Resolving Stress Components and Earthquake Triggering

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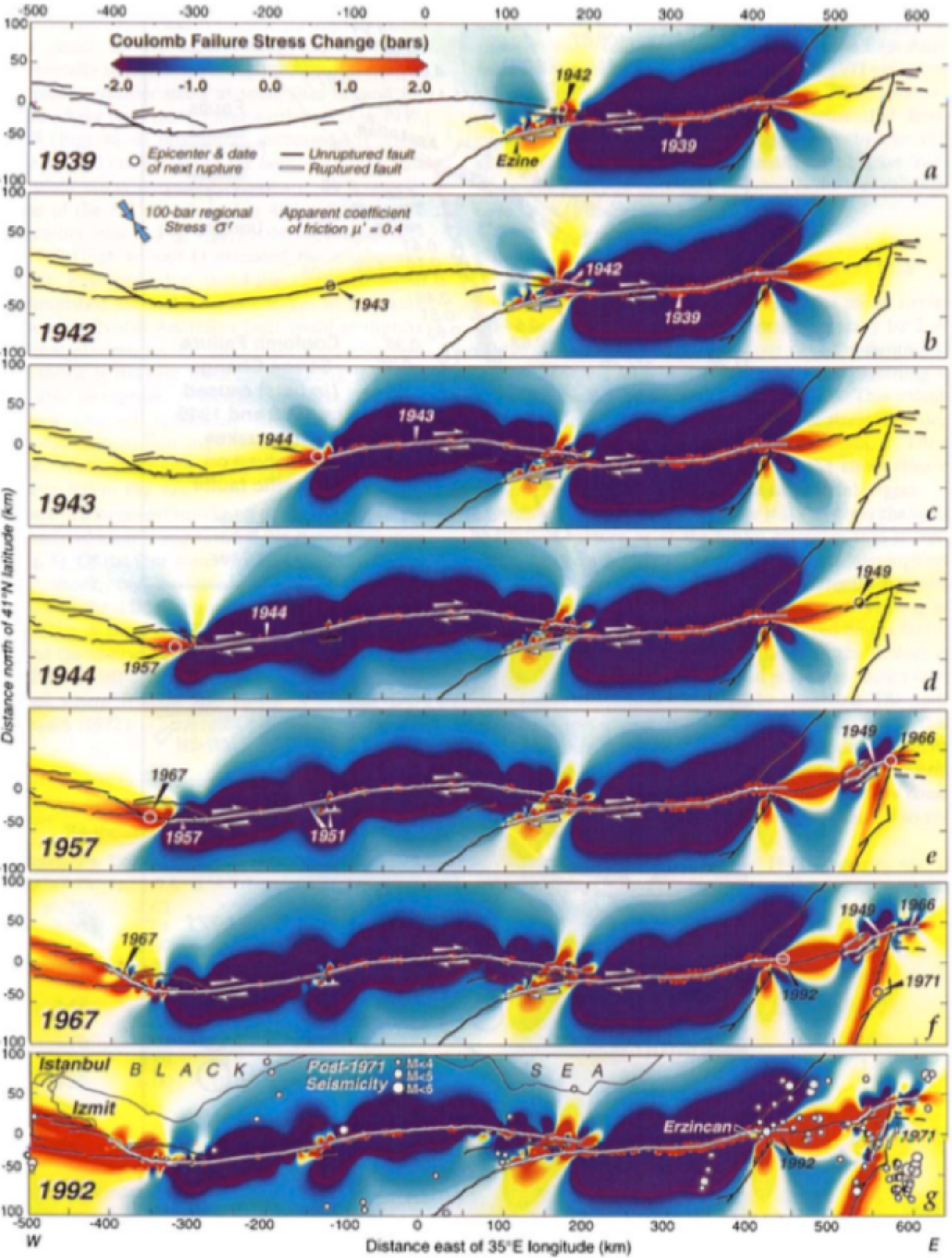
4 February 2020

Earthquake Triggering

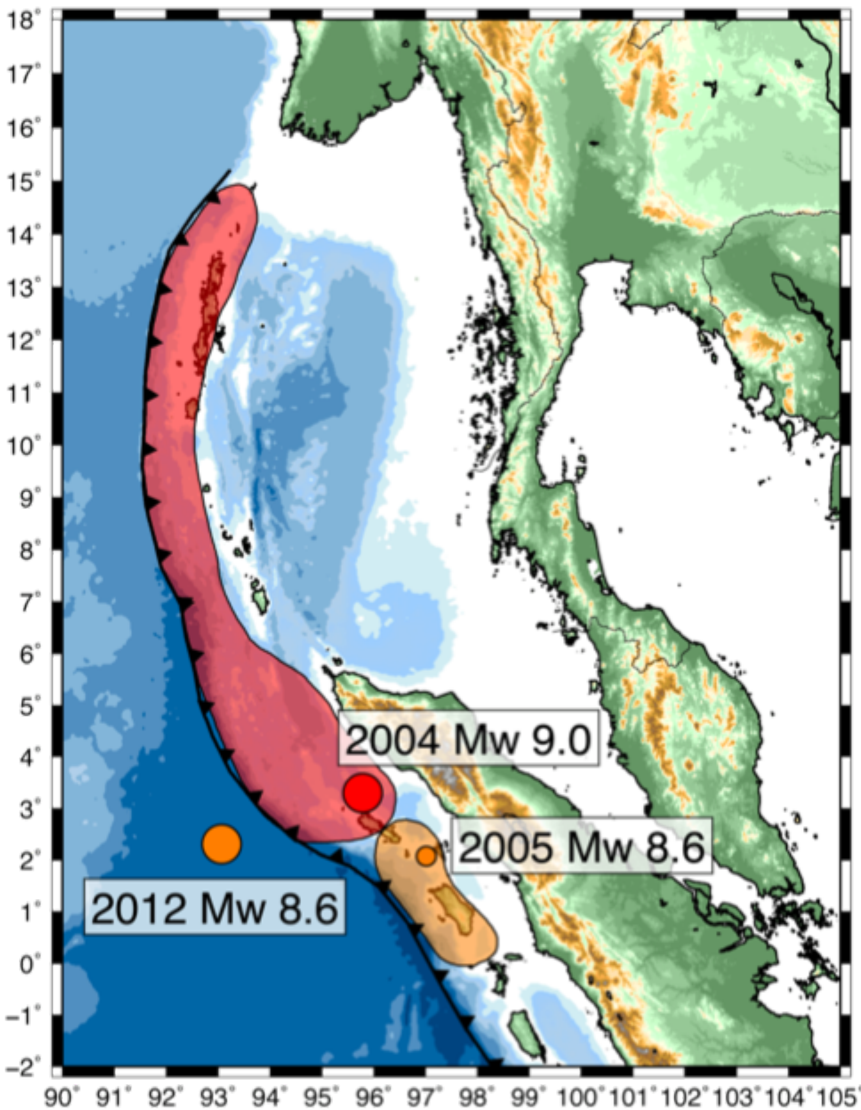
- Do certain events make an earthquake more likely to occur?
  - Earthquakes
  - Slow Slip
  - Wastewater Fluids
  - Dams

The focus of this presentation



- 20th century earthquakes on the N. Anatolian Fault in Turkey progressed systematically westward
- Stein et al. (1997): Each event triggered by the previous

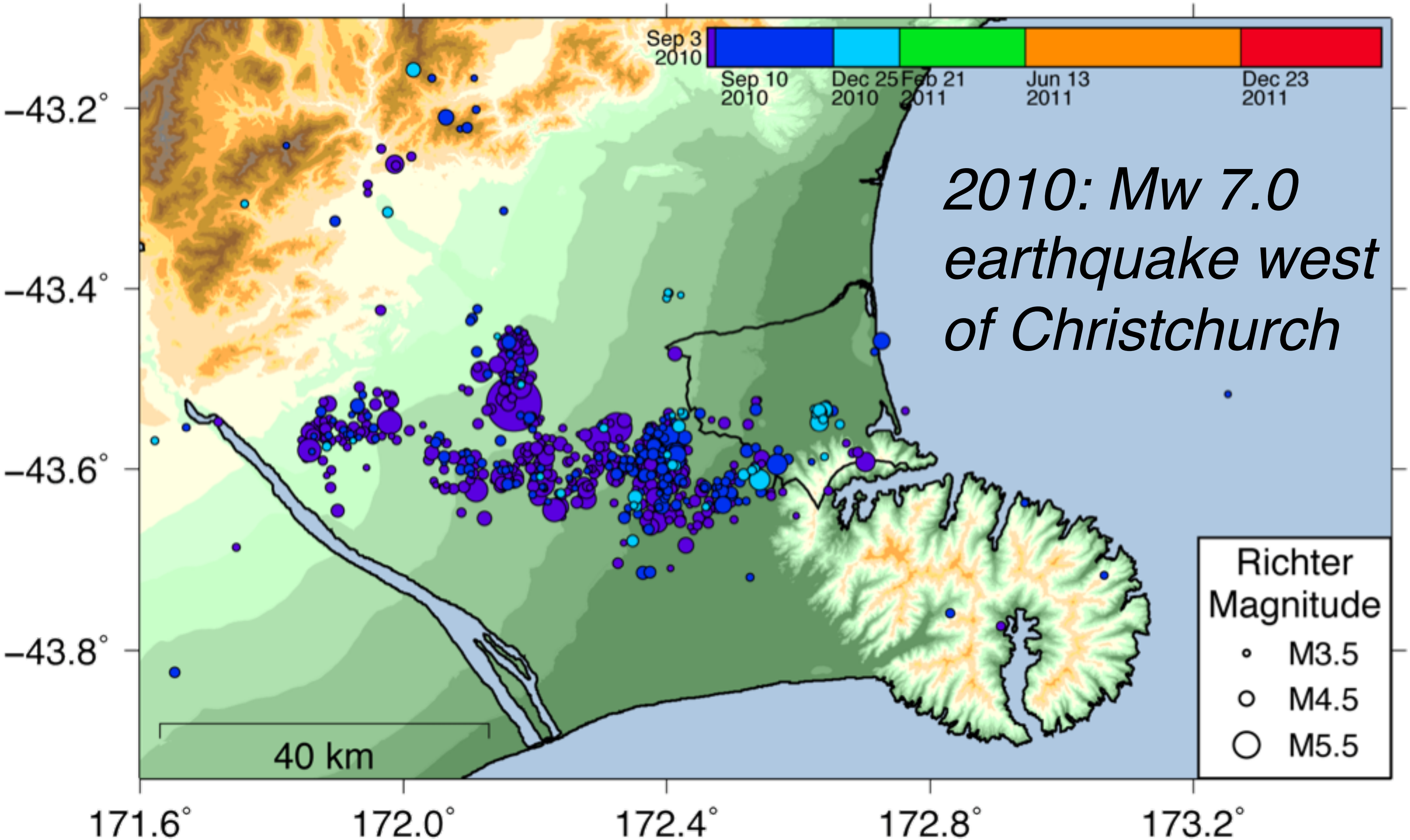
Earthquake Triggering



- 2004 Mw 9.0 Sumatra-Andaman earthquake
- 2005 Mw 8.6 earthquake to south
- 2012 Mw 8.6 strike-slip earthquake outboard of trench

Rupture areas: *USGS Seismicity of the Earth 1900-2012: Sumatra and Vicinity*

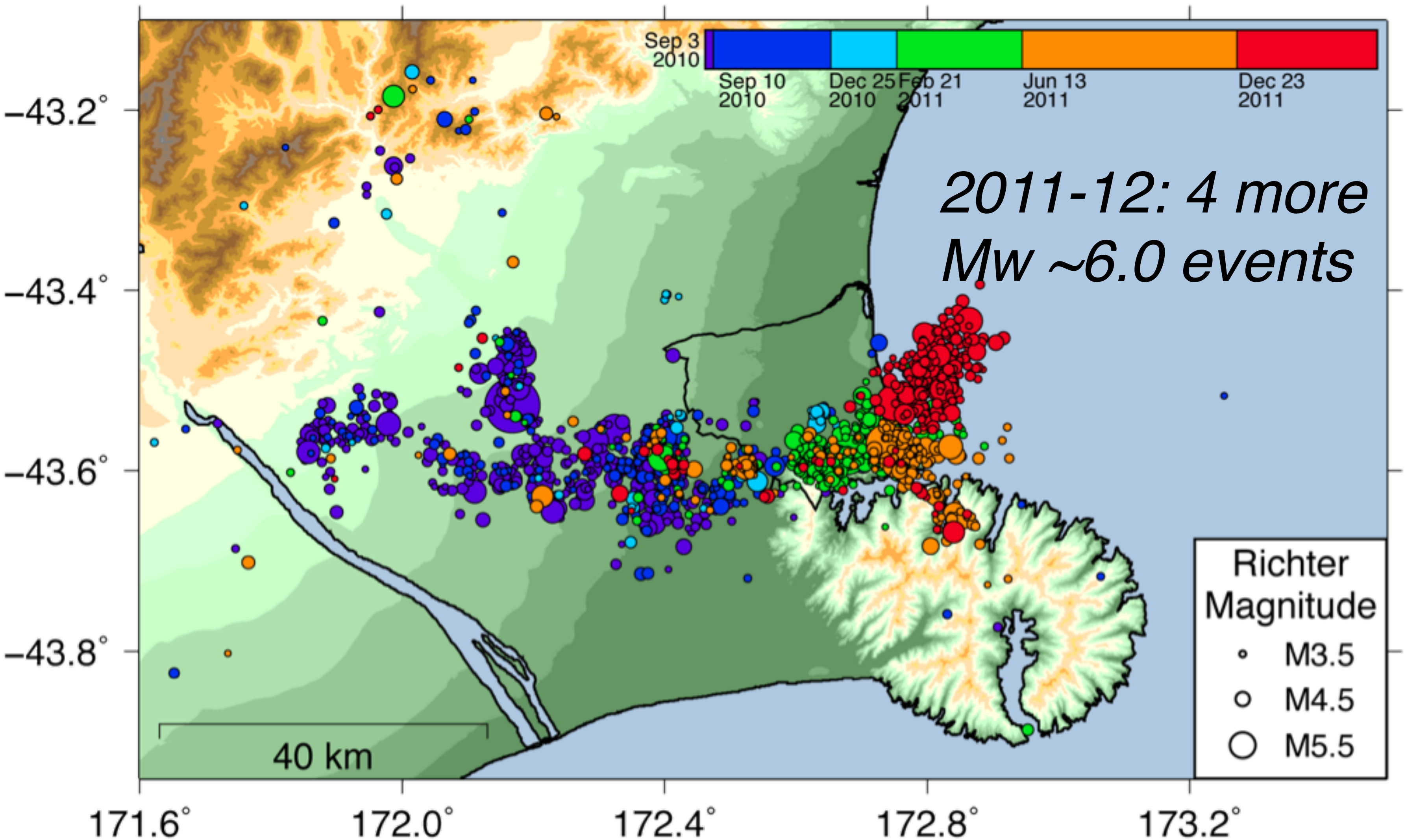
Earthquake Triggering



2010: Mw 7.0 earthquake west of Christchurch

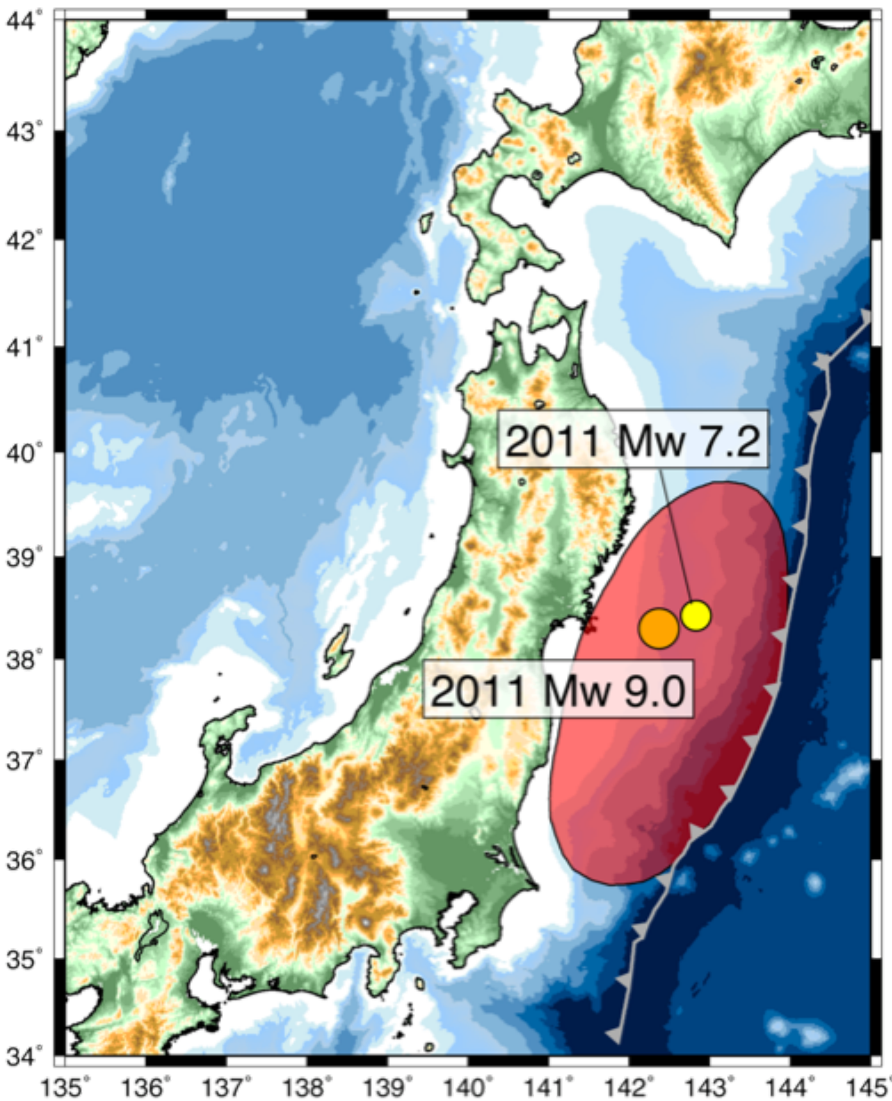
Herman et al. (2014)

Earthquake Triggering



Herman et al. (2014)

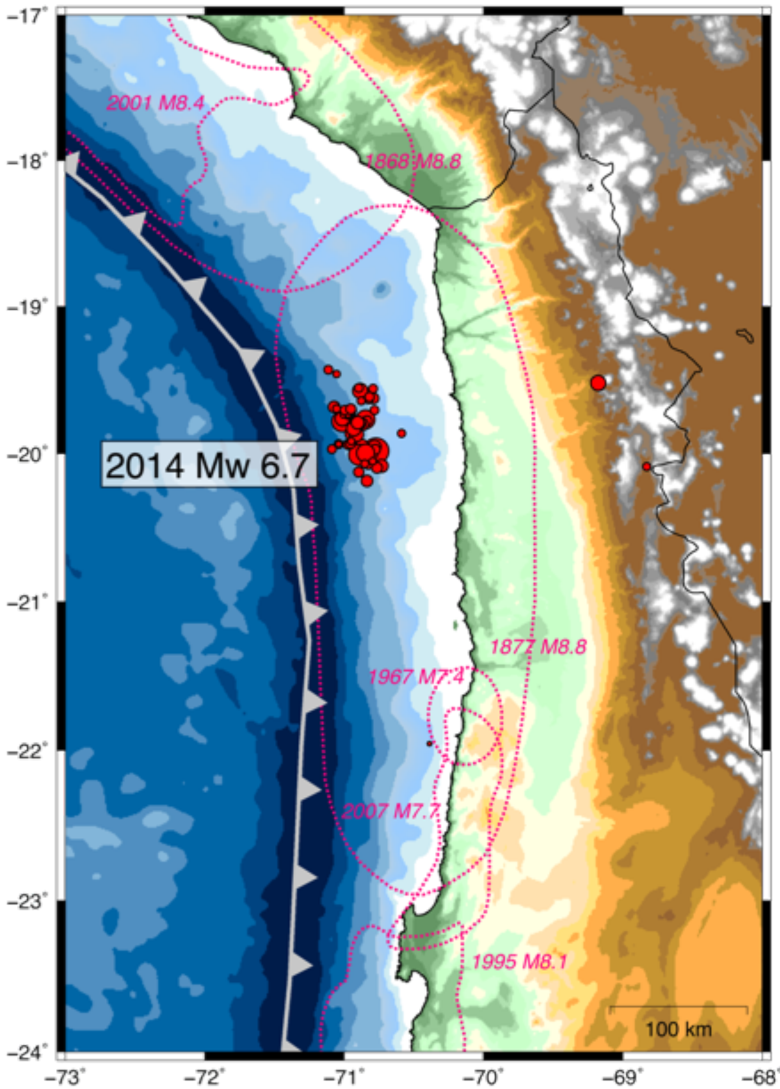
Earthquake Triggering



- 2011 Mw 7.2 earthquake offshore Honshu
- Two days later, great Mw 9.0 Tohoku-oki earthquake

