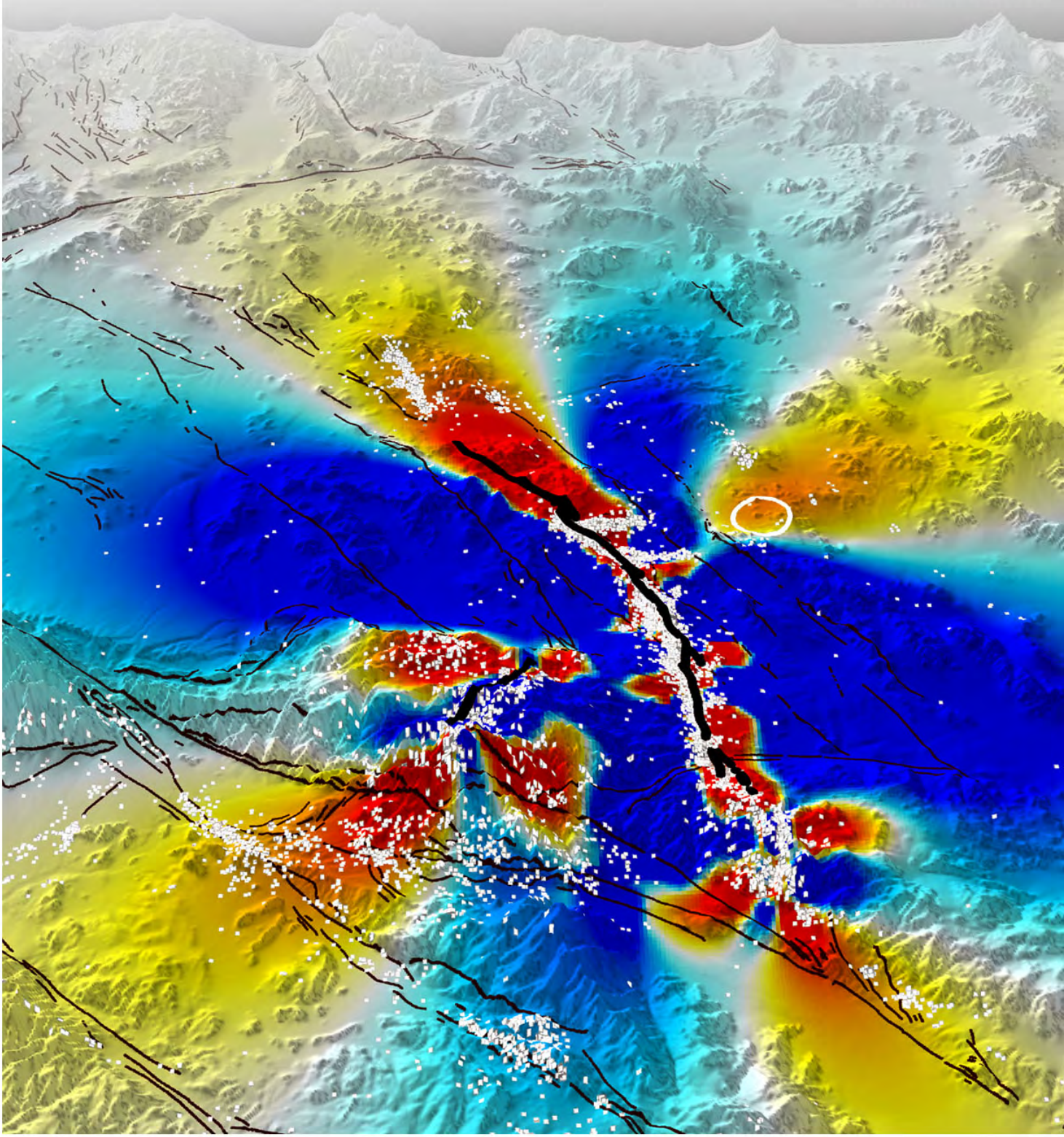
Coulomb 3.1

Graphic-rich deformation & stress-change software
for earthquake, tectonic, and volcano research & teaching

