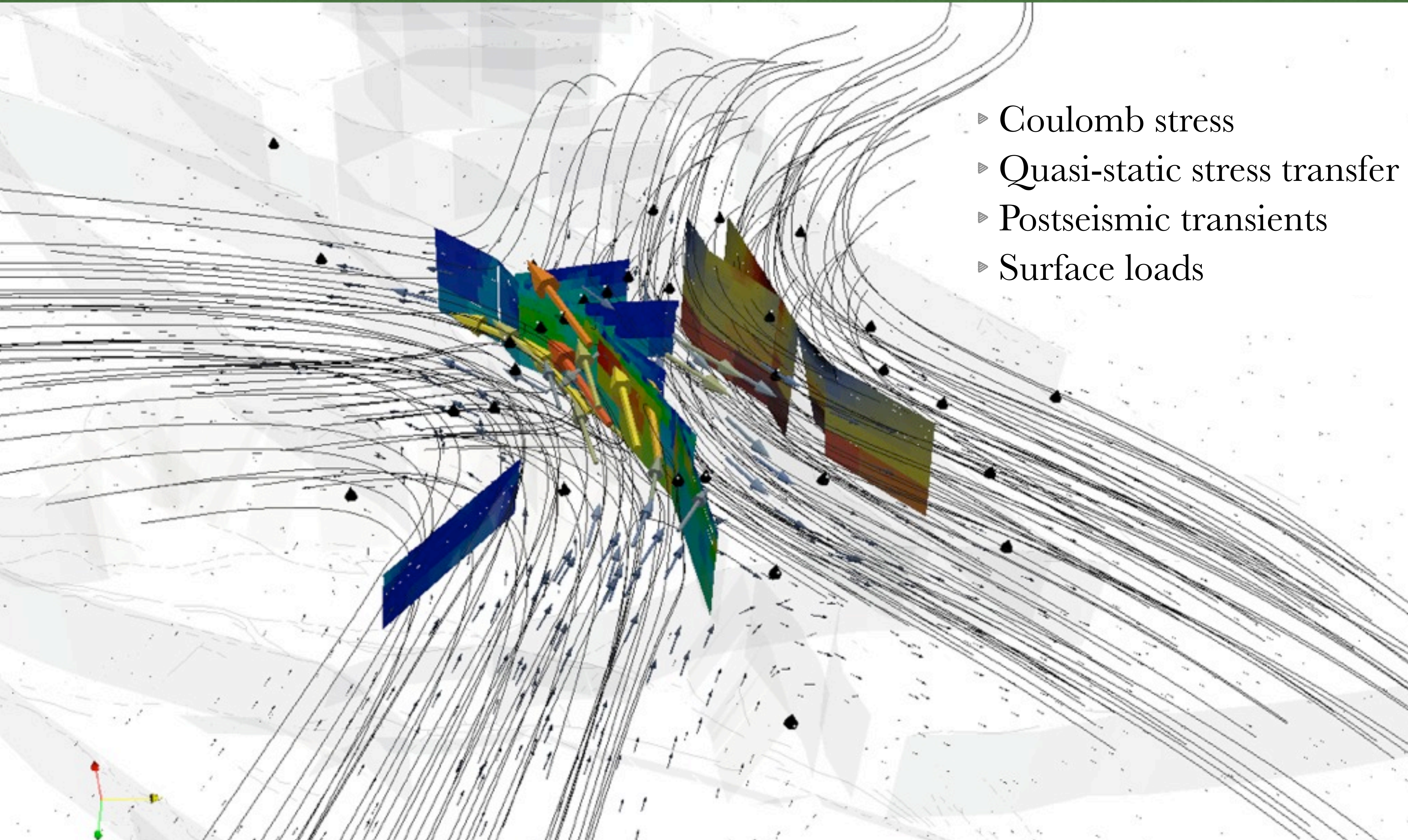
Relax

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

Sylvain Barbot
Earth Observatory of Singapore
Nanyang Technological University

Relax



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

Practical introduction to Relax 1.0.4

We will look at examples of:

- Quasi-static stress transfer between faults,
- Afterslip in a thrust environment,
- Structural data in viscoelastic deformation models.

And we will discuss research examples of postseismic relaxation for:

- the 1999 7.6 Chi-Chi, Taiwan earthquake,
- the 2010 Mw 7.2 El Mayor-Cucapah earthquake.

Relax source code and binaries

The official web page of Relax 1.0.4 is

```
http://www.geodynamics.org/cig/software/relax/
```

where you can find the source code and binaries for Windows, Linux, Mac, and Centos platforms, and documentation.

The developer version of the code (with latest improvements) is controlled with Mercurial. In a terminal, you can obtain the history of modifications with:

```
$ hg clone http://geodynamics.org/hg/short/3D/relax relax
```

Mac users can obtain Relax 1.0.4 and its dependencies from fink with:

```
$ fink install relax
```

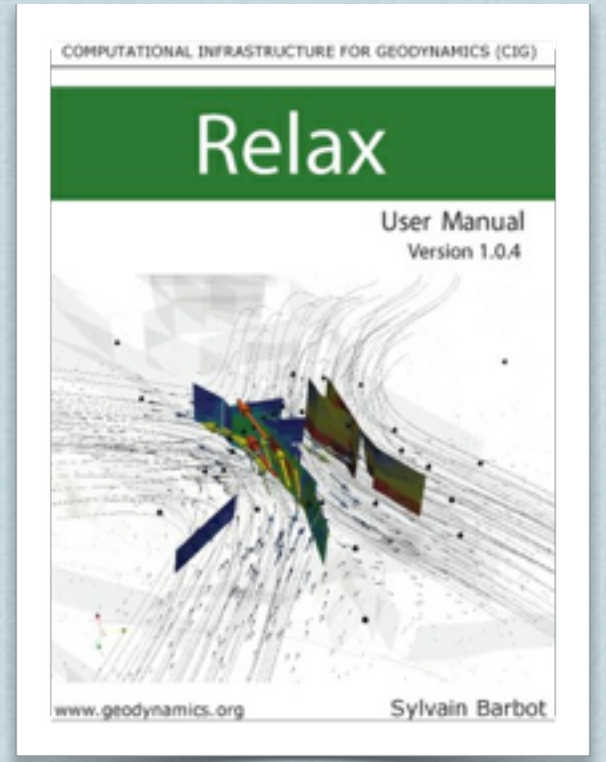
Visualization of simulations can be done with GMT and Paraview

```
http://www.paraview.org            http://gmt.soest.hawaii.edu
```

Relax documentation

- A user manual is available at:

```
http://www.geodynamics.org/cig/software/relax/
relax-documentation.pdf
```



It describes how to run examples and how to visualize the data with GMT and Paraview.

- Detailed documentation of input parameters is available on the unix manual page:

```
$ man relax

man(1)                                                      relax man page

NAME
       relax  -  Evaluates the deformation due to fault slip, surface loading or
       seismic relaxation that follows due to fault creep or viscoelastic flow.

SYNOPSIS
       relax [-h] [--dry-run] [--help] [--no-grd-output]  [--no-proj-output]
       [--no-txt-output] [--no-vtk-output] [--no-xyz-output]
```

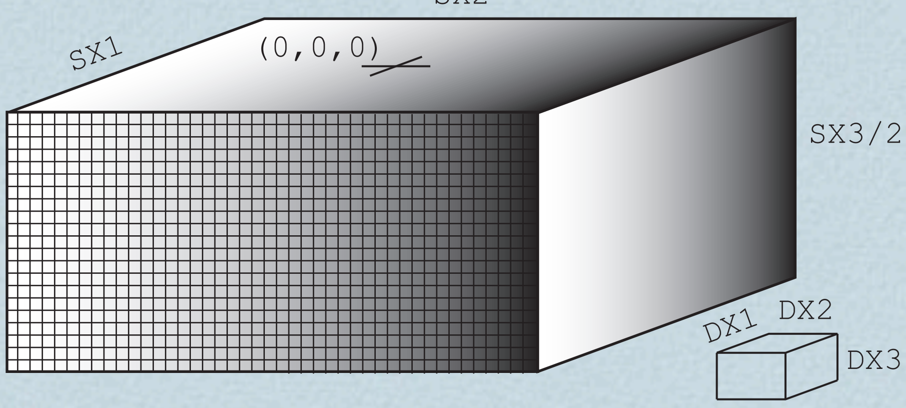
Relax

Understanding input files and visualizing simulations

Coseismic slip - Simplest model

Create a script (run.sh for unix, run.bat for windows). Look at examples in `examples/tutorials/run1.sh`. Type `relax --help` for a list of options.

```
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
...
# elastic parameters and gravity
30e3 30e3 8.33e-4
...
EOF
```