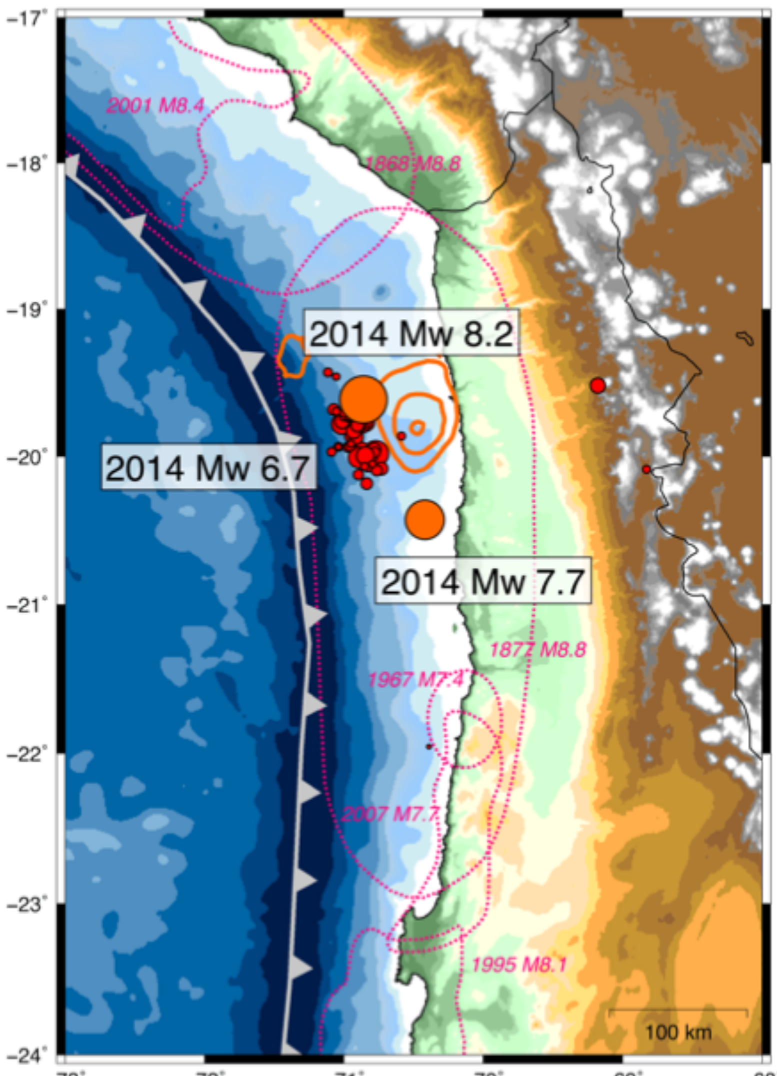
Rupture area: *Ozawa et al. (2011)*

Earthquake Triggering



- March 2014: offshore N. Chile earthquake sequence starts with Mw 6.7

Earthquake Triggering



- March 2014: offshore N. Chile earthquake sequence starts with Mw 6.7
- 1 April 2014: Mw 8.2 Iquique earthquake, followed on 3 April by Mw 7.7 aftershock

Resolving Stresses

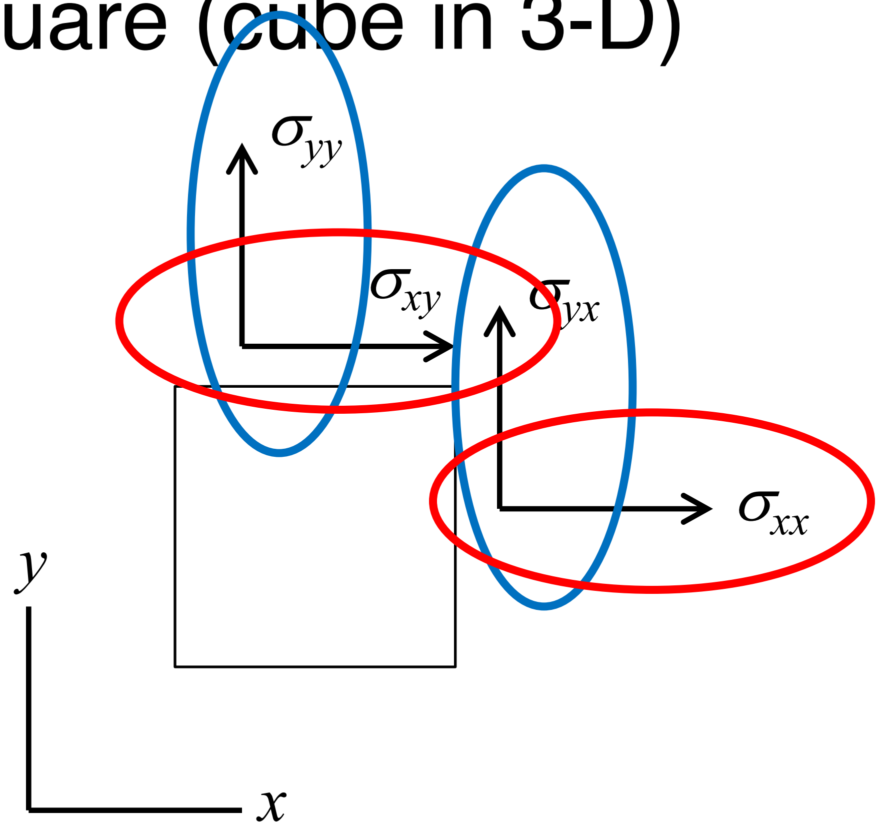
- Recall from earlier: stress tensor
- For simplicity, we will do the following derivations in 2-D, but all of this math can be extended to 3-D (and is in O92UTIL)

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \Rightarrow \sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}$$

Resolving Stresses

- Stress tensor represents tractions on an infinitesimal square (cube in 3-D)

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}$$



X-tractions

Y-tractions

Resolving Stresses

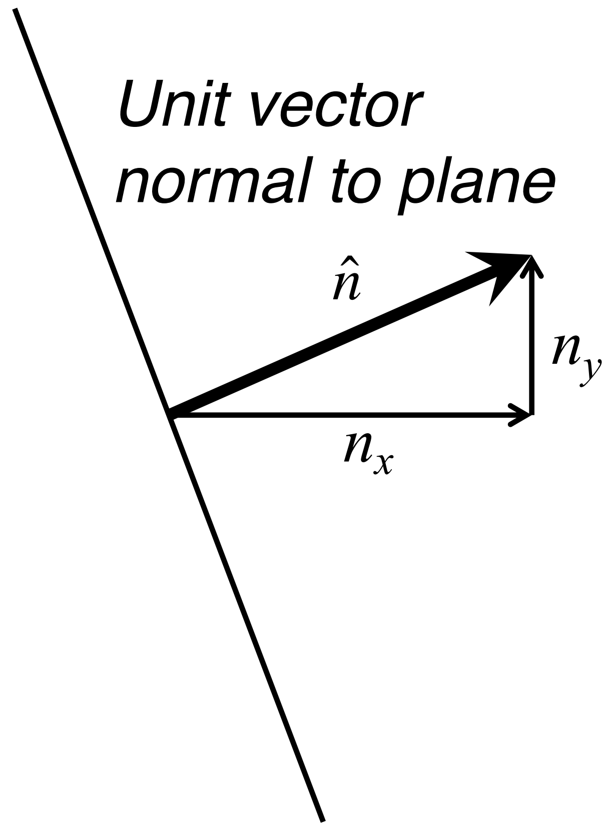
- What about the tractions on an arbitrarily oriented plane?

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}$$

$$t_x = \sigma_{xx} n_x + \sigma_{xy} n_y$$

$$t_y = \sigma_{yx} n_x + \sigma_{yy} n_y$$

Matrix equation!



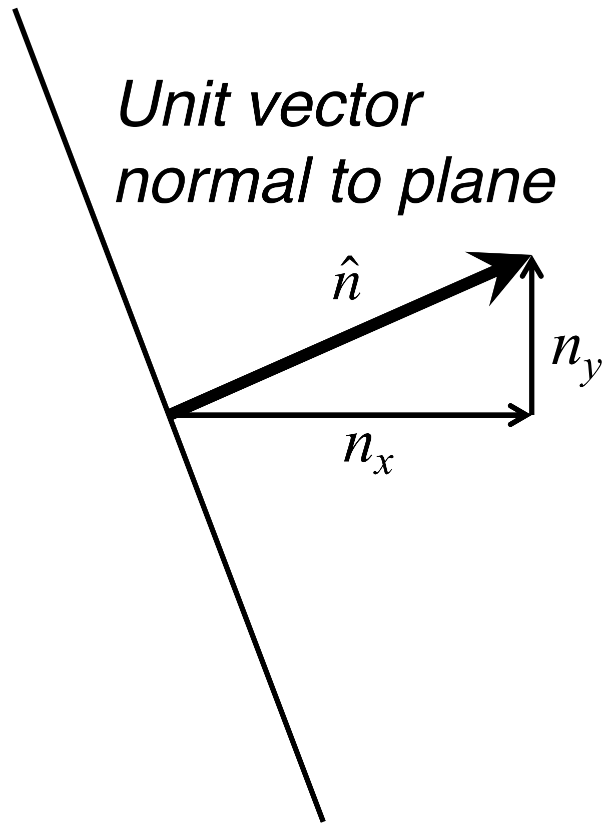
Resolving Stresses

- What about the tractions on an arbitrarily oriented plane?

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}$$

$$\begin{bmatrix} t_x \\ t_y \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix} \begin{bmatrix} n_x \\ n_y \end{bmatrix}$$

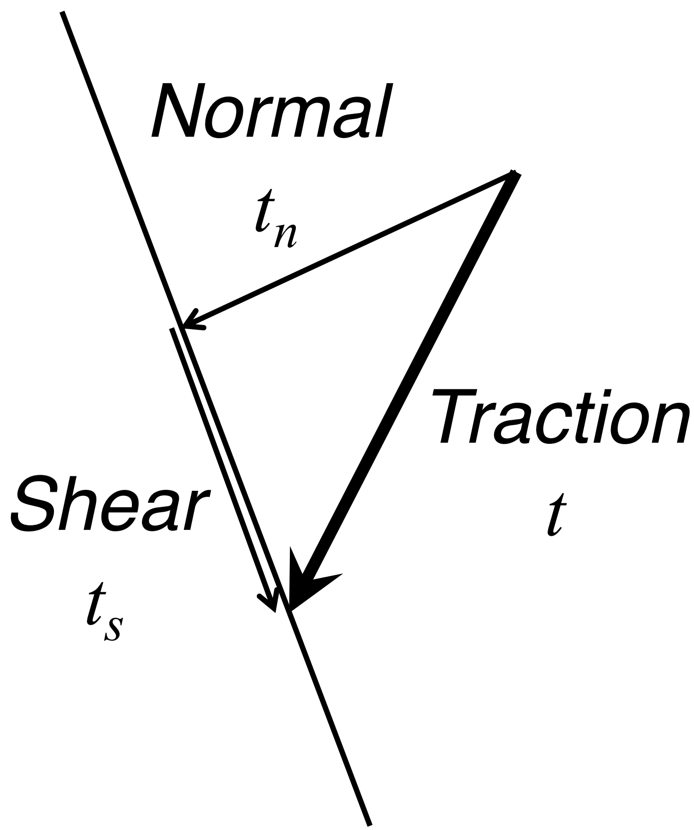
$$\vec{t} = \sigma \hat{n}$$



Resolving Stresses

- Earthquakes occur when the *shear stress* on the fault surface is greater than the frictional resistance (friction coefficient times *normal stress*)
- The traction vector can be divided into shear and normal components

Resolving Stresses



$$\vec{t} = \sigma \hat{n}$$

For the normal component of traction, compute the dot product with the unit normal:

$$t_n = \vec{t} \cdot \hat{n}$$

The shear component is the difference between the traction vector and the normal component:

$$\vec{t}_s = \vec{t} - t_n \hat{n}$$

Resolving Stresses

- O92UTIL computes these quantities from the stresses generated by a slipping fault and can output either shear or normal stress components, or both
- *Requires target (or “receiver”) fault geometry!*

Resolving Stresses

τ σ_n

- Shear and normal stress commonly combined into *Coulomb stress change* (ΔCS)

$$\Delta CS = \tau - \mu\sigma_n$$

- If ΔCS is positive, fault is brought closer to failure
- If ΔCS is negative, fault is inhibited from failure

Modeling Overview

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

<u>OUTPUTS</u>
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*

Now we need target fault geometries to resolve stresses on.

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 properti[es]

Target faults*

OUTPUTS

We will focus on Coulomb stress, but recall it is derived from normal and shear stresses.

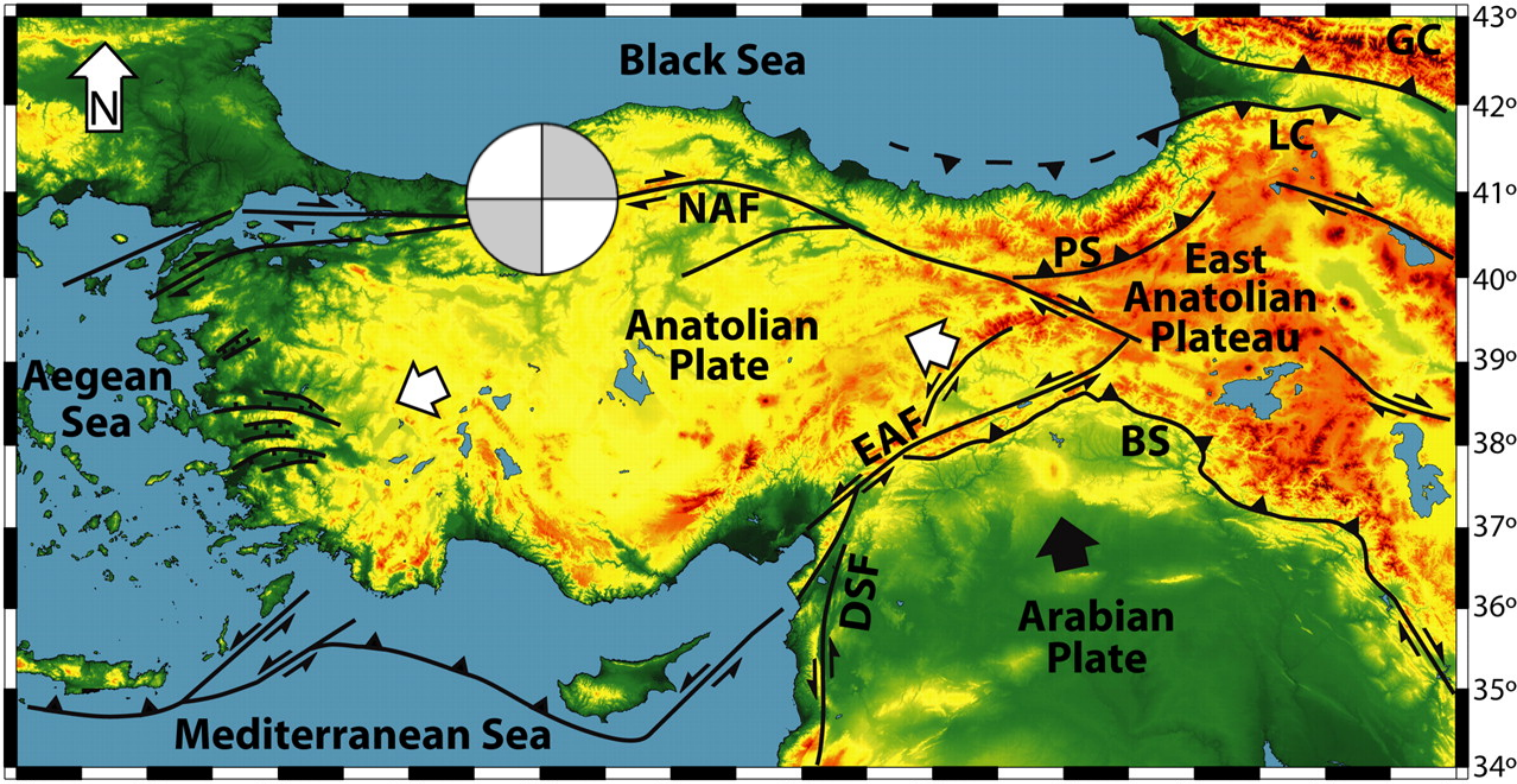
Normal stress*

Shear stress*

Coulomb stress*

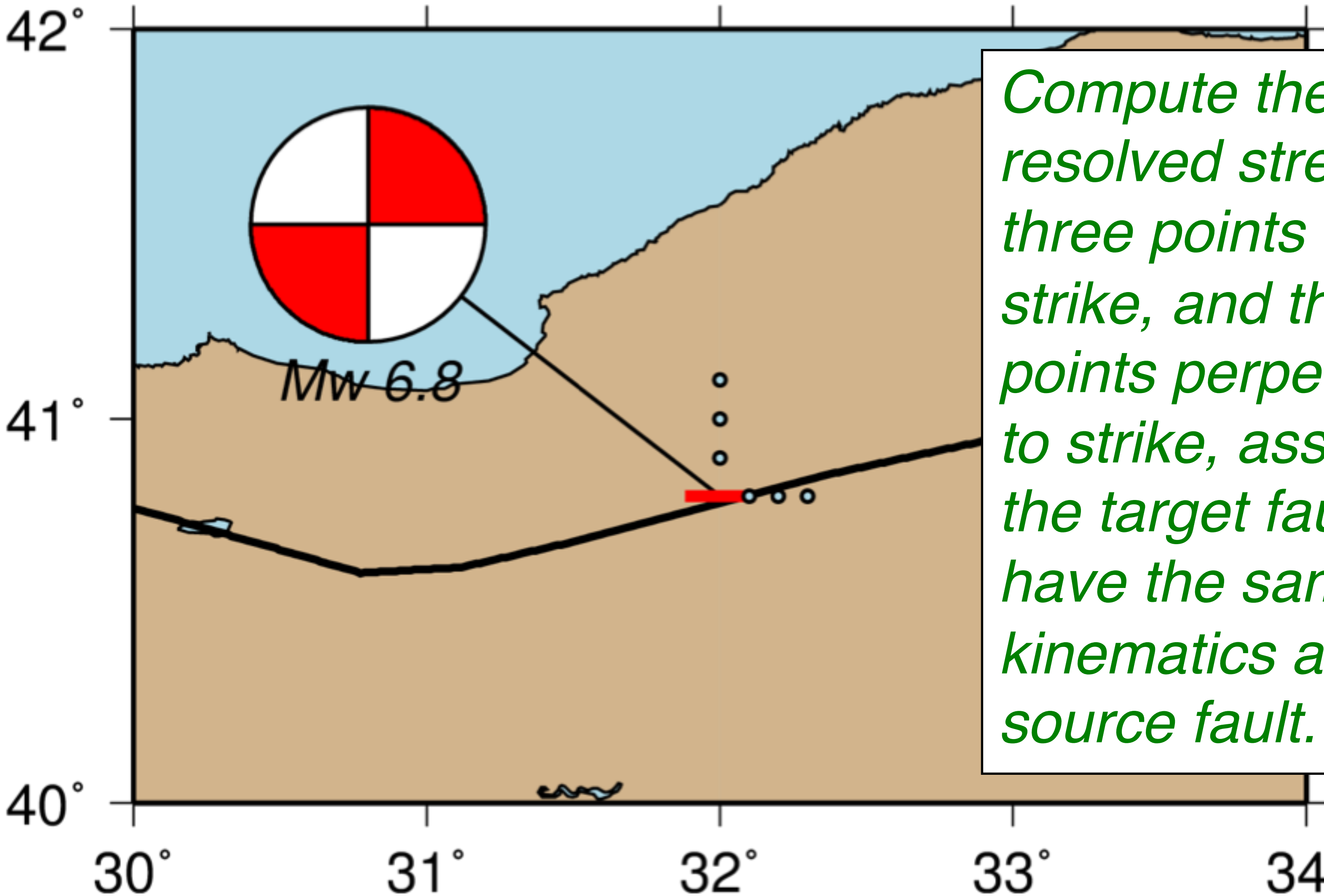
**To resolve stresses on planes in the subsurface, must define target fault orientations*

Activity 1: Strike-Slip Event



Hypothetical Mw 6.8 on the North Anatolian Fault, Turkey

Activity 1: Strike-Slip Event



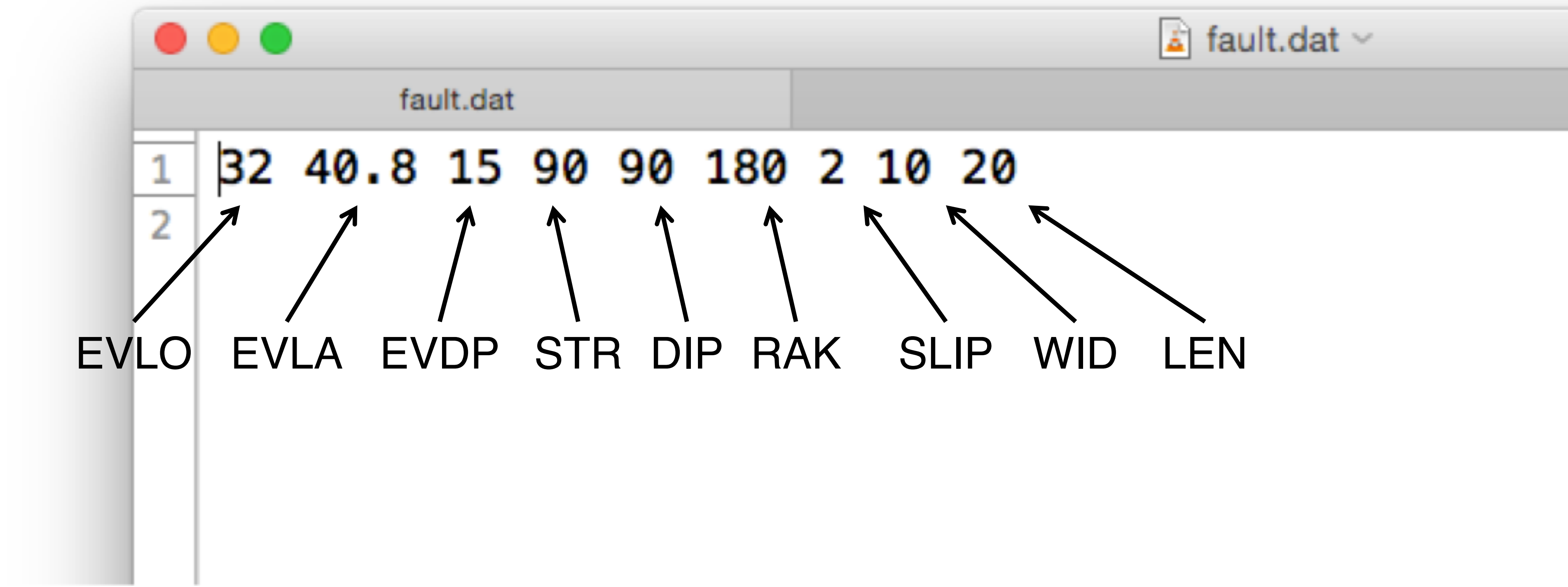
Compute the resolved stresses at three points along strike, and three points perpendicular to strike, assuming the target faults have the same kinematics as the source fault.

