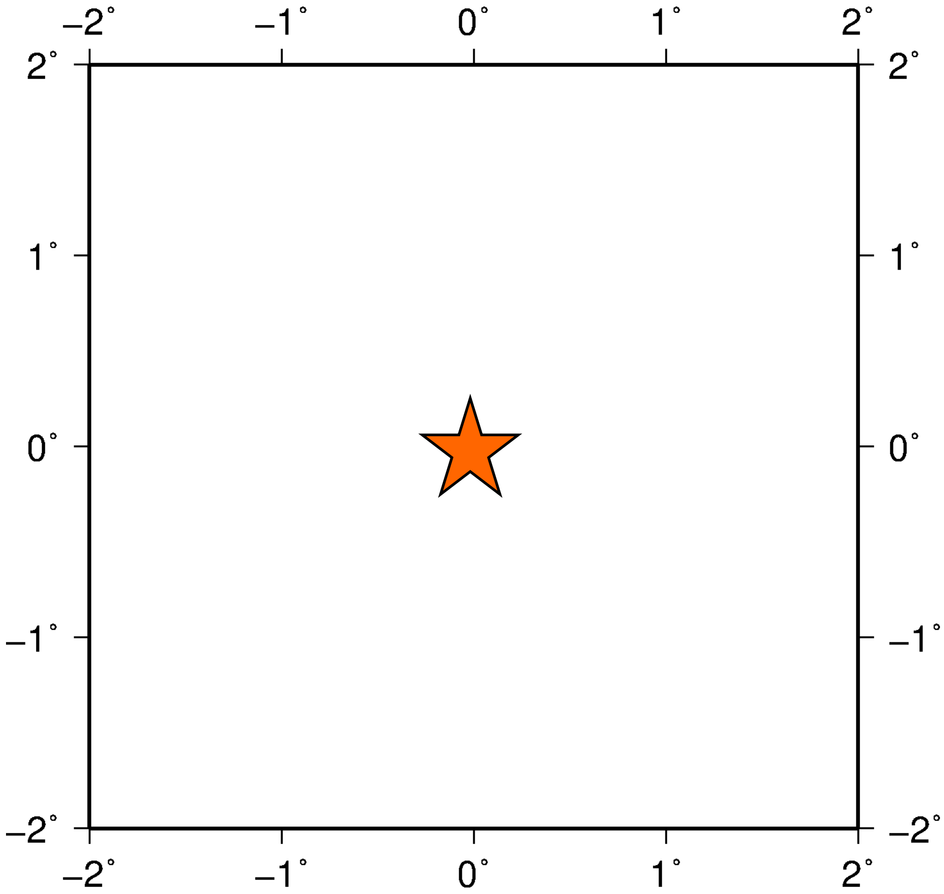
Activity 3: Common Patterns

- *Exercise 3a: compute and compare the surface displacement fields for hypothetical moderate (Mw 7.0) earthquakes of each common earthquake type (strike-slip, normal, thrust)*

Activity 3: Common Patterns

- To systematically compare these fault types:
  - Place each source at the same location

Activity 3: Common Patterns

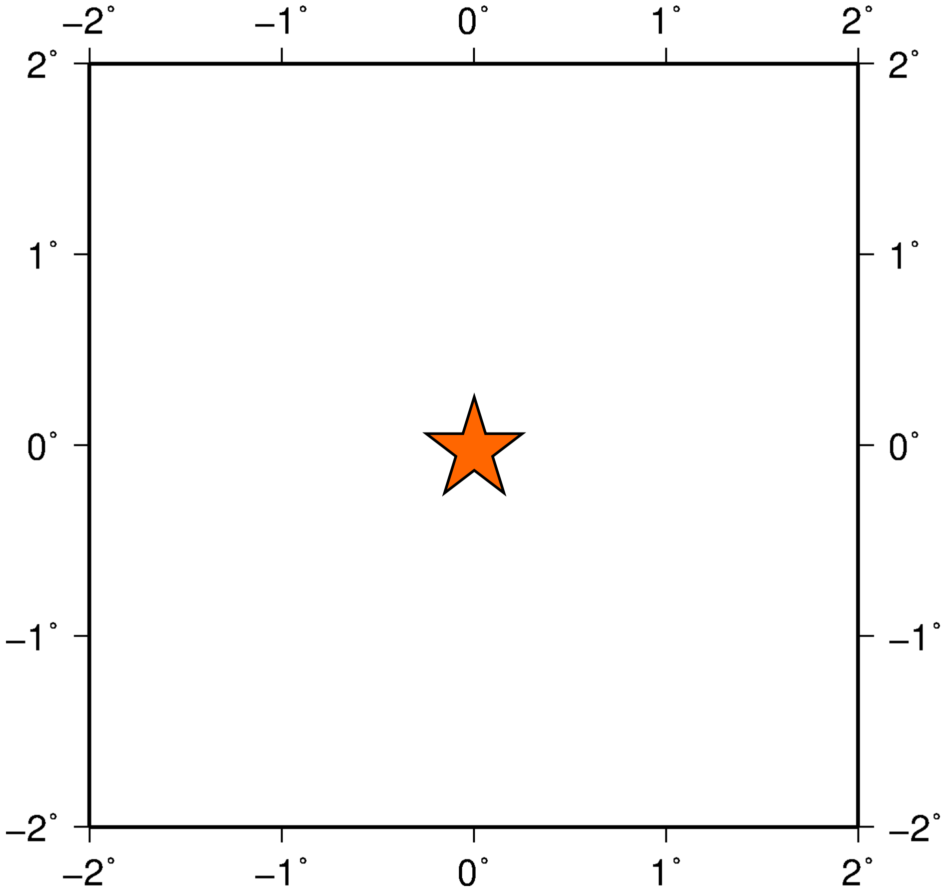


0ºE, 0ºN
15 km deep

Activity 3: Common Patterns

- To systematically compare these fault types:
  - Place each source at the same location
  - Give sources same slip and dimensions

Activity 3: Common Patterns



Mw 7.0:

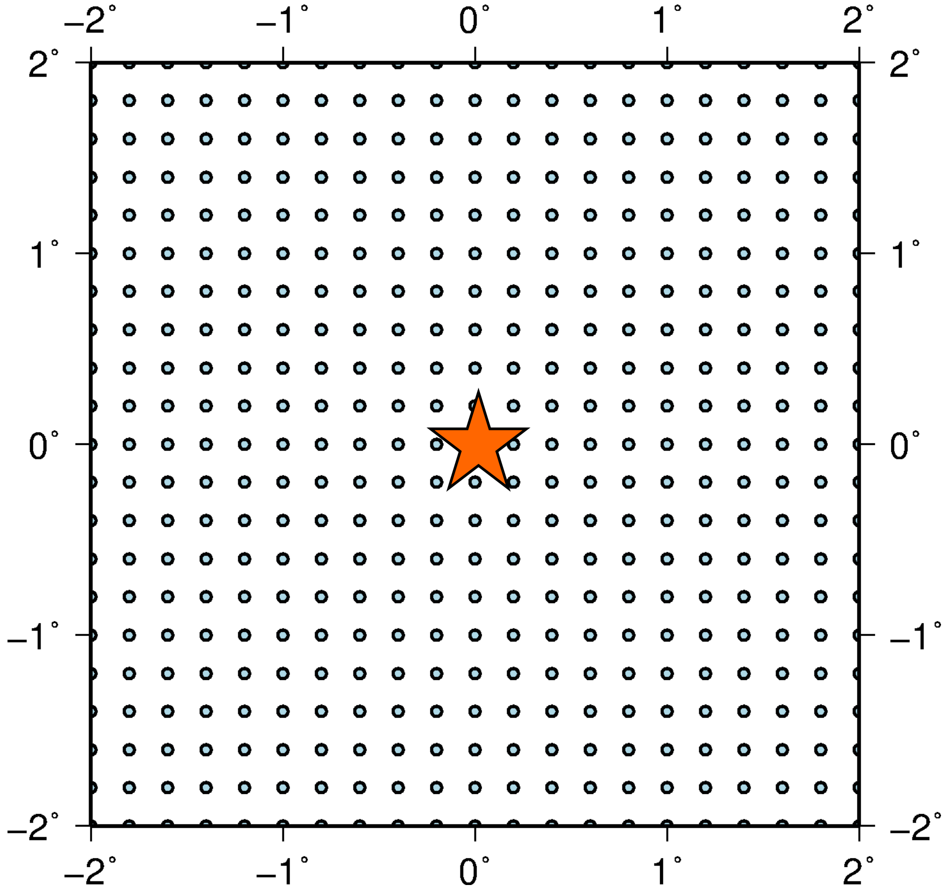
Slip = 5 m

15 km x 15 km

Activity 3: Common Patterns

- To systematically compare these fault types:
  - Place each source at the same location
  - Give sources same slip and dimensions
  - Use the same receiver grid