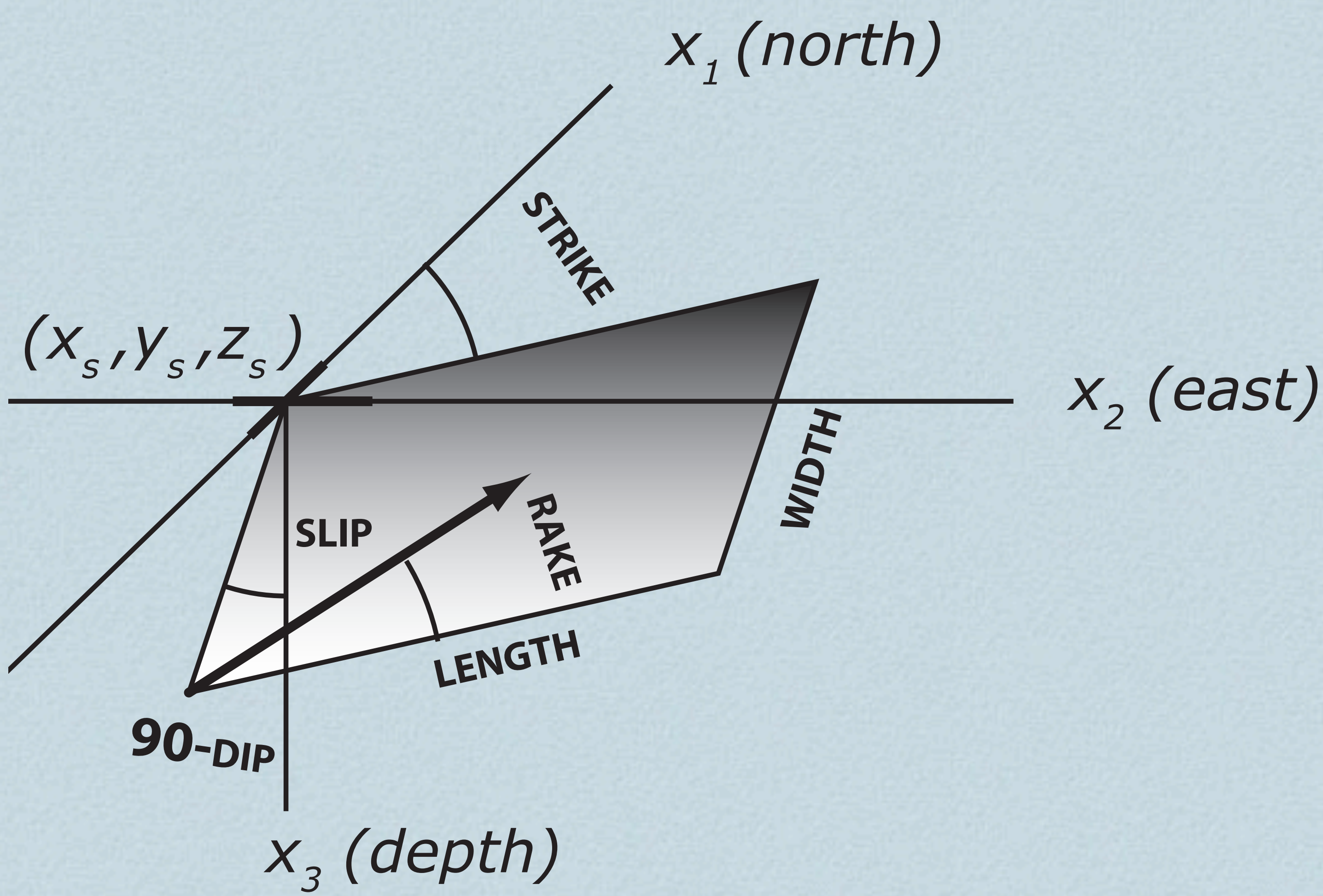
Mesh is uniform and rectangular

list the fault patches:

```
relax --no-proj-output <<EOF
...
#no slip   x1     x2    x3 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
```

Describing fault geometry: conventions

- Default strike-slip displacement is left lateral.
- Default dip-slip displacement is a thrust.



Attention!! x_1 points north. This is to obtain a right-handed reference system.

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
```

define computational grid

define constitutive parameters

define 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)*.

see: `examples/mojave/faults/landers_km.flt`

```
# no slip    x1        x2      x3 length width strike  dip    rake
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
...
426 0.0052909 -3.3563 -14.937 0  0.97 0.914   89.3 91.0   90.0
```

list all the fault patches in input file with `` `cat faults/landers_km.flt` ``, or filter and modify. See: `examples/mojave/landers.sh`

```
...
# number of coseismic events
1
# number of shear dislocations
`awk 'BEGIN{c=0}{if ($5 > 2 && $5 < 20){c=c+1}}END{print c}' faults/landers_km.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}}' faults/landers_km.flt`
# number of tensile cracks
0
...
```

Visualizing fault geometry

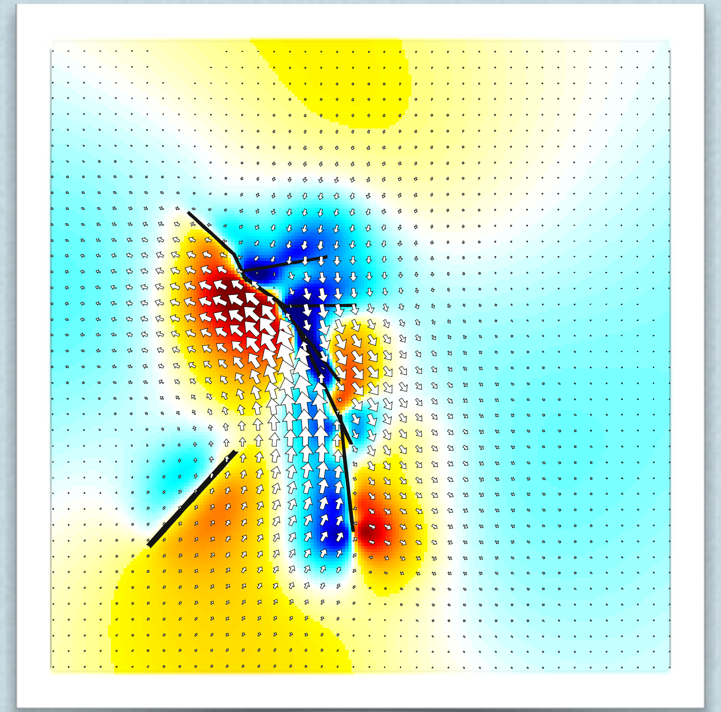
- **GMT display**

```
$ grdmap.sh -b -75/50/-75/50 -v 4 -p -0.2/0.2/0.002
-e ../../util/erpatch.sh landers/000
```

type:

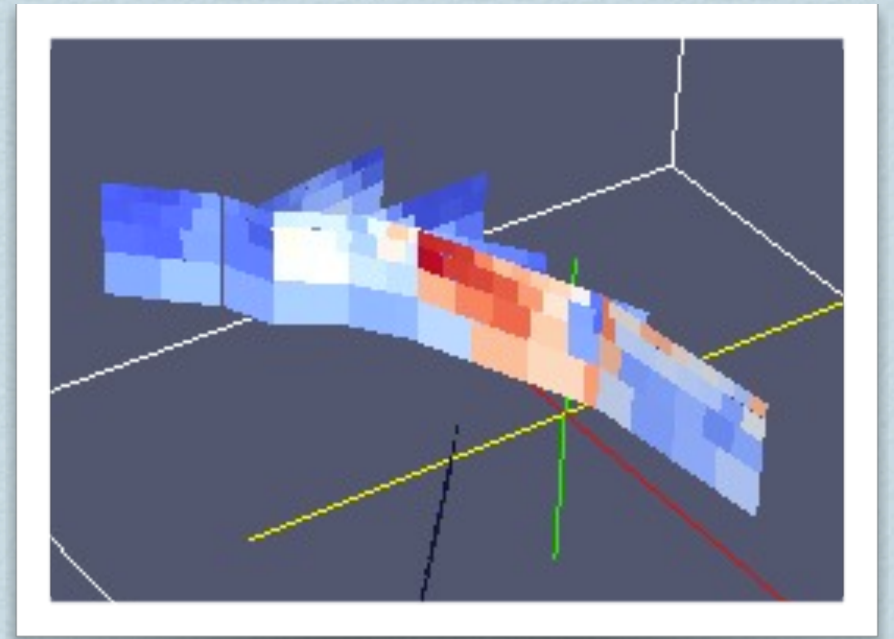
```
$ grdmap.sh -h
```

for more information. Find out later what command you used with `$ tail -n 2 landers/000-plot.ps`



- **Paraview display**

open Paraview
click `File/Open cgrid.vtp`, open click `Apply`
change `Surface` to `Wireframe`
click `File/Open rfaults-001.vtp`, open click `Apply`
change `Solid Color` to `slip`



When creating your own fault geometry, you can visualize it in Paraview with the command:

```
$ flt2vtk.sh faults/slip_distribution.flt
```

Then open `faults/slip_distribution.vtp` in Paraview.

Example I

Quasi-static stress transfer between faults

Coulomb stress calculation

We are going to compute the evolution of stress on the Bullion and Lavik Lake faults, which ruptured during the 1999 Mw 7.1 Hector Mine earthquake *(Simons et al., 2002)*, due to static and viscoelastic displacements following the 1992 Mw 7.3 Landers earthquake. The slip distribution of the Hector Mine earthquake is in `examples/mojave/faults/hector_km.flt.`

The stress calculation example is in `examples/mojave/coulomb.sh`. We need to add the geometry of receiver faults (optimal rake is calculated based on stress orientation):

```
...
# number of Coulomb stress patches
263
# no   x1      x2       x3 length width strike dip friction
1  15.337  -9.987 13.685  7.91   6.31  165.1  91      0.6
2  15.317 -10.063  9.176  7.91   4.51  165.1  91      0.6
...
```

which can be obtained with unix scripting by stripping the fault model of the slip and rake information as follows:

```
...
# number of Coulomb stress patches
`grep -v "#" hector_km.flt | awk '{$2="";$10="";print $0,0.6}' | wc`
# no   x1      x2       x3 length width strike dip friction
`grep -v "#" hector_km.flt | awk '{$2="";$10="";print $0,0.6}'`
...
```

Coulomb stress calculation

Run the `examples/mojave/coulomb.sh` example. The time series of stress at each individual patch of the receiver fault is in `examples/mojave/coulomb/cfaults-sigma-0244.txt` and the like:

```
# center position (north, east, down): -2.86E+01 1.51E+01 1.40E+00
#          t          s11          taus          taud          tau          taun     Coulomb
  0.000E+00 -1.981E-03  -7.694E-03  1.466E-03  7.833E-03 -7.376E-03  3.407E-03
  1.000E-01 -1.984E-03  -7.705E-03  1.483E-03  7.846E-03 -7.467E-03  3.366E-03
  2.000E-01 -1.988E-03  -7.714E-03  1.498E-03  7.858E-03 -7.552E-03  3.327E-03
...
```

You can also look at the cumulative stress evolution or only the postseismic contribution in Paraview with the files `rfaults-sigma-..vtp` and `rfaults-dsigma..vtp`.

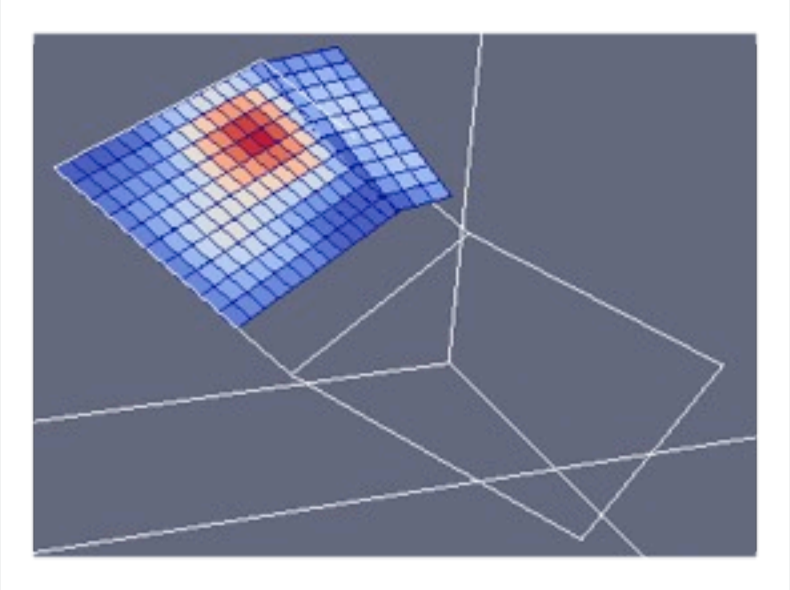
In Paraview, Open "rfaults-dsigma-000*", then click "Apply". Change "Solid Color" to "shear stress". Rescale the color scale to data range (horizontal arrow left from "shear displacement"). Animate the stress evolution the play button.

Example II

Afterslip in thrust environment

Afterslip in a thrust environment

We are going to compute the evolution of slip on the deep extension of the fault that ruptured during the 2005 Mw 7.6 Kashmir, Pakistan earthquake *(Avouac et al., 2006)*, assuming that afterslip is governed by a rate-strengthening friction law *(Barbot et al. 2009)*. The slip distribution of the Kashmir earthquake is in `examples/pakistan/kashmir05/faults/avouac+06.flt`.



We need to define the:

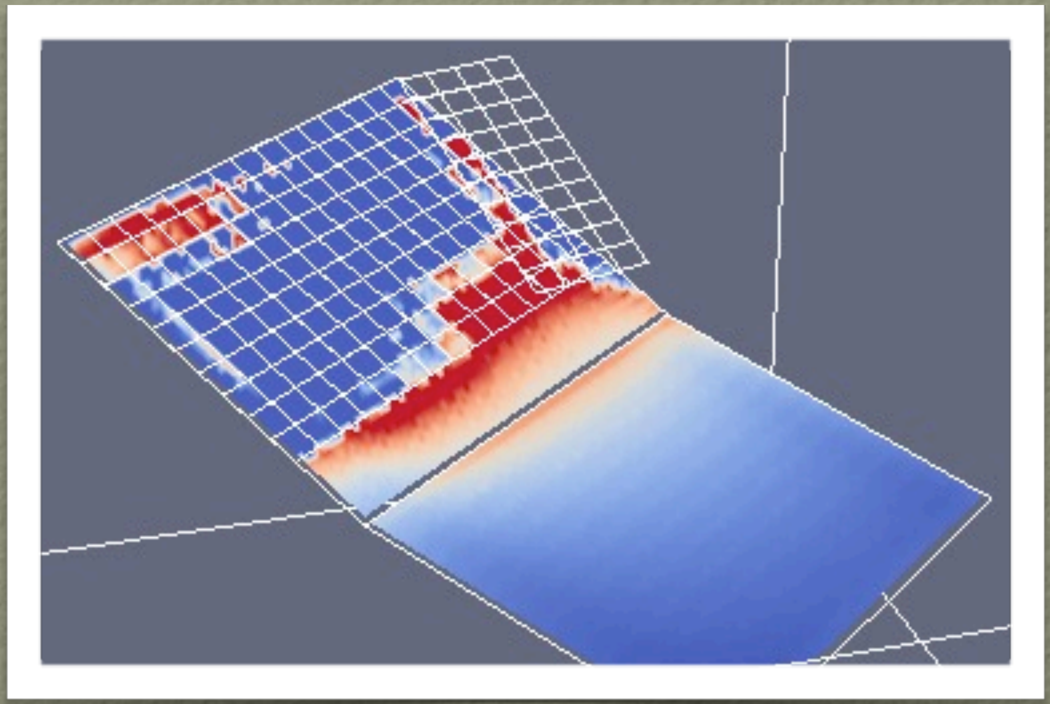
- coseismic slip distribution
- afterslip constitutive properties $\dot{s} = 2\dot{\gamma}_0 \sinh \frac{\tau}{(a-b)\sigma}$
- afterslip fault geometry (orientation and size)

```
...
# number of fault creep interfaces
1
# nb depth gamma0 (a-b)sigma friction cohesion
   1     0   1e-3          5      0.6         0
# number of afterslip planes
2
# nb         x1         x2        x3 length width strike dip rake
   1 -21.46101  18.09357         0     60    45    -40  29   90   ← ±90°
   2  3.837752  48.24346 21.81643     60    45    -40  15   90
...
```

Afterslip in a thrust environment

Run the `examples/pakistan/kashmir05/afterslip.sh` example and read the header information in the script file. Slip, velocity, stress components, and more, for each fault segment is in `examples/pakistan/kashmir05/afterslip/001.s00001.creep.dat`. The first index `001` corresponds to the time step; the second `s00001` corresponds to the fault plane number.

```
#    x1      x2      x3          y1          y2        slip    velocity        taus       sig11
  2.40   -4.89   7.272   1.309E+00   8.420E+00   2.757E+00   6.359E-05   3.856E-05   5.056E-05
 -6.95    9.01   1.309   1.112E+01   2.757E+00   2.598E-05   1.609E-05   2.039E-05   7.871E-04
 -9.02   10.74   1.309   1.382E+01   2.757E+00   3.911E-05   1.185E-03   3.840E+00  -7.337E+00
-11.10   12.48   1.309   1.652E+01   2.757E+00   4.930E-05   2.036E-05   4.490E-05   1.494E-03
...
```



Coordinates `x1, x2, x3` correspond to absolute location; coordinates `y1` and `y2` correspond to distances in strike and dip directions in a reference frame aligned with the fault.

Slip and velocity at each time step, for each fault segment is available in .grd format for visualization in GMT. For time series of displacements:

```
$ grdmap.sh -b -40/60/-30/70 \
   -p -0.001/0.001/0.00001 -v 0.0005 \
   -e erpatch.sh afterslip/0{00,01,02,03,04,05,06,07}-relax
```

Example III

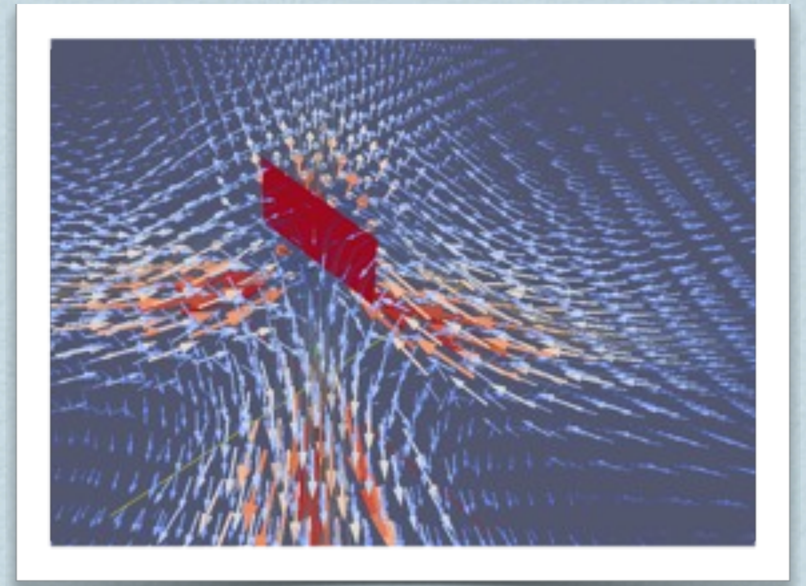
Viscoelastic models with structural data

Viscoelastic flow models

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
...
```