Activity 1: Strike-Slip Event

- Input files
  - Fault file (fault.dat)

Activity 1: Strike-Slip Event

- fault.dat

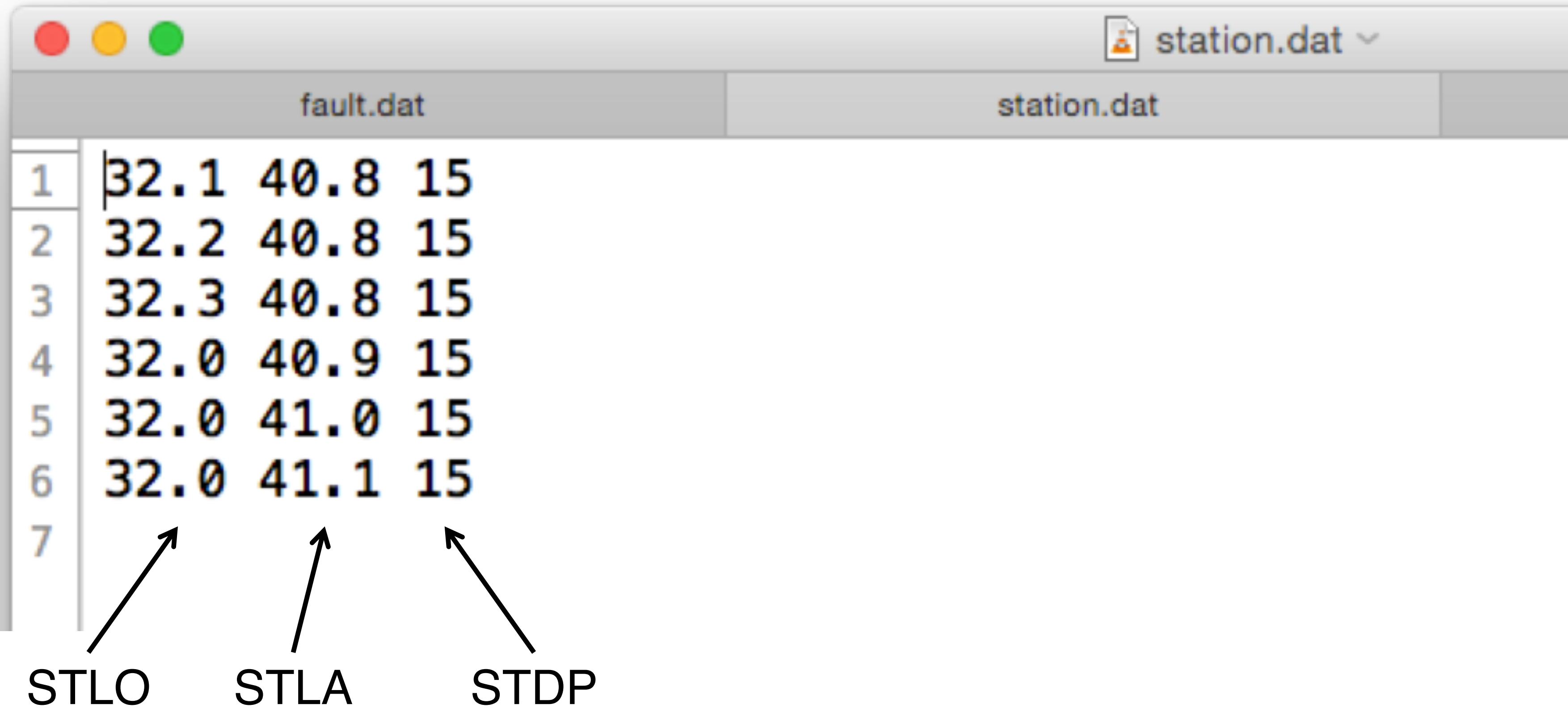


Activity 1: Strike-Slip Event

- Input files
  - Fault file (fault.dat)
  - Receiver locations (station.dat)

Activity 1: Strike-Slip Event

- station.dat



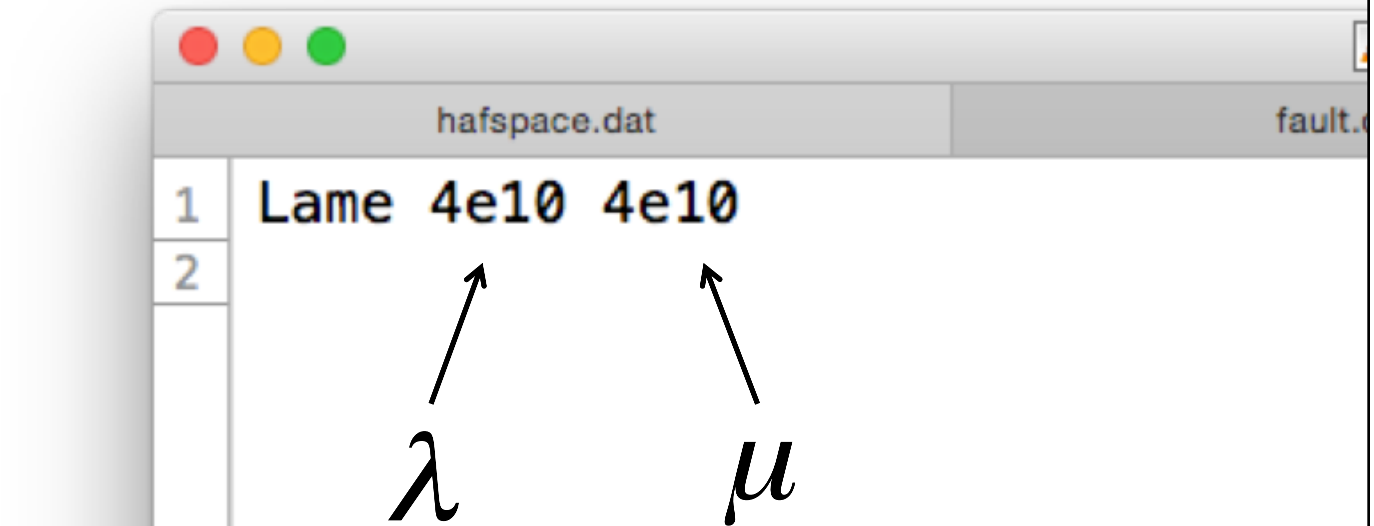
Activity 1: Strike-Slip Event

- Input files
  - Fault file (fault.dat)
  - Receiver locations (station.dat)
  - Half-space properties (hafspace.dat)

Activity 1: Strike-Slip Event

- hafspace.dat

New file format!



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

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

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

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

The half-space elastic properties file can be either:

`vp vs dens`

(as in previous activities), or:

`Lame lamda mu`

where `lamda` and `mu` are the Lame parameters.

Activity 1: Strike-Slip Event

This input format is similarly deprecated. It also 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:
lame 40e9 shear 40e9

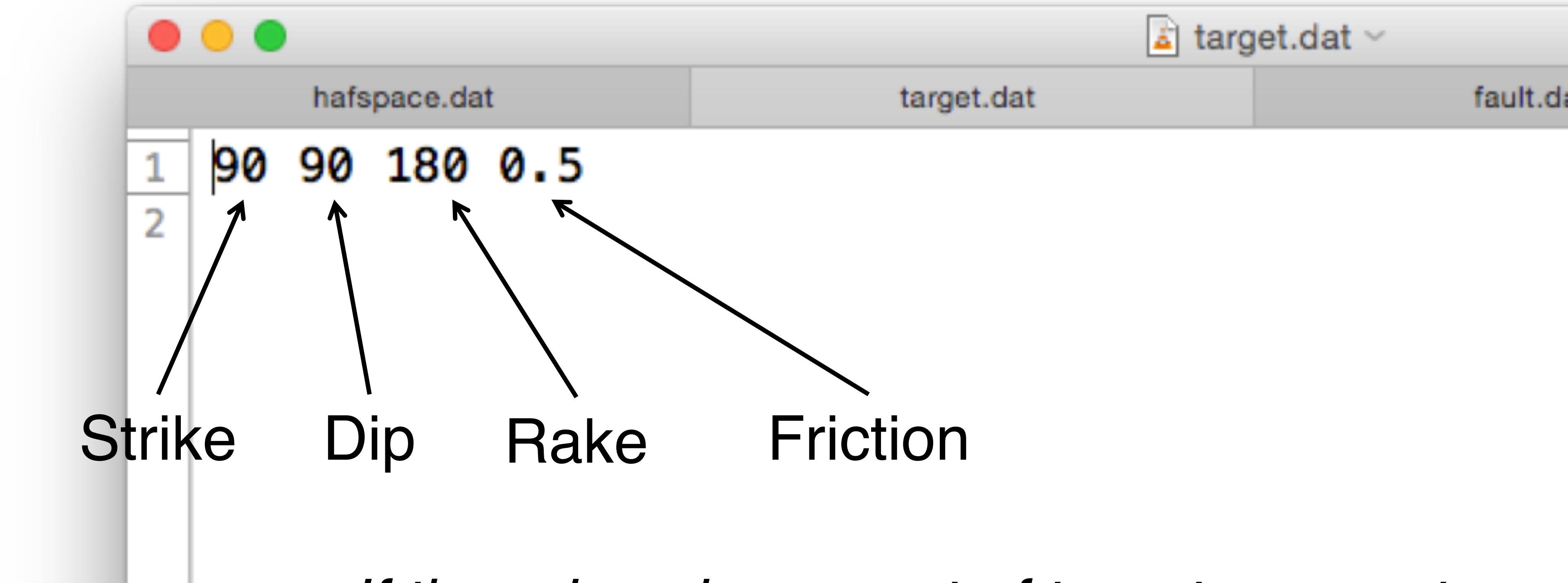
where `lamda` and `mu` are the Lame parameters.

Activity 1: Strike-Slip Event

- Input files
  - Fault file (fault.dat)
  - Receiver locations (station.dat)
  - Half-space properties (hafspace.dat)
  - *NEW!* Target fault parameters (target.dat)

Activity 1: Strike-Slip Event

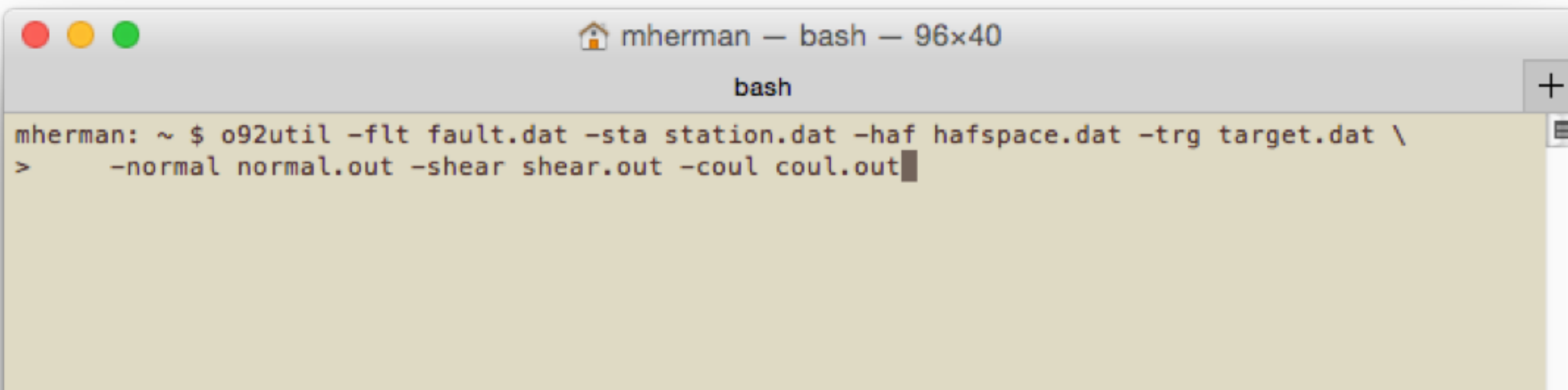
- target.dat



If there is only one set of target parameters, then these values are used for every receiver location in station.dat

Activity 1: Strike-Slip Event

- Output files
  - Normal stress (normal.out)
  - Shear stress (shear.out)
  - Coulomb stress (coul.out)



Activity 1: Strike-Slip Event

- Output files
  - Normal stress (normal.out)
  - Shear stress (shear.out)
  - Coulomb stress (coul.out)

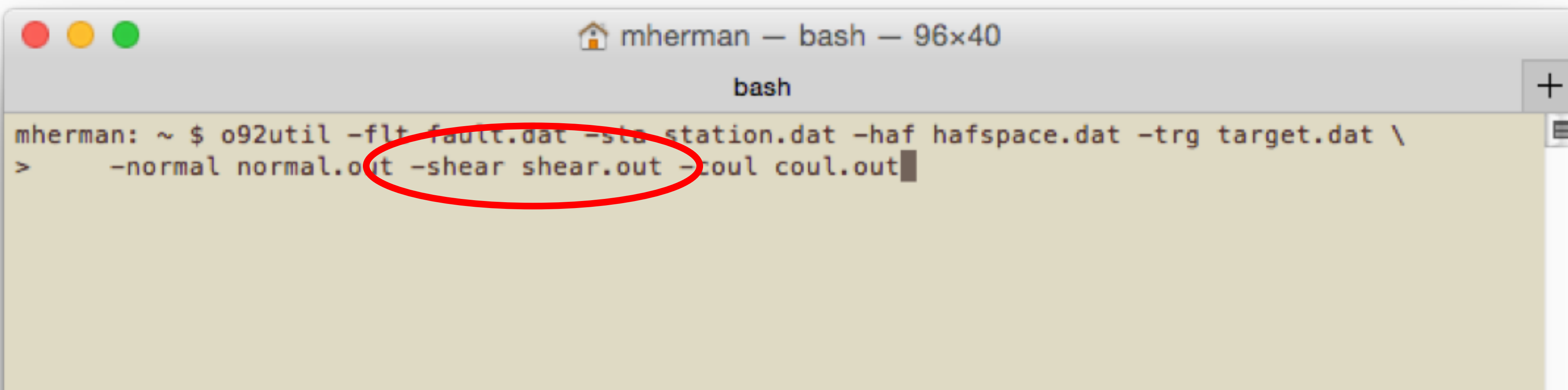
mherman — bash — 96×40

bash

```
mherman: ~ $ o92util -flt fault.dat -sta station.dat -haf hafspace.dat -trg target.dat \
>    -normal normal.out -shear shear.out -coul coul.out
```

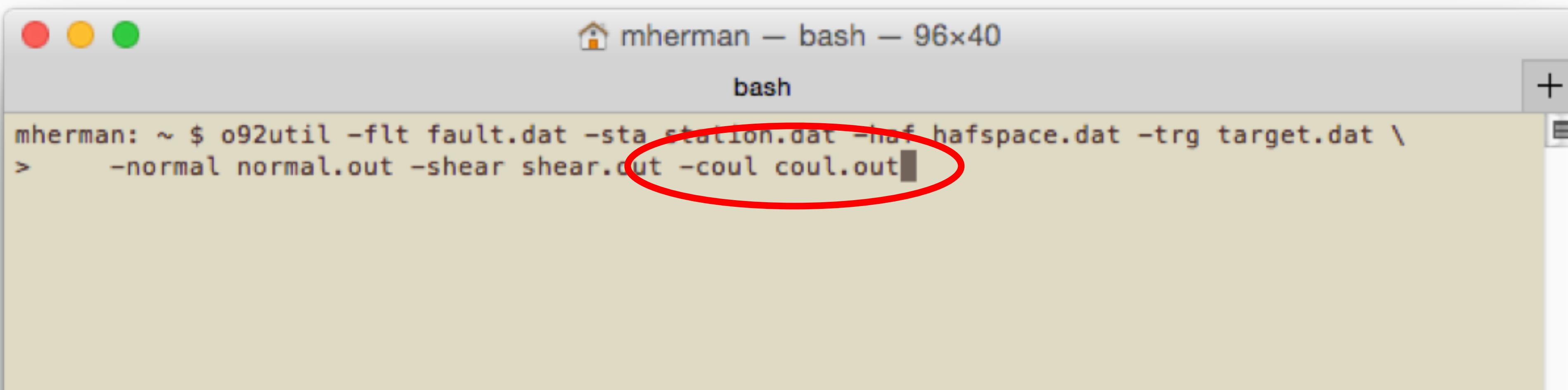
Activity 1: Strike-Slip Event

- Output files
  - Normal stress (normal.out)
  - Shear stress (shear.out)
  - Coulomb stress (coul.out)



Activity 1: Strike-Slip Event

- Output files
  - Normal stress (normal.out)
  - Shear stress (shear.out)
  - Coulomb stress (coul.out)



Activity 1: Strike-Slip Event

- normal.out

normal.out

normal.out | shear.out | coul.out

1	32.1000	40.8000	15.0000	0.309422E+05
2	32.2000	40.8000	15.0000	0.399728E+04
3	32.3000	40.8000	15.0000	0.865425E+03
4	32.0000	40.9000	15.0000	0.505608E-10
5	32.0000	41.0000	15.0000	0.676025E-10
6	32.0000	41.1000	15.0000	-0.103824E-09
7				

STLO | STLA | STDP | Normal Stress (Pa)

Negative normal stress implies compression, positive is dilation.

Activity 1: Strike-Slip Event

- shear.out

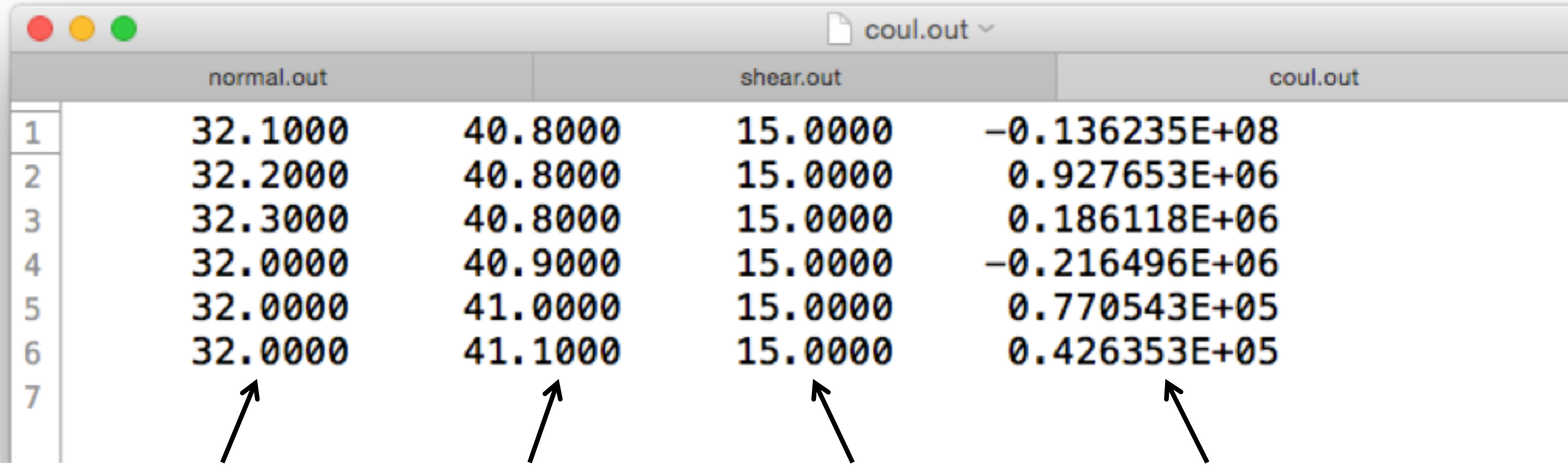
STLO	STLA	STDP	Shear Stress (Pa)
32.1000	40.8000	15.0000	-0.136390E+08
32.2000	40.8000	15.0000	0.925655E+06
32.3000	40.8000	15.0000	0.185685E+06
32.0000	40.9000	15.0000	-0.216496E+06
32.0000	41.0000	15.0000	0.770543E+05
32.0000	41.1000	15.0000	0.426353E+05

Shear stress is reported as projected onto the slip vector.