Activity 3: Common Patterns

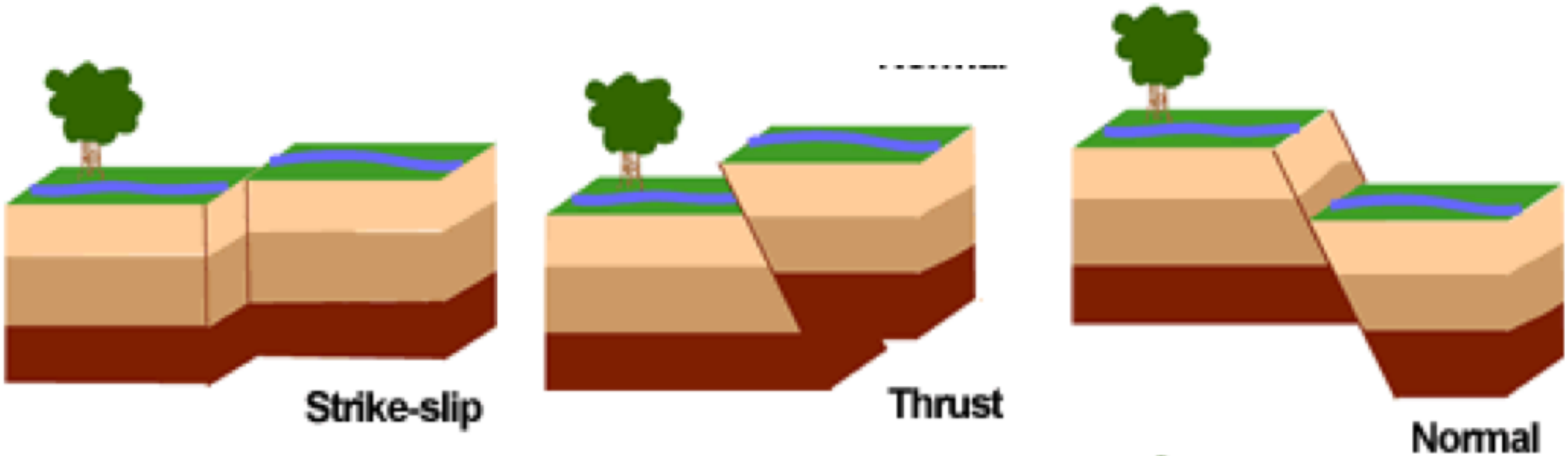


Grid Increment: 0.2º

Activity 3: Common Patterns

- To systematically compare these fault types:
  - Place each source at the same location
  - Give sources same slip and dimensions
  - Use the same receiver grid
  - Only difference should be fault kinematics

Activity 3: Common Patterns



Dip = 90º
Rake = 0º (left lat)
OR
Rake = 180º (right lat)

Dip = 30º
Rake = 90º

Dip = 50º
Rake = -90º

All have strike = 0º

Activity 3: Common Patterns

Receiver file (station.dat) using GRID

x-limits and spacing, y-limits and spacing, z-value, output file

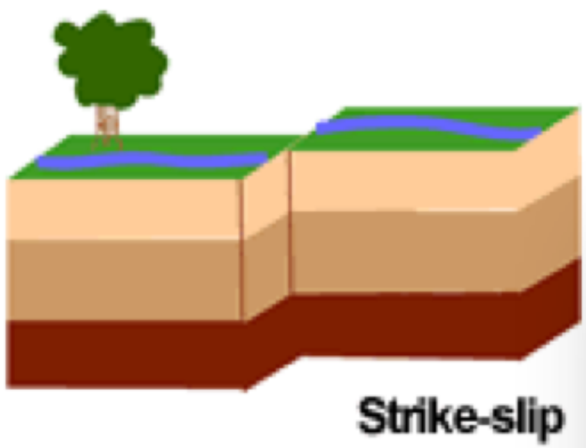
```
grid -x -1 1 -dx 0.2 -y -1 1 -dy 0.2
    -z 0.0 -o station.dat
```

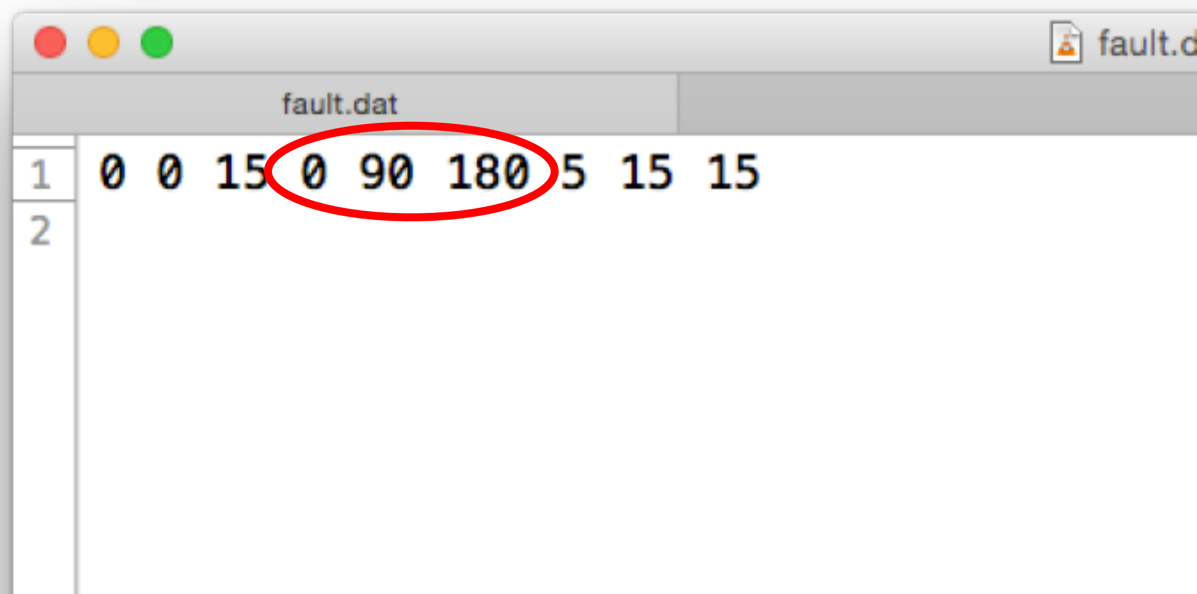
Activity 3: Common Patterns

<u>Input fault file (fault.dat) with strike-slip event</u>

location of center, kinematics, slip, dimensions

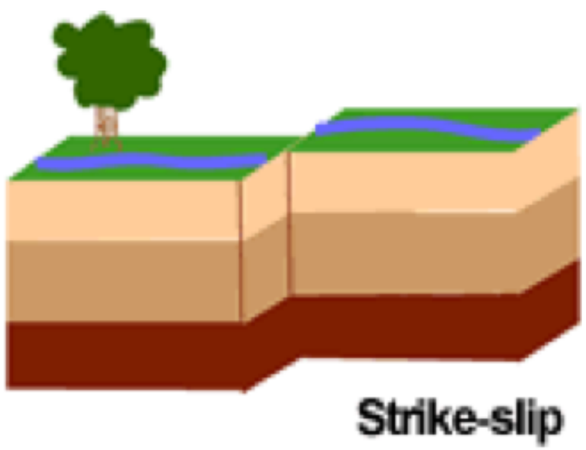
Place each fault center at (0°E, 0°N, 15km) for direct comparison.

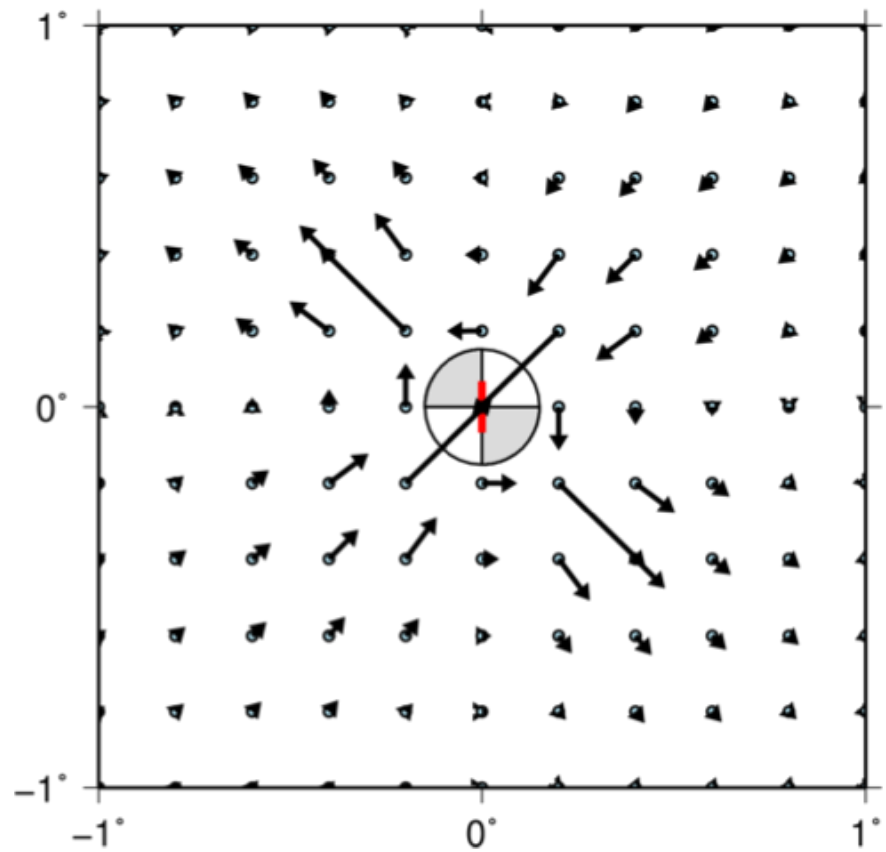




Activity 3: Common Patterns

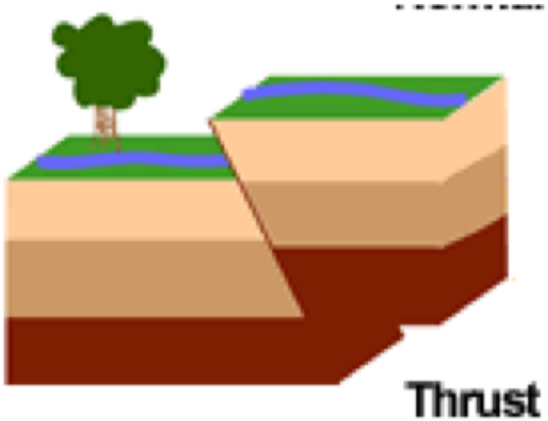
- Right lateral strike-slip earthquake on vertical fault