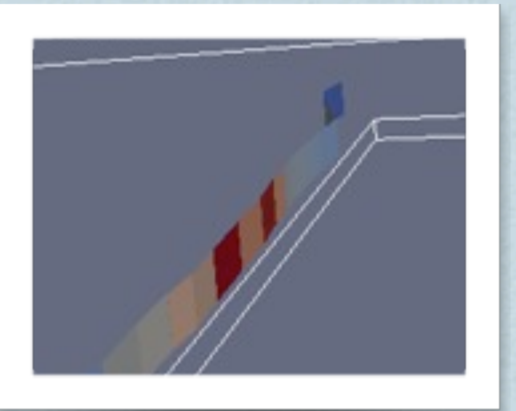
setup the mechanical structure

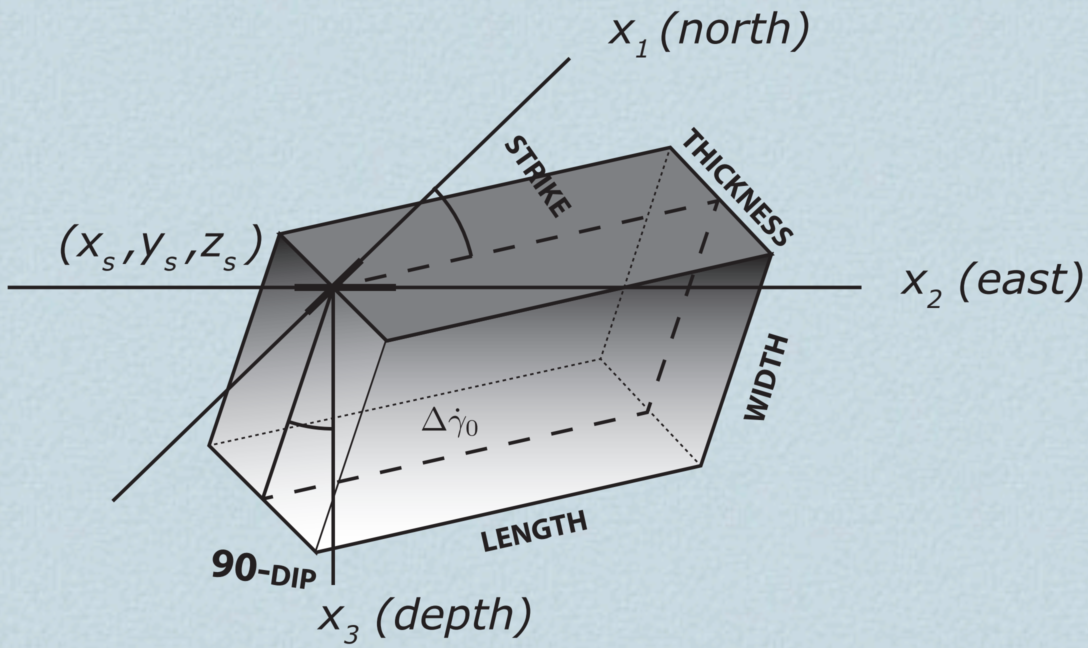
```
...
# number of powerlaw viscous interfaces
2
# no depth gammadot0 power cohesion
   1   2.0       5e3   3.0       0.0
   2   8.0       5e3   3.0       0.0
# ductile zones corresponds to volumes where viscous properties change.
# number of power-law ductile zones
0
```

Viscoelastic flow models with structural data

viscoelastic relaxation following the 2001 Mw 7.8 Kokoxili earthquake, Western China. Location: `examples/examples/tibet/kokoxili_vs3d.sh`

```
# number of linear viscous interfaces (where viscosity changes)
1
# i depth gammadot0 cohesion
  1    20        0.1         0
# number of linear ductile zones
1
# i dgammadot0 x1  x2 x3 length width thickness strike dip
  1        -0.1 40 300 20     500    10         200    -81  90
```





elementary 3d ductile zone

Ductile zones are volumes where the background viscosity is ammended. `dgammadot0` is the modifier to the background fluidity, `x1, x2, x3`, length, width, thickness, strike and dip are the position, dimension and orientation of the rectangular volume. The fluidity used to drive viscoelastic flow is `gammadot0+dgammadot0`.

Viscoelastic flow models with structural data

Viscoelastic deformation in a subduction zone context, the case of the Sunda Megathrust, Indonesia.

```
# no      x1     x2  x3 length width strike  dip  rake
001 -1008.1 976.5 8.5  50.00 50.09 -53.29 3.52 76.73
002  -969.8 944.3 8.9  50.00 50.08 -51.10 3.43 78.91
003  -931.5 912.2 9.4  50.00 50.13 -50.40 4.14 79.62
...
```

look at it with:

```
$ cat sunda_50km.flt | flt2vtk.sh > sunda_50km.vtp
```

extrude the slab interface and setup the mechanical structure:

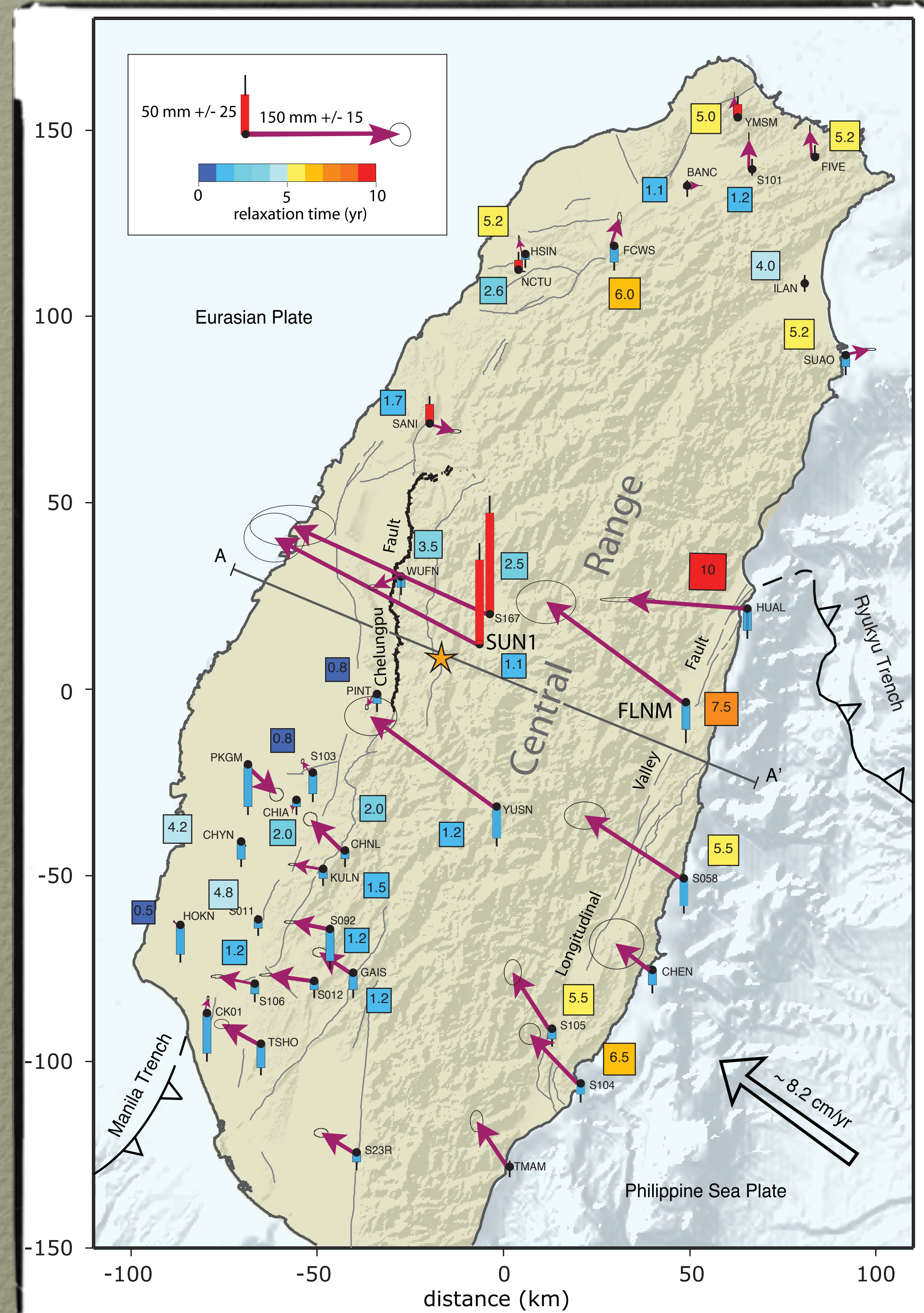
```
...
# number of linear viscous interfaces
1
# no depth gammadot0 cohesion
   1  80.0        1e0       0.0
# number of linear ductile zones
`grep -v "#" faults/sunda_50km_deep.flt | wc`
# nb dgammadot0 x1 x2 x3 len. width thickn. strike dip
`grep -v "#" faults/sunda_50km_deep.flt | awk '{print
NR,-10,$2,$3,$4,$5,80,$6,$7,$8+90}'`
...
```

Relax
Research Examples

From geological settings to geophysical modeling

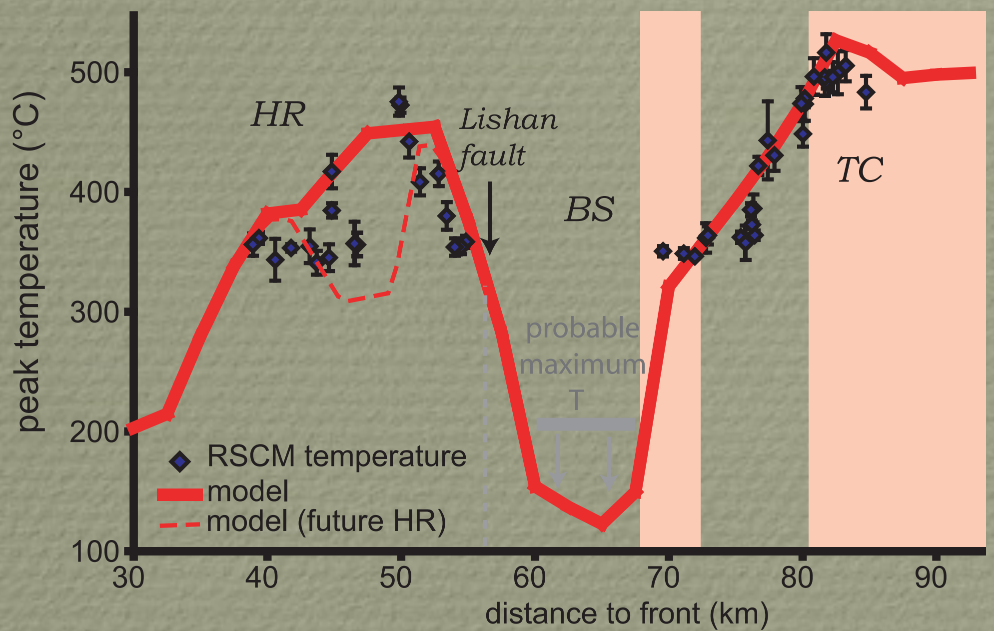
Postseismic relaxation following the 1999 Mw 7.6 Chi-Chi earthquake

- 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.