The maximum shear stress is printed in the 5th column (not shown)

Activity 1: Strike-Slip Event

- coul.out



1	32.1000	40.8000	15.0000	-0.136235E+08
2	32.2000	40.8000	15.0000	0.927653E+06
3	32.3000	40.8000	15.0000	0.186118E+06
4	32.0000	40.9000	15.0000	-0.216496E+06
5	32.0000	41.0000	15.0000	0.770543E+05
6	32.0000	41.1000	15.0000	0.426353E+05
7				

STLO STLA STDP Coulomb Stress (Pa)

Positive ΔCS: target fault brought closer to failure by the source

Activity 1b: Plotting Stress

- Sometimes it can be insightful to resolve stress at a point (e.g., to determine the stress change on a known fault)
- Other times, it is more useful to plot the stress distribution, as we did this morning
- Start by assuming all target faults have the same kinematics and are at same depth as the source

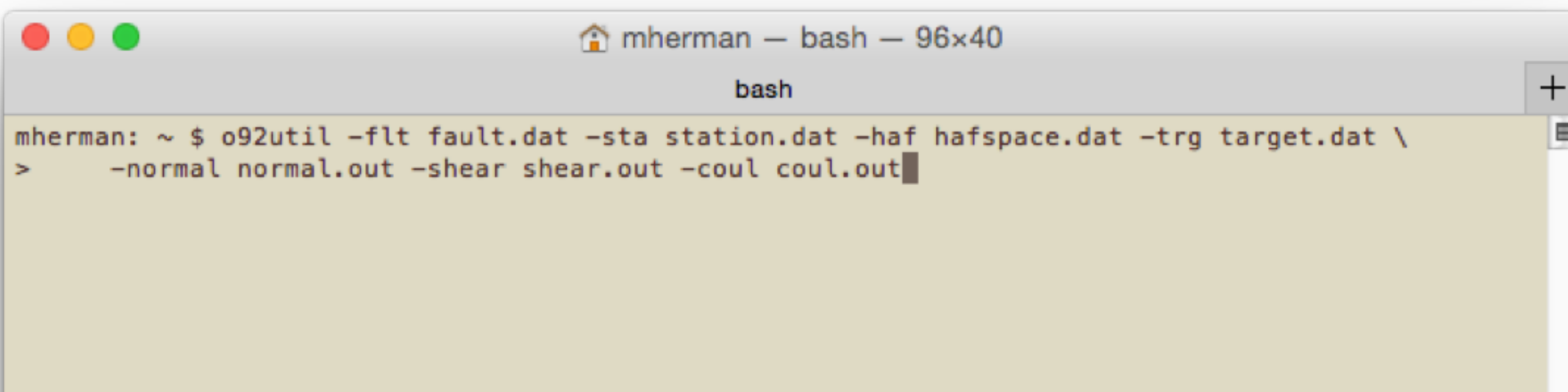
Activity 1b: Plotting Stress

- Use GRID to create dense set of receivers in station.dat
- Try an increment of 0.02

```
mherman — bash — 96×40
bash
mherman: ~ $ grid -x 31 33 -dx 0.02 -y 40 42 -dy 0.02 -z 15 -o station.dat
```

Activity 1b: Plotting Stress

- Run O92UTIL again with same output files
  - Normal stress (normal.out)
  - Shear stress (shear.out)
  - Coulomb stress (coul.out)



Activity 1b: Plotting Stress

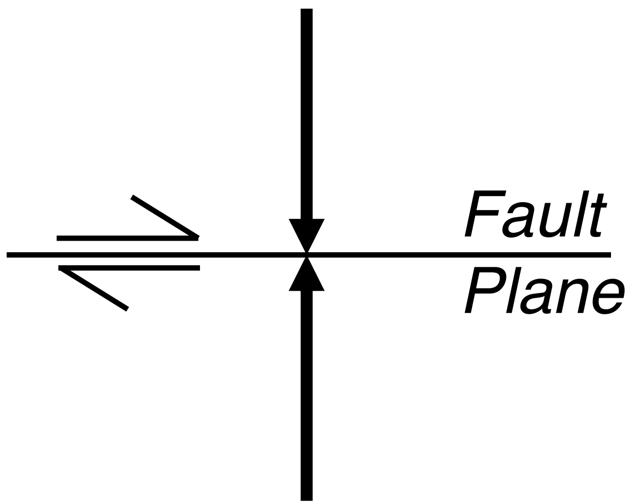
Plot results (basic plotting script provided) plot_stress.sh

plot_stress.sh

```
#!/bin/sh

#####
#       BOURNE SHELL SCRIPT FOR PLOTTING RESOLVED STRESS COMPONENTS
#####

#####
#       INPUT/OUTPUT FILES FROM O92UTIL
#####
# Input source fault file
FLT_FILE="fault.dat" # EVLO EVLA EVDP STR DIP RAK SLIP WID LEN
# Output normal/shear/Coulomb stress file
STS_FILE="normal.out" # STLO STLA STDP STRS

#####
#       GMT PLOTTING VARIABLES
#####
# Map projection (use 'man psbasemap' to see options)
PROJ="-JM4i -P"
# Map limits (-RXMIN/XMAX/YMIN/YMAX)
LIMS="-R31/33/40/42"
# Output PostScript file name
PSFILE="stress.ps"

#####
#       GMT PLOTTING COMMANDS
#####
# Generate color palette for plotting Coulomb stresses
makecpt -Cno_green -T-1e5/1e5/1e4 -D > stress.cpt

# Convert stress output to NetCDF grid file
# -Ixincr/yincr specifies the grid increments, and should be the same
# as the increment used in the grid command
awk '{print $1,$2,sqrt($4)}' $STS_FILE |\
    xyz2grd -Gstress.grd $LIMS -I0.2/0.2
# Plot stress grid, using color palette generated above
grdimage stress.grd $PROJ $LIMS -Cstress.cpt -K > $PSFILE

# Draw coastline (-W) and national boundaries (-N1)
pscoast $PROJ $LIMS -Dh -W0.75p -N1/0.5p -K -O >> $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,darkgreen -K -O >> $PSFILE

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

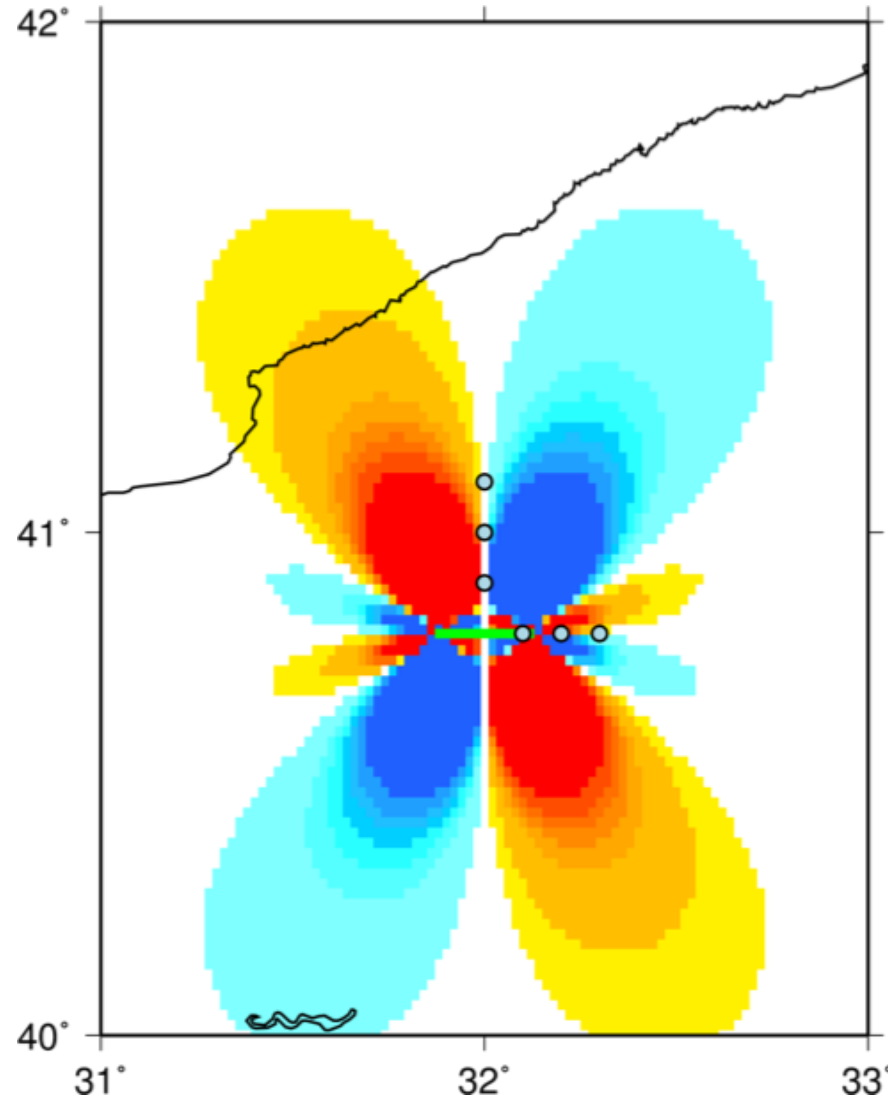
Activity 1b: Plotting Stress

- Normal stress



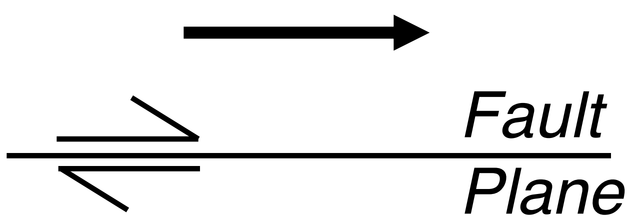
$$t_n = \sigma_n$$

Common notation for normal stress is the Greek letter, sigma.



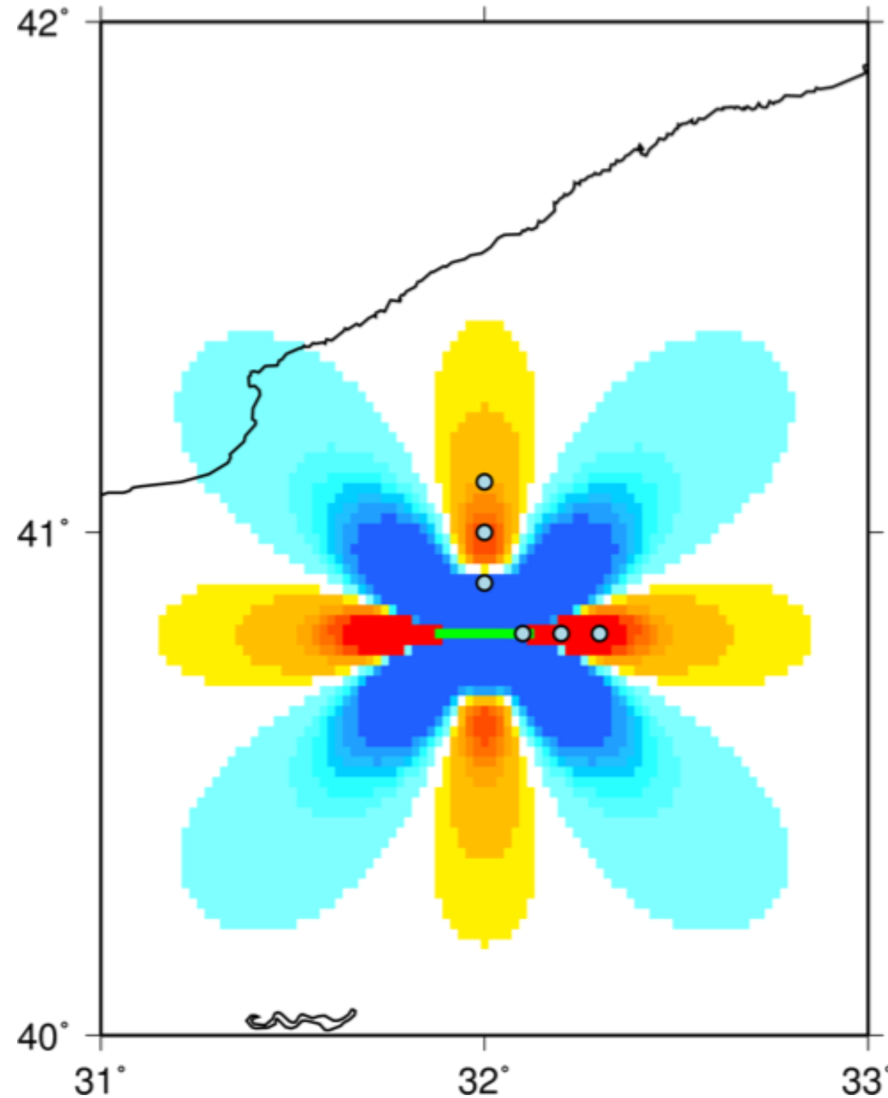
Activity 1b: Plotting Stress

- Shear stress



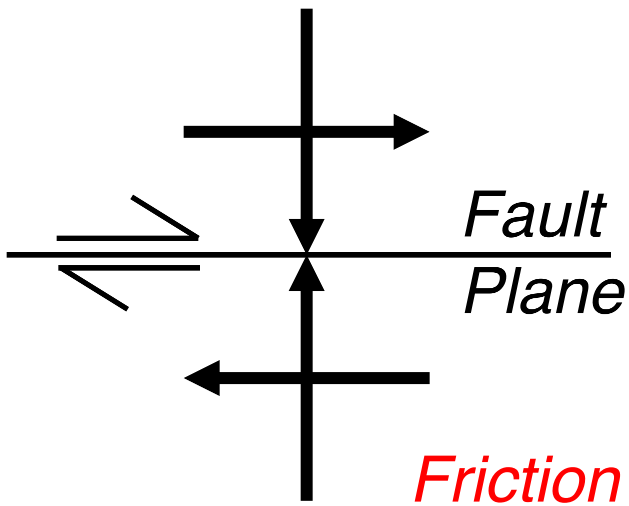
$$t_s = \tau$$

Common notation for shear stress is the Greek letter, tau.



Activity 1b: Plotting Stress

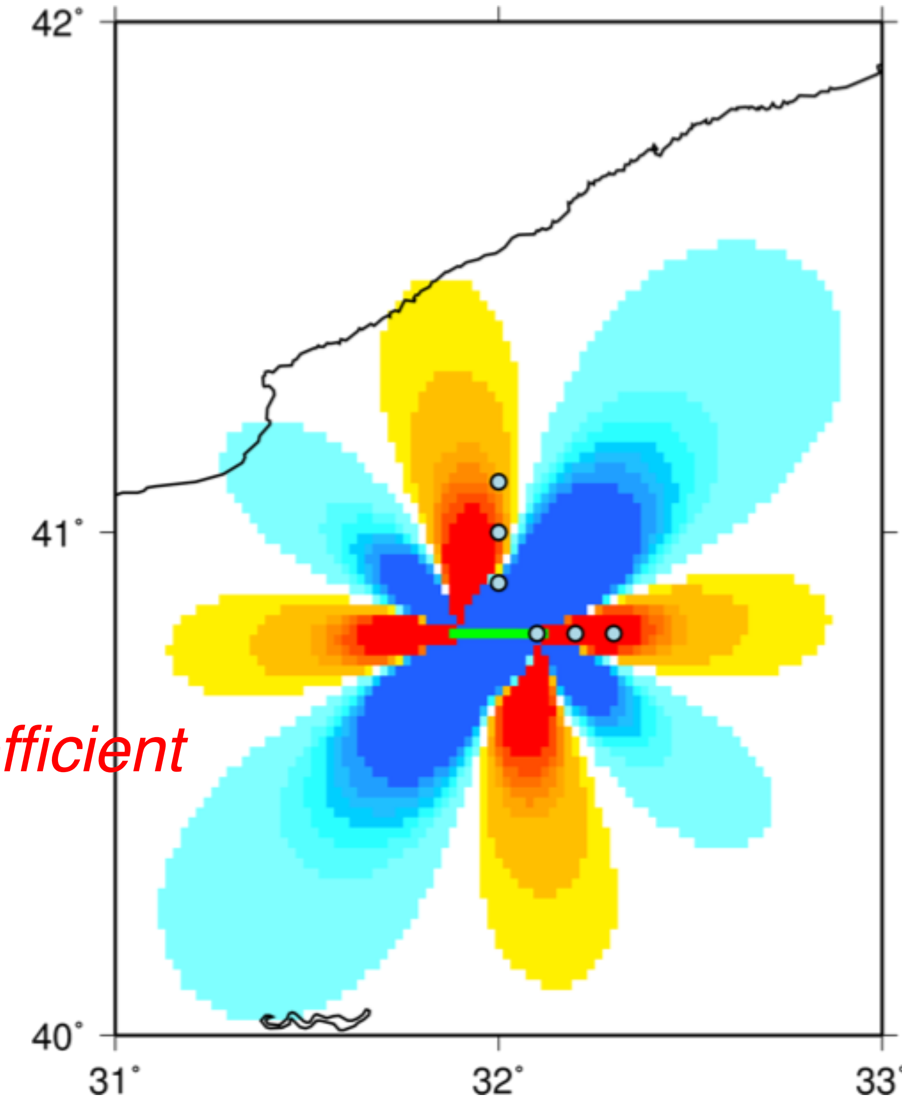
- Coulomb stress



Friction coefficient

$$\Delta CS = t_s - \mu t_n$$

$$\Delta CS = \tau - \mu \sigma_n$$



Activity 2: Thrust EQ Stress

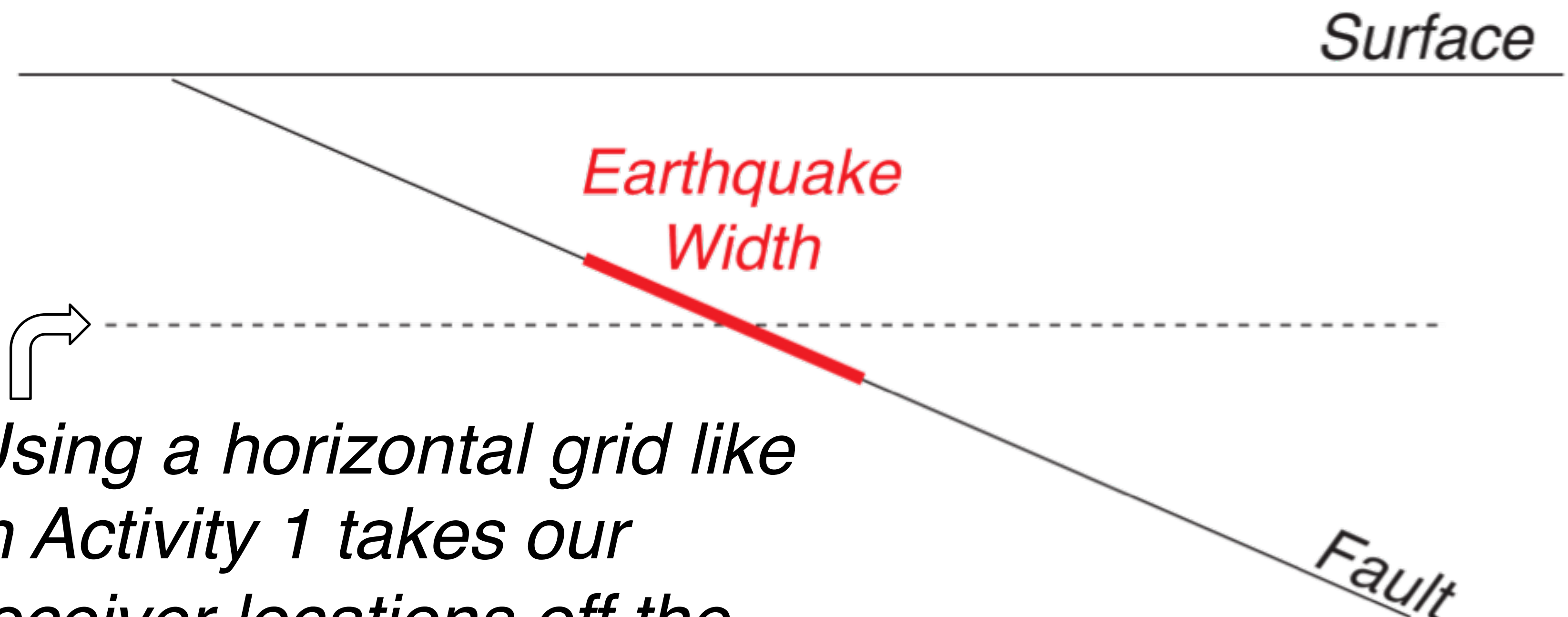
- Most difficult aspect of ΔCS analysis is target fault location and geometry
- This aspect is often ambiguous and occasionally incorrect in literature
- Let us use a thrust faulting earthquake to demonstrate the concept

Activity 2: Thrust EQ Stress

- Thrust faulting earthquakes occur on dipping surfaces (e.g. 2015 Mw 7.8 Nepal, 2014 Mw 8.2 Chile, 2010 Mw 9.0 Tohoku)
- We might think about how stress has changed on the fault around the earthquake

Activity 2: Thrust EQ Stress

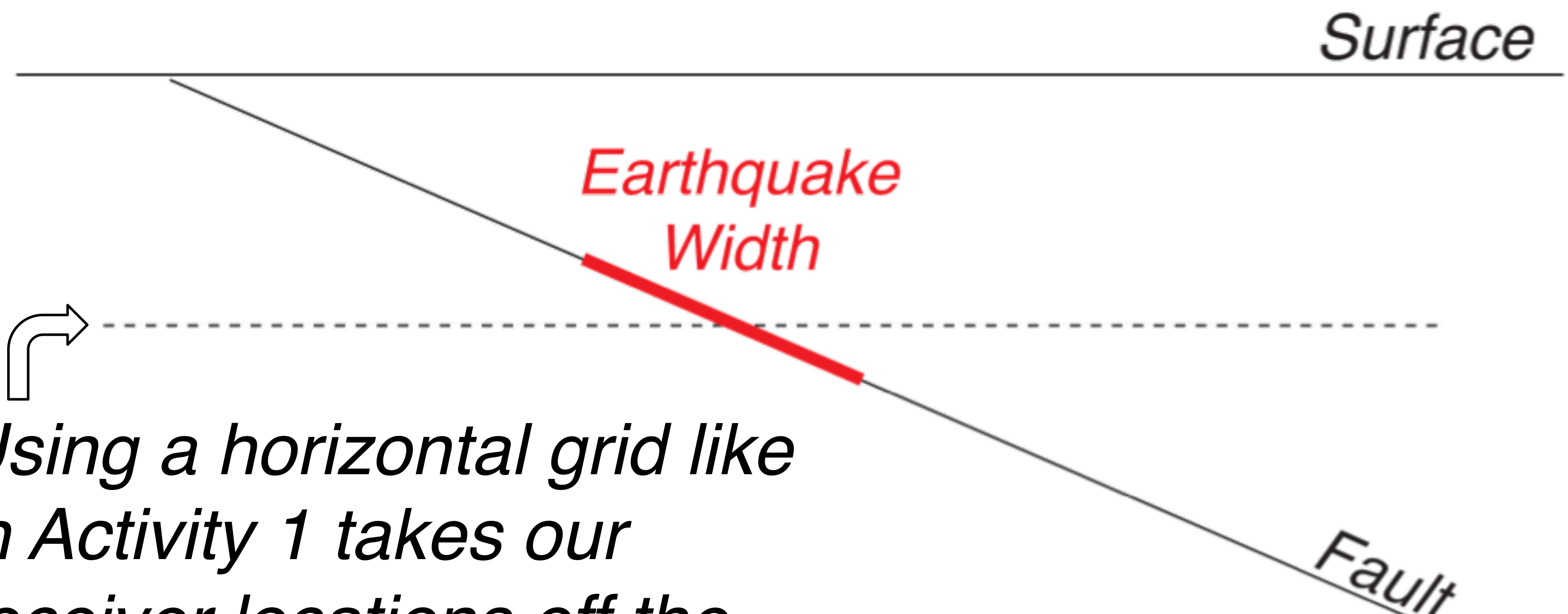
- Cross-section through a thrust fault hosting an earthquake



Using a horizontal grid like in Activity 1 takes our receiver locations off the fault of interest

Activity 2: Thrust EQ Stress

- Cross-section through a thrust fault hosting an earthquake

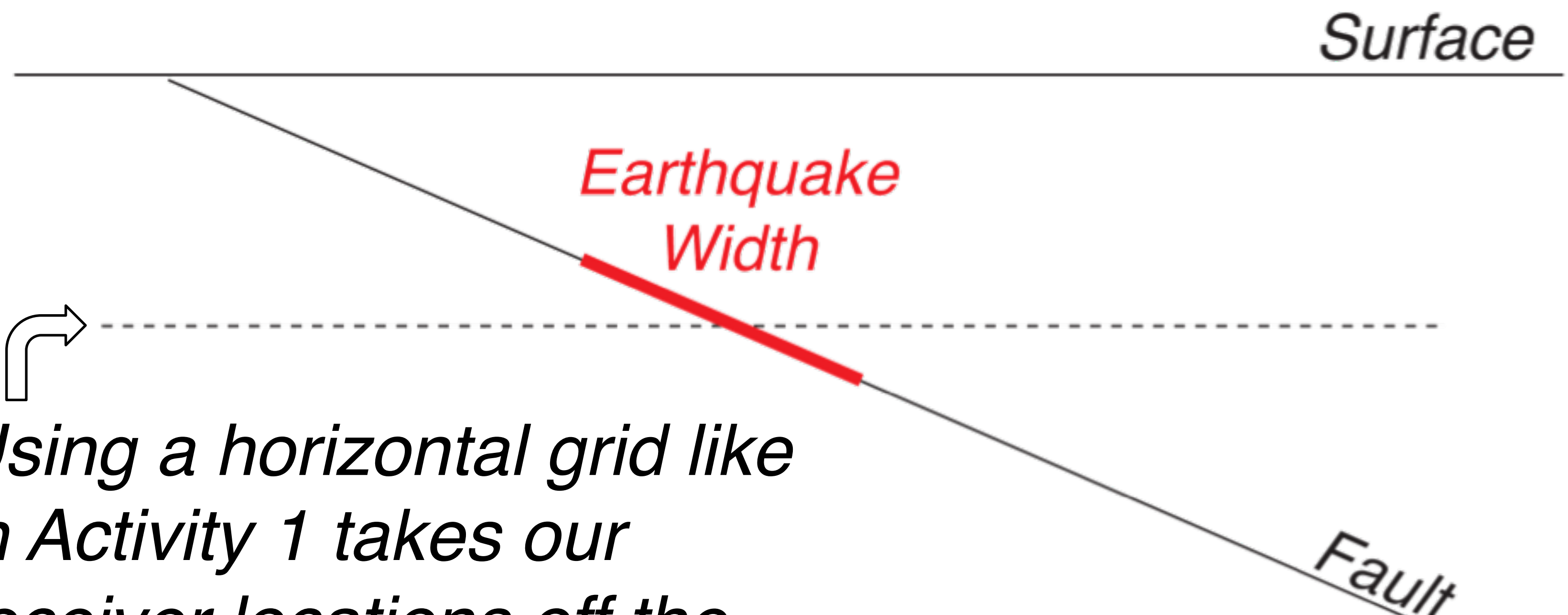


Using a horizontal grid like in Activity 1 takes our receiver locations off the fault of interest

Solution 1: use a grid that lies on the dipping plane.

Activity 2: Thrust EQ Stress

- Cross-section through a thrust fault hosting an earthquake

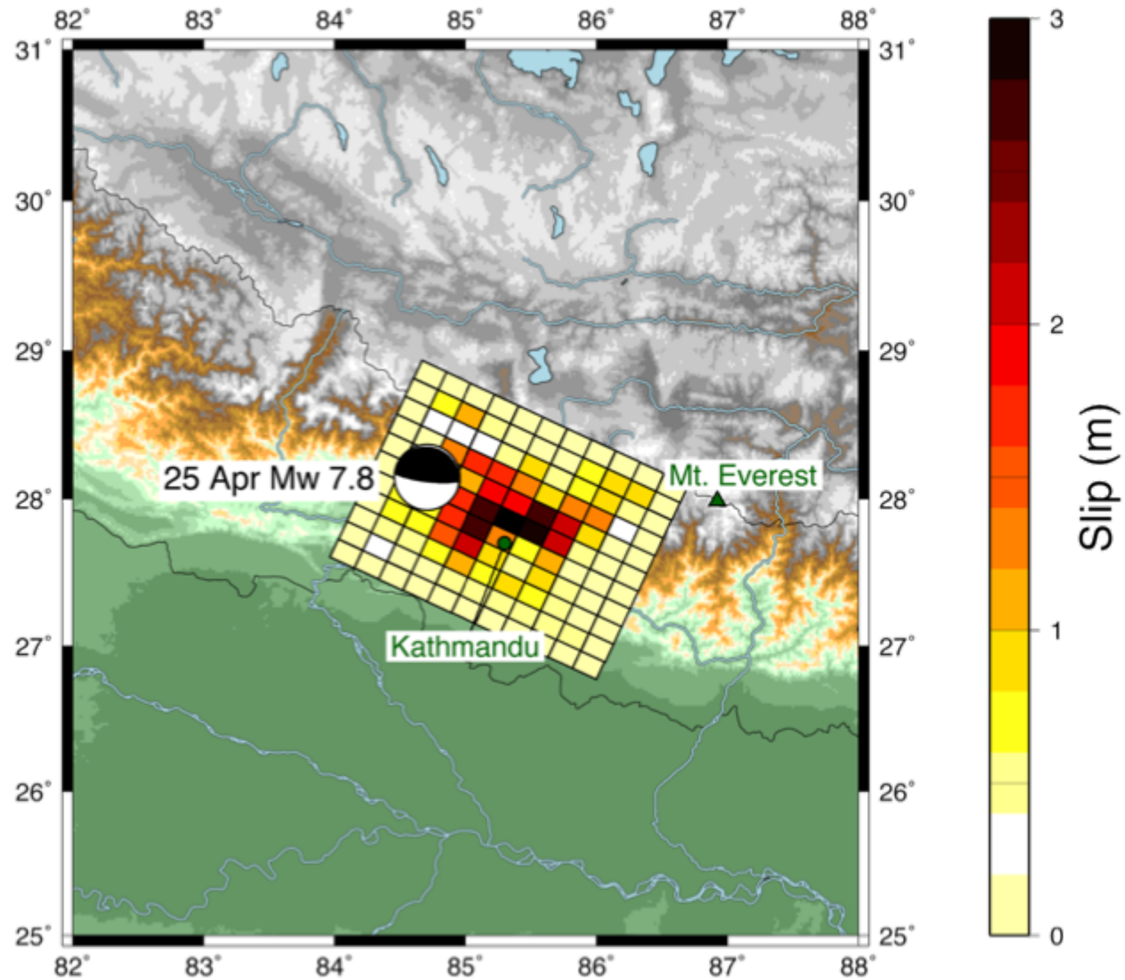


Using a horizontal grid like in Activity 1 takes our receiver locations off the fault of interest

Solution 2: look at the stress in cross-section.

Activity 2: Thrust EQ Stress

- Case study: 2015 Mw 7.8 Nepal earthquake
- Thrust faulting event on shallowly dipping plane



USGS Finite Fault Model (we will talk about these in more detail soon!)

Activity 2: Thrust EQ Stress

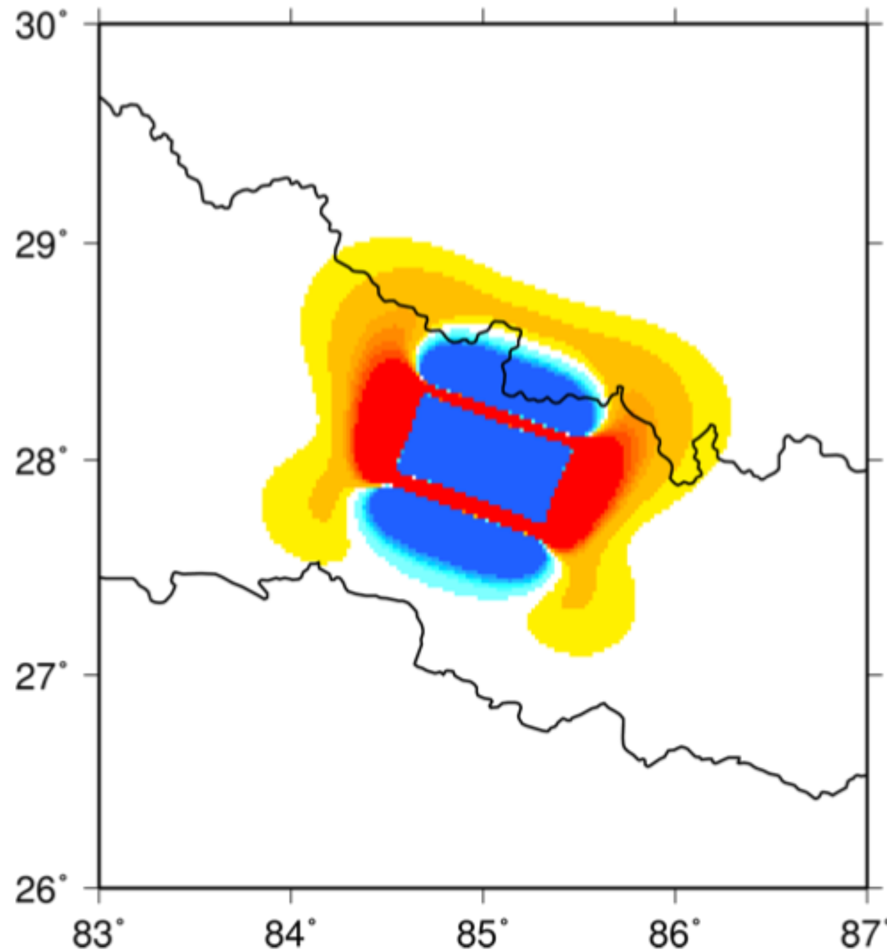
- 2015 Mw 7.8 Nepal earthquake
  - Location: 28ºN, 85ºE, 15 km
  - Kinematics: strike=-70º, dip=15º, rake=90º
  - Slip: 3.5 m
  - Dimensions: 80 km long, 50 km wide

Activity 2: Thrust EQ Stress

- 2015 Mw 7.8 Nepal earthquake
- *Exercise 2a: resolve the Coulomb stress change onto a horizontal grid, as in the previous activity*
  - *What should the depth of this grid be?*
  - *Remember to define target fault kinematics!*

Activity 2: Thrust EQ Stress

- Map view of stress on horizontal plane



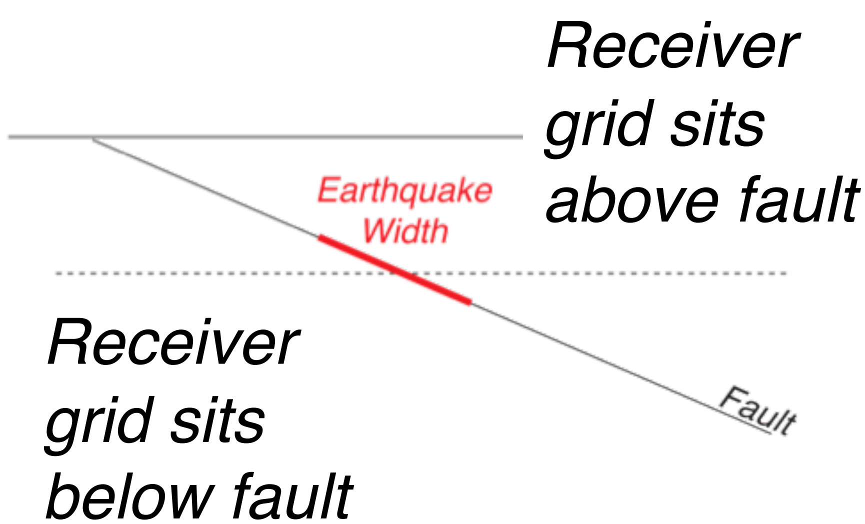
Activity 2: Thrust EQ Stress

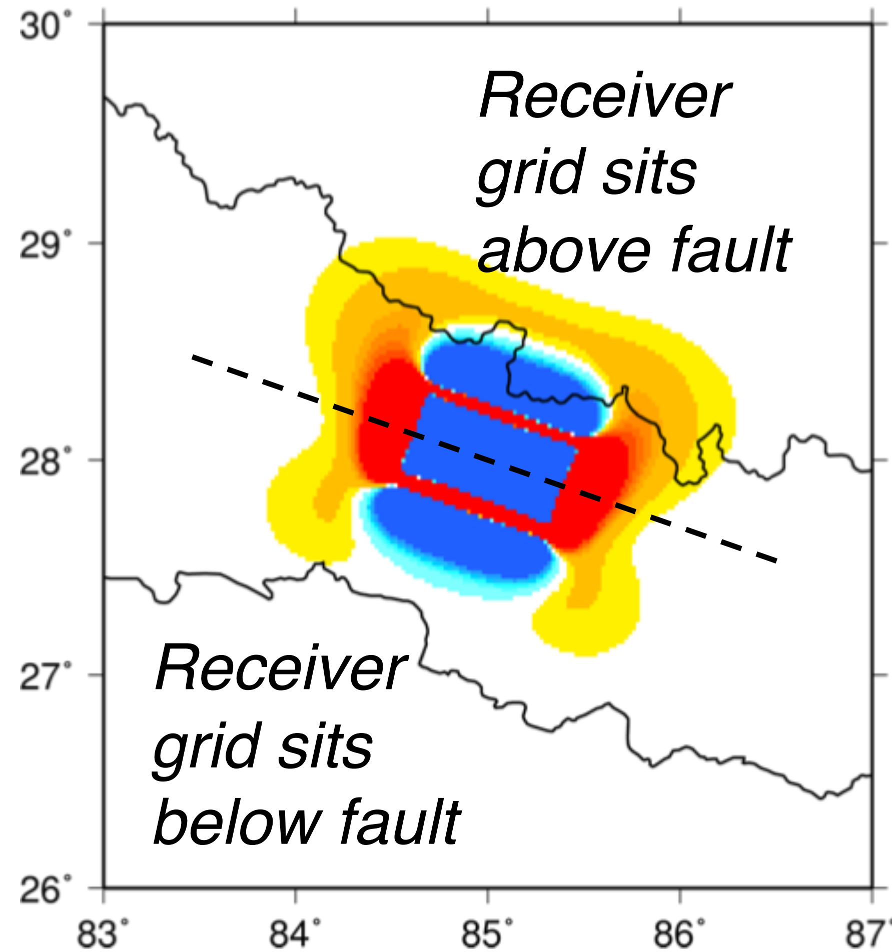
script.sh

