Relax

Semi-analytic Fourier-domain solver and equivalent body forces for quasi-static relaxation of stress perturbation

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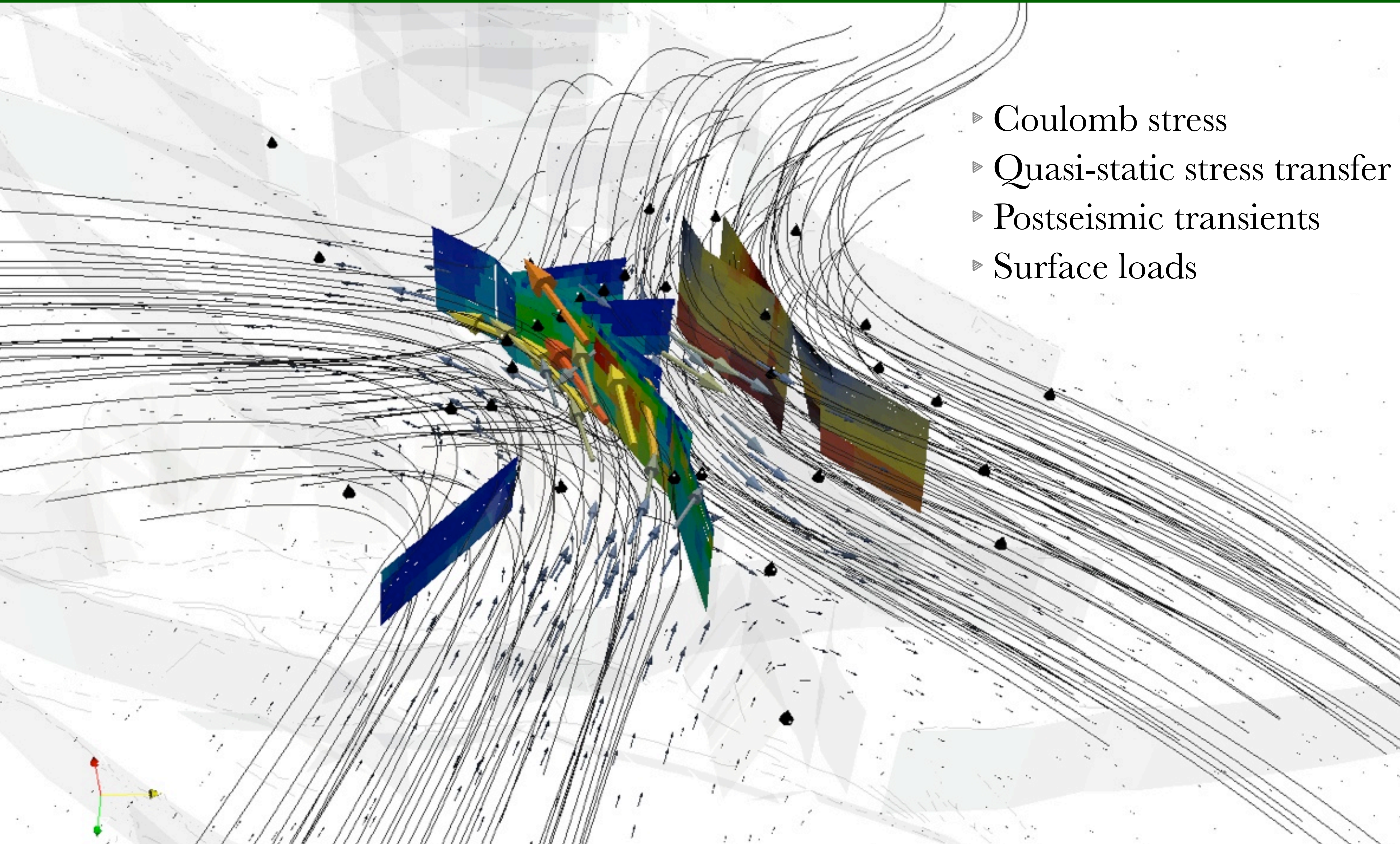
Relax



- Coulomb stress
- Quasi-static stress transfer
- Postseismic transients
- Surface loads

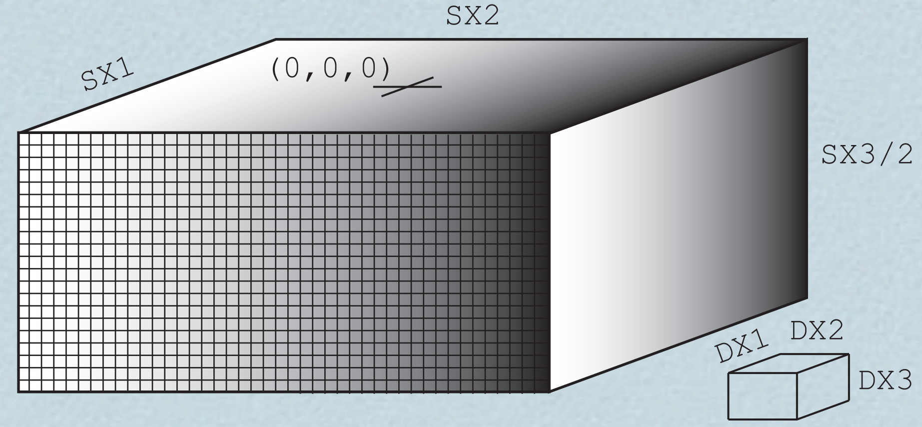
Relax Examples

- Coseismic slip
  - Simplest input file
  - Complex fault geometry
- Viscoelastic flow
  - Simple nonlinear viscoelastic flow model
  - El Mayor-Cucapah
- Research examples
  - 2010 Mw 7.2 El Mayor-Cucapah earthquake
  - 1999 Mw 7.6 Chi-Chi earthquake
  - GRACE surface loads in the Himalayas

Coseismic slip - Simplest model

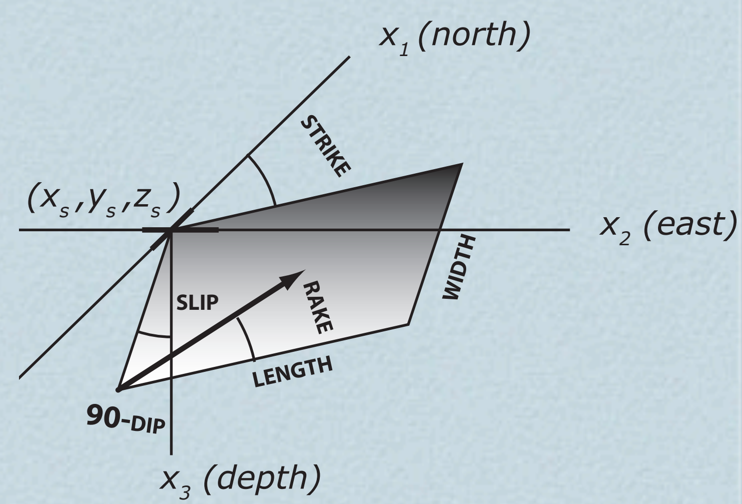
Mesh is uniform and rectangular

```
relax --no-proj-output <<EOF
# SX1,SX2,SX3 (grid size)
256 256 256
# dx1,dx2,dx3 (km),beta (0-0.5),nq 2
0.5 0.5 0.5 0.2 2
...
EOF
```



list the fault patches

```
relax <<EOF
...
#no slip   xs     ys   zs length width strike dip   rake
  1 1.34 14.2 -45.43 10.0    5.6  4.94  132.7  91 -114.7
  2 1.89 10.4 -41.31 10.0    5.6  4.94  132.7  91 -151.8
  3 0.46 14.2 -45.41  6.5   3.74  3.53  132.7  91 -150.6
...
EOF
```



Coseismic slip - Simplest model

```
relax --no-proj-output <<EOF
# SX1,SX2,SX3 (grid size)
256 256 256
# dx1,dx2,dx3 (km),beta (0-0.5),nq (2)
0.5 0.5 0.5 0.2 2
# origin position & rotation
0 0 0
# observation depths for displacement and for stress
0 5
# output directory (all output written here)
output_directory
# lambda (MPa), mu (MPa), gamma (1/km)
3e4 3e4 8.33e-4
# integration time, time step and scaling
0 -1 1
# number of viscous observation slice
0
# number of observation points
0
# number of Coulomb patches
0
# number of prestress interfaces
0
# number of linear viscous interfaces
0
# number of power-law viscous interfaces
0
# number of friction faults
0
# number of interseismic loading strike-slip and opening
0
0
```

computational grid

constitutive parameters

sources

```
# number of events
1
# number of shear dislocations
1
# no slip  xs ys zs length width strike dip rake
   1    1 -10  0  0      10     10       0  90     0
# number of tensile cracks
0
# number of dilatation sources
0
# number of surface traction
0
EOF
```

Coseismic slip - Complex fault geometry

Coseismic slip distribution of Fialko (2004).
Location: `examples/mojave/landers.sh`

```
1 1.3475 14.246 -45.439 10.056 5.6 4.94 132.7 91.0 -114.7
2 1.8921 10.446 -41.319 10.056 5.6 4.94 132.7 91.0 -151.8
3 0.46688 14.201 -45.481 6.5269 3.74 3.53 132.7 91.0 -150.6
4 0.38986 11.668 -42.734 6.5269 3.74 3.53 132.7 91.0 -175.6
5 1.3331 9.1346 -39.987 6.5269 3.74 3.53 132.7 91.0 172.8
6 0.20179 14.168 -45.511 4.0058 2.8 2.52 132.7 91.0 157.4
7 0.29966 12.268 -43.45 4.0058 2.8 2.52 132.7 91.0 144.0
...
426 0.0052909 -3.3563 -14.937 0 0.97 0.914 89.3 91.0 90.0
```

list all the fault patches, filter, modify:

```
...
# number of coseismic events
1
# number of shear dislocations
`awk 'BEGIN{c=0}{if ($5 > 2 && $5 < 20){c=c+1}}END{print c}' $FLT`
# index slip x1 x2 x3 length width strike dip rake
`awk 'BEGIN{c=1}{if ($5 > 2 && $5 < 20){$1=c;print $0;c=c+1}}' $FLT`
# number of tensile cracks
0
...
```