User Guide

November 13, 2007

Shinji Toda, Ross Stein, Jian Lin, and Volkan Sevilgen



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is gratefully acknowledged

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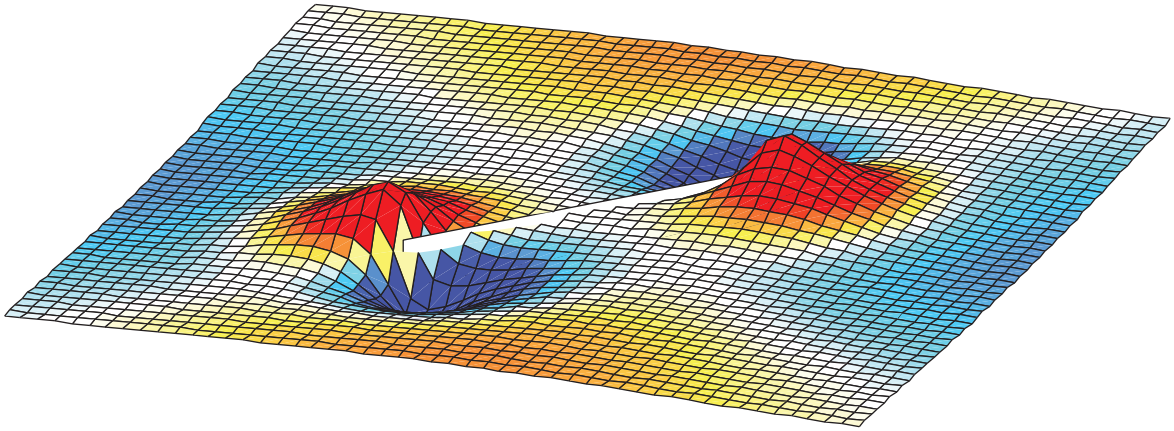

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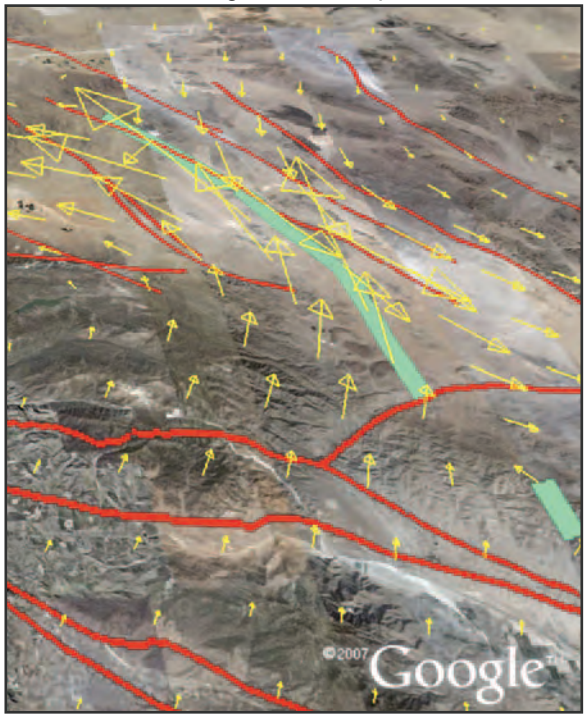
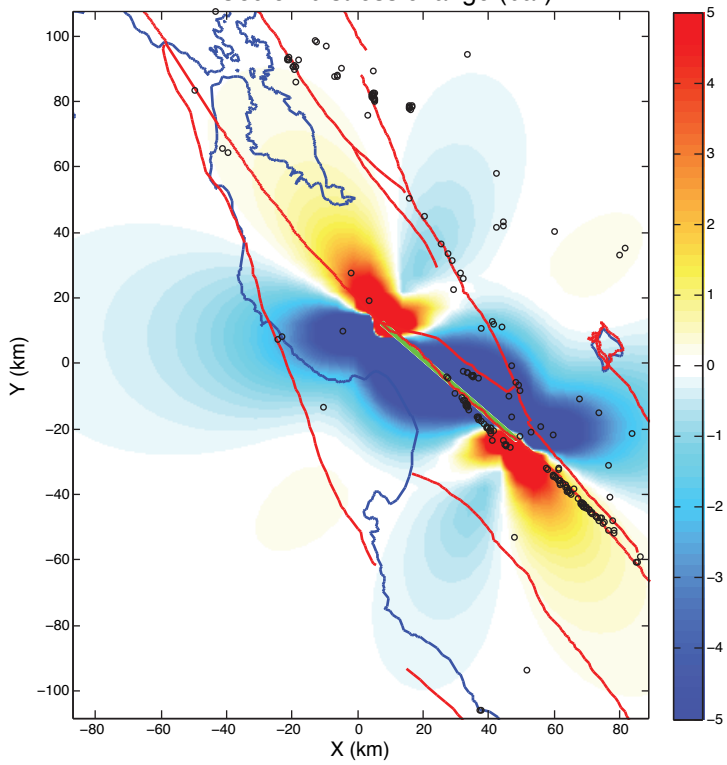
Google Earth Output