```sh
#!/bin/sh

gmtset BASEMAP_TYPE plain

#####
#       INPUT FILES
#####
# Fault input (Mw 7.8)
echo "85 28 15 -70 15 90 3.5 50 80" > fault.dat
# Receiver locations
D=0.02
grid -x 83 87 -dx $D -y 26 30 -dy $D -z 15 -o station.dat
# Elastic half-space parameters
echo "Lame 35e9 35e9" > hafspace.dat
# Target faults
echo "-70 15 90 0.5" > target.dat

#####
#       COMPUTE COULOMB STRESS
#####
o92util -flt fault.dat -sta station.dat -haf hafspace.dat -trg target.dat -coul coul.out

#####
#       PLOT RESULTS
#####
makecpt -Cno_green -T-1e5/1e5/1e4 -D > coul.cpt
PROJ="-JM4i -P"
LIMS="-R83/87/26/30"
PSFILE="coul.ps"
awk '{print $1,$2,$4}' coul.out |\
    xyz2grd -Gcoul.grd $LIMS -I$D/$D
grdimage coul.grd $PROJ $LIMS -Ccoul.cpt -K > $PSFILE
pscoast $PROJ $LIMS -N1/1p -Dh -K -O >> $PSFILE
psbasemap $PROJ $LIMS -Ba1WeSn -O >> $PSFILE
```

Activity 2: Thrust EQ Stress

- Map view of stress on horizontal plane





Activity 2: Thrust EQ Stress

- 2015 Mw 7.8 Nepal earthquake
- *Exercise 2b: resolve the Coulomb stress change onto the dipping fault*

Activity 2: Thrust EQ Stress

- 2015 Mw 7.8 Nepal earthquake
- *Exercise 2b: resolve the Coulomb stress change onto the dipping fault*
- Requires computing depth of each point on fault relative to reference point on fault
- GRID is capable of this!

Activity 2: Thrust EQ Stress

Dipping fault using GRID

x-limits and spacing, y-limits and spacing

```
grid -x 83 87 -dx 0.02 -y 26 30 -dy 0.02
```

Geographical parameters are defined the same way as for horizontal grid.

Activity 2: Thrust EQ Stress

<u>Dipping fault using GRID</u>

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

reference point and geometry, output file

```
grid -x 83 87 -dx 0.02 -y 26 30 -dy 0.02
    -dip 85 28 15 -70 15 -geo -o station.dat
```

Longitude Latitude Depth (km)

Location of reference point on plane

Activity 2: Thrust EQ Stress

<u>Dipping fault using GRID</u>

x-limits and spacing, y-limits and spacing, reference point and geometry, output file