Coseismic slip - Complex fault geometry

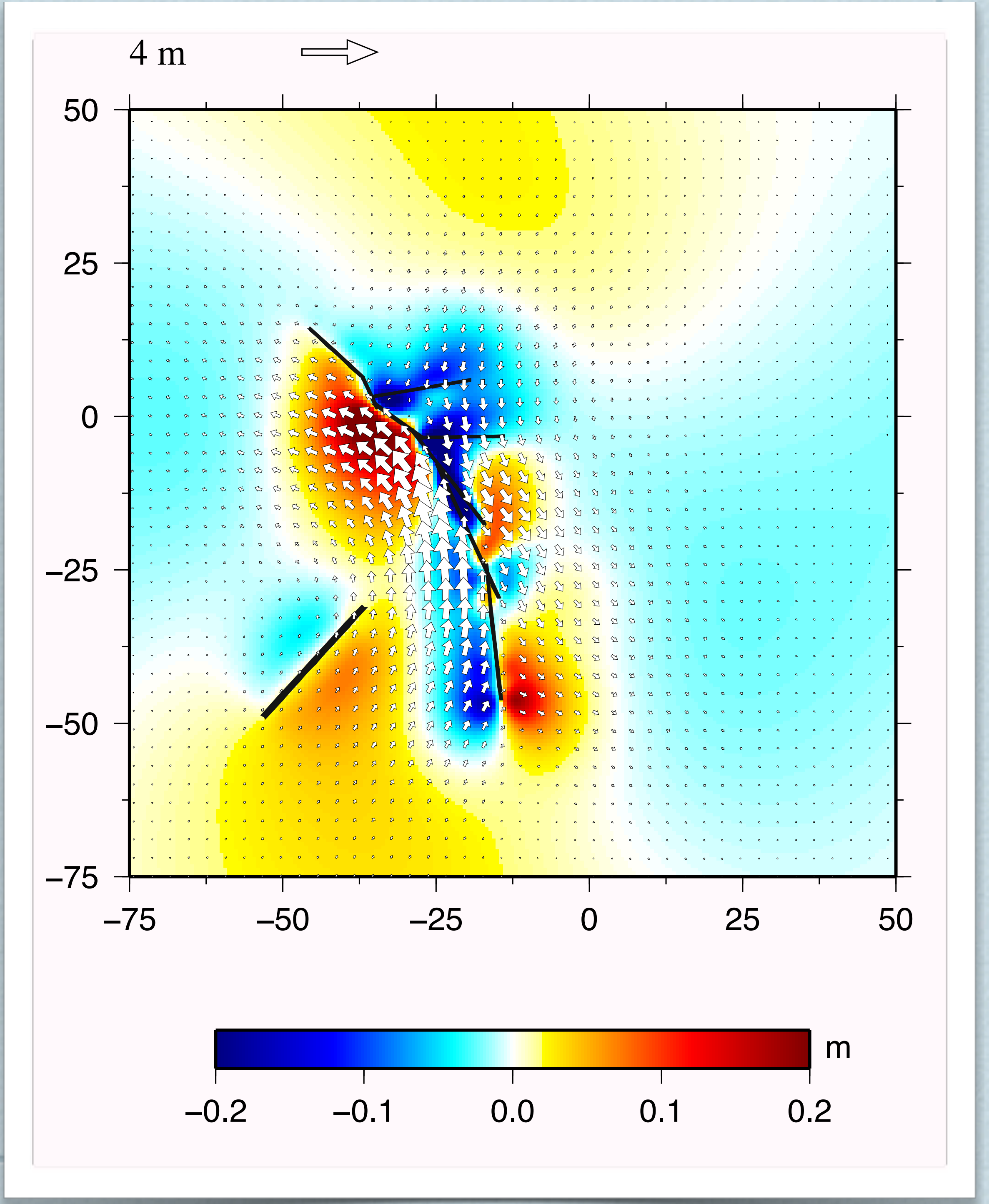
GMT plots with the postprocessing tool `grdmap.sh`

```
grdmap.sh -b -75/50/-75/50 -v 4 -t 25
-p -0.2/0.2/0.002 -u m -e ../../util/
erpatch.sh landers/000
```

type:

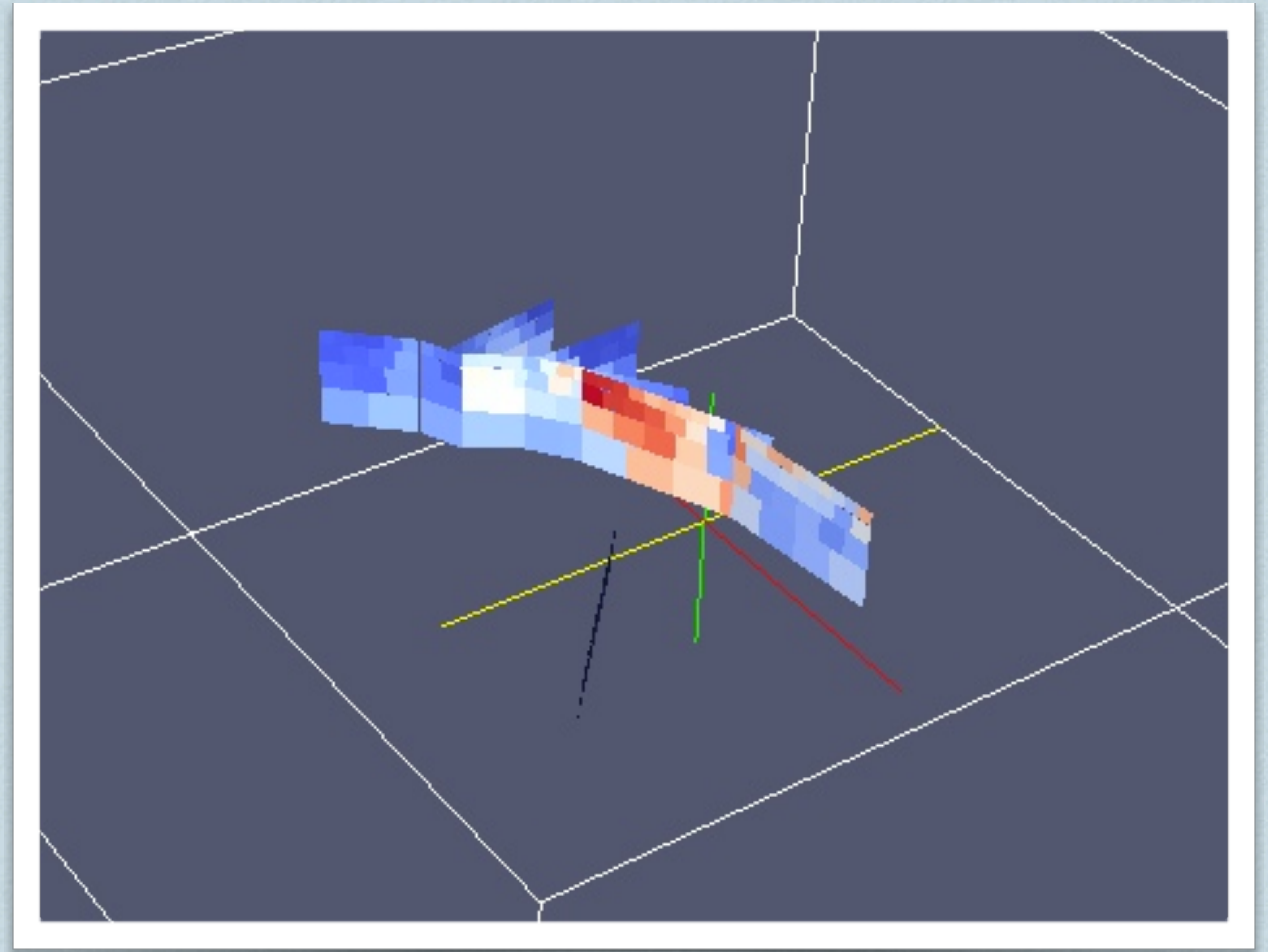
```
grdmap.sh -h
```

for more information.