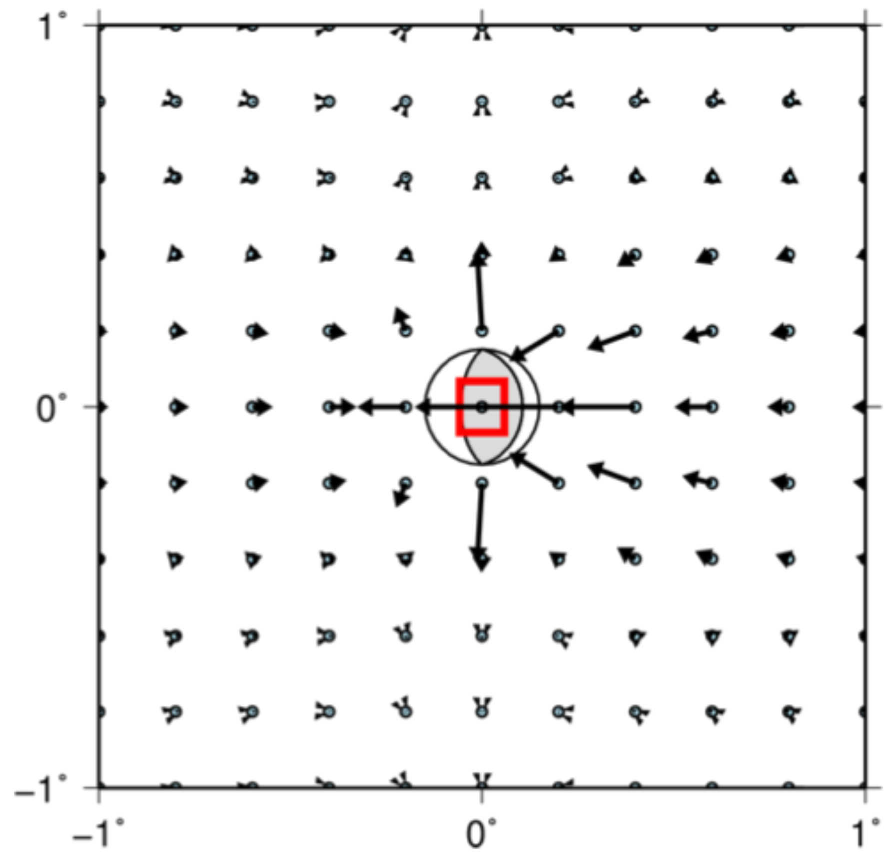




Activity 3: Common Patterns

- Thrust earthquake
  - Dip = 30°
  - Rake = 90°



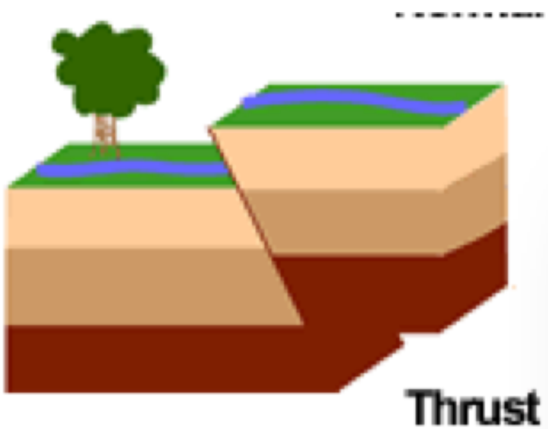


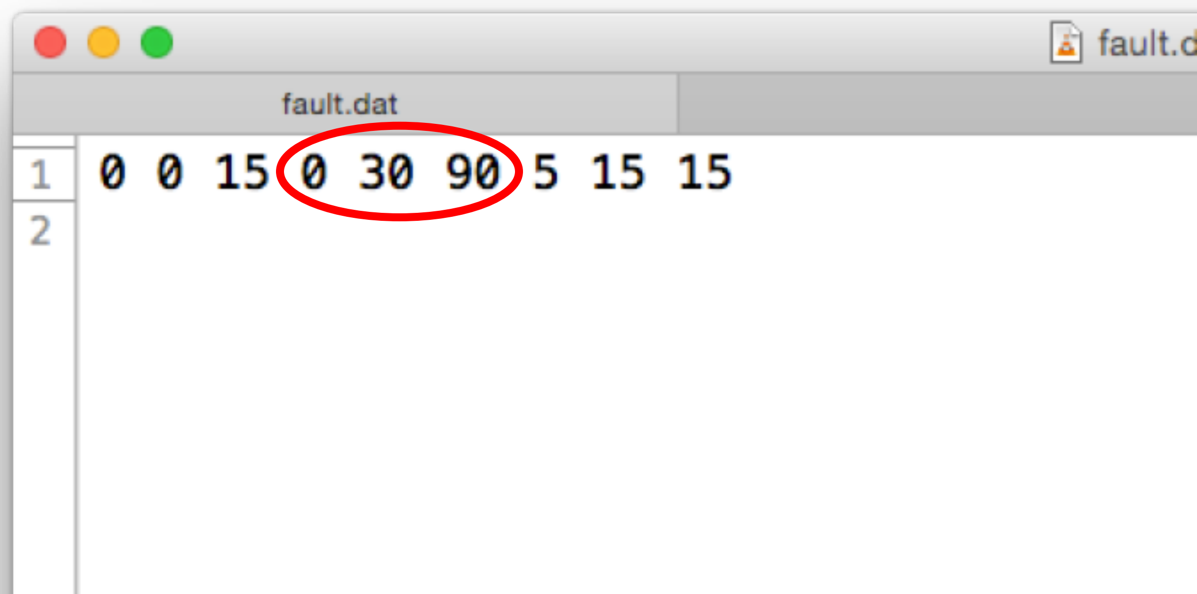
Do you get the same result?

Activity 3: Common Patterns

Input fault file (fault.dat) with reverse event

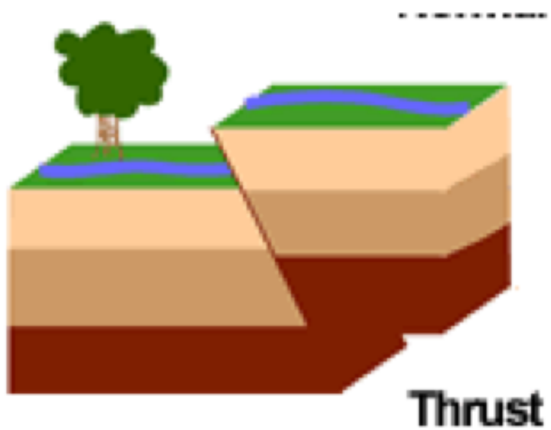
location of center, kinematics, slip, dimensions