```
grid -x 83 87 -dx 0.02 -y 26 30 -dy 0.02
    -dip 85 28 15 -70 15 -geo -o station.dat
```

Strike Dip *Orientation of plane*

Activity 2: Thrust EQ Stress

Dipping fault using GRID

x-limits and spacing, y-limits and spacing, reference point and geometry, output file

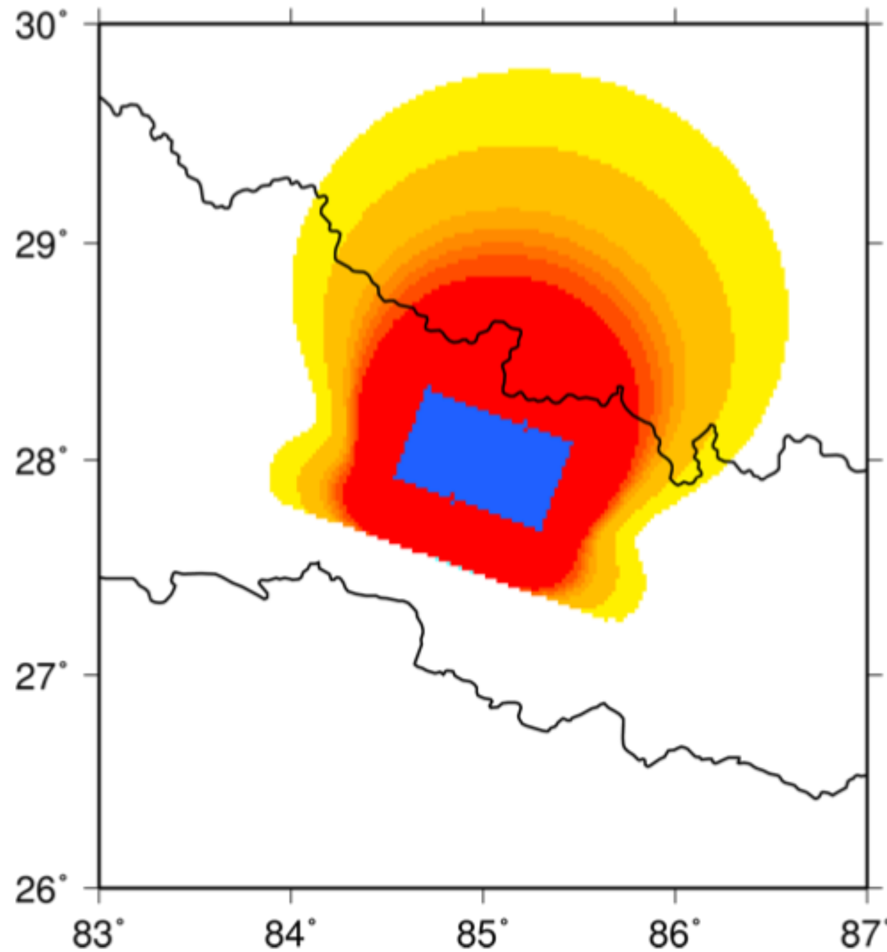
```
grid -x 83 87 -dx 0.02 -y 26 30 -dy 0.02
    -dip 85 28 15 -70 15 -geo -o station.dat
```

The origin definition is in geographic coordinates

Orientation of plane

Activity 2: Thrust EQ Stress

- Map view of stress on dipping plane



Activity 2: Thrust EQ Stress

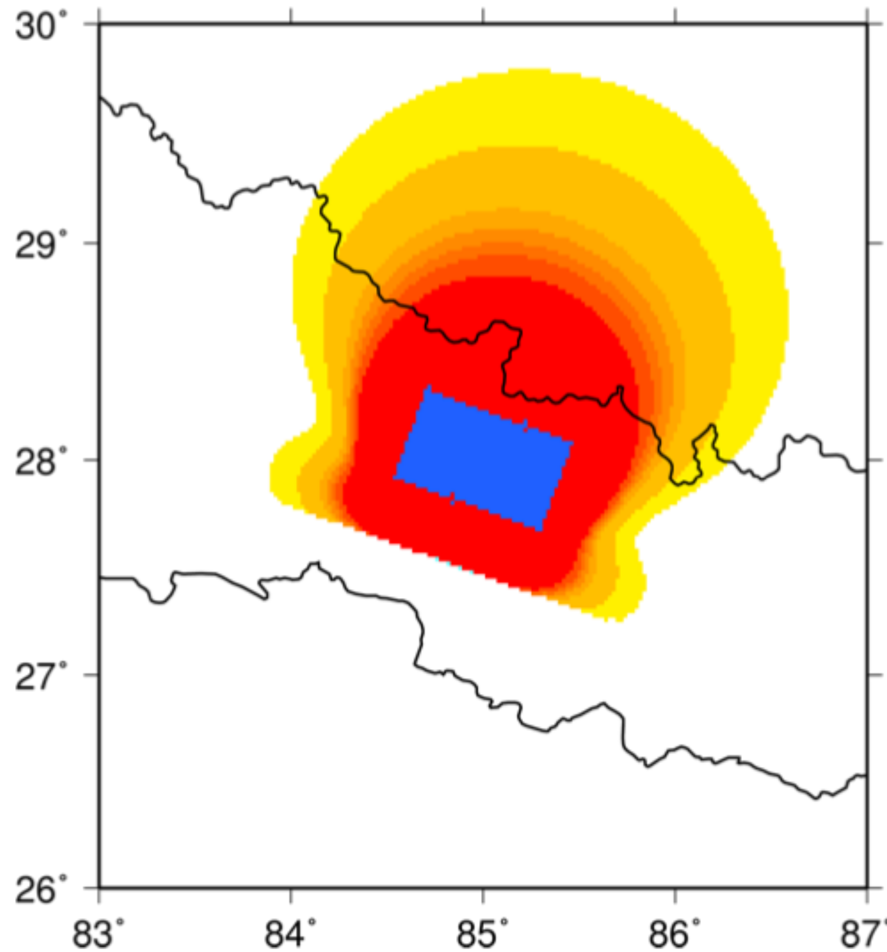
script.sh

```
#!/bin/sh

gmtset BASEMAP_TYPE plain

#####
#       INPUT FILES
#####
# Fault input (Mw 7.8)
echo "85 28 15 -70 15 90 3.5 50 80" > fault.dat
# Receiver locations
D=0.02
grid -x 83 87 -dx $D -y 26 30 -dy $D -dip 85 28 15 -70 15 -o station.dat
# Elastic half-space parameters
echo "Lame 35e9 35e9" > hafspace.dat
# Target faults
echo "-70 15 90 0.5" > target.dat

#####
#       COMPUTE COULOMB STRESS
#####
o92util -flt fault.dat -sta station.dat -haf hafspace.dat -trg target.dat -coul coul.out

#####
#       PLOT RESULTS
#####
makecpt -Cno_green -T-1e5/1e5/1e4 -D > coul.cpt
PROJ="-JM4i -P"
LIMS="-R83/87/26/30"
PSFILE="coul.ps"
awk '{print $1,$2,$4}' coul.out |\
    xyz2grd -Gcoul.grd $LIMS -I$D/$D
grdimage coul.grd $PROJ $LIMS -Ccoul.cpt -K > $PSFILE
pscoast $PROJ $LIMS -N1/1p -Dh -K -O >> $PSFILE
psbasemap $PROJ $LIMS -Ba1WeSn -O >> $PSFILE
```

Add -geo!

Activity 2: Thrust EQ Stress

- Map view of stress on dipping plane
- More consistent with our intuition:
  - ΔCS lowered in rupture zone
  - Up- and down-dip are loaded
  - Minor effect along-strike



Activity 2: Thrust EQ Stress

- 2015 Mw 7.8 Nepal earthquake
- *Exercise 2c: resolve the Coulomb stress change in cross-section*

Activity 2: Thrust EQ Stress

- 2015 Mw 7.8 Nepal earthquake
- *Exercise 2c: resolve the Coulomb stress change in cross-section*
- Now we need a very different grid from the map views we have been using.
- Again, GRID can do this!

Activity 2: Thrust EQ Stress

<u>Vertical cross-section using GRID</u>

x-limits and spacing, z-limits and spacing

```
grid -x -100 100 -dx 1 -z 0 100 -dz 1
```

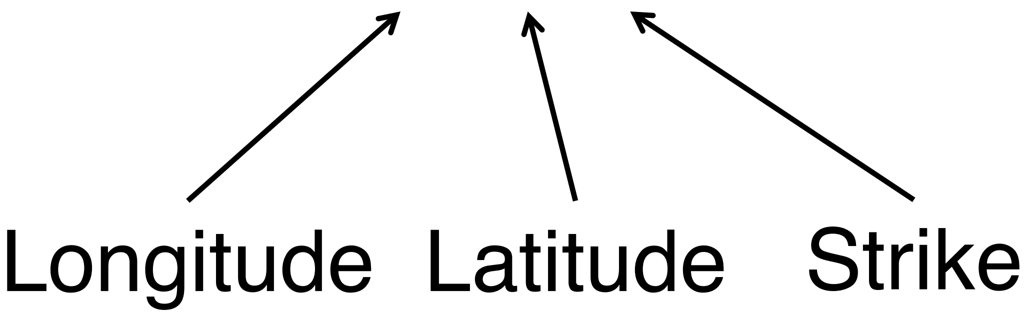
- -100: Along-section minimum (km)
- 100: Along-section maximum (km)
- 0: Minimum Depth (km)
- 100: Maximum Depth (km)

Activity 2: Thrust EQ Stress

Vertical cross-section using GRID

x-limits and spacing, z-limits and spacing, reference point and orientation, output file

```
grid -x -100 100 -dx 1 -z 0 100 -dz 1
    -xsec 85 28 20 -geo -o station.dat
```



Location of origin of cross-section, and strike of section

Activity 2: Thrust EQ Stress

Vertical cross-section using GRID

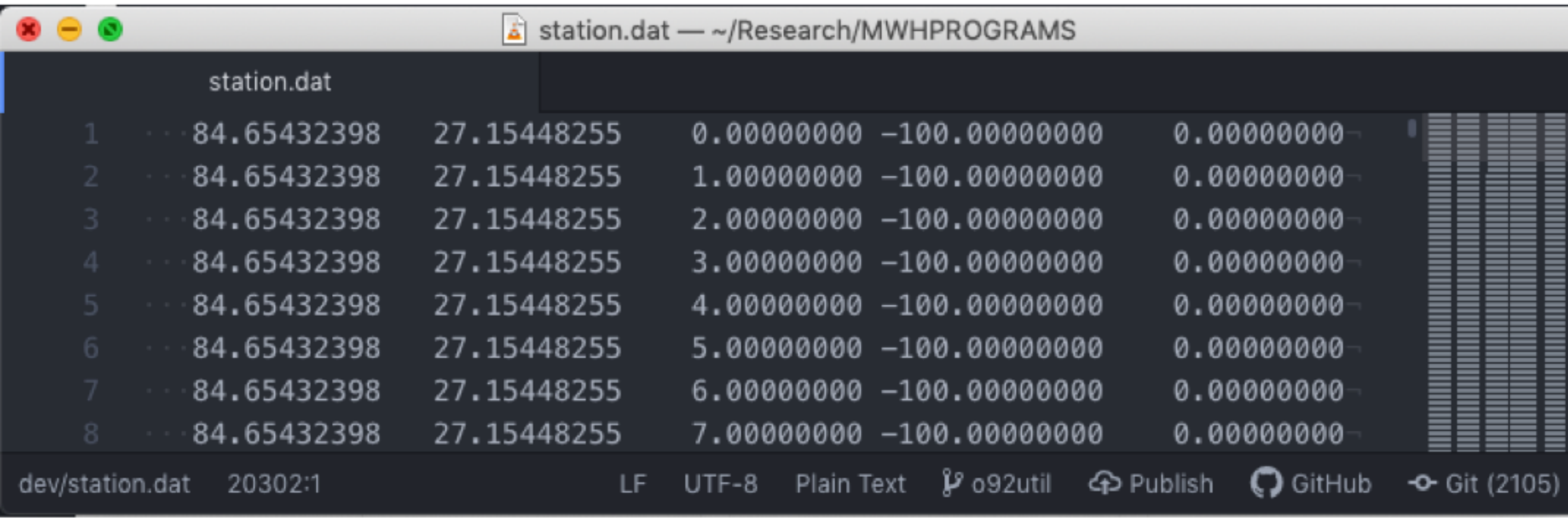
x-limits and spacing, y-limits and spacing, reference point and orientation, output file

```
grid -x -100 100 -dx 1 -z 0 100 -dz 1
   -xsec 85 28 20 -geo -o station.dat
```

This produces a file with longitude, latitude and depth (for use with O92UTIL), plus two extra columns for the distance along the cross-section (x) and the perpendicular distance (y).

Activity 2: Thrust EQ Stress

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

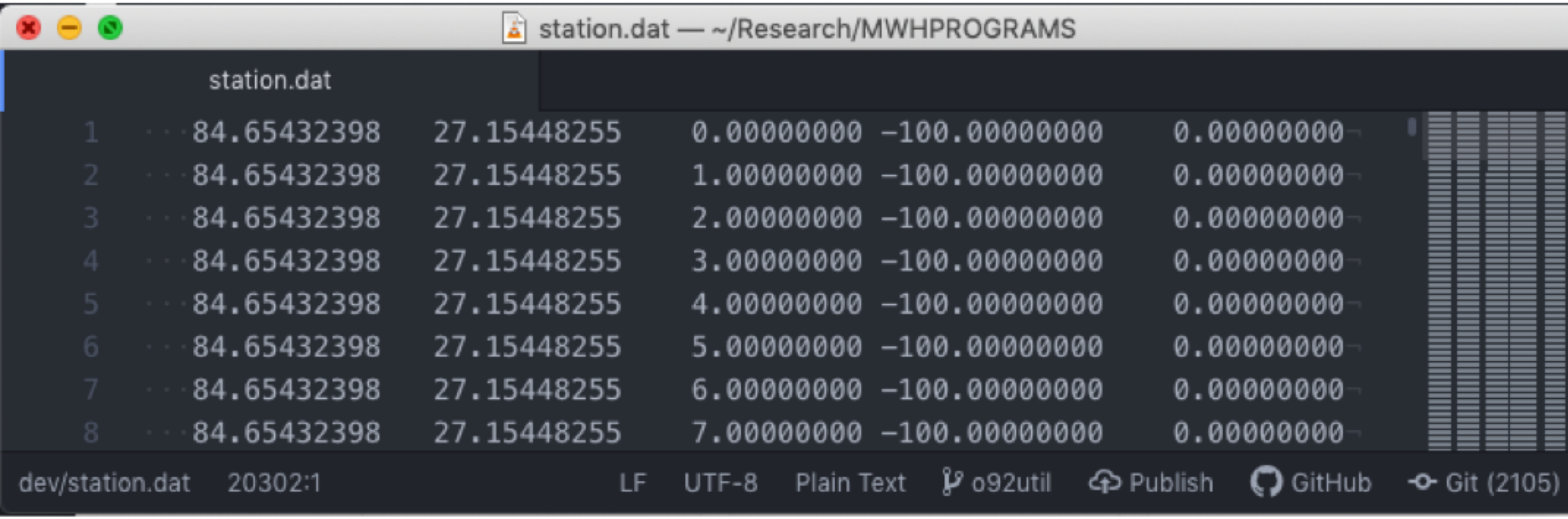



```
84.65432398   27.15448255   0.00000000 -100.00000000   0.00000000
84.65432398   27.15448255   1.00000000 -100.00000000   0.00000000
84.65432398   27.15448255   2.00000000 -100.00000000   0.00000000
84.65432398   27.15448255   3.00000000 -100.00000000   0.00000000
84.65432398   27.15448255   4.00000000 -100.00000000   0.00000000
84.65432398   27.15448255   5.00000000 -100.00000000   0.00000000
84.65432398   27.15448255   6.00000000 -100.00000000   0.00000000
84.65432398   27.15448255   7.00000000 -100.00000000   0.00000000
```

Longitude Latitude Depth

Activity 2: Thrust EQ Stress

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



To plot the cross-section, we will also want a file with X-Z values.

Distance along cross-section

Perp. distance to cross-section

Activity 2: Thrust EQ Stress

Plot results (basic plotting script provided)

plot_xsec.sh

plot_xsec.sh

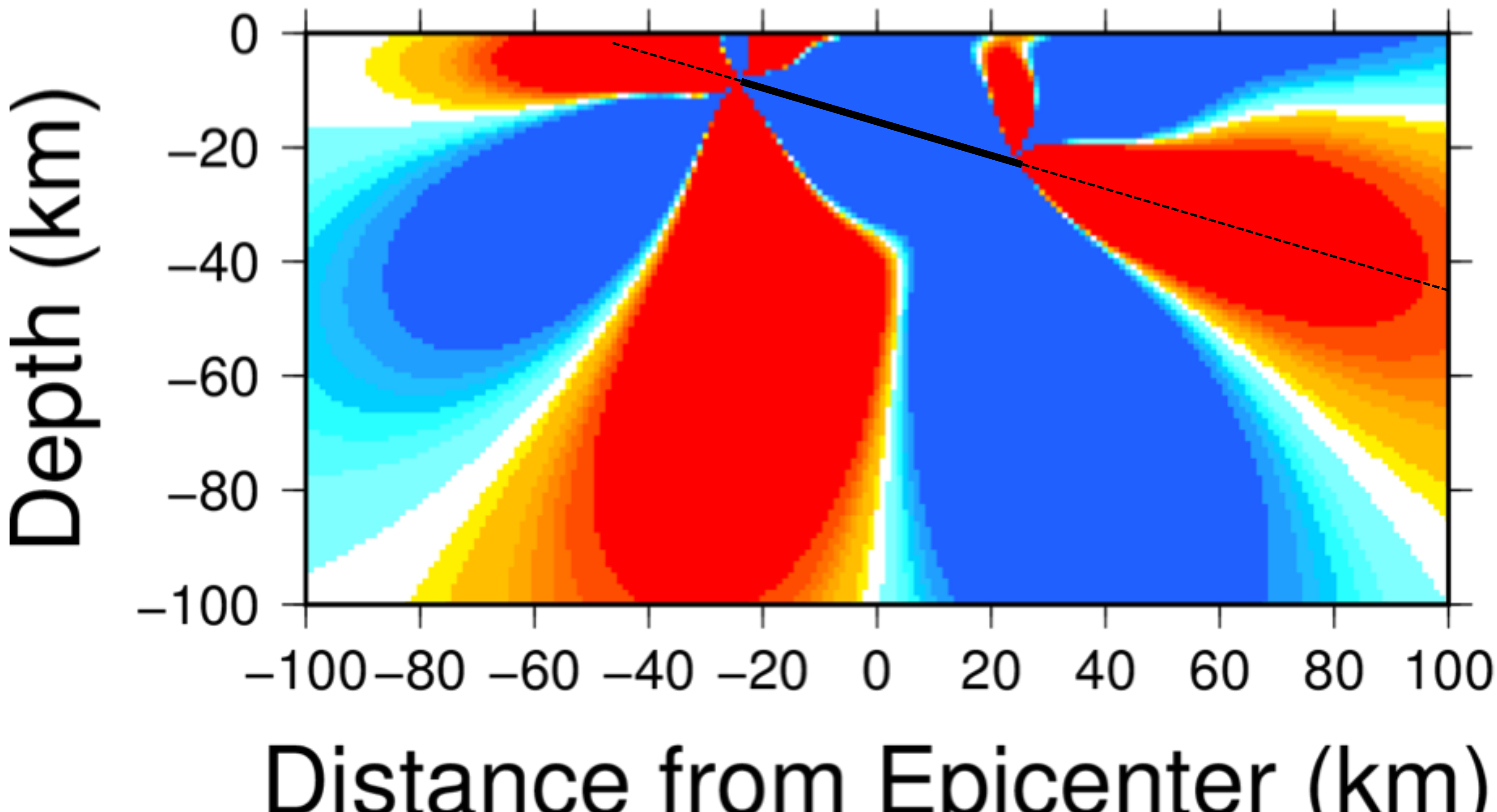
```
#!/bin/sh

makecpt -Cno_green -T-1e5/1e5/1e4 -D > stress.cpt

PROJ="-Jx0.02i -P"
LIMS="-R-100/100/-100/0"
PSFILE="xsec.ps"

# Paste is a UNIX tool that appends two text files.
# These two files correspond line by line, so we use paste,
# then extract the x-distance, depth and CS with awk.
paste coul.out xsec.dat |\
    awk '{print $5, $6,$4}' |\
    xyz2grd -Gcoul.grd $LIMS -I0.02/0.02
grdimage coul.grd $PROJ $LIMS -Ccoul.cpt -K > $PSFILE
psbasemap $PROJ $LIMS -Ba20WeSn -O >> $PSFILE
```