Coseismic slip - Complex fault geometry

Paraview display



Nonlinear viscoelastic flow

nonlinear viscoelastic relaxation following slip on a strike-slip fault
Location: `examples/tutorials/run2.sh`

setup the duration of the simulation

```
...
# integration time (in years), time step, scaling factor
20 -1 0.5
...
```

setup the mechanical structure

```
...
# viscous interfaces are depths where the viscous properties change.
# number of linear viscous interfaces
0
# number of powerlaw viscous interfaces
2
# no depth gammadot0 power cohesion
   1   2.0       5e3   3.0      0.0
   2   8.0       5e3   3.0      0.0
# ductile zones corresponds to volumes where viscous properties change.
# number of power-law ductile zones
0
```

Nonlinear viscoelastic flow

nonlinear viscoelastic relaxation following slip on a strike-slip fault
Location: `examples/tutorials/run2.sh`

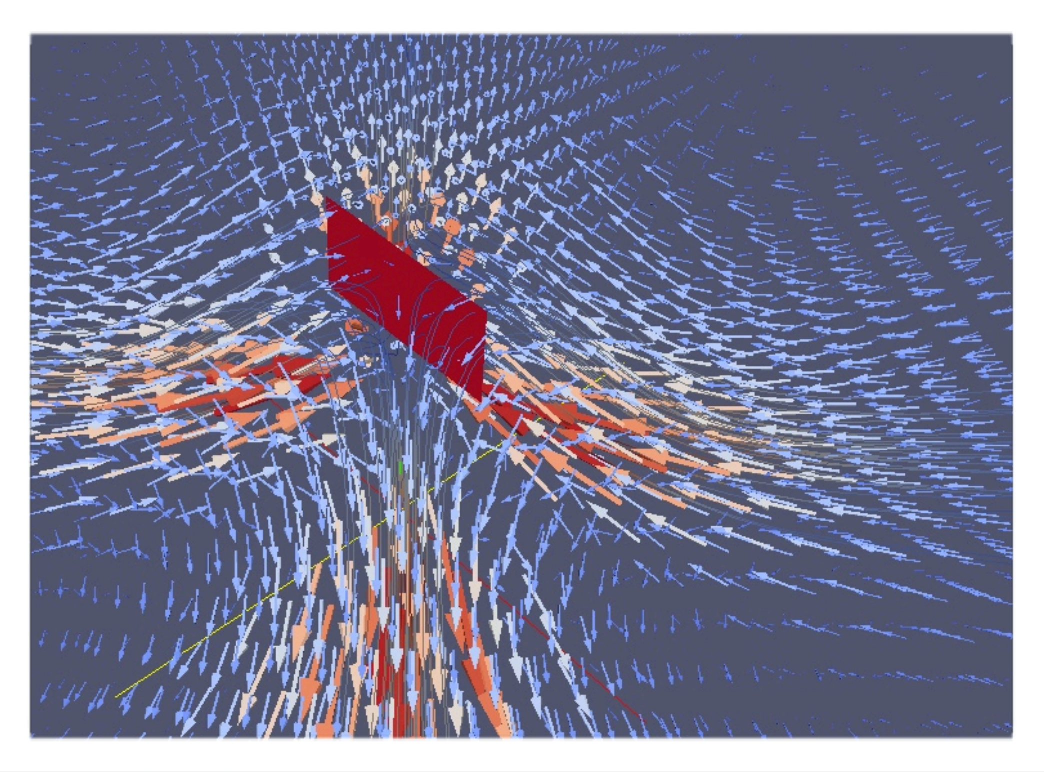
GMT plot of the coseismic deformation

```
> grdmap.sh -b -3/3/-3/3 -v 0.5 -p -0.05/0.05/0.001 -e ../../util/erpatch.sh
output2/000
```

GMT plot of the postseismic deformation

```
> grdmap.sh -b -5/5/-5/5 -v 0.01 -p -0.005/0.005/0.0001 -s 0.5 -
e ../../util/erpatch.sh output2/050-relax
```

Paraview rendering of
the postseismic transient

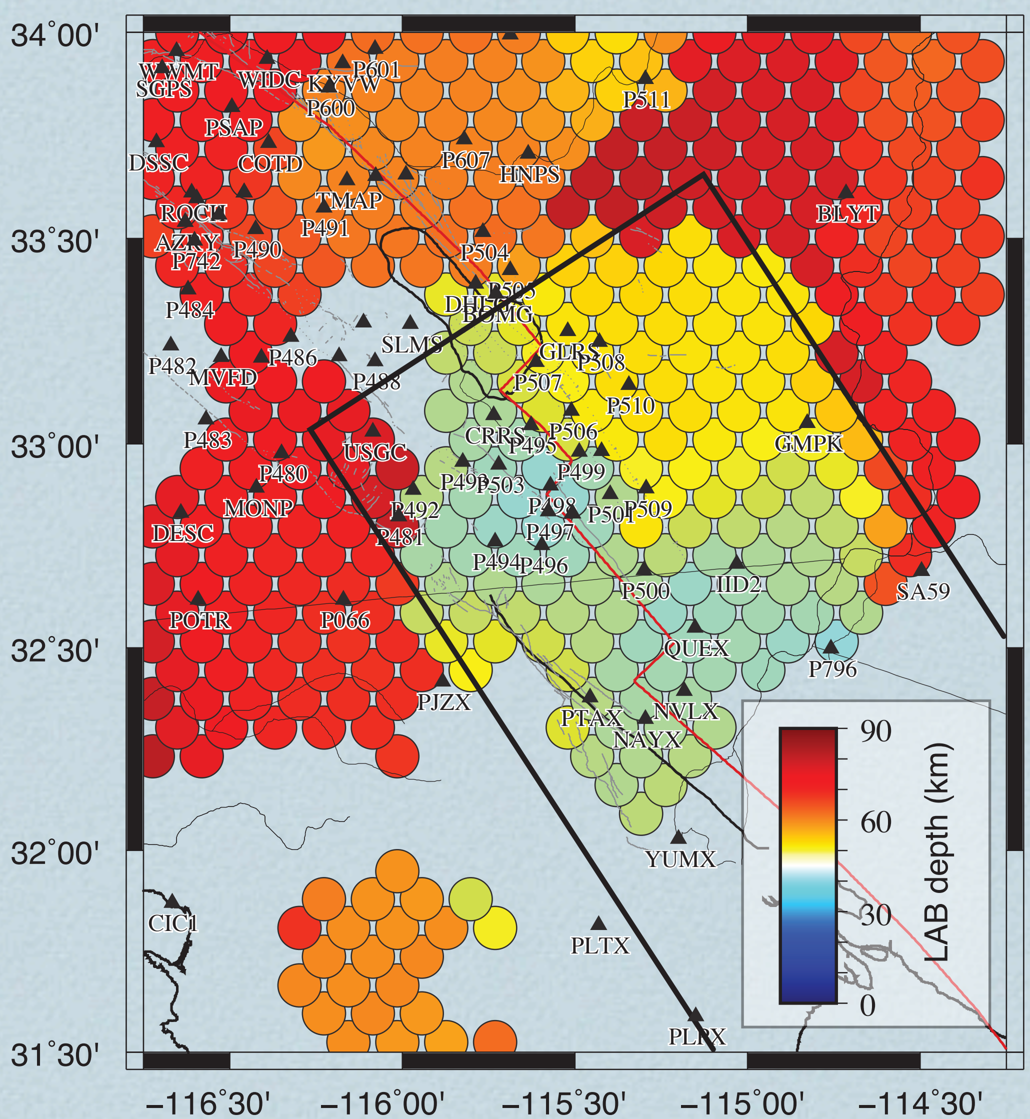


Relax
Research Examples

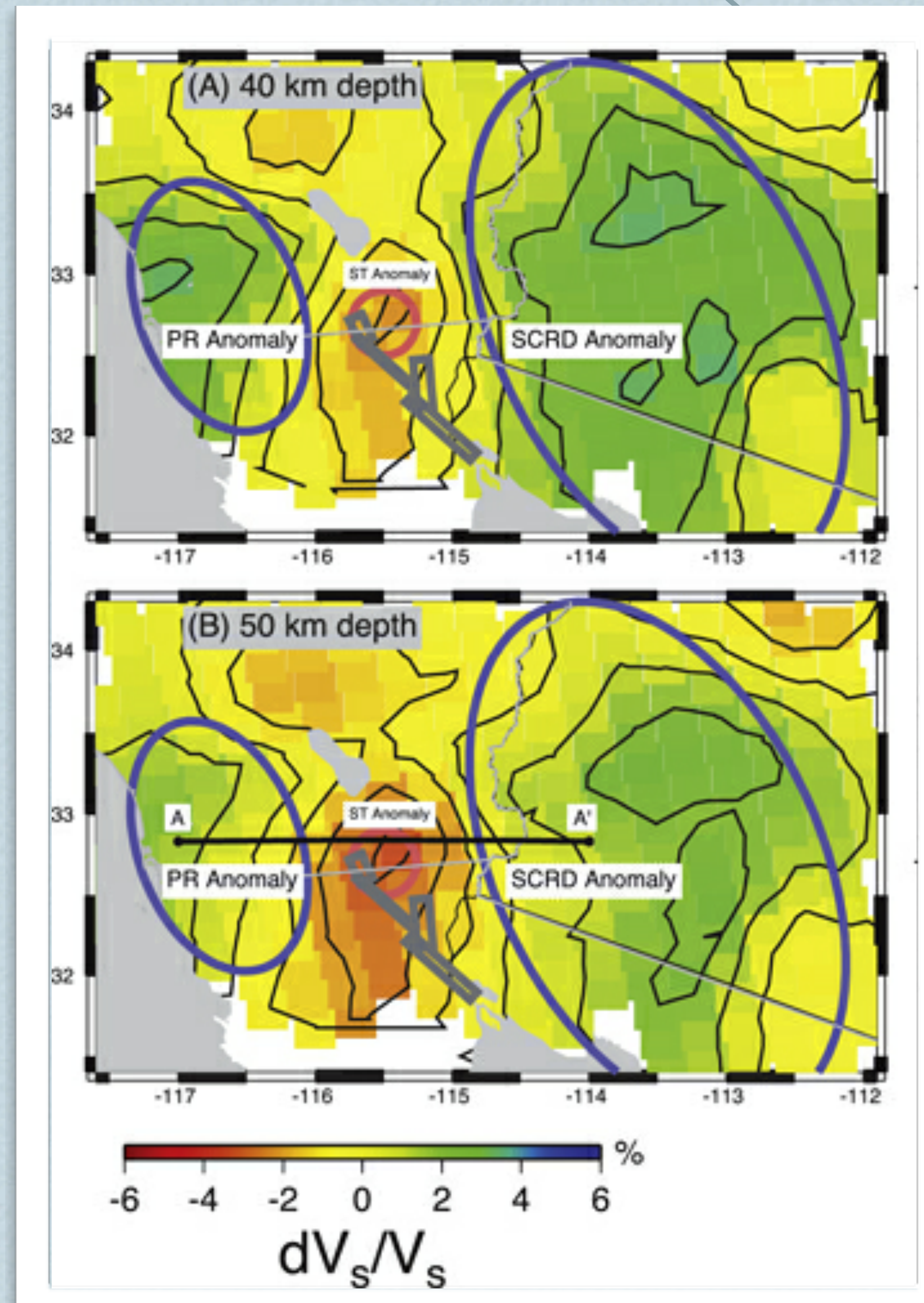
From geological settings to geophysical modeling