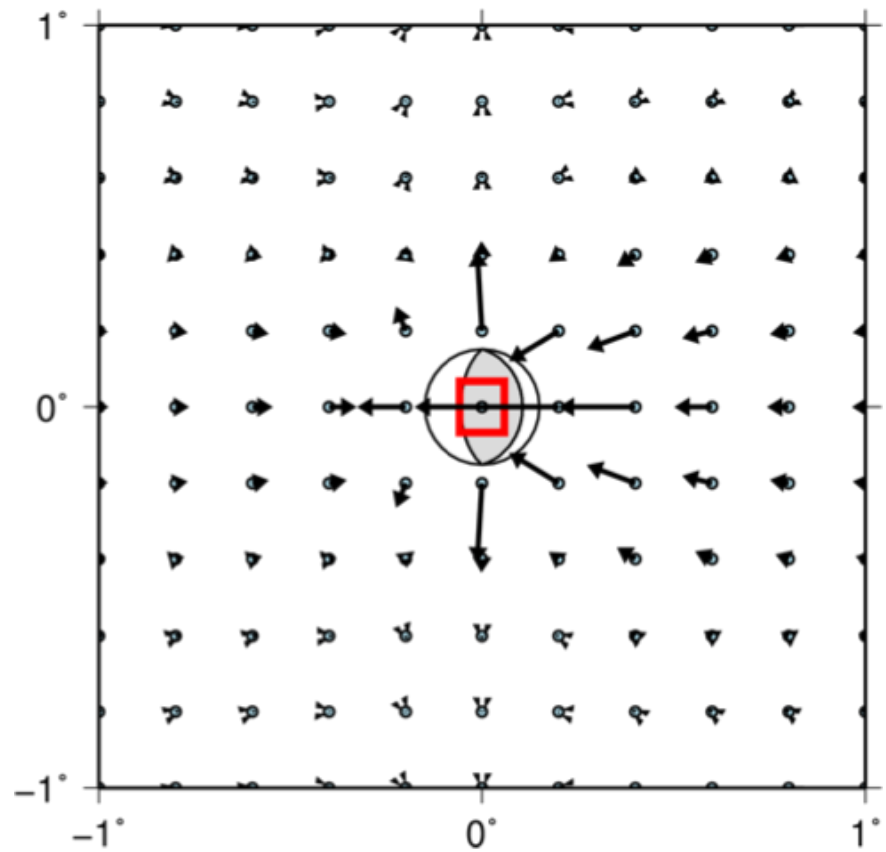




Activity 3: Common Patterns

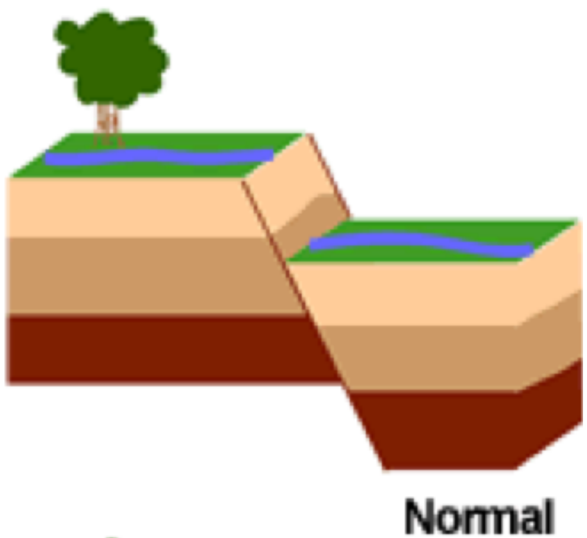
- Thrust earthquake
  - Dip = 30º
  - Rake = 90º

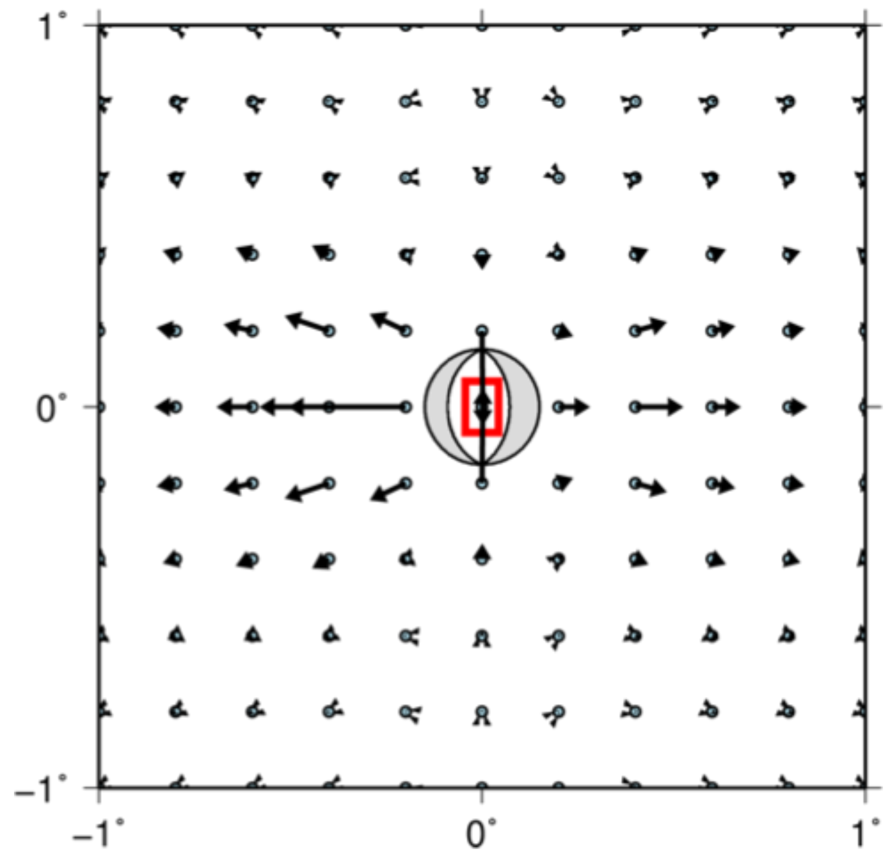




Activity 3: Common Patterns

- Normal earthquake
  - Dip = 50°
  - Rake = -90°



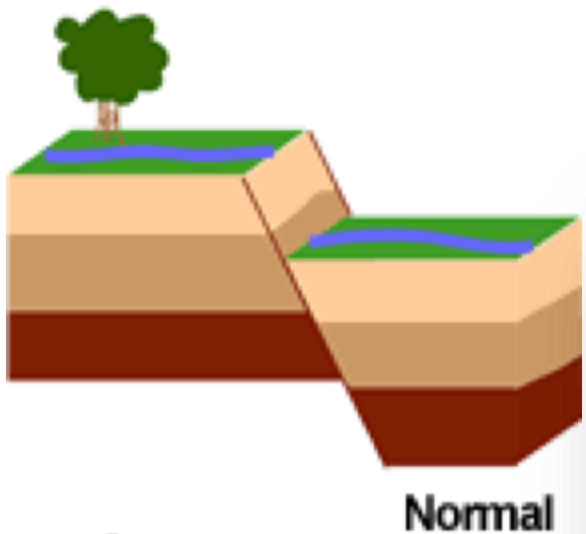


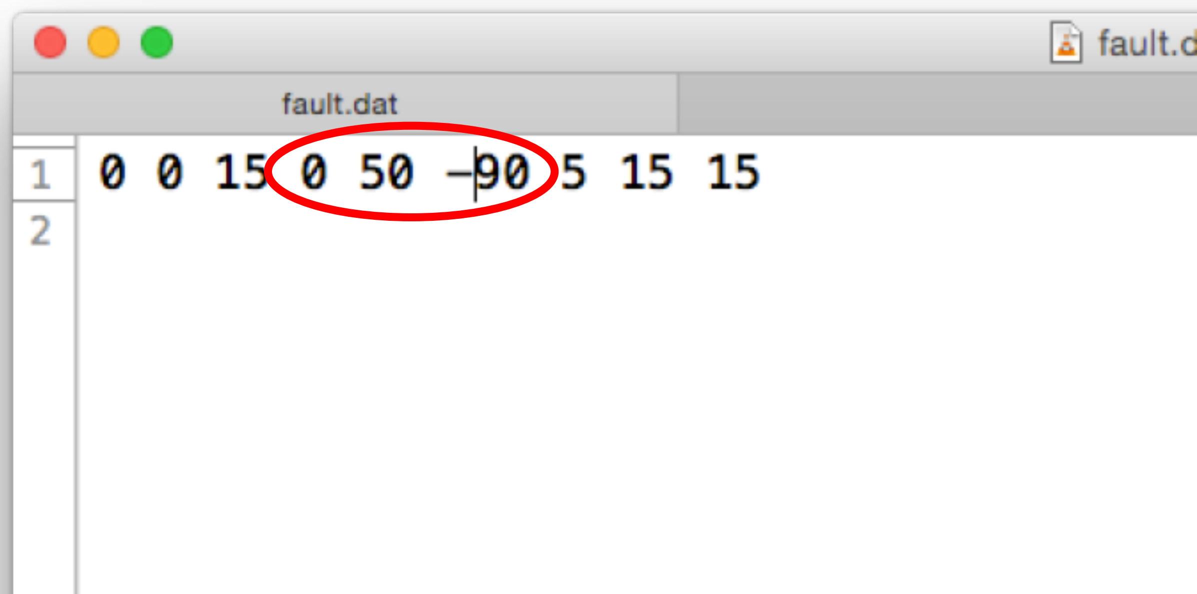
Do you get the same result?