```
paste coul.out station.dat |\
    awk '{print $8,-$7,$4}' |\
```

```
-I1/1
```

Activity 2: Thrust EQ Stress

- Cross-section of Coulomb stress

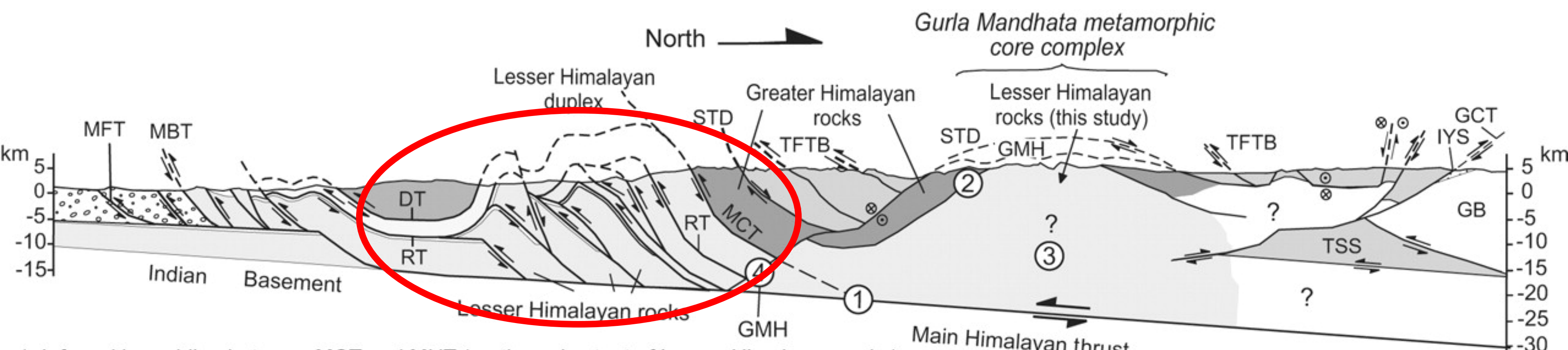


Activity 2: Thrust EQ Stress

- 2015 Mw 7.8 Nepal earthquake
- *Exercise 2d: resolve the Coulomb stress change <u>on faults dipping 35º</u> in cross-section*
  - *The faults in the upper plate of the collision zone likely dip more steeply than the main plate boundary detachment*

Activity 2: Thrust EQ Stress

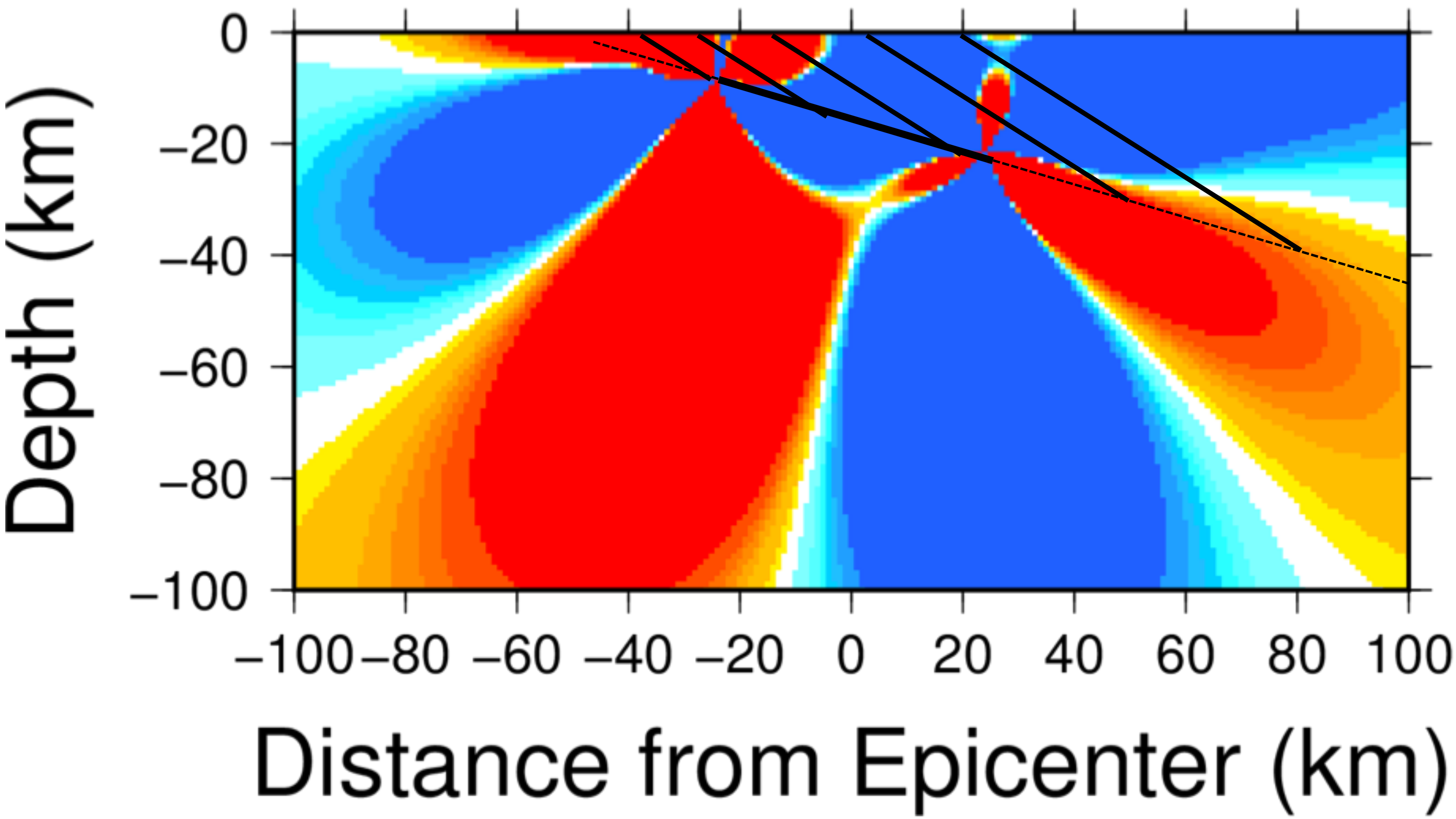
- 2015 Mw 7.8 Nepal earthquake
- *Exercise 2d: resolve the Coulomb stress change on faults dipping 35º in cross-section*



1. Inferred branchline between MCT and MHT (northward extent of Lesser Himalayan rocks) based on surface geology (Decelles et al., 2001) and microseismicity (Pandey et al., 1999).
2. Position of contact between rocks isotopically linked to Greater Himalayan and Lesser Himalayan rocks (this study).
3. Region interpreted to consist of thickened Lesser Himalayan rocks possibly by duplex structures or crustal-scale thrust fault.
4. Depth of GMH based on surface geology (Murphy and Copeland, 2005) and isotopic data (this study).

Activity 2: Thrust EQ Stress

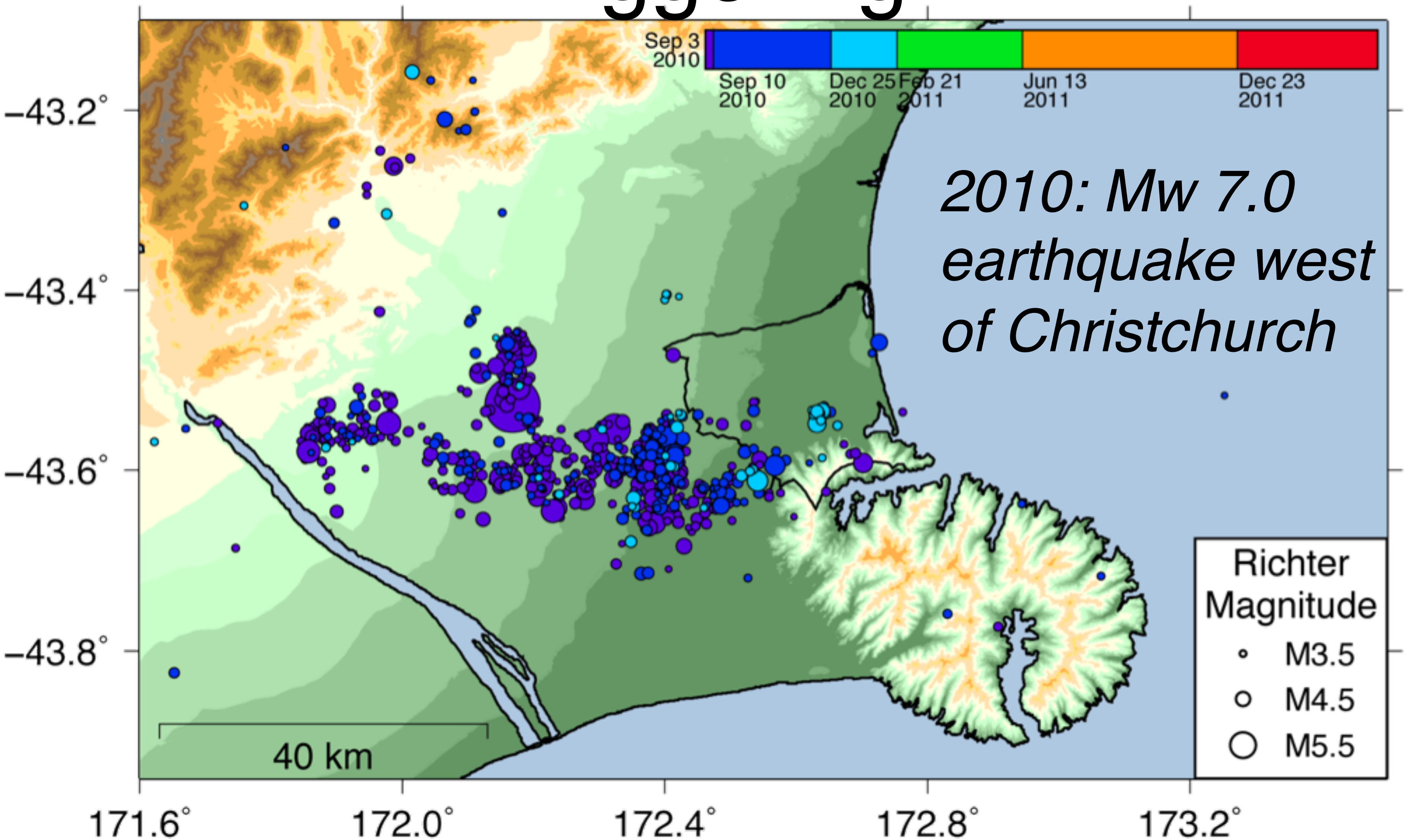
- Cross-section of Coulomb stress



Activity 3: Earthquake Triggering

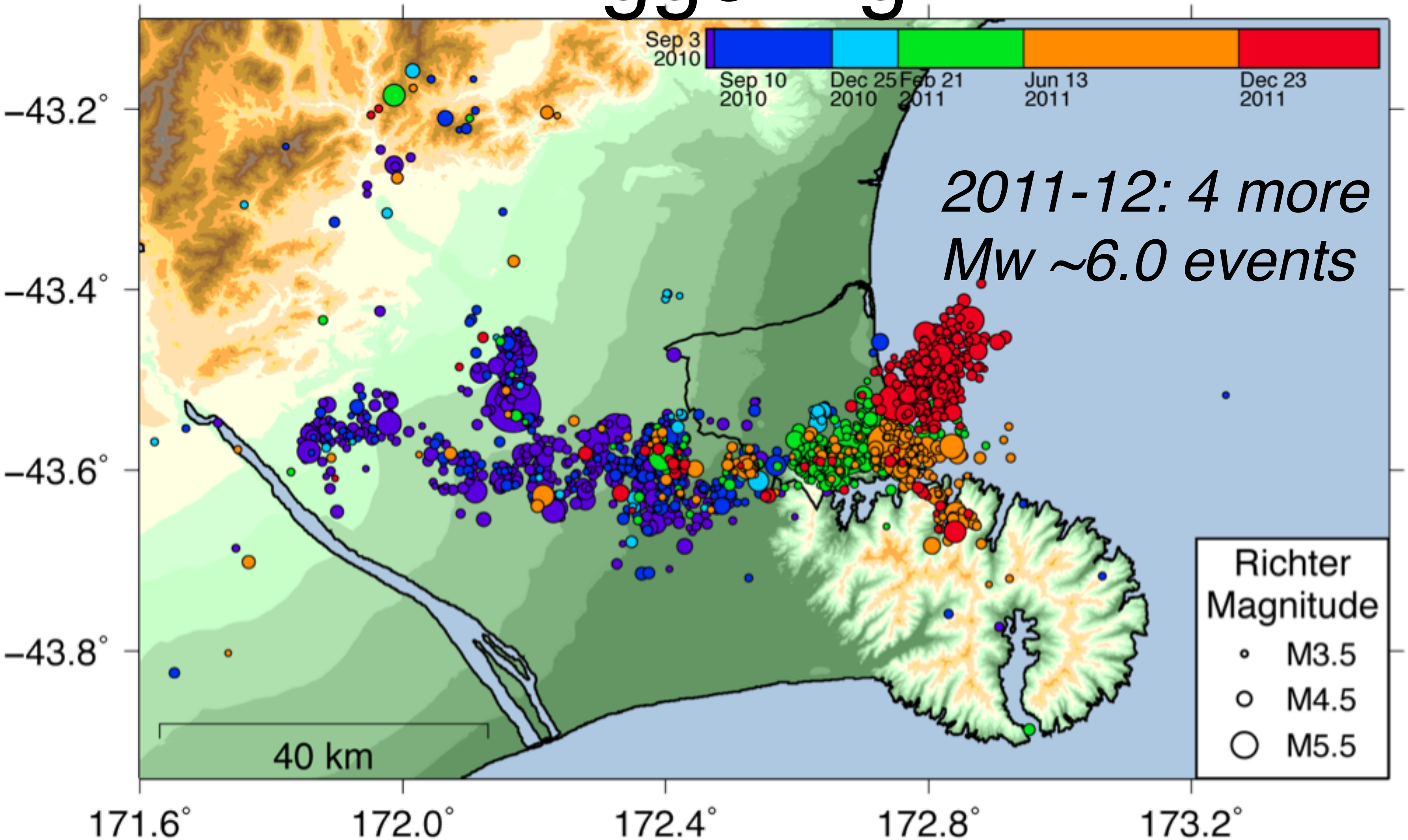
- Observation: earthquakes commonly occur near previous events
- Does the previous event trigger the subsequent earthquake?
- Correlation in space and time not sufficient to conclude triggering
- ΔCS is a mechanism for earthquake triggering

Activity 3: Earthquake Triggering



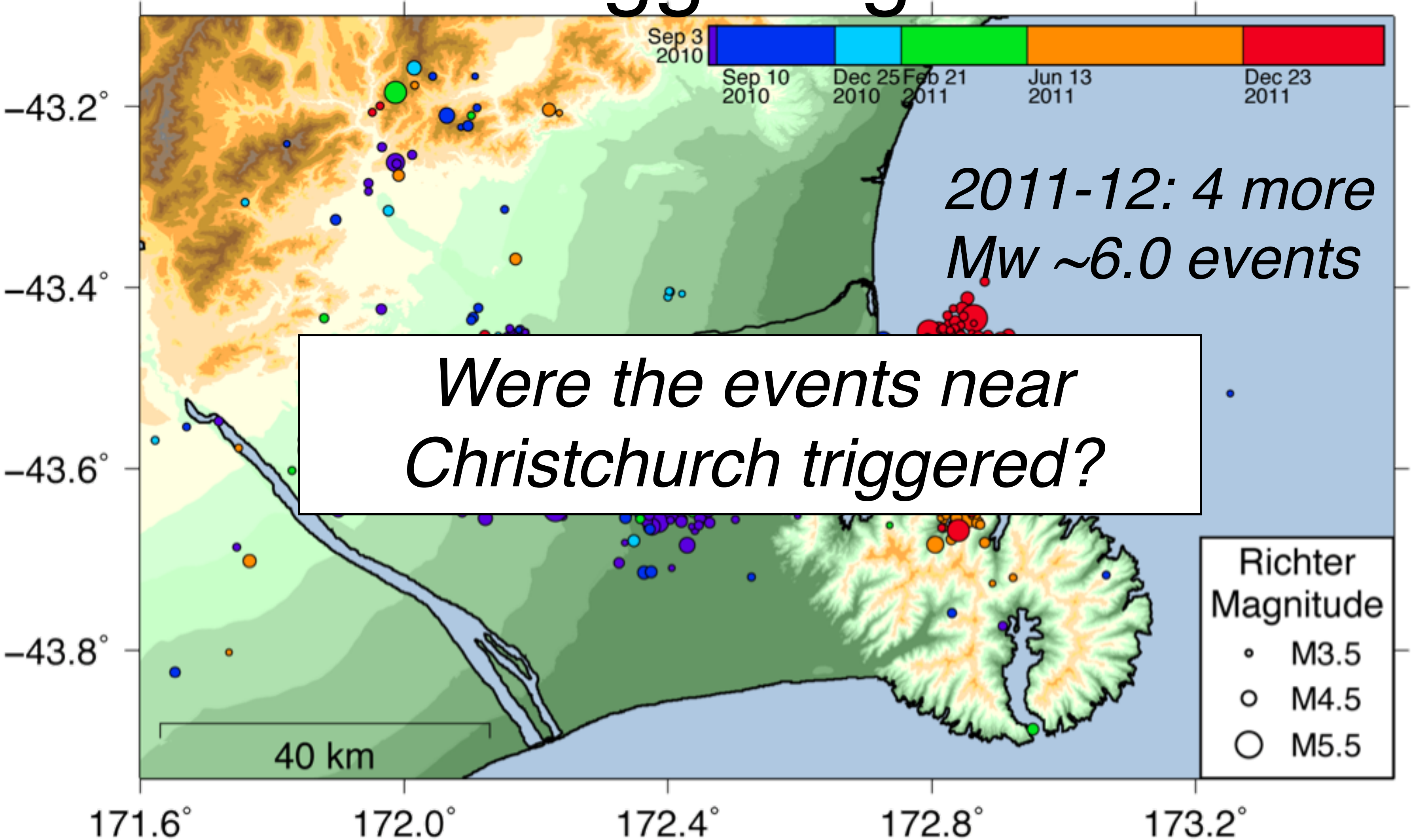
Herman et al. (2014)

Activity 3: Earthquake Triggering



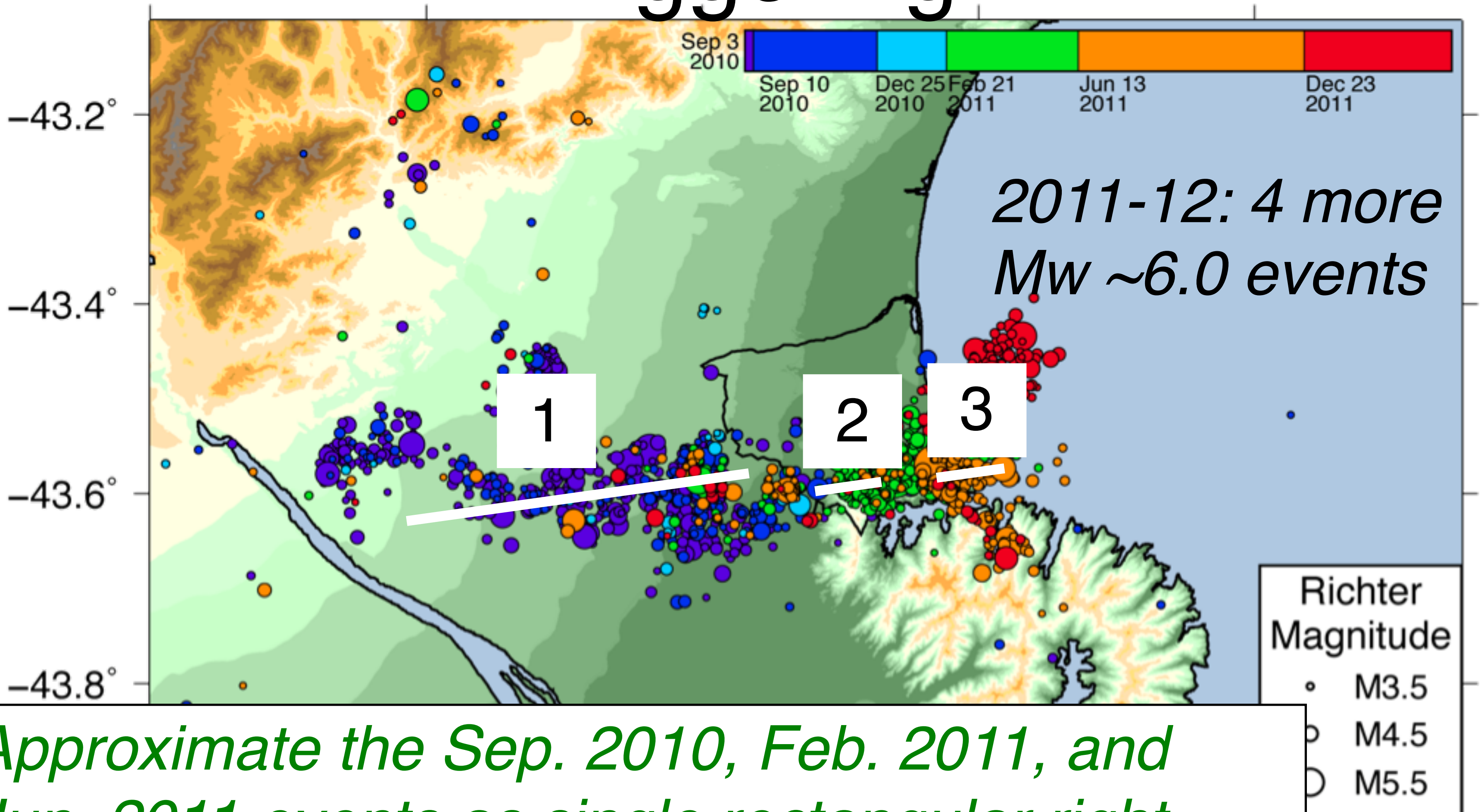
Herman et al. (2014)

Activity 3: Earthquake Triggering



Herman et al. (2014)

Activity 3: Earthquake Triggering



Approximate the Sep. 2010, Feb. 2011, and Jun. 2011 events as single rectangular right lateral strike-slip earthquakes.

Activity 3: Earthquake Triggering

- *Exercise: Compute the ΔCS resulting from the Sep. 2010 main shock on target faults with the same kinematics. Compare the locations of the Feb. and Jun. 2011 earthquakes with the ΔCS distribution.*

Activity 3: Earthquake Triggering

- Sep. 2010 Mw 7.0

```
172.20 -43.63 15 80 90 180 2 15 35
```

- Feb. 2011 Mw 6.1

```
172.60 -43.60 15 80 90 180 1  6  8
```

- Jun. 2011 Mw 6.0

```
172.77 -43.58 15 80 90 180 1  4  6
```

Activity 3: Earthquake Triggering

- Sep. 2010 Mw 7.0 *fault.dat*