Case of the El Mayor-Cucapah earthquake

Total strain is decomposed in elastic and inelastic strain components

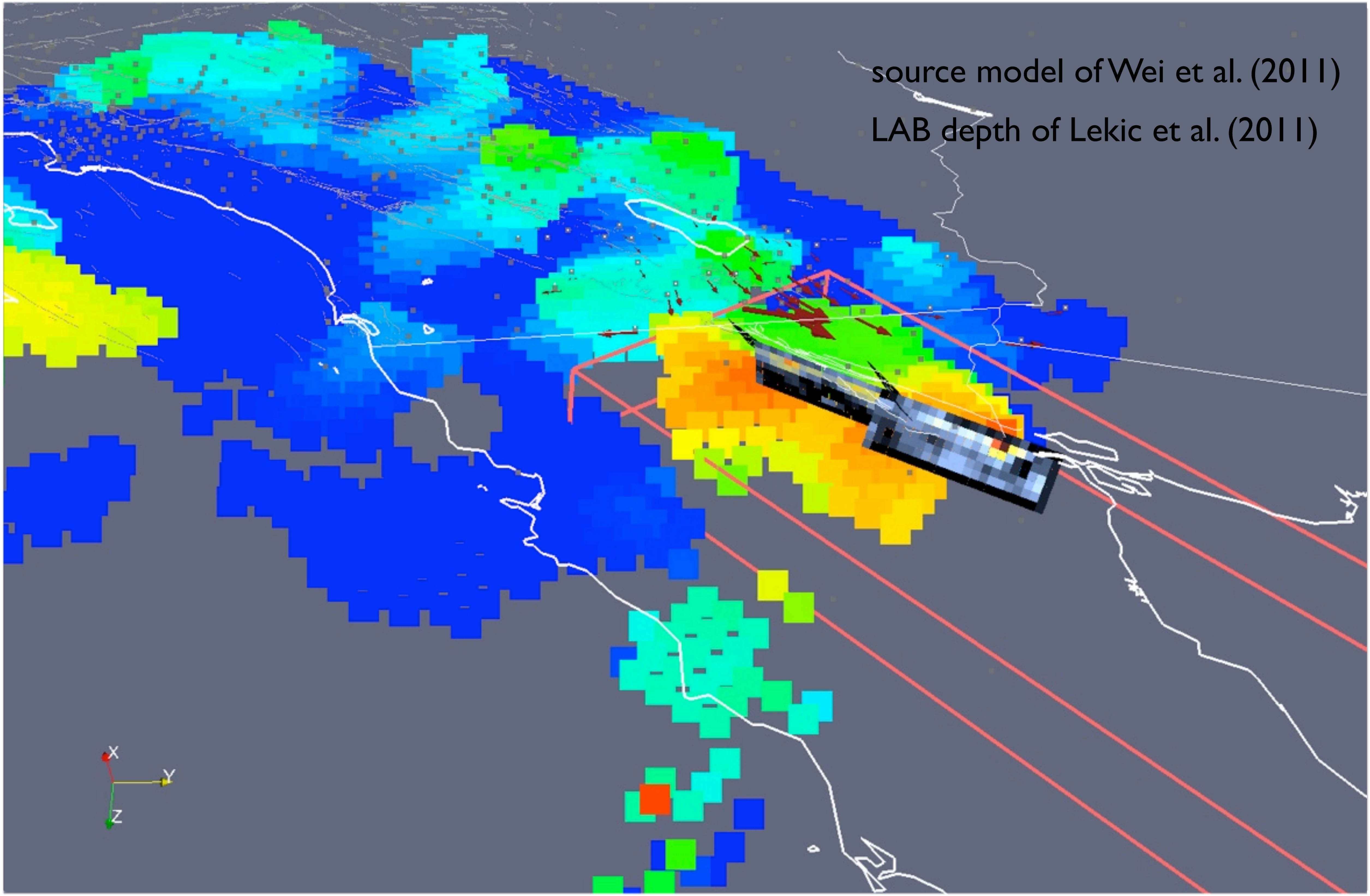


adapted from Lekic et al. (2011)



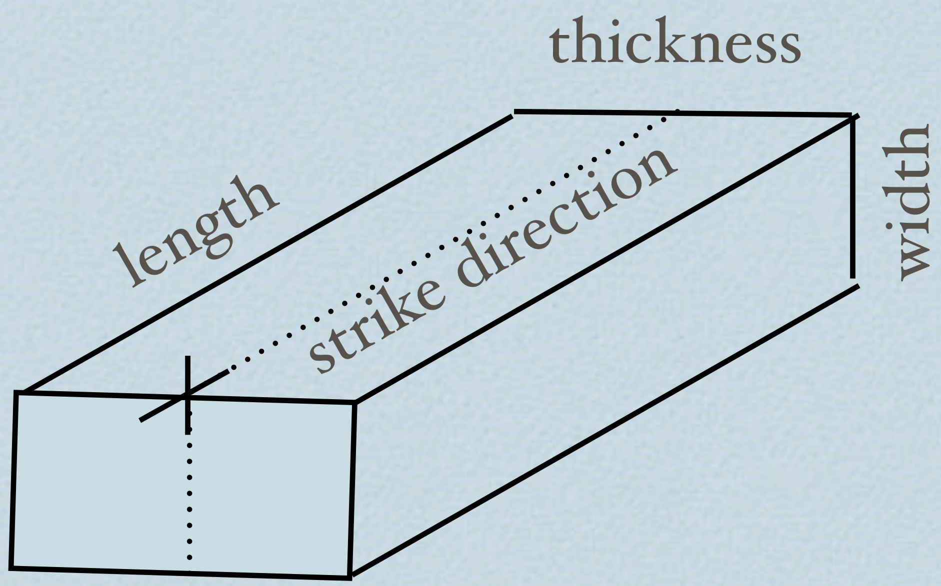
Pollitz et al. (2012)

Case of the El Mayor-Cucapah earthquake



Case of the El Mayor-Cucapah earthquake

Setup a mechanical structure with lateral variations in viscous properties




```
...
# number of linear viscous interfaces
0
# number of powerlaw viscous interfaces
1
# no depth gammadot0 power cohesion
   1    70         1   1.0      0.0
# number of nonlinear ductile zones
2
# no dgammadot0 x1  x2 x3 length width thickness strike dip
   1          1 90 -20 40    400    30        140    147  90
   2          1 90 -20 55    100    15        140    -33  90
# number of fault creep interface
0
...
```

Case of the El Mayor-Cucapah earthquake

file `$OPTS` contains a list of stations

```
NAYX 19.5234 -19.1933 -0.023816
NVLX 29.9628 -11.3416 -0.0211503
PTAX 4.29884 -13.5242 1.06037
QUEX 32.4871 5.96725 -0.0162088
YUMX 29.1409 -51.9288 -0.0284696
P796 69.5972 0.98512 0.0101659
...
```

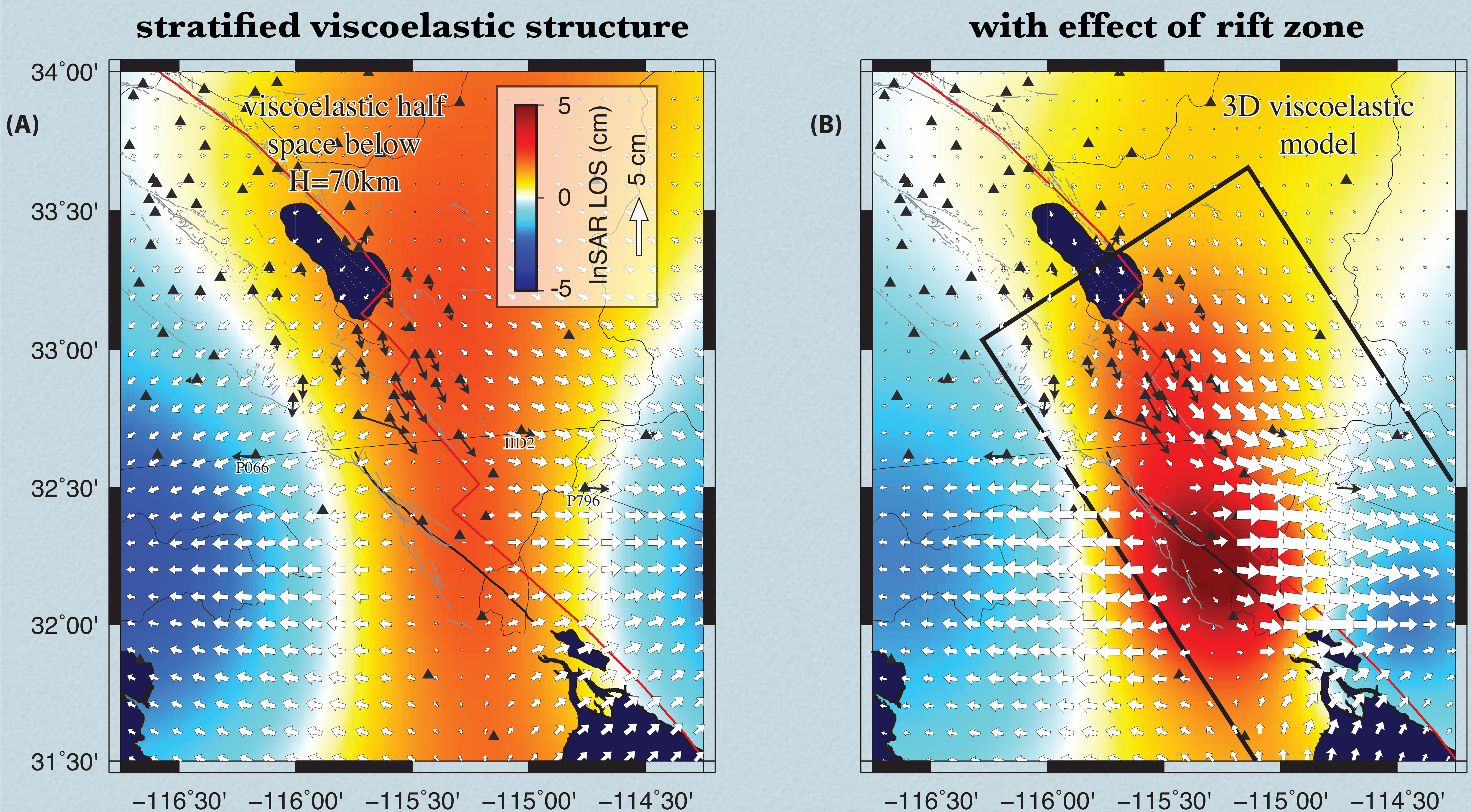
file `$OPTS` contains a list of stations

```
...
# number of observation points
`grep -v "#" $OPTS | awk -v l=$LEN \
        'function abs(x){return (0>x)?-x:x}
         BEGIN{i=0}
         {if (abs($2)<l && abs($3)<l){i=i+1;}}
         END{print i}'`
# no NAME x1 x2 x3
`grep -v "#" $OPTS | awk -v l=$LEN \
        'function abs(x){return (0>x)?-x:x}
         BEGIN{i=0}
         {if (abs($2)<l && abs($3)<l){i=i+1;print i,$1,$3,$2,0}}'`
# number of stress observation segments
0
```