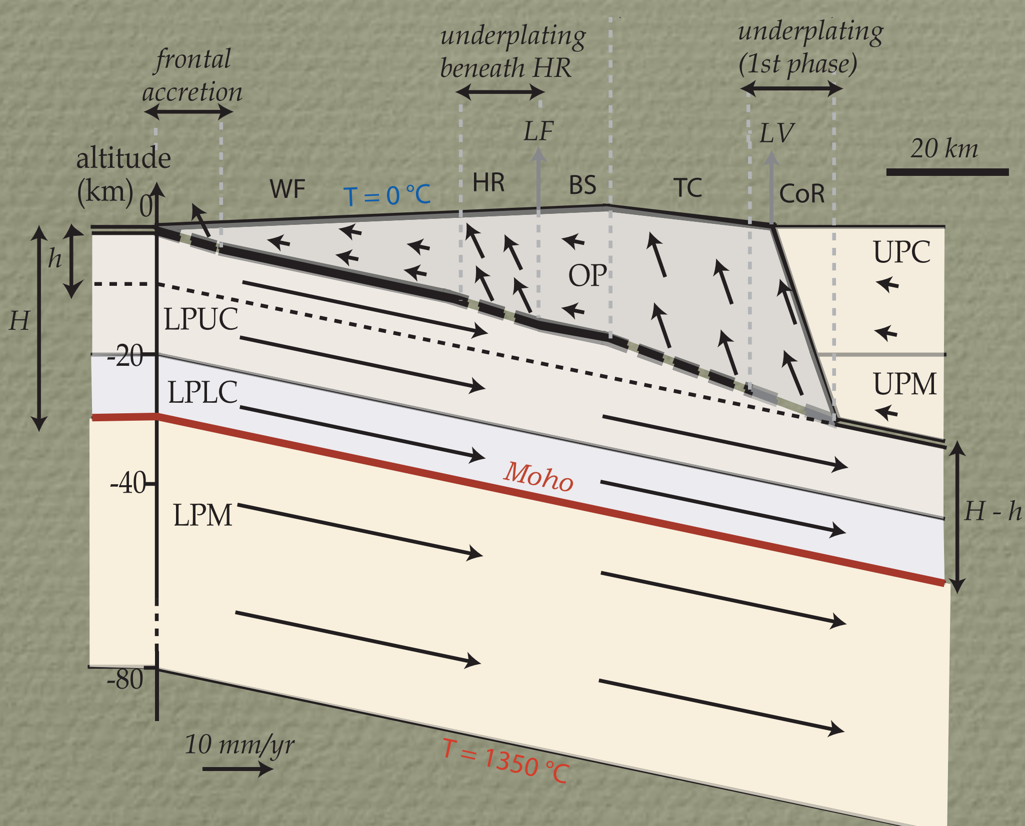
Uplift and exhumation of the Central Range

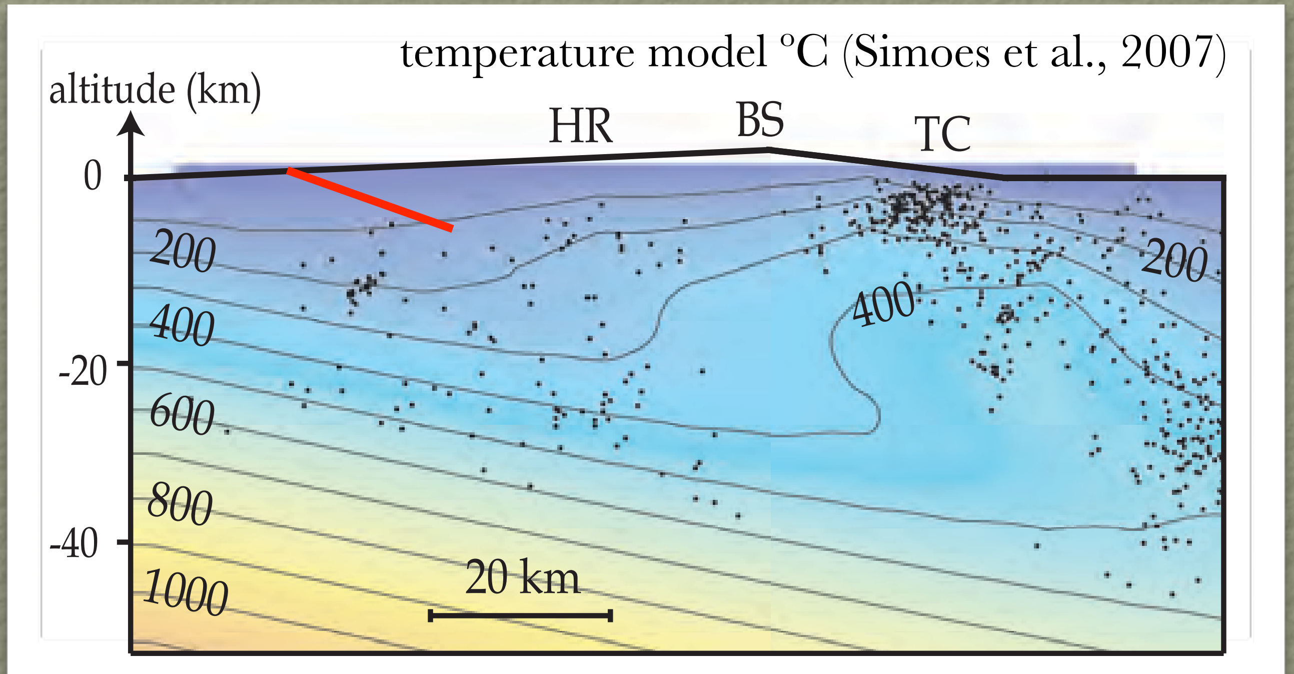
Beissac et al. (2007), Simoes et al. (2007)



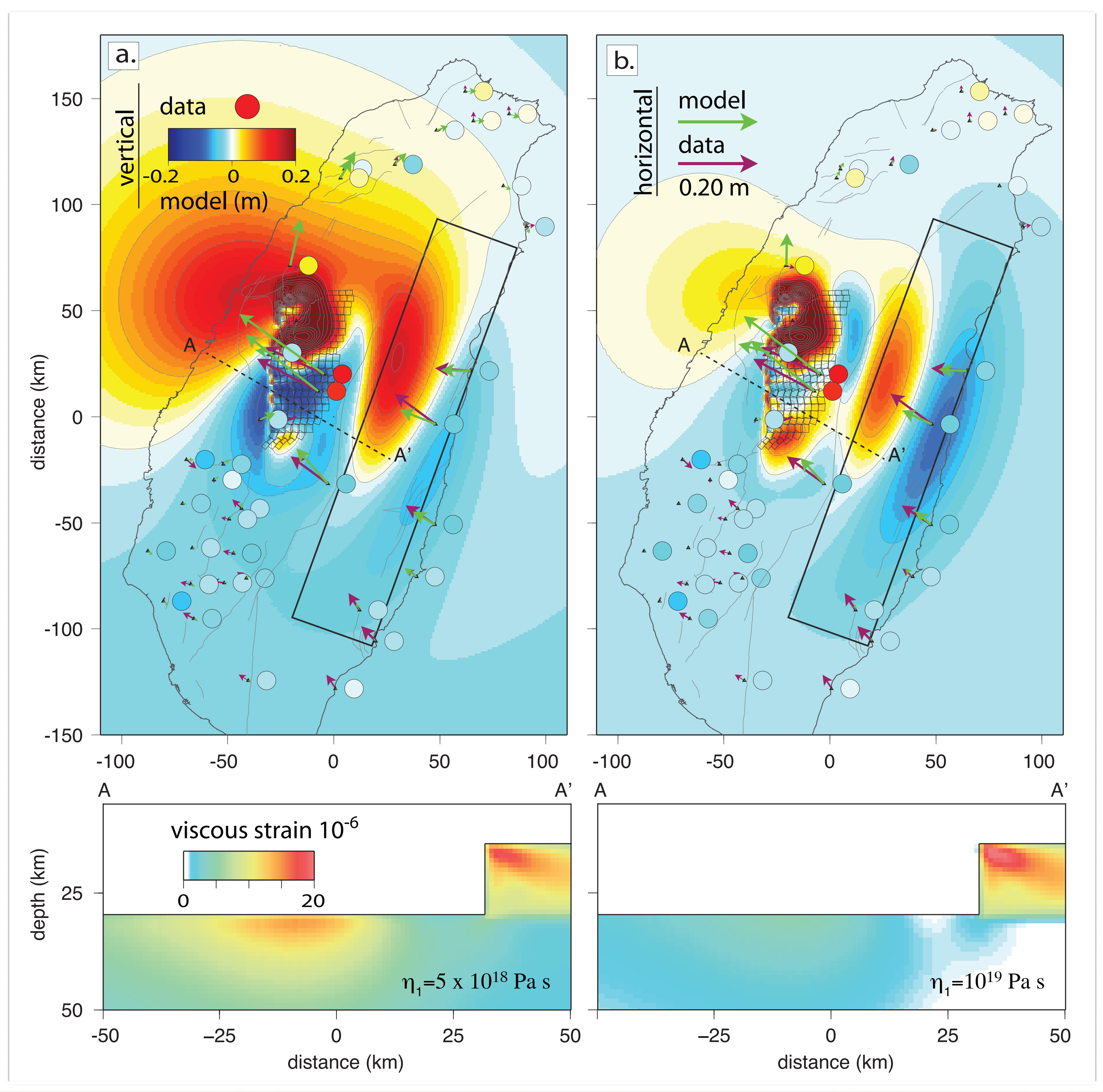
- Geothermology markers indicate high temperature anomalies below the Hsuehshan Range (HR) and the Tananao Complex (TC) around a colder the Backbone Slate (BS) units.