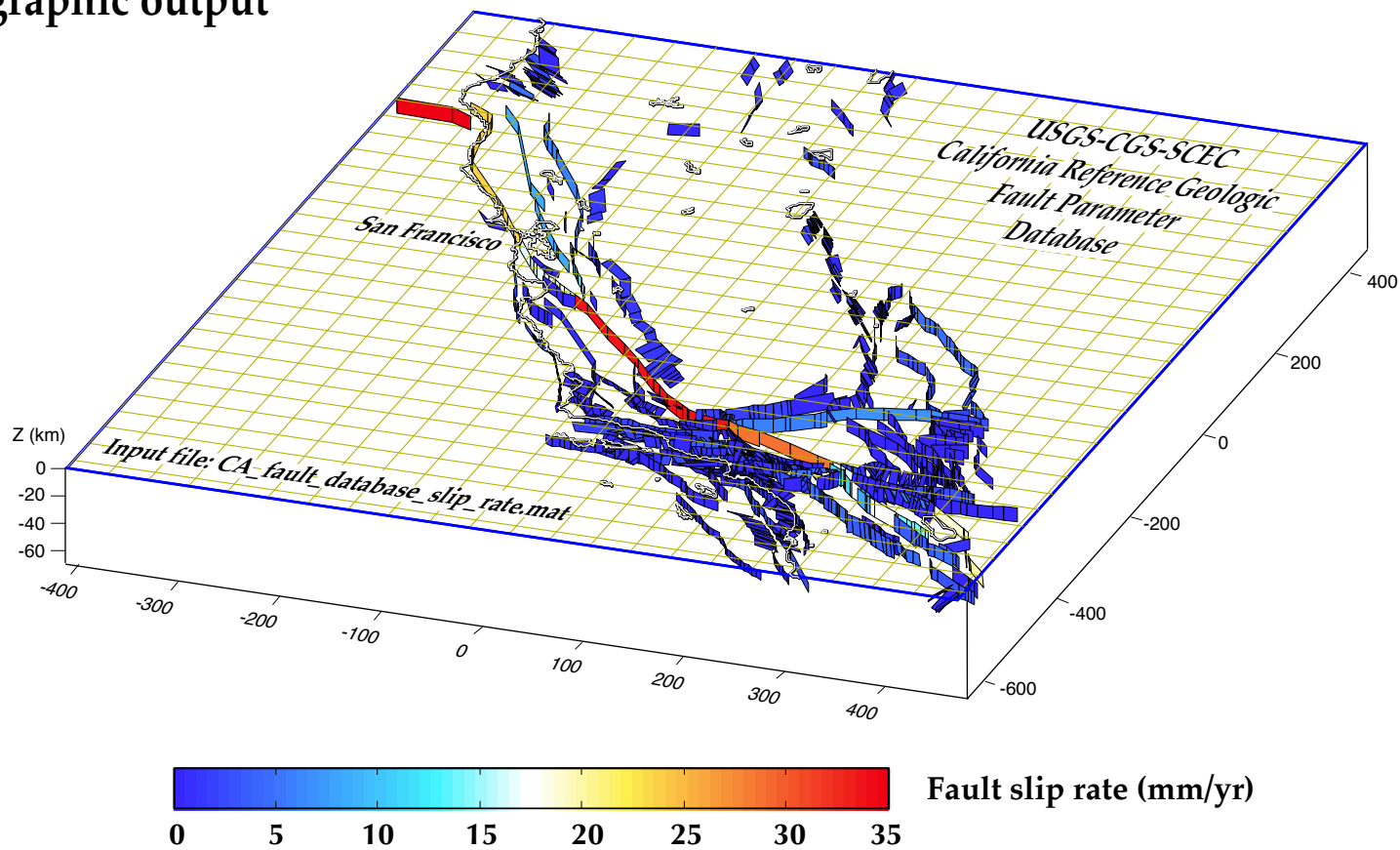


Coulomb stress change (bar)