```
172.20 -43.63 15 80 90 180 2 15 35
```

- Feb. 2011 Mw 6.1

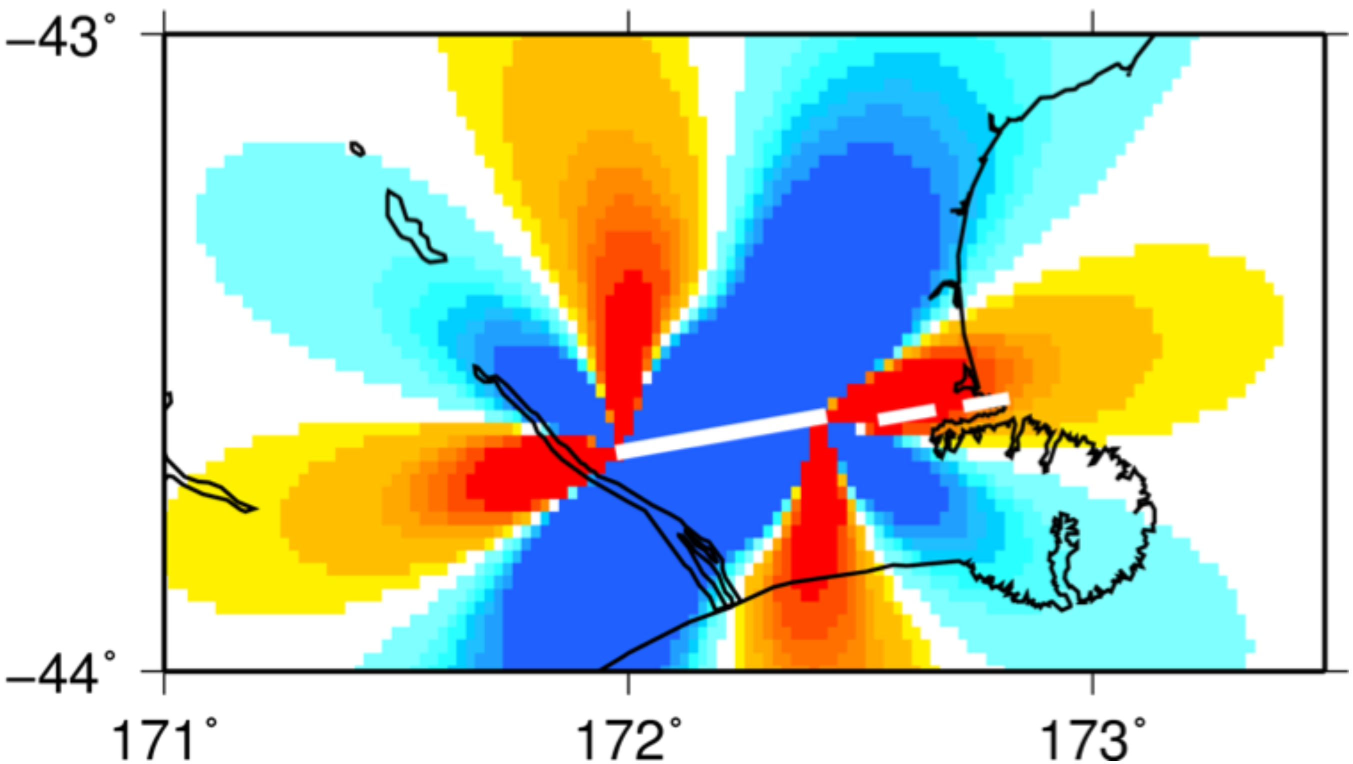
```
172.60 -43.60 15 80 90 180 1  6  8
```

- Jun. 2011 Mw 6.0

```
172.77 -43.58 15 80 90 180 1  4  6
```

Activity 3: Earthquake Triggering

- Sep. 2010 Mw 7.0 earthquake puts the east in a lobe of positive ΔCS



Activity 3: Earthquake Triggering

- NOTE: The color scheme is chosen with the following criteria:
  - The ΔCS colors saturate at ± 0.1 MPa. Anything larger than this is considered a very large stress change.
  - The minimum colored value is ± 0.01 MPa (0.1 bar). Past studies indicate this is a minimum ΔCS threshold correlated with increased seismicity.

Activity 3: Earthquake Triggering

- *Add the ΔCS resulting from the Feb. 2011 aftershock to the Sep. 2010 main shock ΔCS and see what effect this has on the distribution of ΔCS.*

Activity 3: Earthquake Triggering

- Sep. 2010 Mw 7.0

fault.dat

```
172.20 -43.63 15 80 90 180 2 15 35
```

- Feb. 2011 Mw 6.1

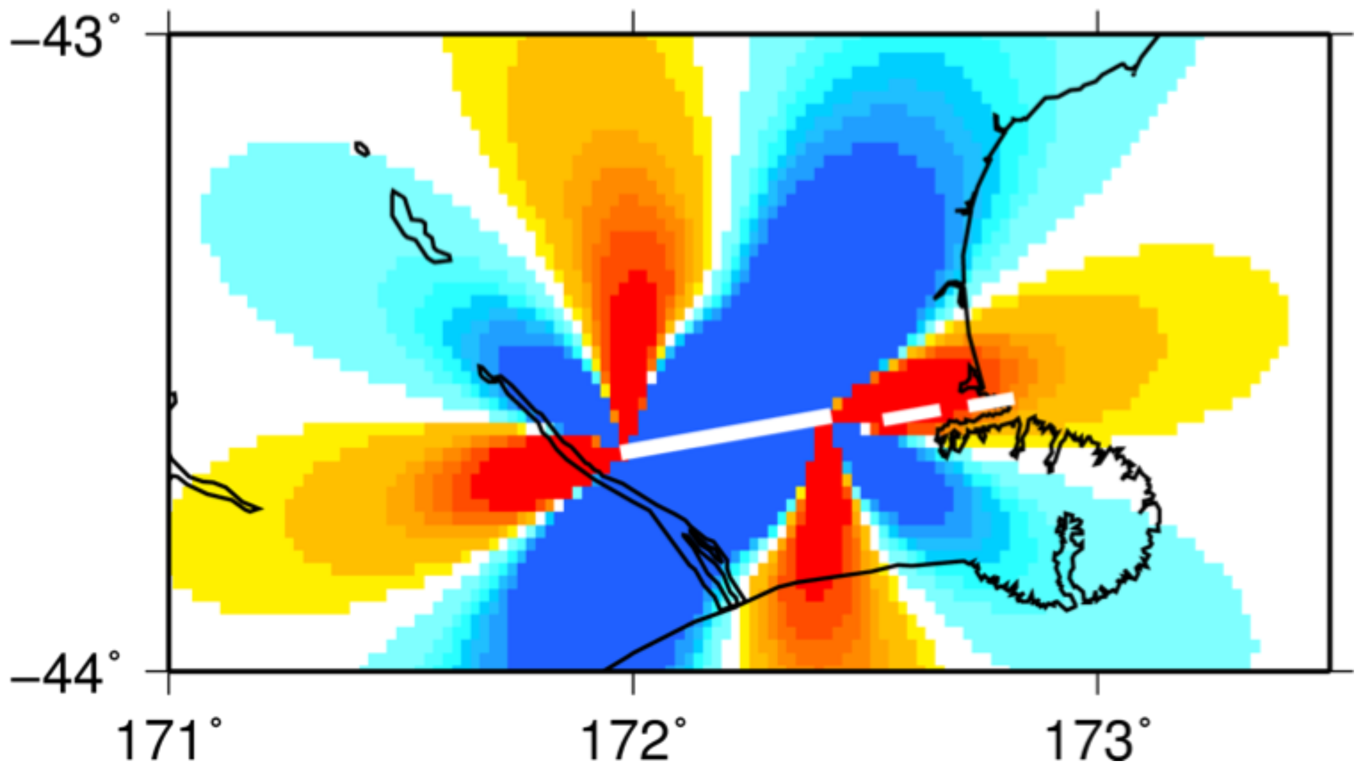
```
172.60 -43.60 15 80 90 180 1  6  8
```

- Jun. 2011 Mw 6.0

```
172.77 -43.58 15 80 90 180 1  4  6
```

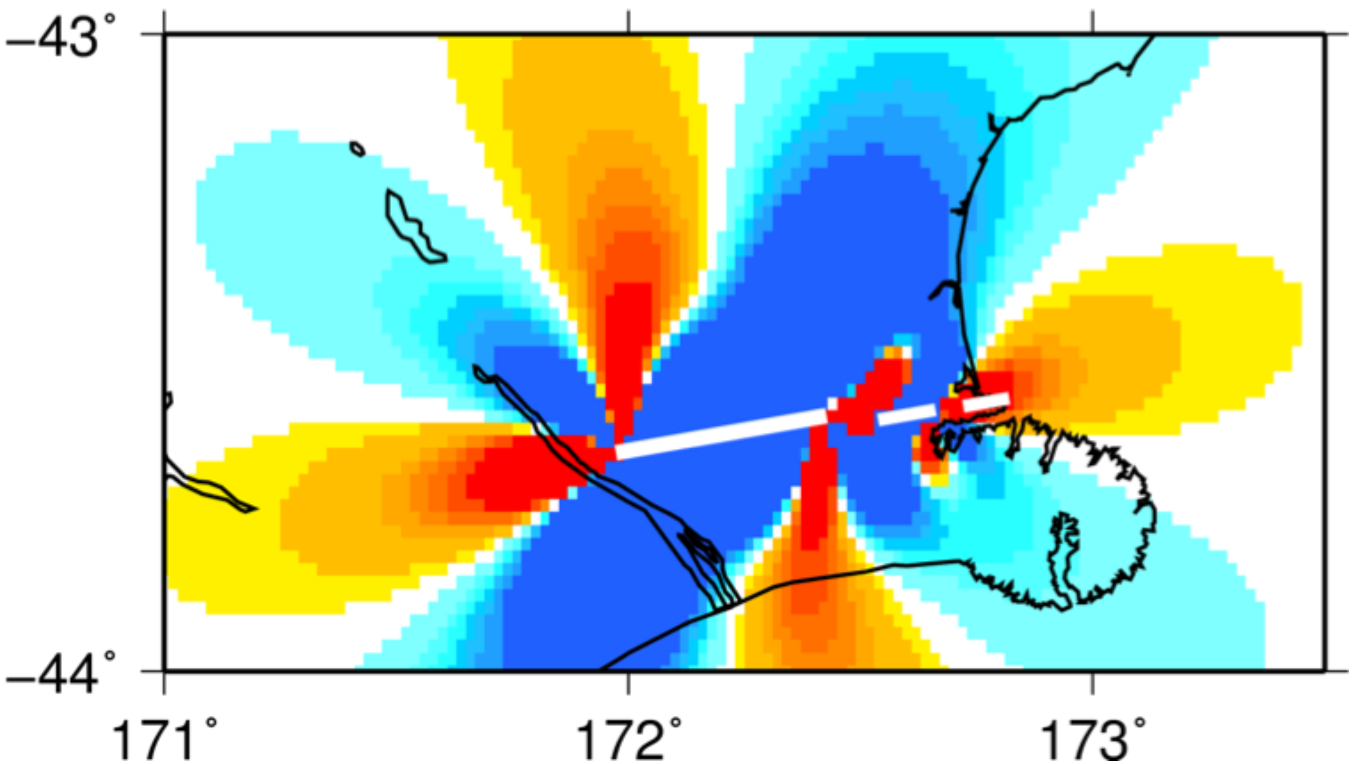
Activity 3: Earthquake Triggering

- Sep. 2010 Mw 7.0 earthquake puts the east in a lobe of positive ΔCS



Activity 3: Earthquake Triggering

- Feb. 2011 Mw 6.1 extends a lobe of positive ΔCS to the June epicenter.



Activity 3: Earthquake Triggering

- *What is the final distribution of ΔCS after all three earthquakes?*

Activity 3: Earthquake Triggering

- Sep. 2010 Mw 7.0 *fault.dat*

```
172.20 -43.63 15 80 90 180 2 15 35
```

- Feb. 2011 Mw 6.1

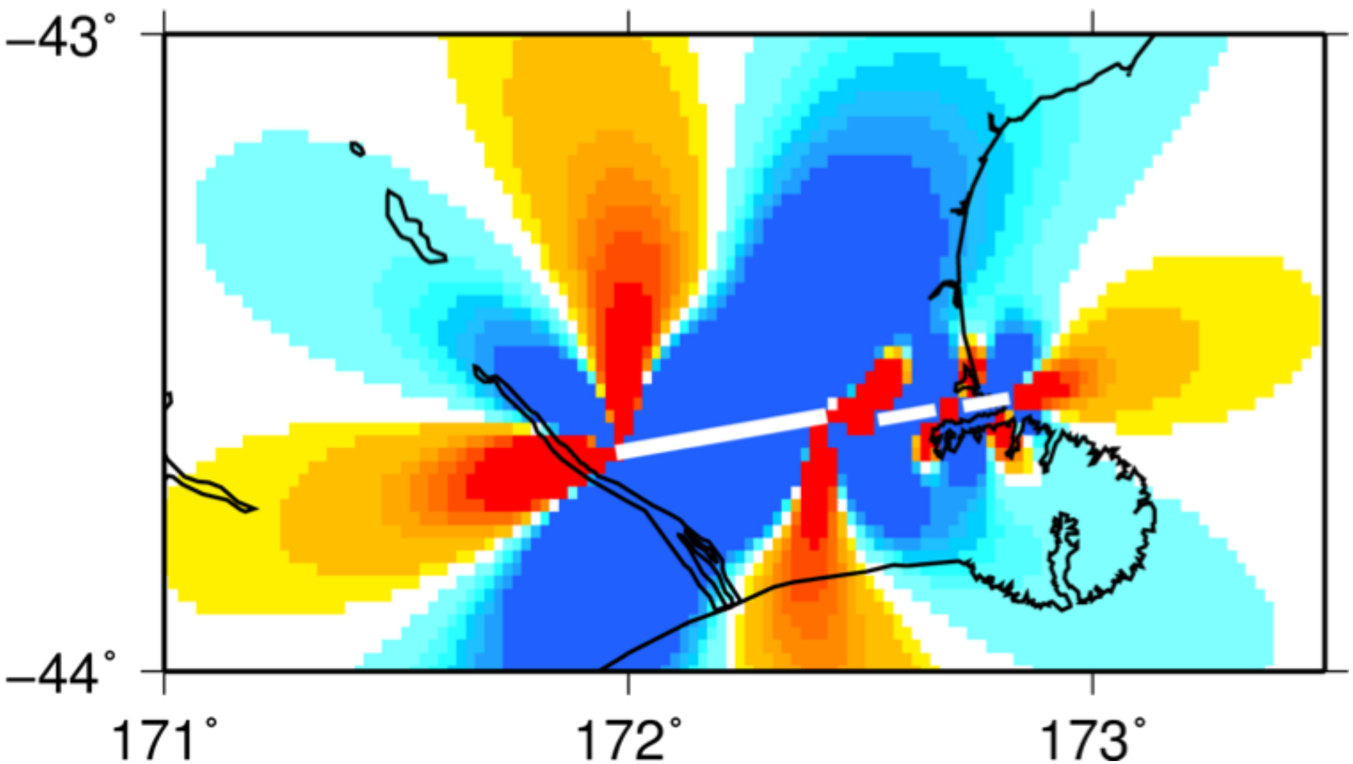
```
172.60 -43.60 15 80 90 180 1  6  8
```

- Jun. 2011 Mw 6.0

```
172.77 -43.58 15 80 90 180 1  4  6
```

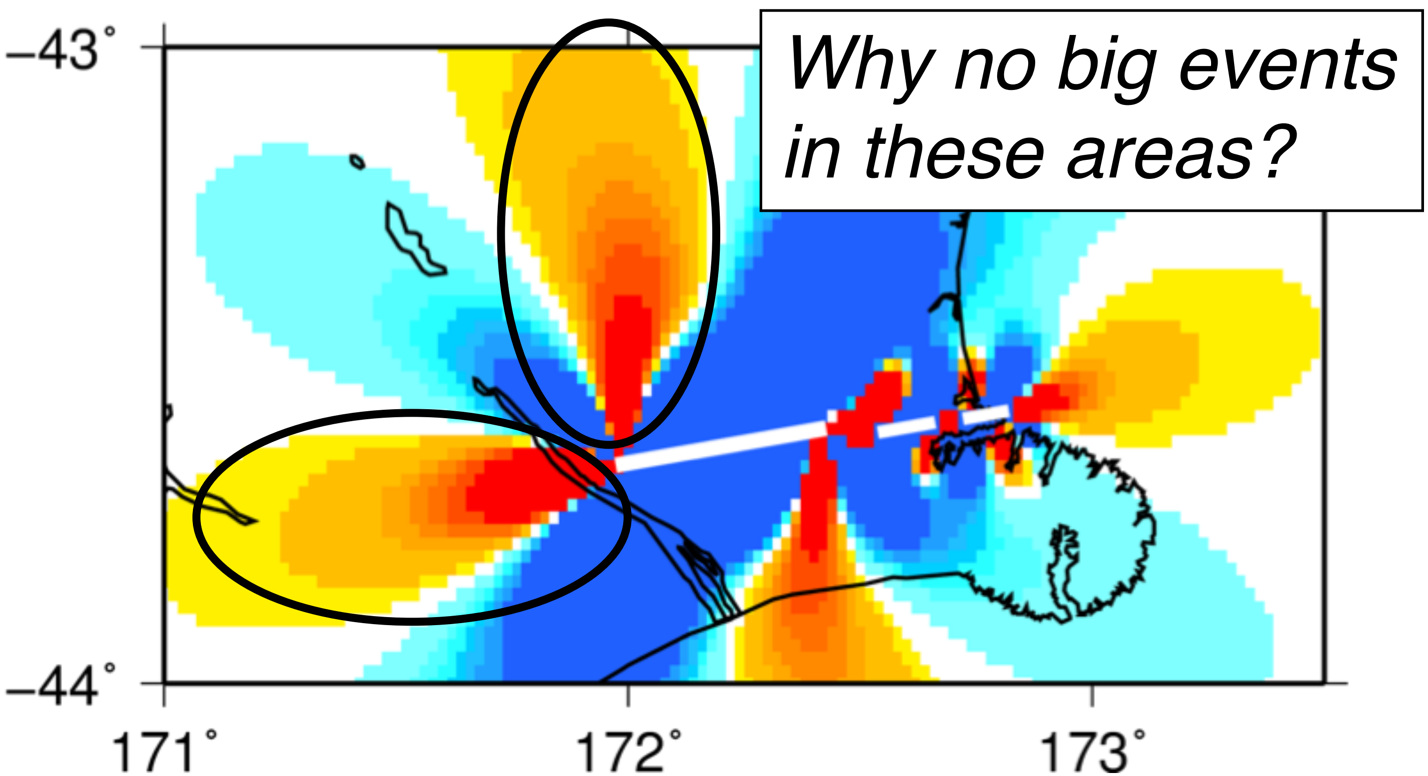
Activity 3: Earthquake Triggering

- Final ΔCS picture after all three earthquakes



Activity 3: Earthquake Triggering

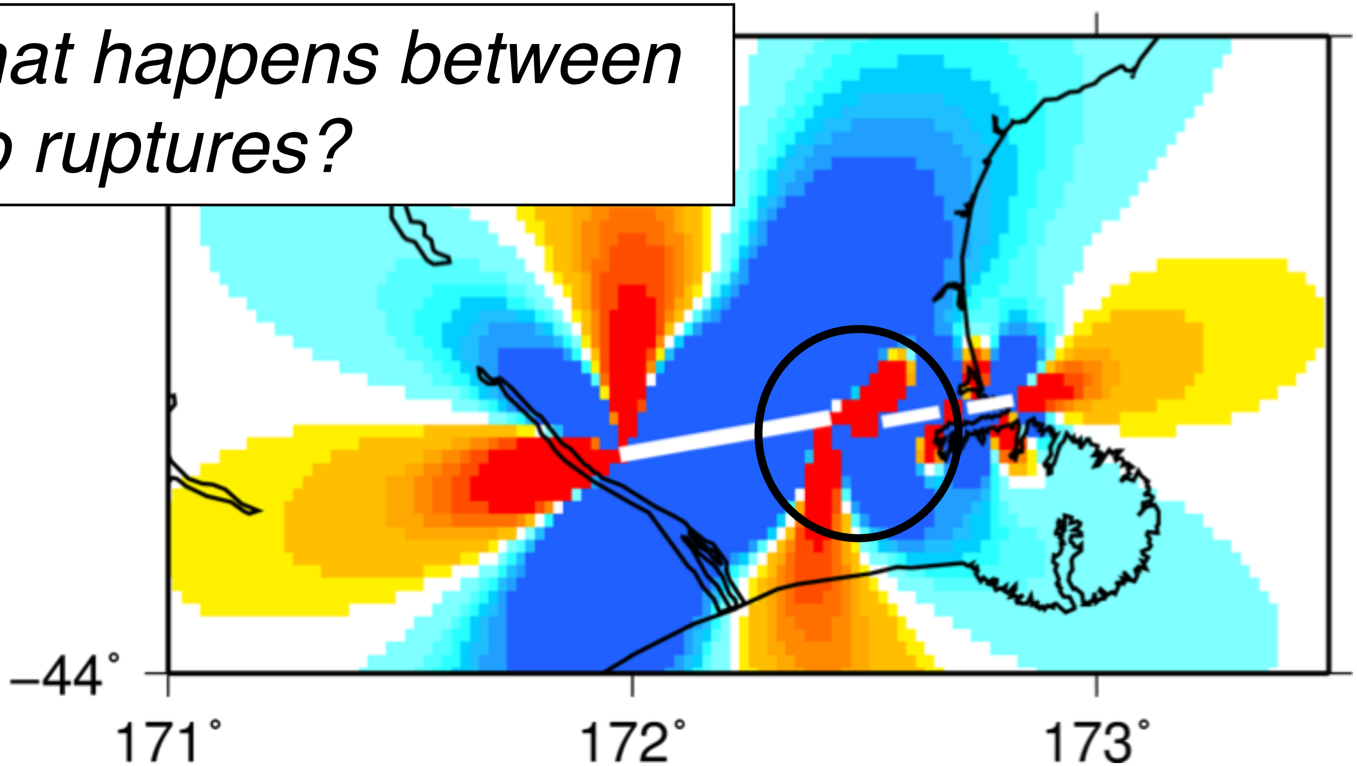
- Final ΔCS picture after all three earthquakes



Activity 3: Earthquake Triggering

- Final ΔCS picture after all three earthquakes

What happens between two ruptures?



Resolving Stress Components and Earthquake Triggering Completed