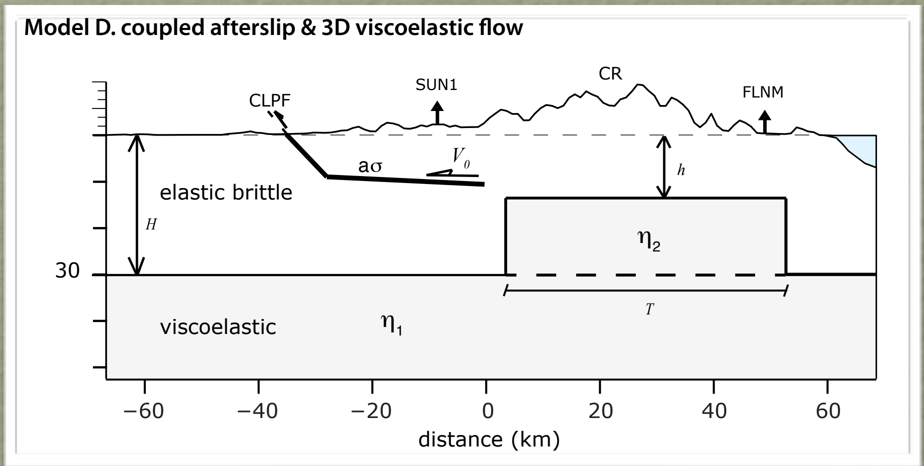
- A thermo-kinematic model indicates that the high background thermal gradient of 30-35 °C/km in Taiwan is uplifted to reach 400 °C at 10 km depth.





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.

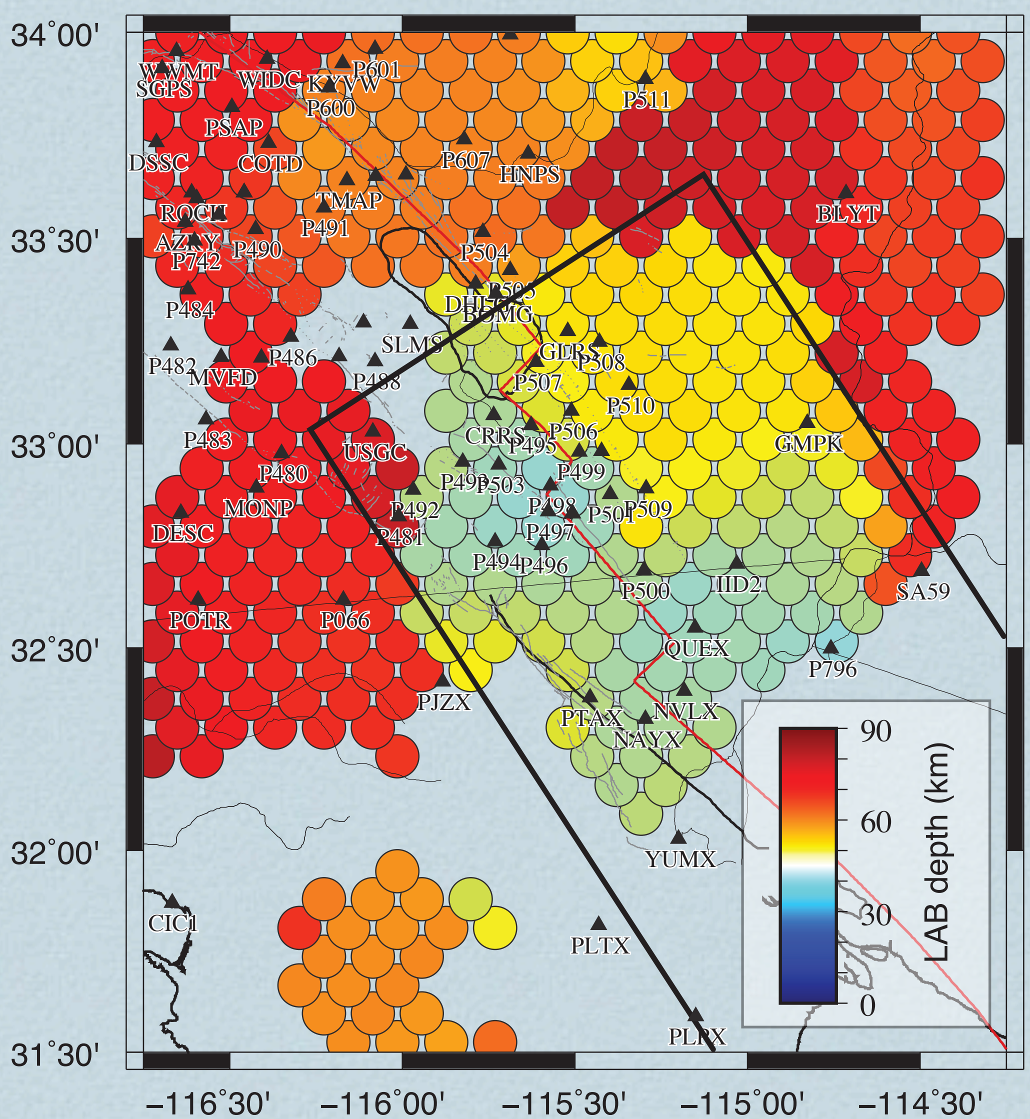
friction properties for fault slip

creeping fault planes

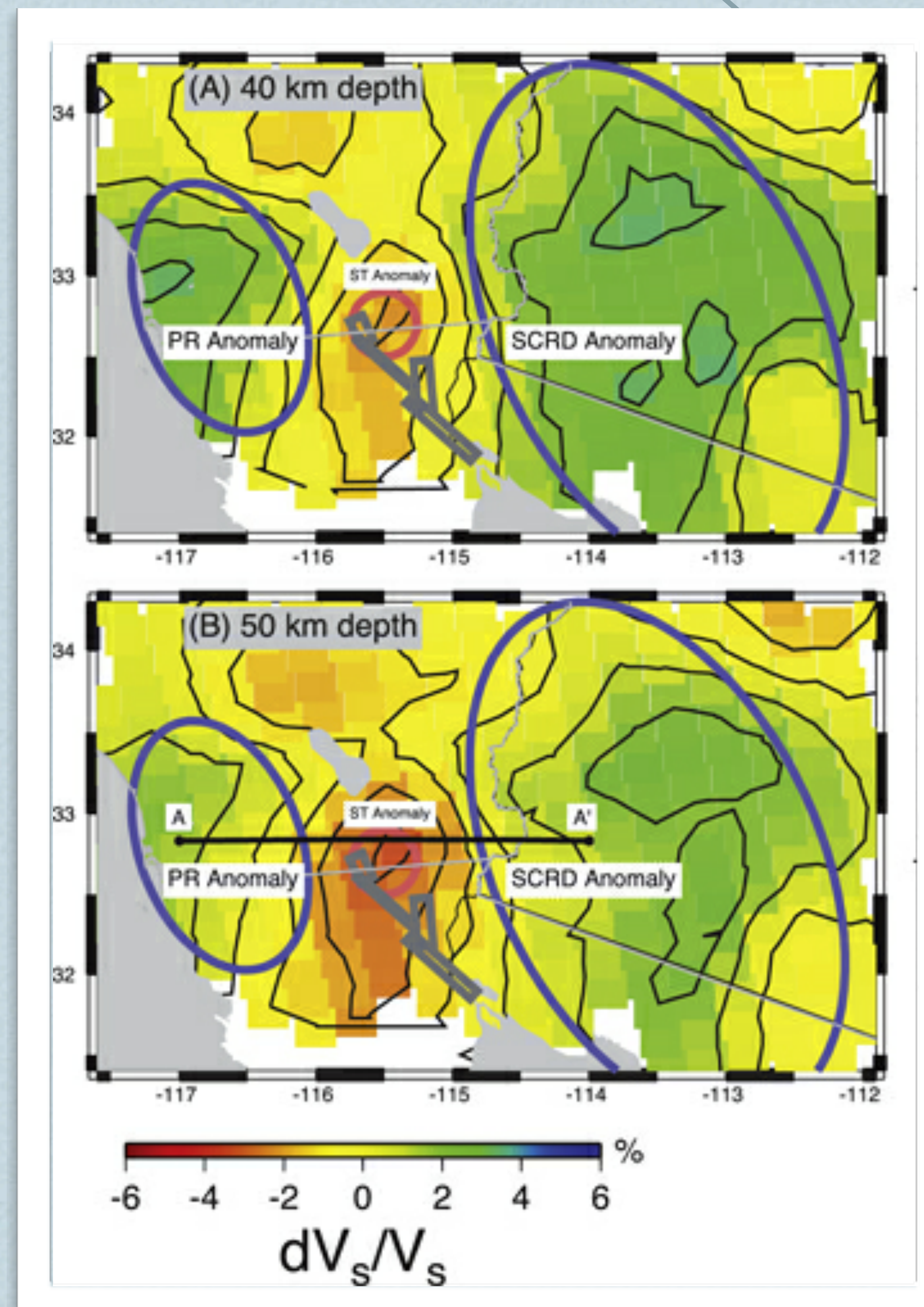
quick Paraview displays with the `--dry-run` option.