Activity 3: Common Patterns

<u>Input fault file (fault.dat) with normal event</u>

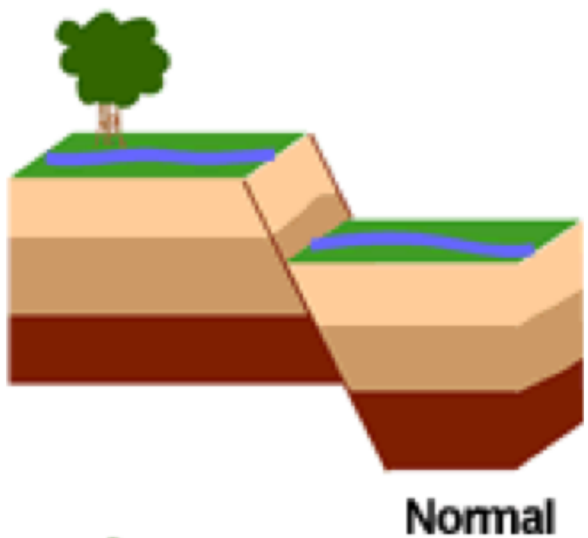
location of center, kinematics, slip, dimensions

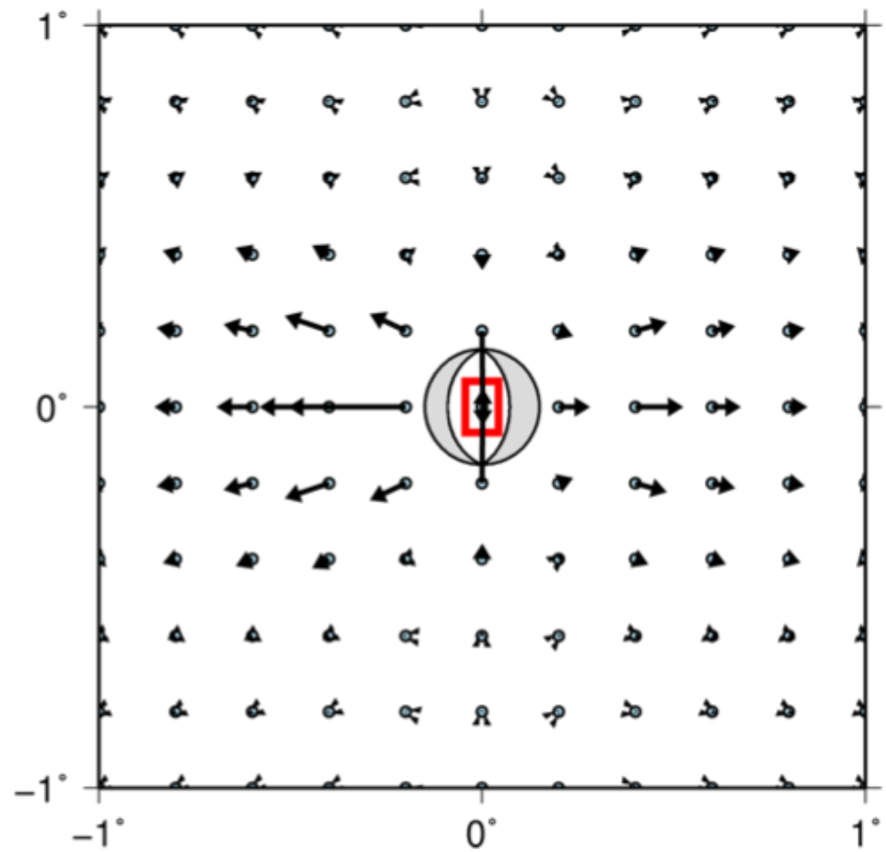




Activity 3: Common Patterns

- Normal earthquake
  - Dip = 50º
  - Rake = -90º

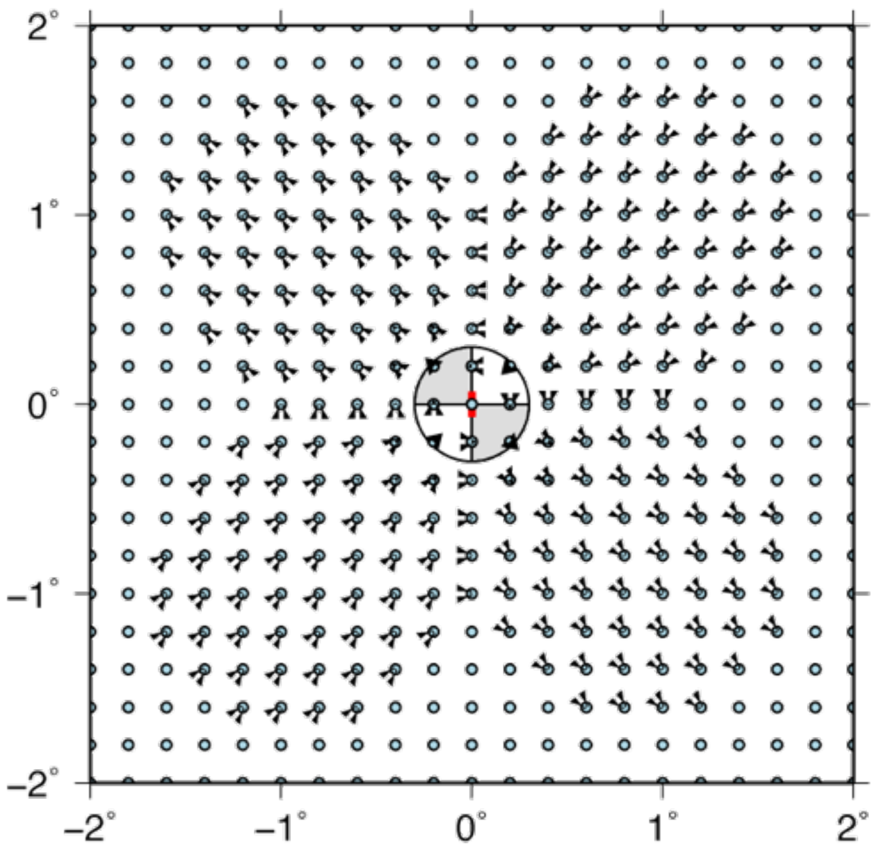


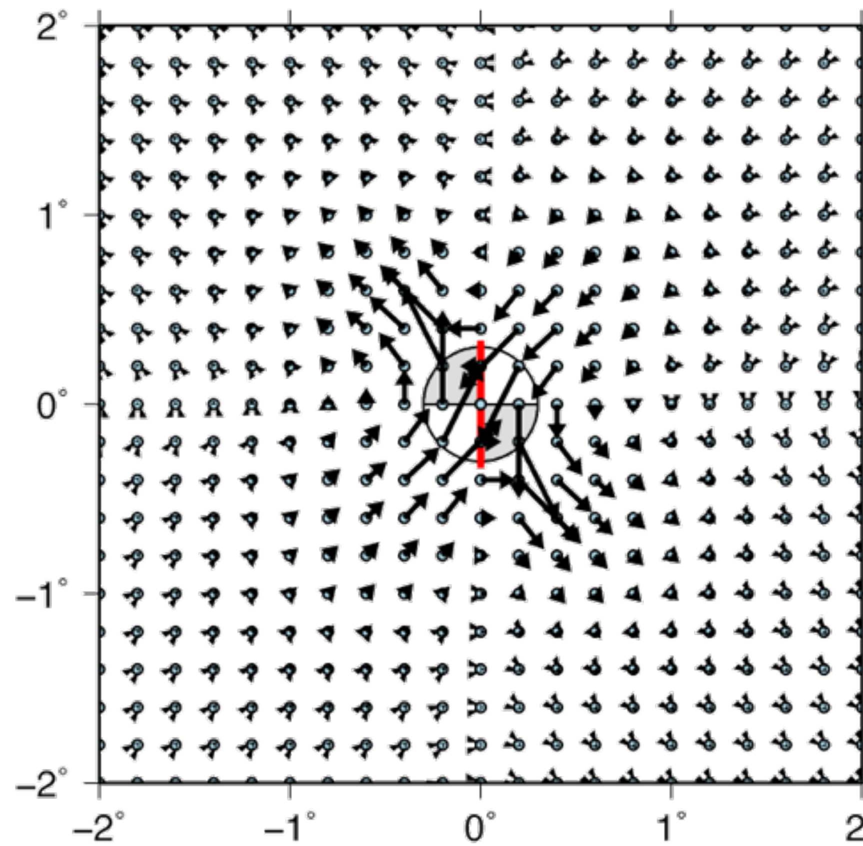


Activity 3: Common Patterns

- *Exercise 3b: compare the surface displacement fields for hypothetical moderate (Mw 7.0) and large (Mw 7.8) earthquakes, of each common earthquake type (strike-slip, normal, thrust)*
- *Mw 7.8:*
  - *8 m of slip*
  - *25 km wide x 75 km long*