filter out GPS stations outside the computation grid

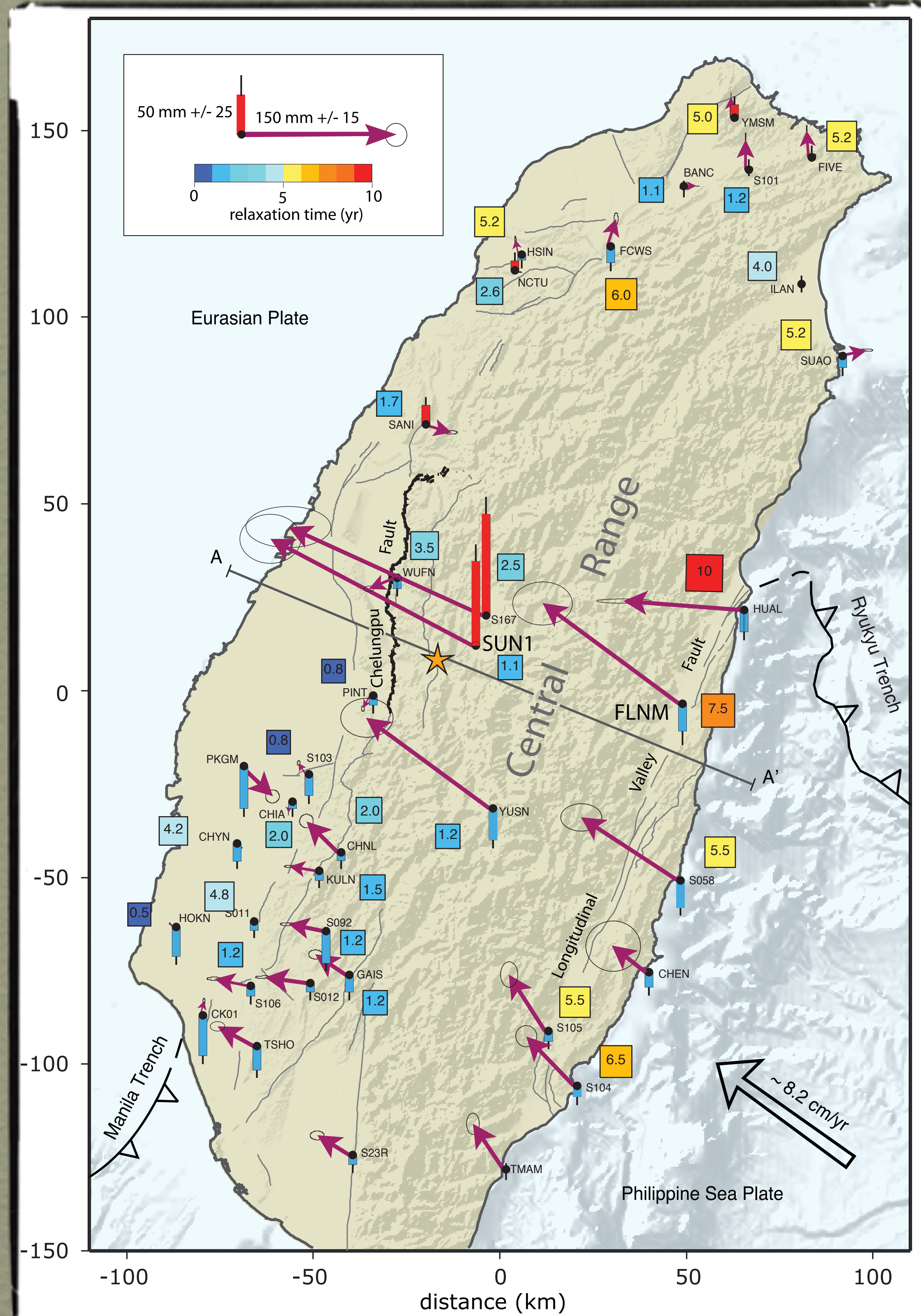
Case of the El Mayor-Cucapah earthquake

Investigating the effect of rifting on postseismic relaxation



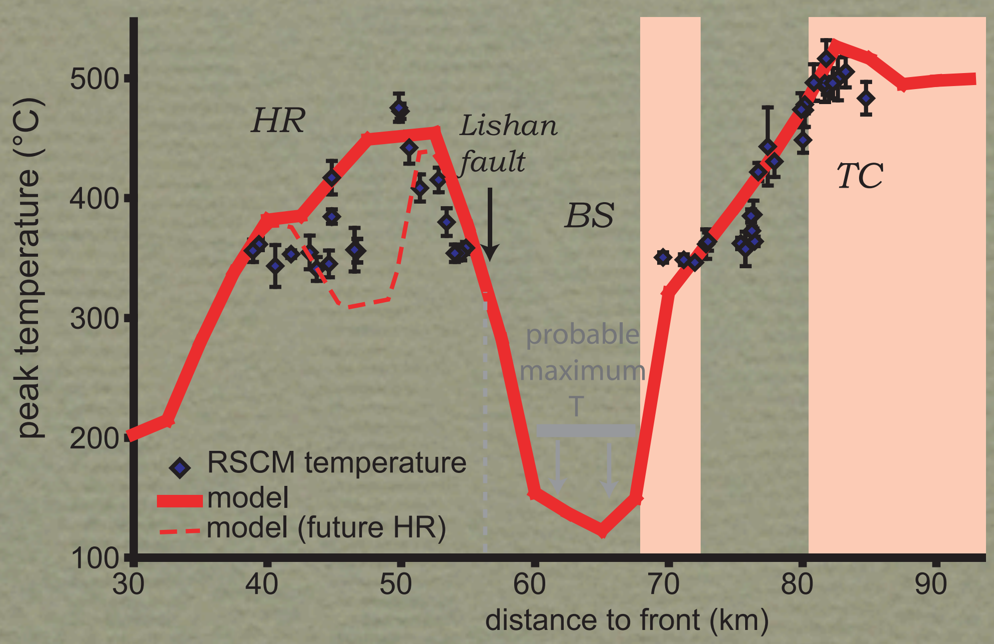
Postseismic relaxation following the 1999 Mw 7.6 Chi-Chi earthquake

- Largest displacements in the near field of the rupture in a direction compatible with thrusting.
- Anomalously high cumulative displacements 10 yr after the quake along the Longitudinal Valley.
- Localized deformation along the south extension of the Chelungpu Fault.
- Escape motion of the northern stations.
- Large heterogeneities of characteristic relaxation times with factors up to a factor of 10 or more.