Case of the El Mayor-Cucapah earthquake

Total strain is decomposed in elastic and inelastic strain components

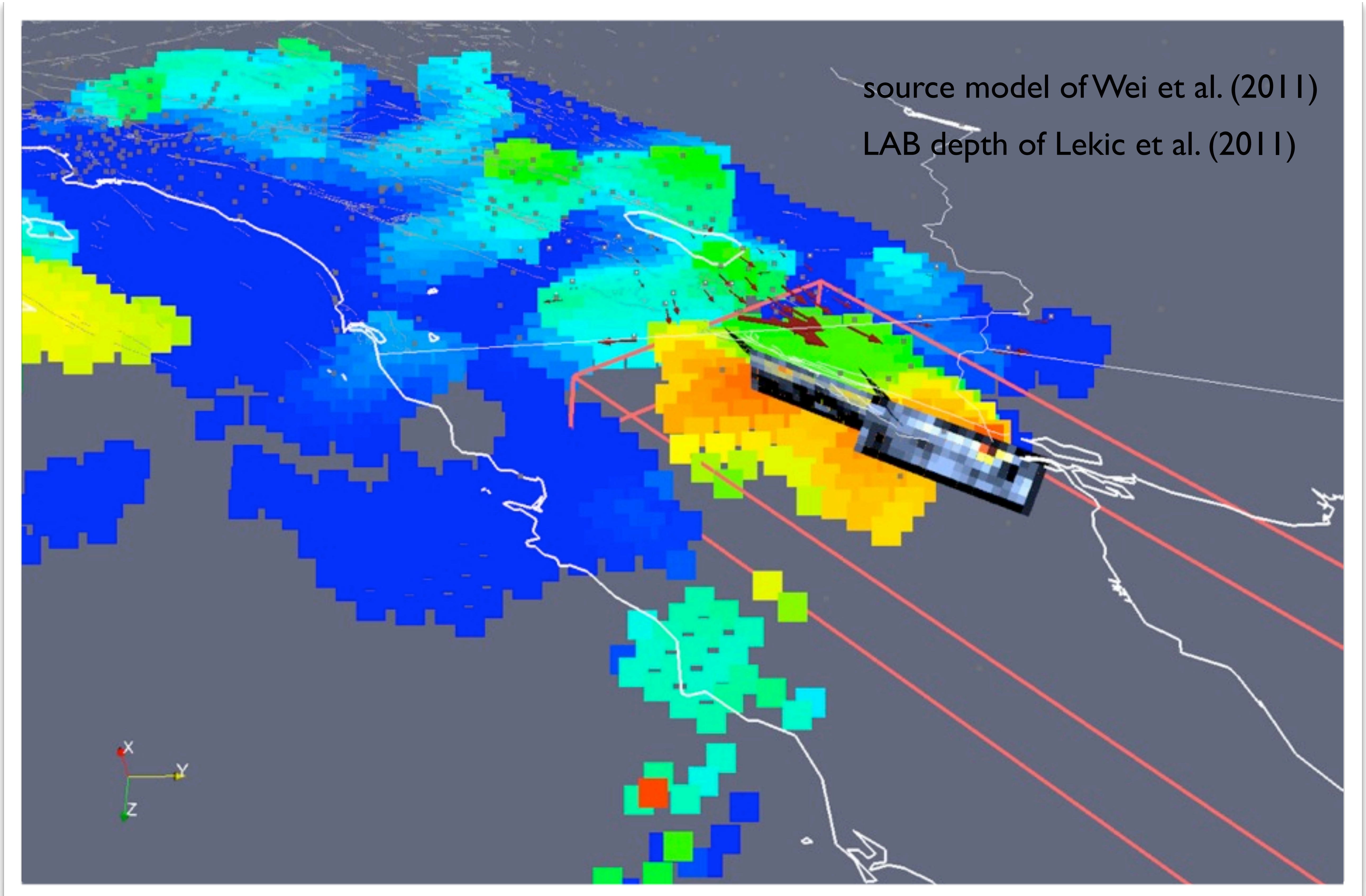


adapted from Lekic et al. (2011)



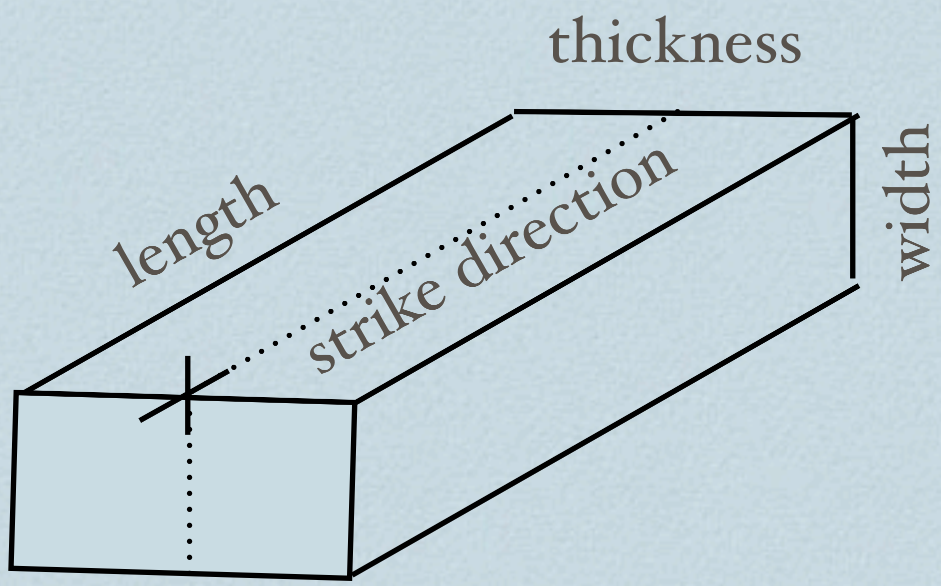
Pollitz et al. (2012)

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
...
```

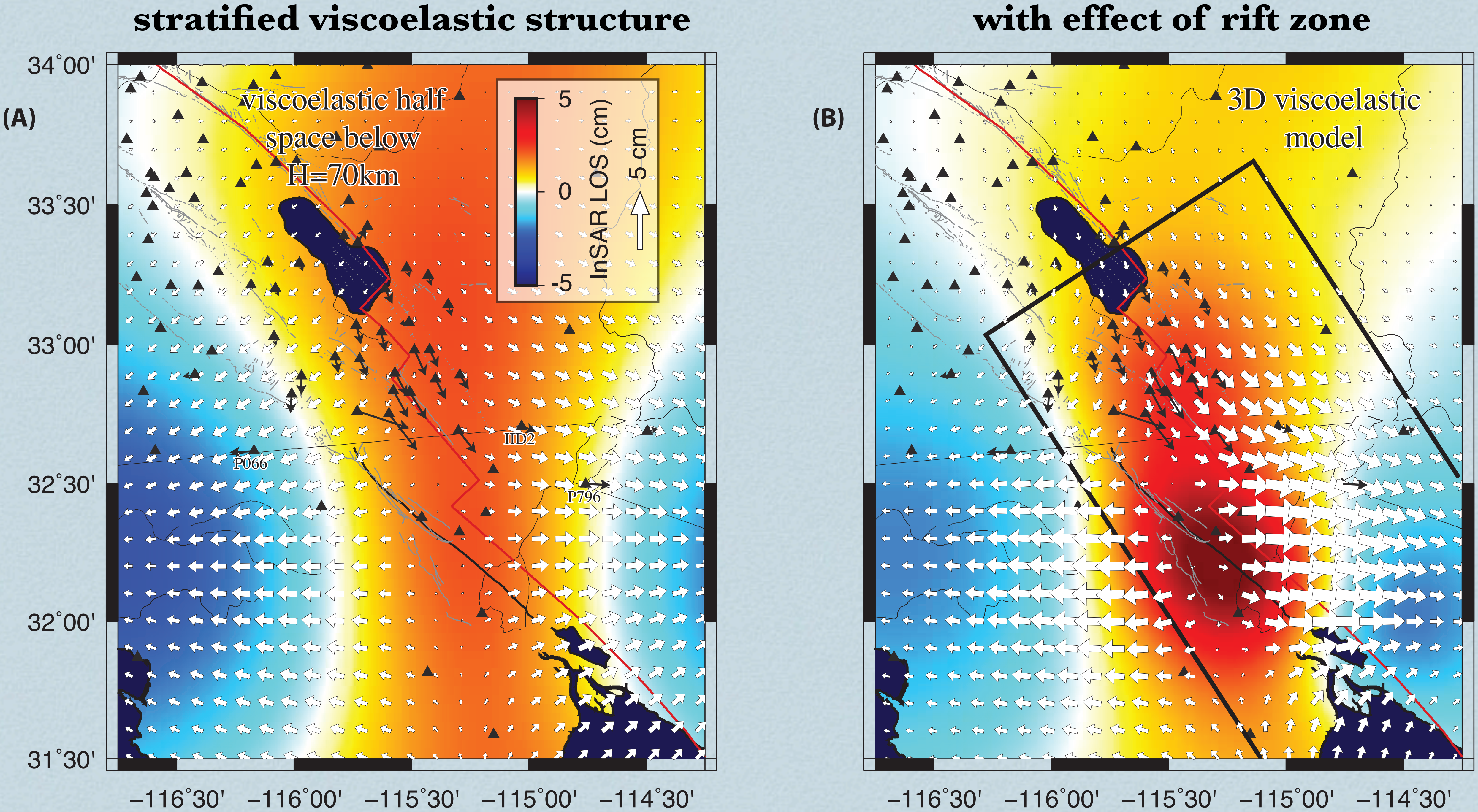
file $OPTS contains a list of stations