Activity 3: Common Patterns

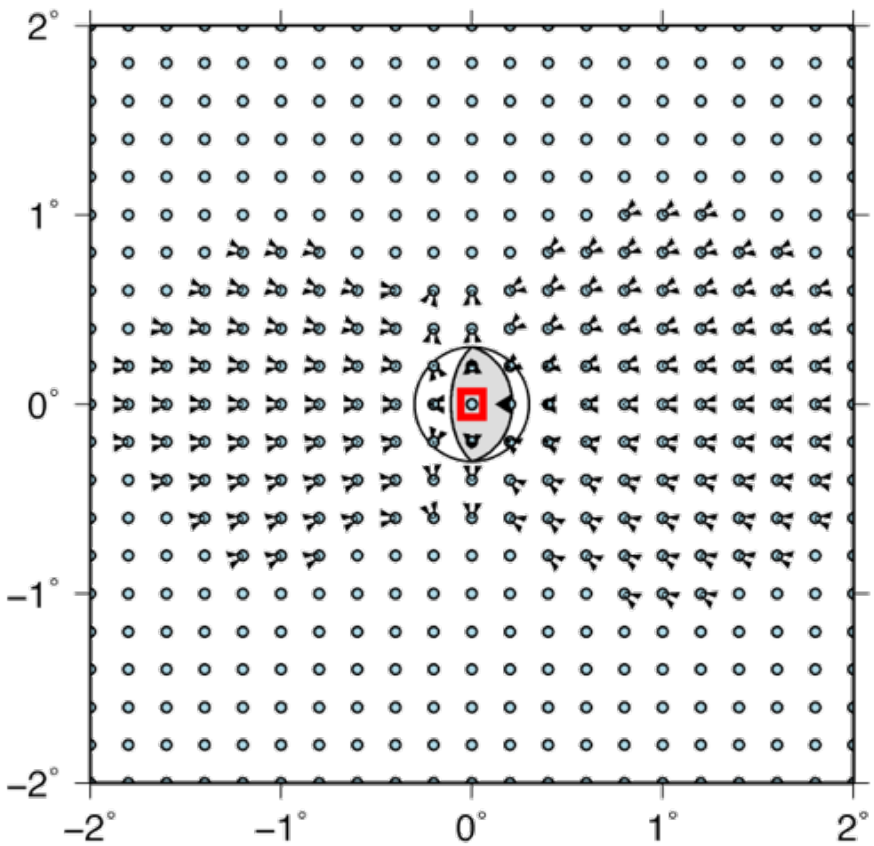


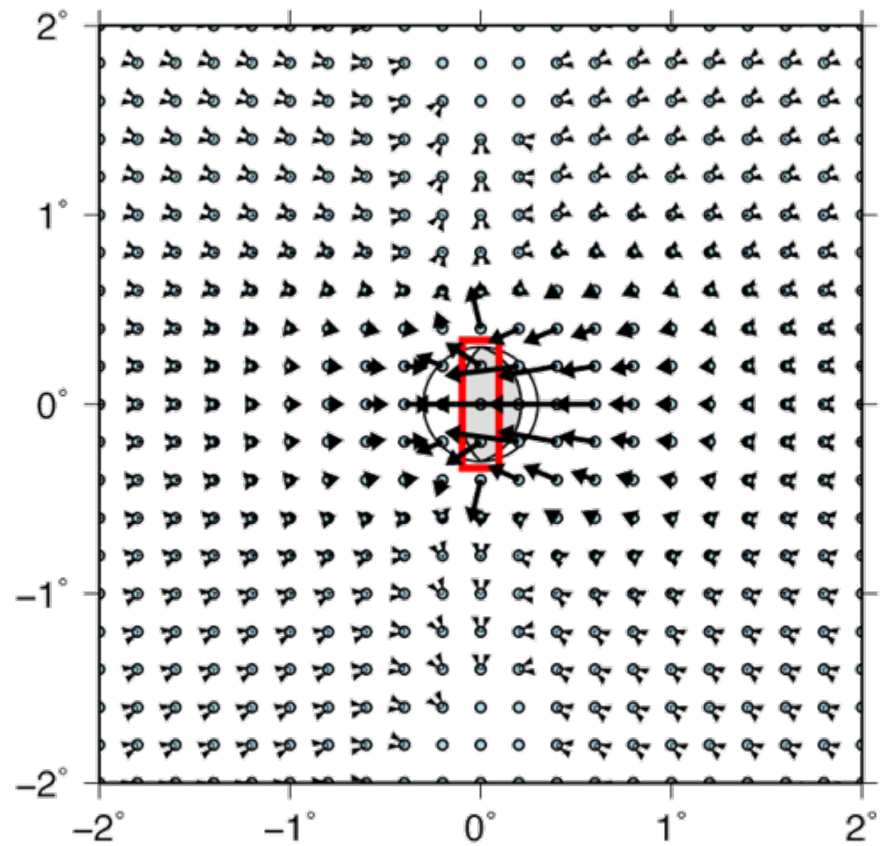


Mw 7.0 Mw 7.8

(Plotted on the same scale)

Activity 3: Common Patterns



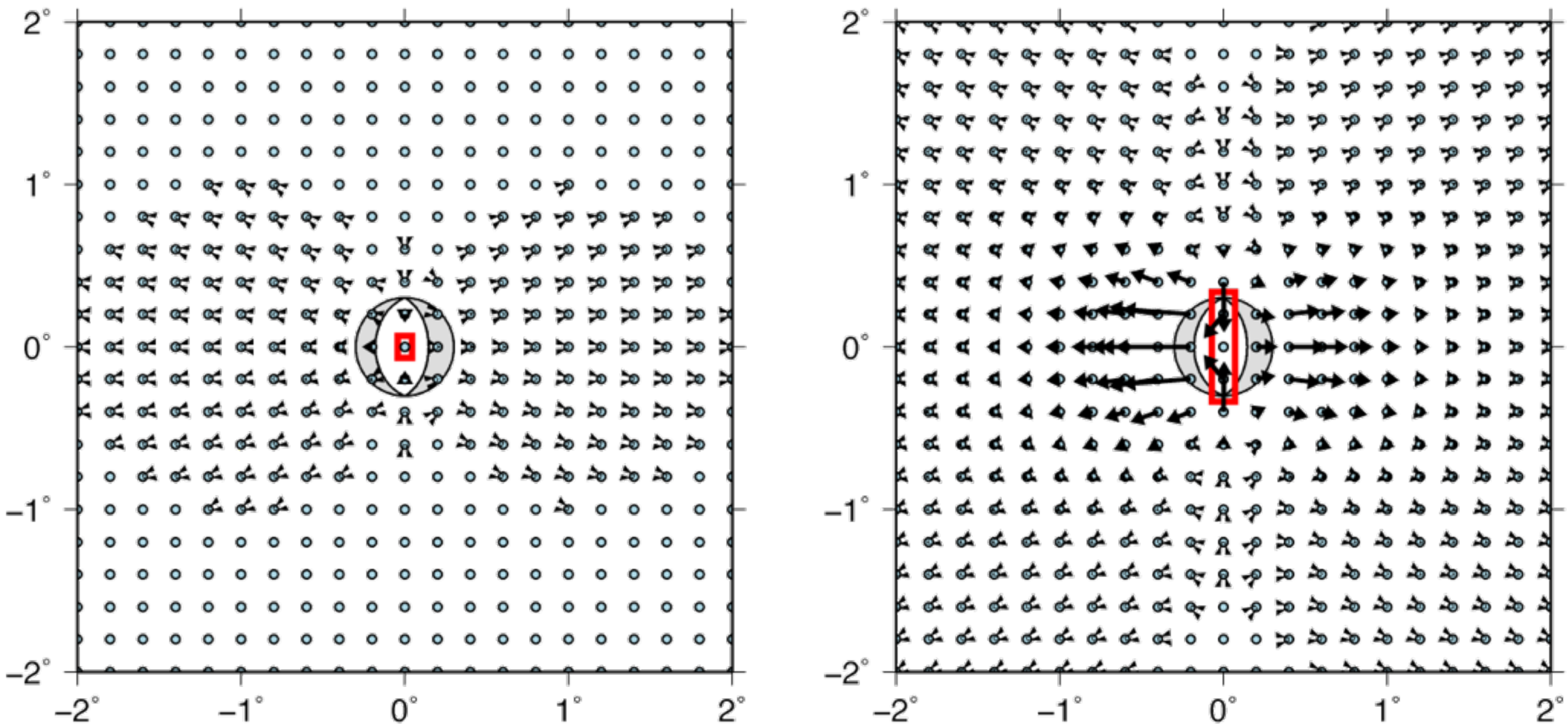


Mw 7.0

Mw 7.8

(Plotted on the same scale)

Activity 3: Common Patterns



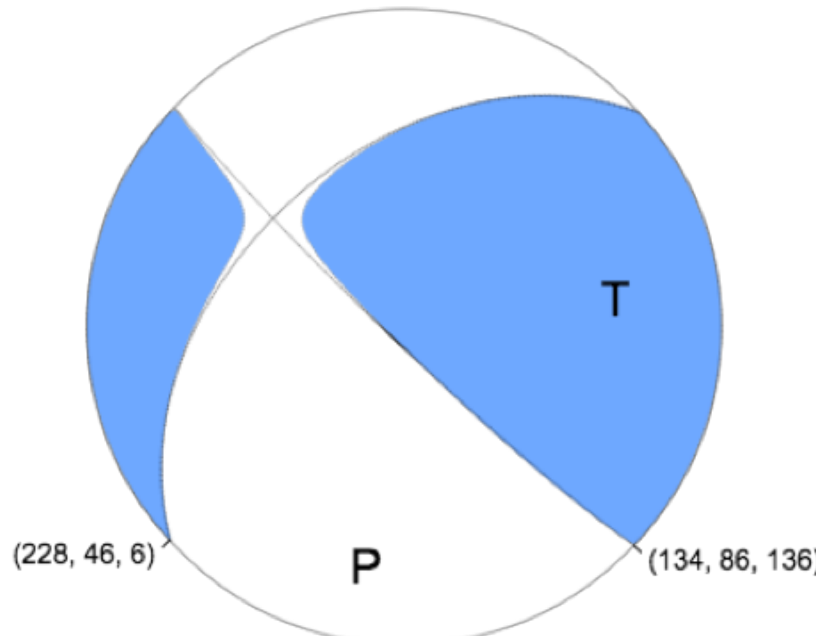
Mw 7.0 Mw 7.8

(Plotted on the same scale)

Activity 4: Multiple Faults

- Simple, small earthquakes can be represented by a single rectangular fault
- Multiple earthquakes and complex events require multiple fault segments
- O92UTIL incorporates multiple faults easily
- Case Study: 2013 Mw 7.7 Pakistan earthquake