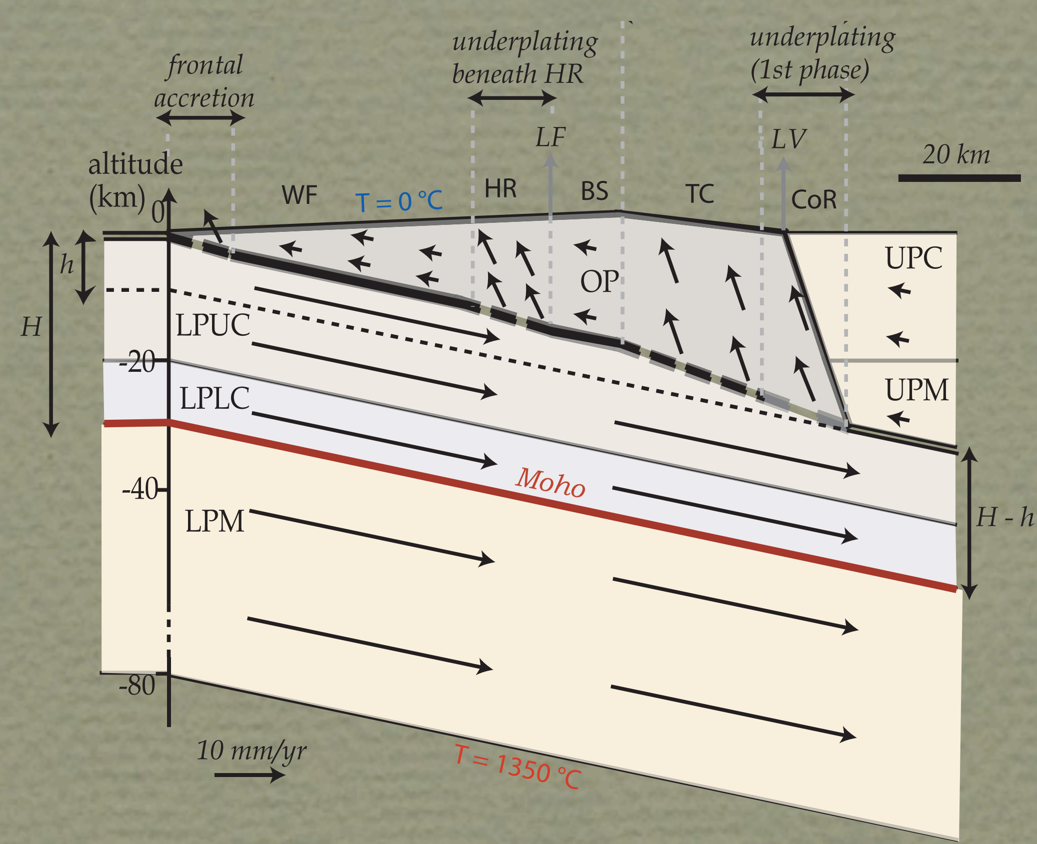
Uplift and exhumation of the Central Range

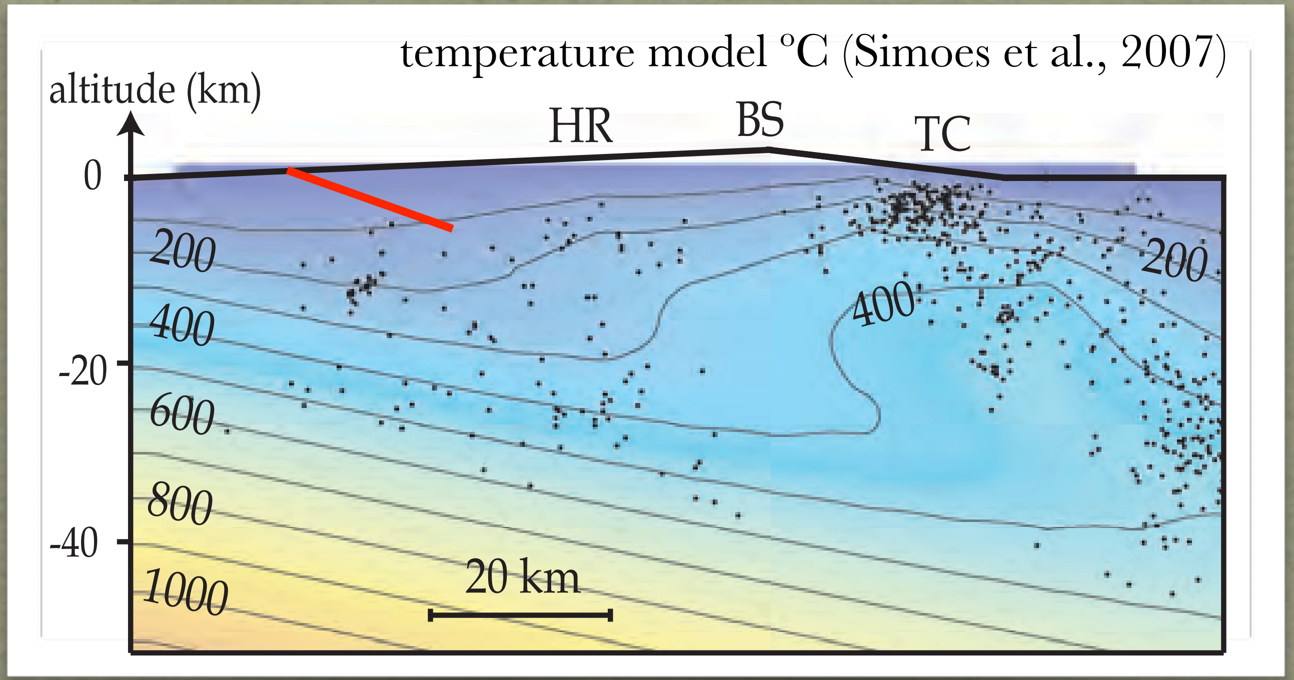
Beissac et al. (2007), Simoes et al. (2007)



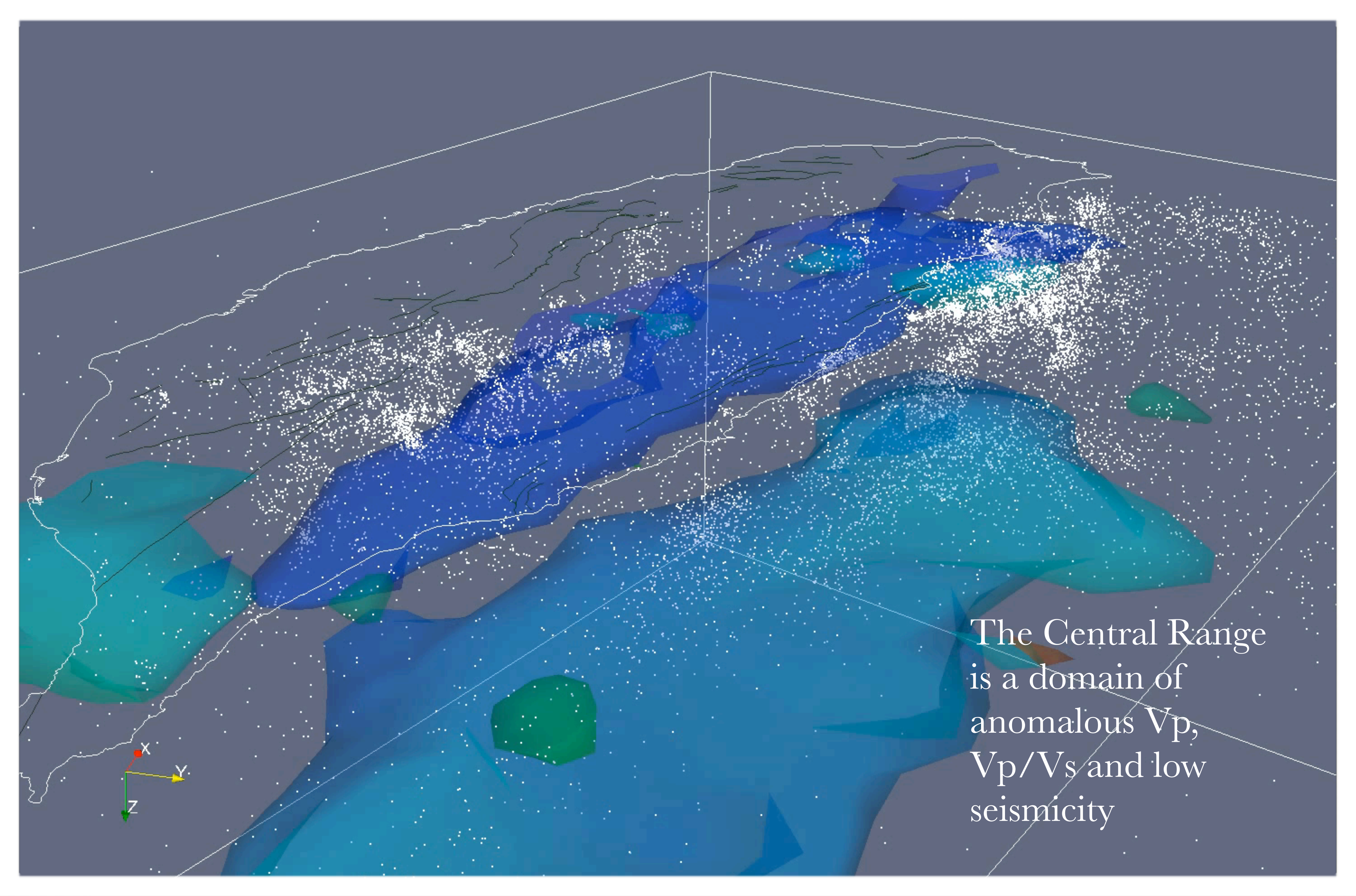
- Geothermologic markers indicate high temperature anomalies below the Hsuehshan Range (HR) and the Tananao Complex (TC) around a colder the Backbone Slate (BS) units.

- A thermo-kinematic model indicates that the high background thermal gradient of 30-35 °C/km in Taiwan is uplifted to reach 400 °C at 10 km depth.