```
...
# 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
```

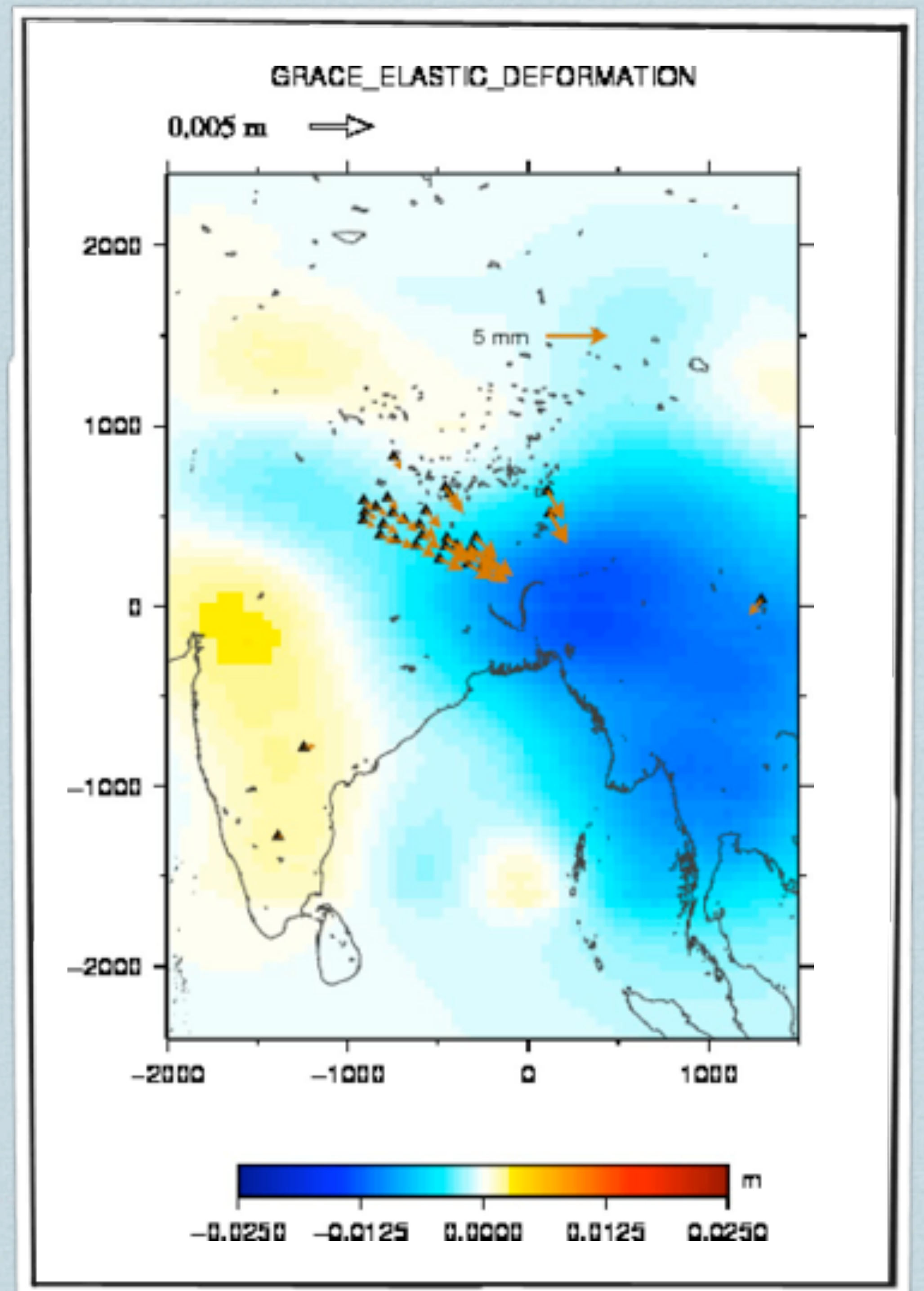
← filter out GPS stations outside the computation grid

Case of the El Mayor-Cucapah earthquake

Investigating the effect of rifting on postseismic relaxation

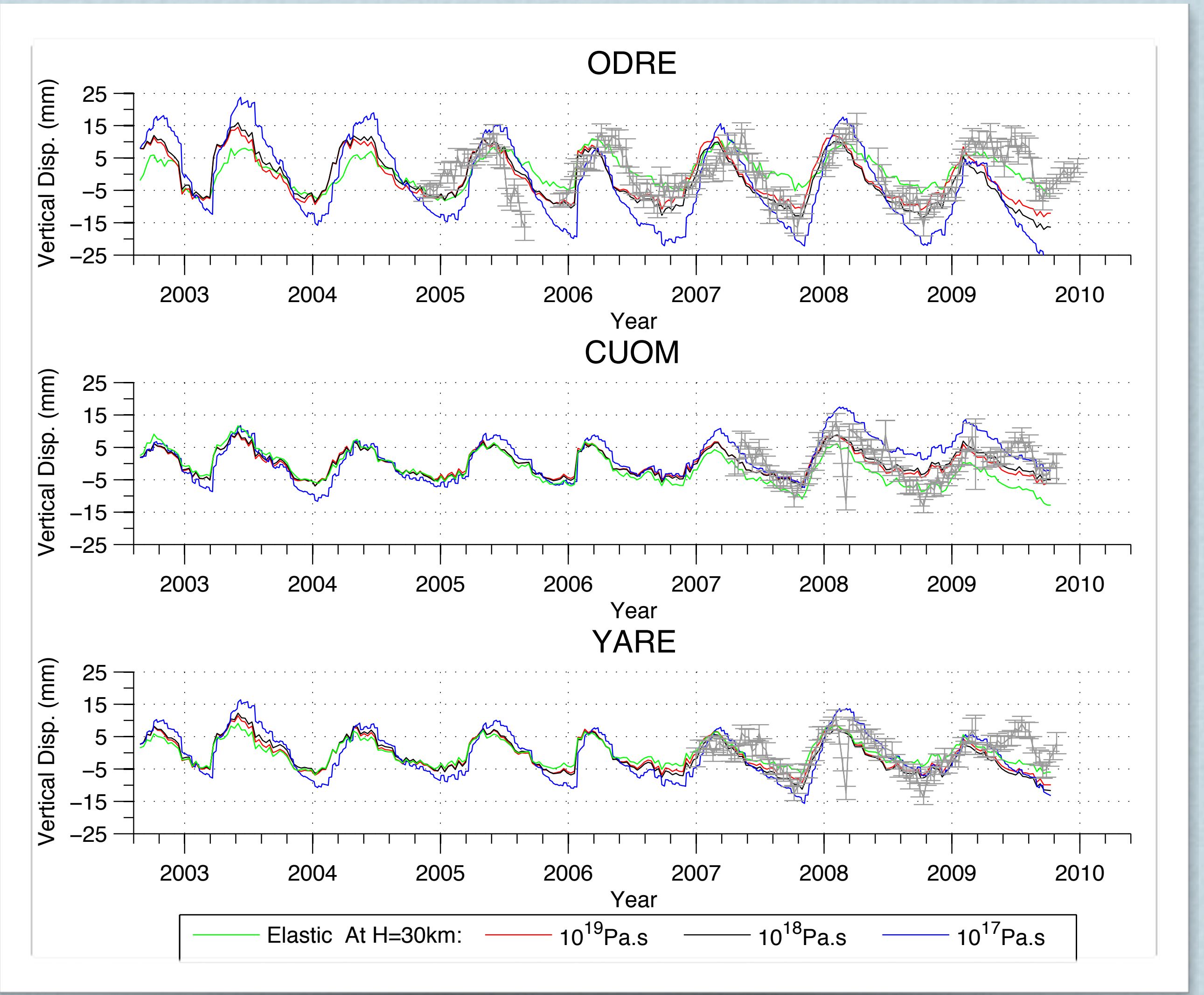


Monsoon excitation of the lower crust



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

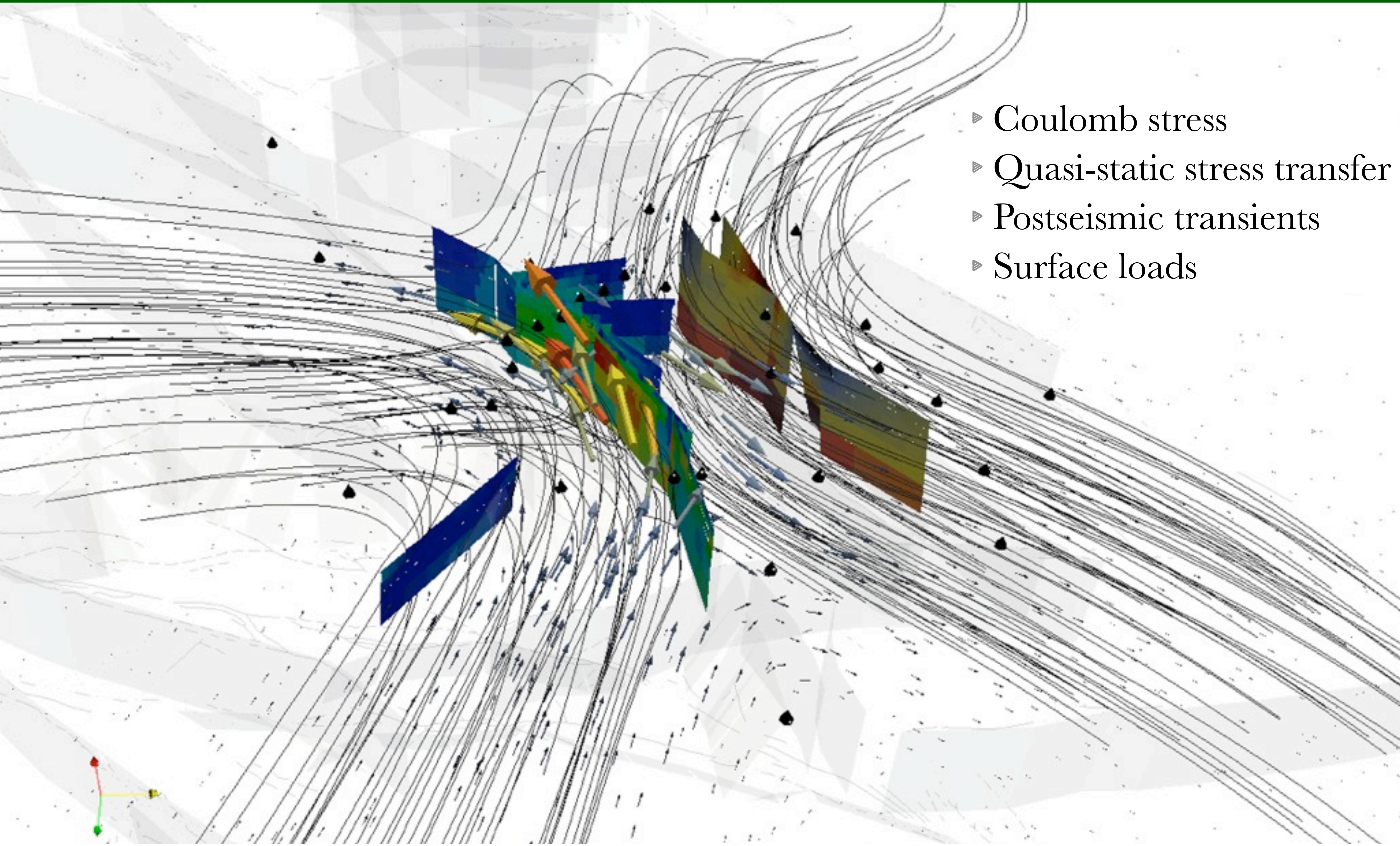
```
# number of coseismic events (when slip distribution is prescribed)
`wc $DDIR/$CATALOG`
`awk -v d=$DDIR '{
   if (0!=$1){print $1};
   print 0;
   print 0;
   print 0;
   system("wc "d"/"$2);
   system("cat "d"/"$2)}' $DDIR/$CATALOG`
EOF
```

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