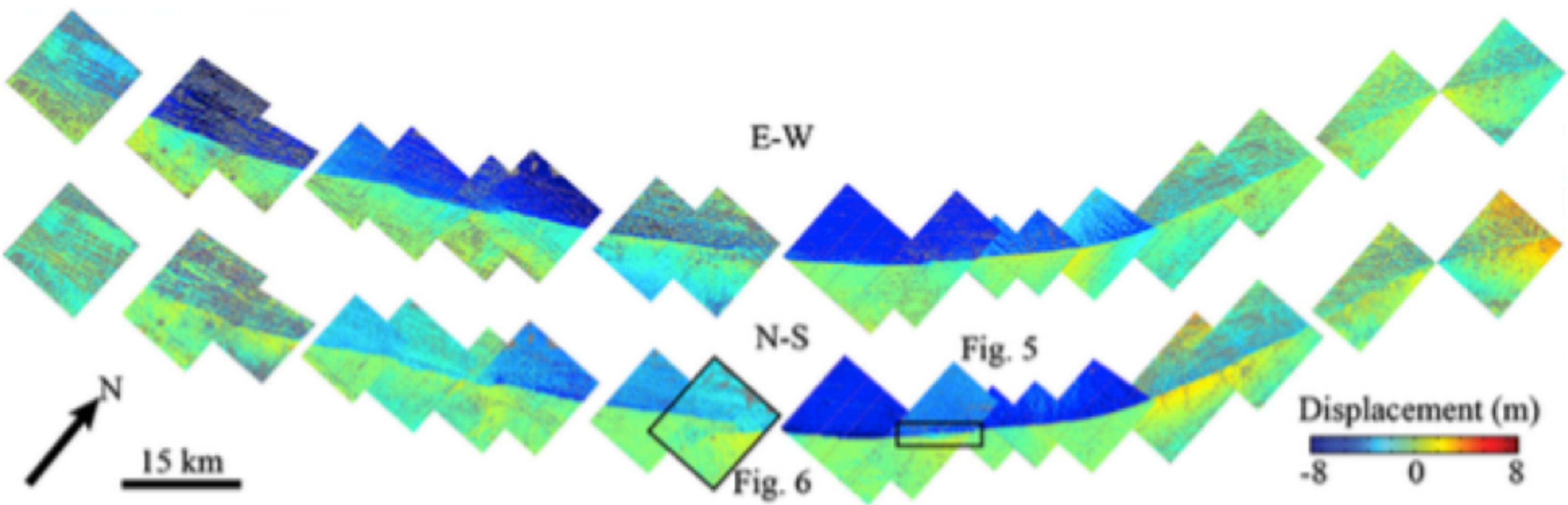
Activity 4: Multiple Faults



U.S. Geological Survey
W-phase Moment Tensor

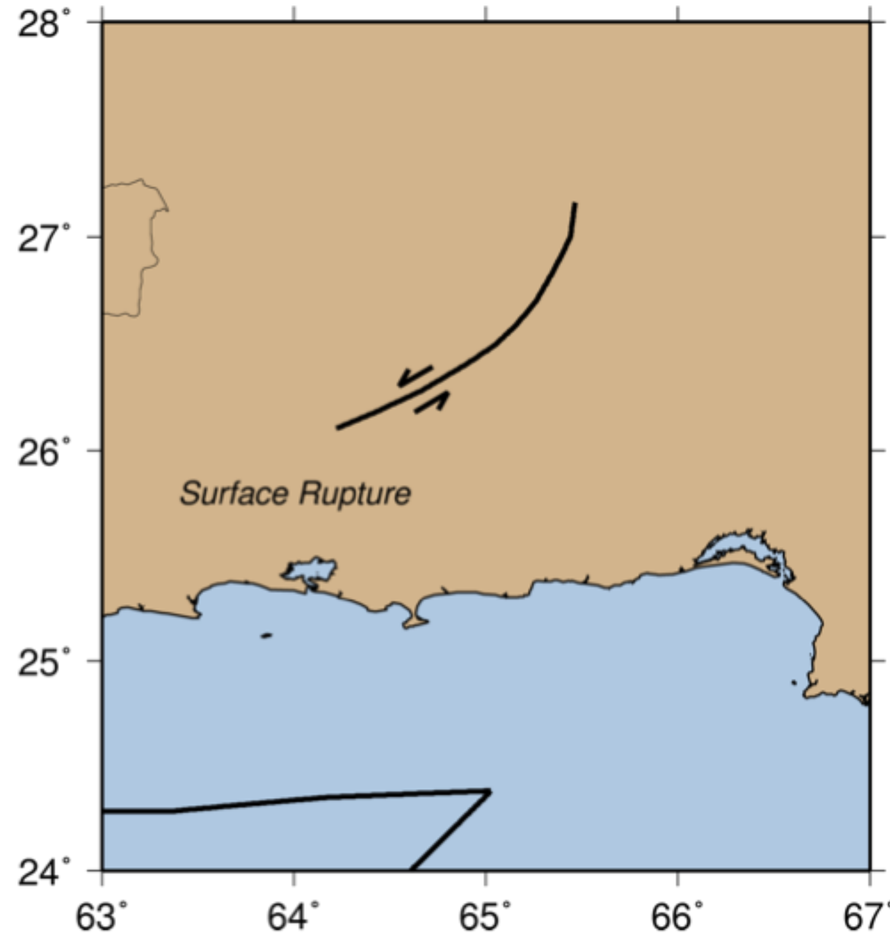
Activity 4: Multiple Faults

Components of surface displacement derived from optical imagery (Barnhart et al., 2015). The curvature of the fault is clear, and obviously cannot be represented by a single rectangular plane.