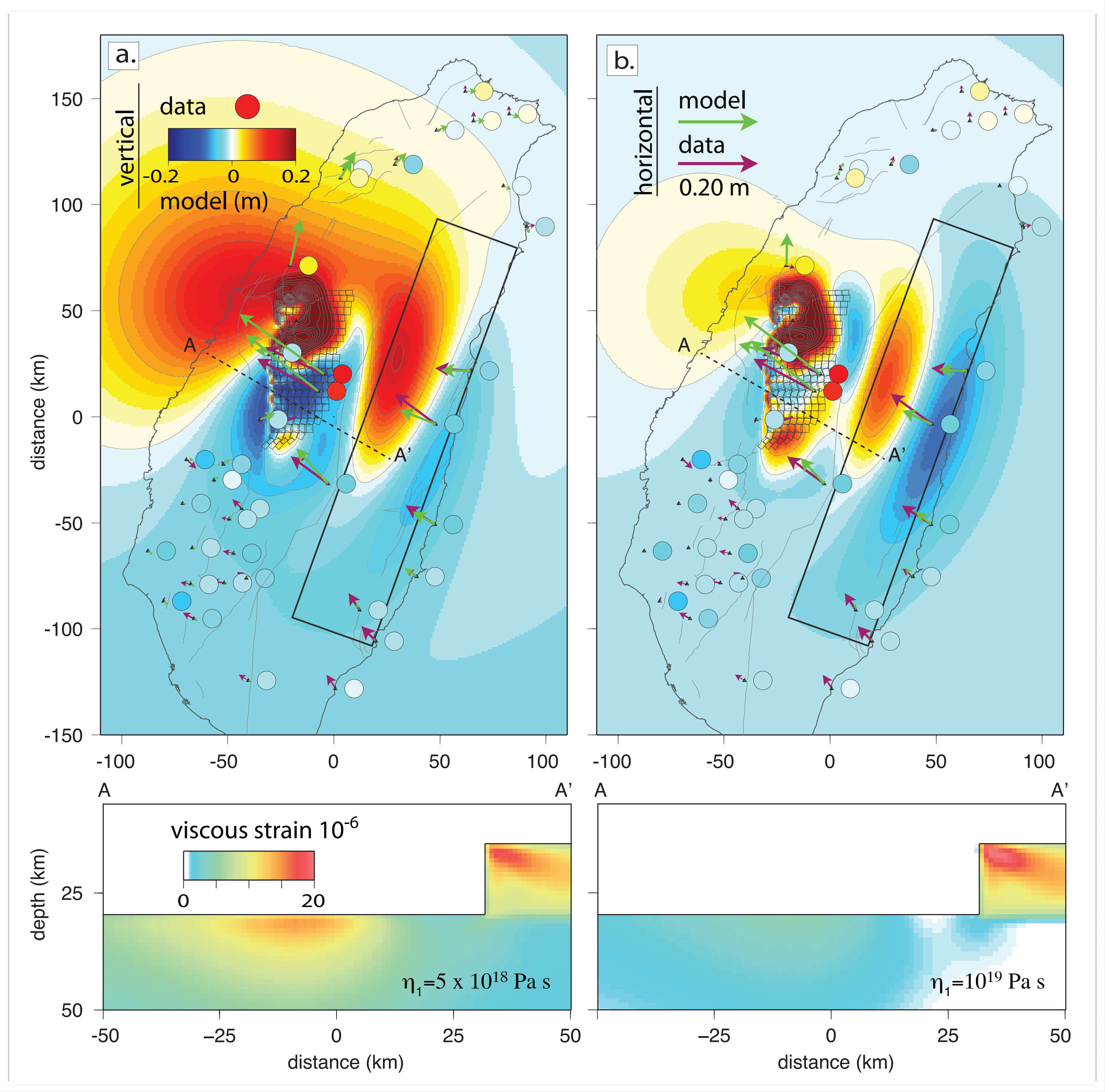


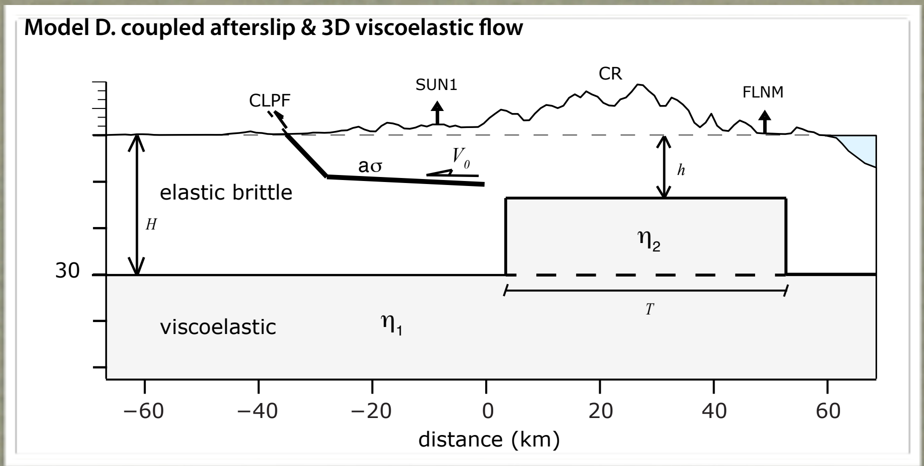
The Central Range Vp and seismic anomaly



data from (Wu et al., 1997, 2007)

Fully-coupled afterslip-viscoelastic models





- Explains many simultaneous features of the observations:
  - ➡ Near-field displacement
  - ➡ Long. Valley large displacements
  - ➡ Long. Valley vertical polarity
  - ➡ Extrusion of northern stations
  - ➡ Different time scales in the near field and far field
- Vertical polarity in the near field greatly depends on the details of the viscoelastic structure.
- Lower-crust viscosity: 0.5-1x10^{19} Pa s
- Mid-crust viscosity: 0.5x10^{17} Pa s

1999 Mw 7.6 Chi-Chi, Taiwan, earthquake

Setup the mechanical structure

```
...
# number of linear viscous interfaces
1
# no. x3 gammadot0 (1/tm) cohesion
    1 30       0.5                  0
# number of viscous zone
1
# no. dgammadot0      x1    x2 x3 length width thickness strike dip
   1            5 -101.48 -0.90 15    200    15         40      20  90
# number of nonlinear viscous interfaces
0
# number of fault creep interfaces
1
# no. x3  Vo (a-b)sigma friction cohesion
    1  0  30          1       0.6         0
# number of creeping faults
2
# no.     x1      x2 x3 length width strike dip rake
    1 -25.00 -32.00  0      80    20      5  30    90
    2 -26.51 -14.75 10      80    20      5   5    90
...
```

viscous substrate below 30km depth.

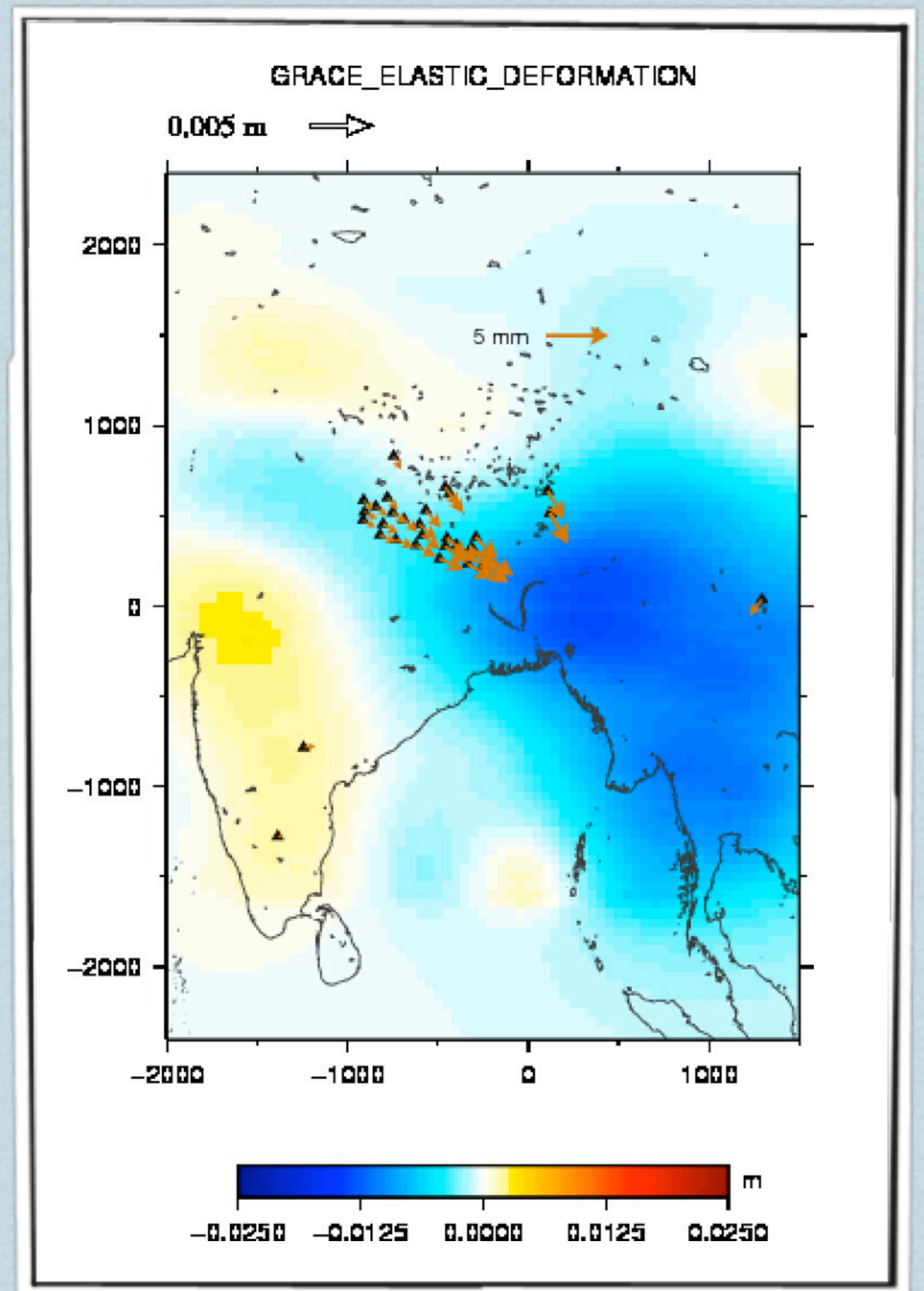
ductile zone below the Central Range.

friction properties for fault slip

creeping fault planes

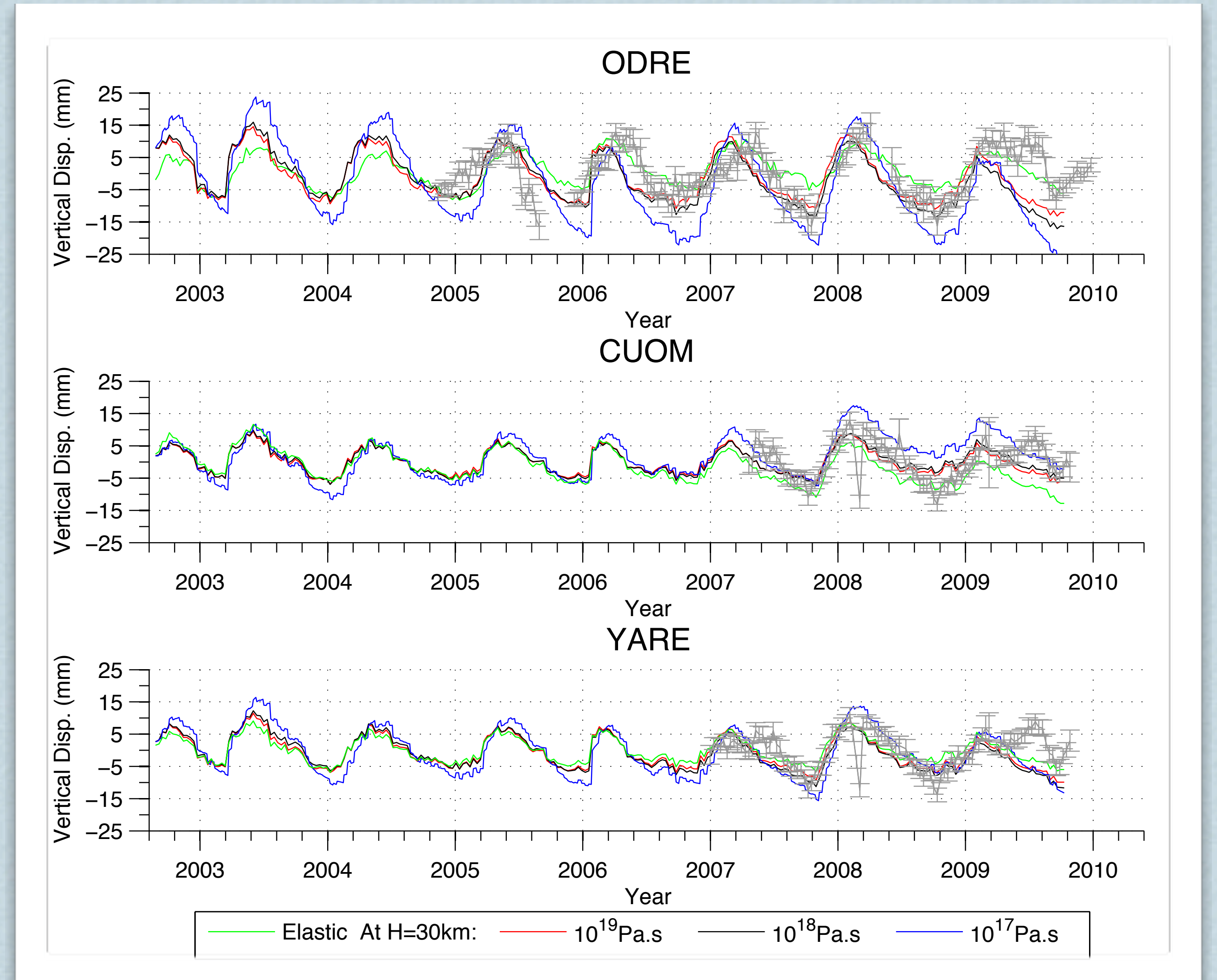
quick Paraview displays with the `--dry-run` option.

Monsoon excitation of the lower crust



Chanard et al. (in prep.)

Elastic or viscoelastic response to surface loads monitored by GRACE are modeled to compare with GPS time series.



Monsoon excitation of the lower crust

loads the list of GPS stations and setup the mechanical structure

```
# elastic parameters and gamma
80e6 80e6 8.33e-4
# integration time (years), time step (years)
7.12329 0.0273973
...
# number of observation points
`wc ../gps/gps_km.dat`
# no. NAME x1   x2 x3
`awk '{print NR,$1,$3,$2,0}' ../gps/gps_km.dat`
..
# number of linear viscous interfaces
1
# no depth gammadot0 cohesion (gammadot0=1/tm)
   1  20.0       10      0.0
# number of linear ductile zones
0
```

Monsoon excitation of the lower crust

with a database of GRACE loads as a function of time

```
0               20020728_20020806_km.dat
0.0273973       20020807_20020816_km.dat
0.0547945       20020817_20020826_km.dat
0.0821918       20020827_20020905_km.dat
0.1095890       20020906_20020915_km.dat
0.1369860       20020916_20020925_km.dat
...
7.0411000       20100329_20100407_km.dat
7.0684900       20100408_20100417_km.dat
7.0958900       20100418_20100427_km.dat
```

long list of surface loads

construct a complex history of loading

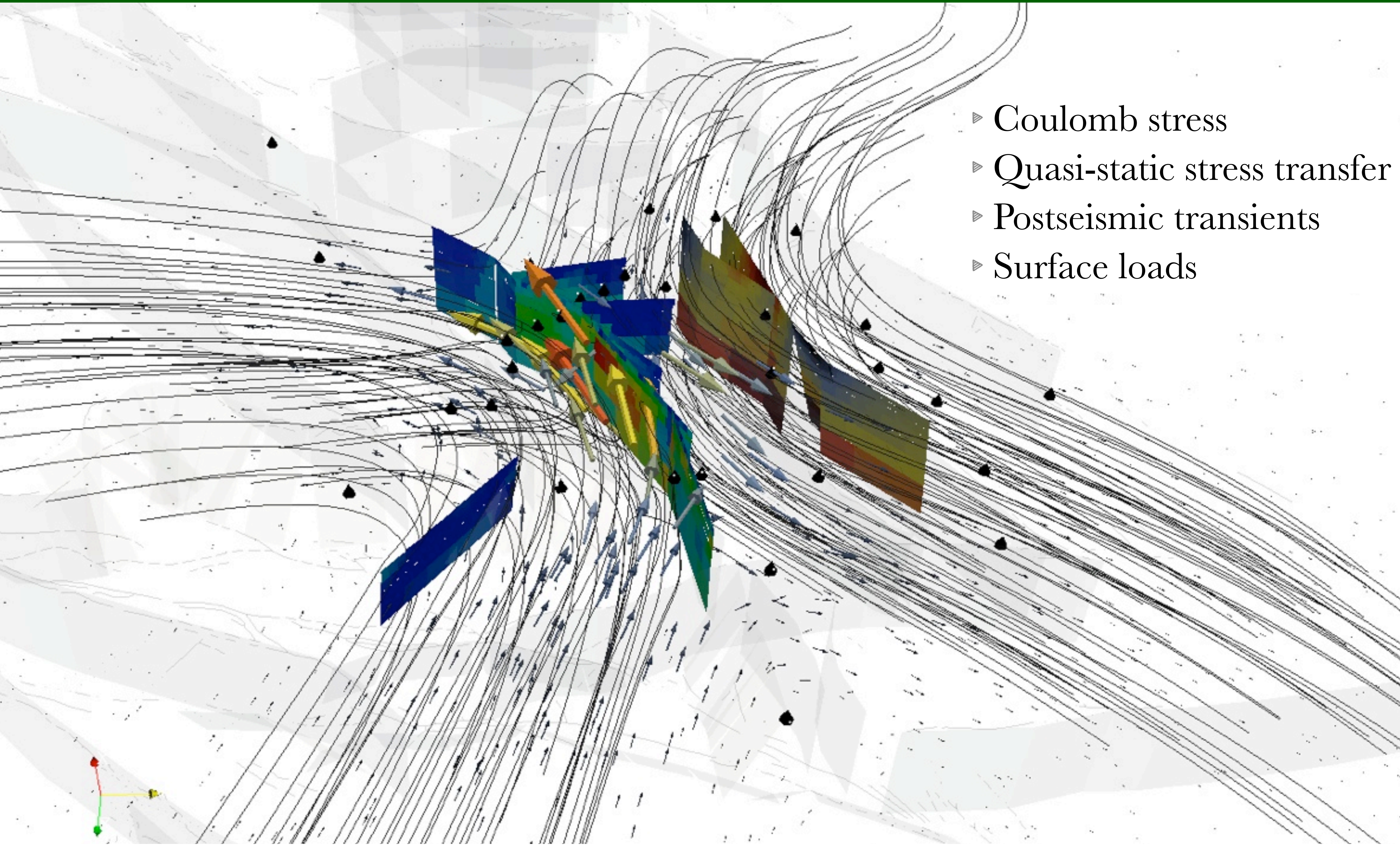
```
# number of coseismic events (when slip distribution is prescribed)
`wc $DDIR/$CATALOG`
`awk -v d=$DDIR '{
  if (0!=$1){print $1};
  print 0;
  print 0;
  print 0;
  system("wc "d"/"$2);
  system("cat "d"/"$2)}' $DDIR/$CATALOG`
EOF
```

More real-world examples

Explore the database of published coseismic slip models and their input file before starting your own

- Database of coseismic slip models and input files
  - 1964 Mw 9.2 Alaska earthquake
  - 1992 Mw 7.3 Landers, CA earthquake
  - 1999 Mw 7.1 Hector Mine, CA earthquake
  - 1999 Mw 7.6 Chi-Chi, Taiwan earthquake
  - 2001 Mw 7.8 Kokoxili, Tibet earthquake
  - 2004 Mw 6.0 Parkfield, CA earthquake
  - 2010 Mw 6.8 Yushu, Qinghai, China earthquake
  - 2011 Mw 9.0 Tohoku, Japan earthquake
  - 2010-2011 Canterbury earthquakes, New Zealand

Relax



- Coulomb stress
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