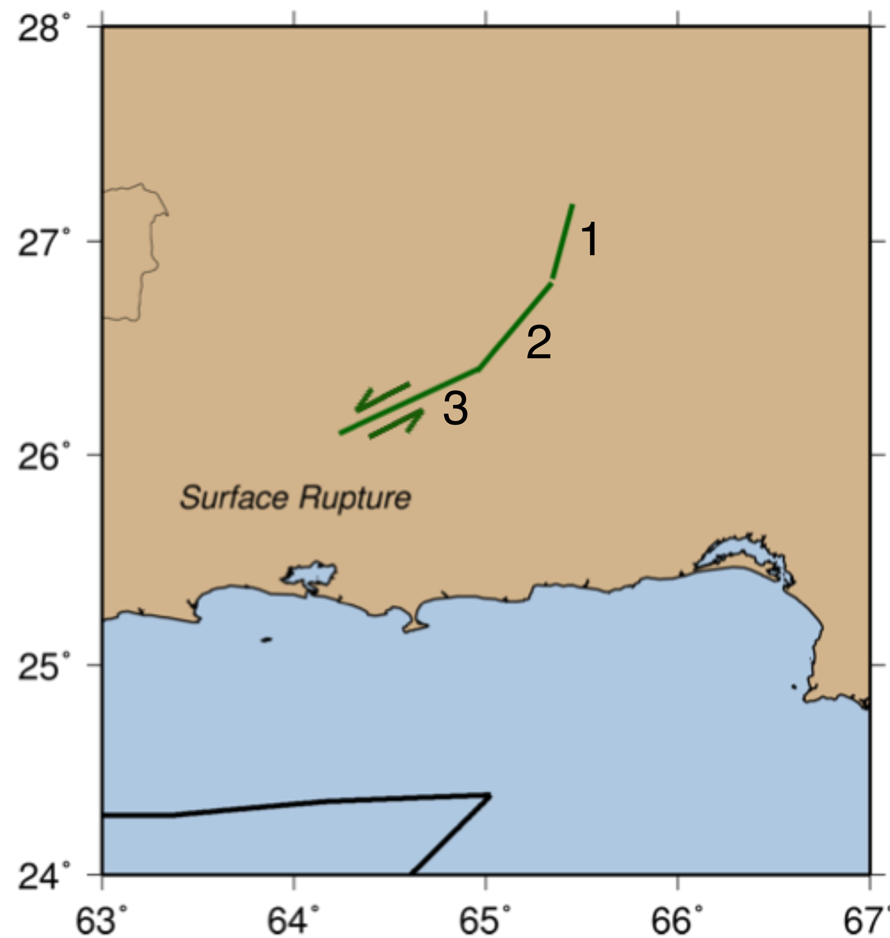
Activity 4: Multiple Faults

- Rupture on fault that changes strike direction along length



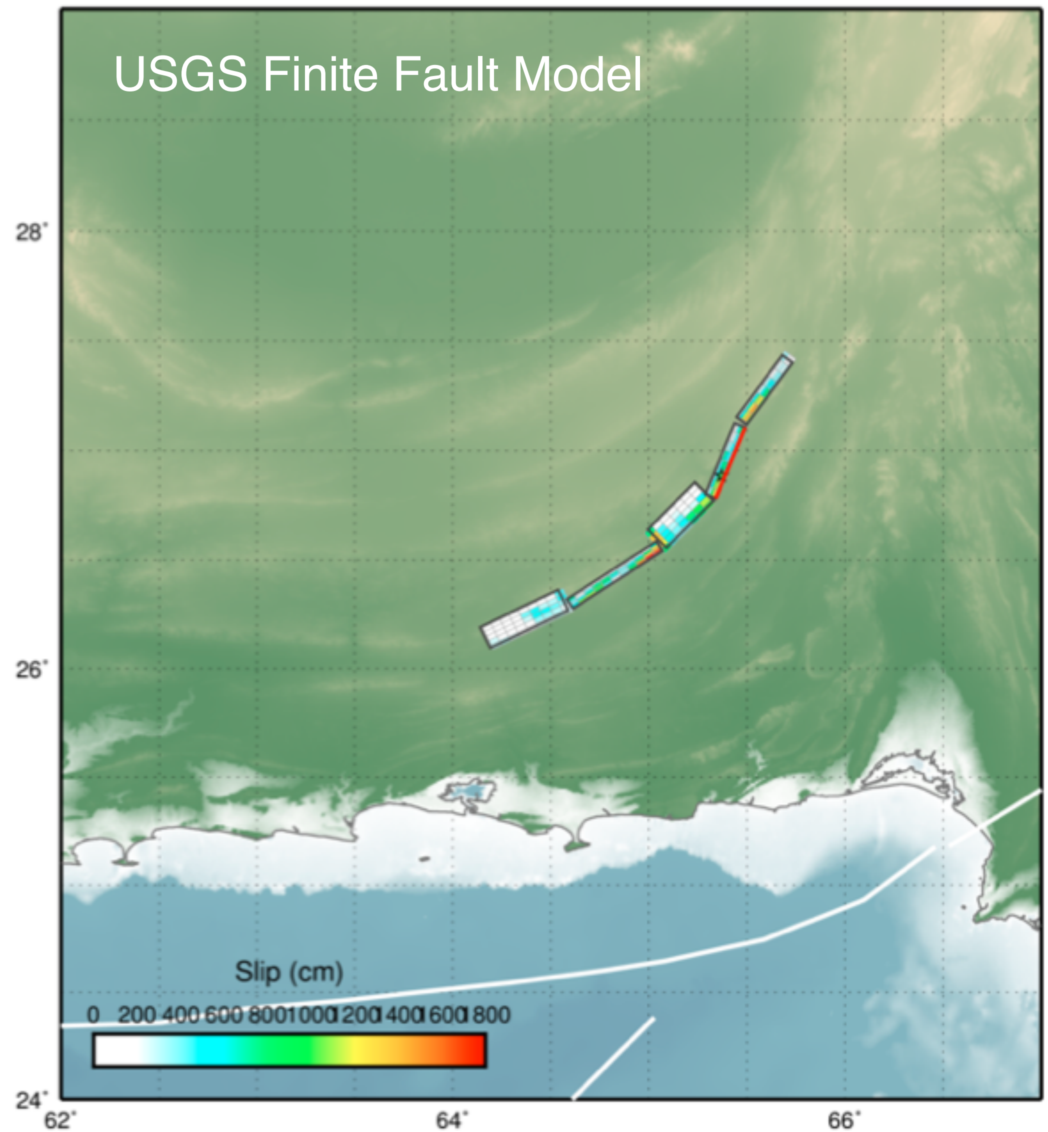
Activity 4: Multiple Faults

- Rupture on fault that changes strike direction along length
- Divide into three rectangular segments



Activity 4: Multiple Faults

- Rupture on fault that changes strike direction along length
- Divide into three rectangular segments
- For comparison, USGS FFM has 5 main segments



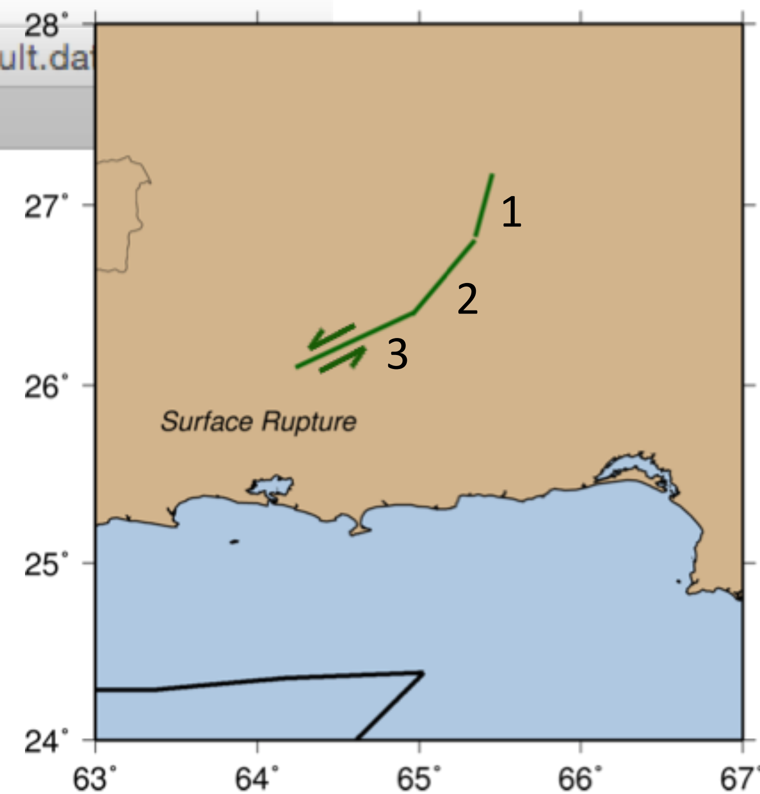
Activity 4: Multiple Faults

Input faults file (fault.dat)

location of center, kinematics, slip, dimensions

fault.dat

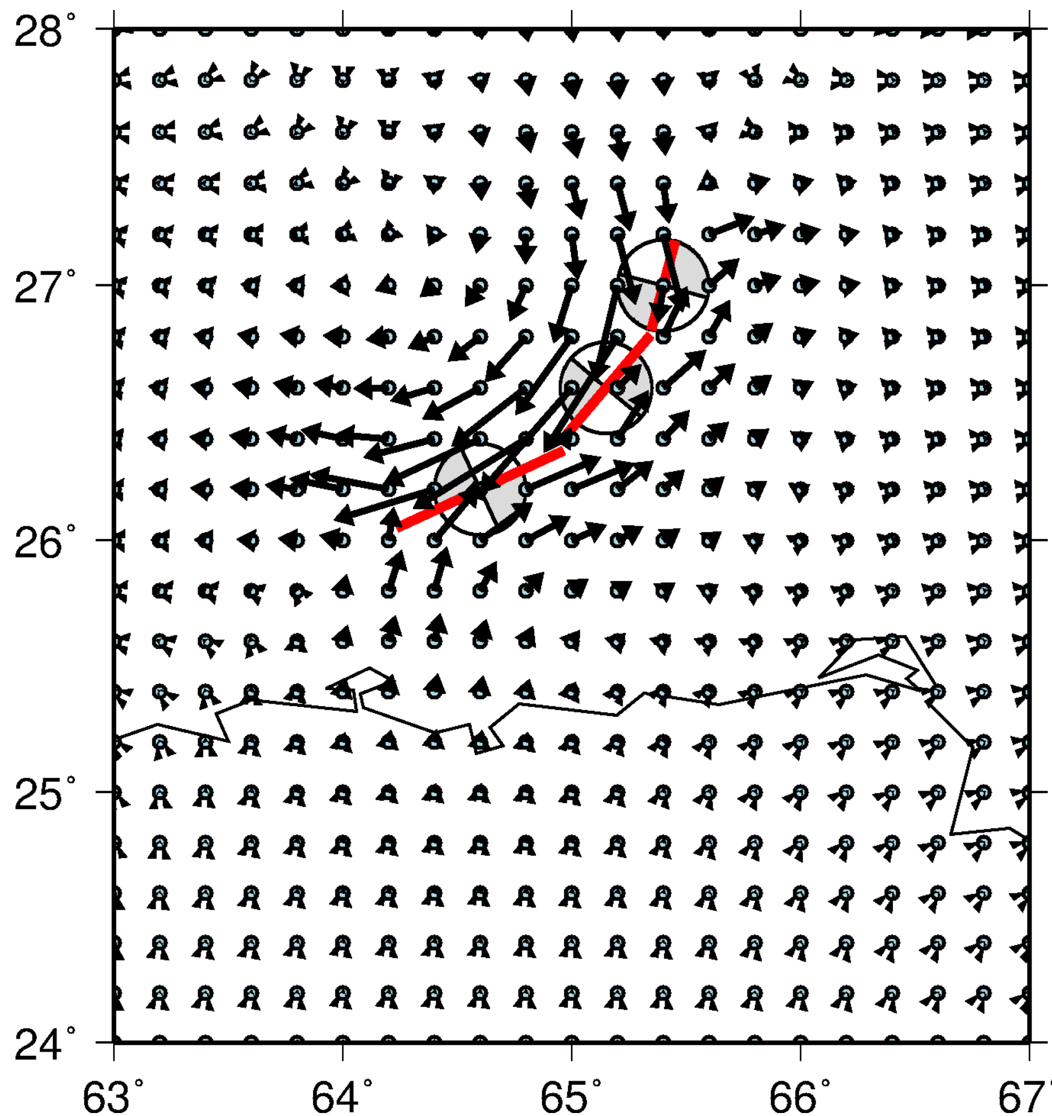
```
65.40 27.00 15 15 90 0 2.75 20 40
65.15 26.60 15 40 90 0 2.75 20 60
64.60 26.20 15 65 90 0 2.75 20 80
```



Deformation from each fault in input file is added together at each receiver. Maximum of 150,000 fault segments.

Activity 4: Multiple Faults

- *How does this displacement field differ from a single segment displacement field?*



Introduction to Displacement Modeling Completed