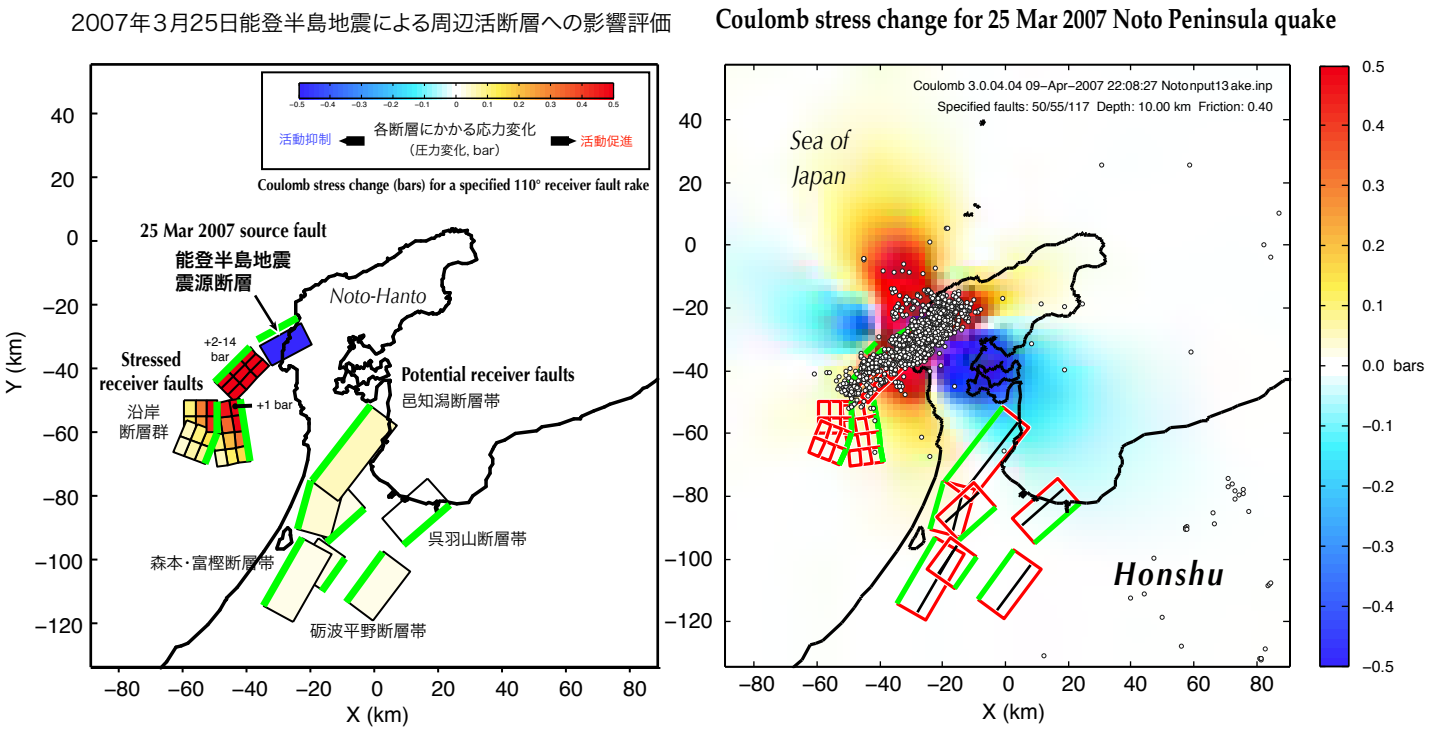


http://www.coulombstress.org

Examples of Coulomb 3.1 graphic output



Receiver fault traces digitized from active fault map, dip and upper/lower depth added to input file
Coulomb stress change calculated on receiver faults (left) and in mapview at 10 km depth (right)



What's new in Coulomb 3

Coulomb now runs on Mac, PC, and Unix computers: The program is very fast on a PC, has not yet been tested on the *Vista* operating system. For Mac, the operating system must be OS 10.X and later.

Matlab 7.X or higher is required to run Coulomb. Coulomb 3.1 is now a Matlab application (www.mathworks.com), so you will need to install Matlab first. Make sure you also install the Matlab *Mapping tool box* in your Matlab library.

Many features were added or enhanced:

- You can now use *latitude/longitude* directly in the input and output files, and can now add *active fault traces*, *coastlines*, and *earthquakes* from online catalogs, websites, or Coulomb-bundled files. These overlays can then be included compactly in the saved input files in .mat (Matlab binary) format so they automatically plot when the input file is re-run.

- Stress changes can be *resolved on faults in their individual rake directions*, or on specified rakes. Resolved stress changes can be viewed graphically in 3D or output to tables. Shear and normal stress changes can also be imaged, and the friction can be changed on the fly. *Draped wireframe and 3D deformation* graphic outputs can be spun and tilted.

- The Coulomb output files can now be exported automatically to *Google Earth*. This is implemented by using the 'coulomb2googleearth' plug-in.

- You can use comprehensive moment centroids and M_W to quickly create input faults with lengths, widths, and slip scaled by empirical relations. The slip on these sources can then be easily tapered for more realistic stress distributions.

- Any of the 150 variable-slip source models for earthquakes in Martin Mai's SCRMOD online database can be loaded into Coulomb as input files.

- Active fault files for California, Japan and Turkey (both *Le Pichon et al* and *Armijo et al* interpretations of the Marmara sea faults) are included. Earthquake catalogs in any of 14 formats can be filtered from websites and loaded into Coulomb. You can now graphically plot the Coulomb stress imparted to *earthquake nodal planes*.

- The 1377-patch Fault-Section Database (part of the USGS-California Geological Survey California Reference Geologic Fault Parameter Database) is included as a Coulomb input file in three formats. These files supply all geometrical features needed to use the database faults as sources or receivers, including the top and bottom of each fault patch, the patch slip rate and rake. The fault network can be used to find the stress change caused by any earthquake on the known surrounding faults given their presumed rakes, and it can be also used to implement simple interseismic stressing by using the sources as virtual dislocations, which uses negative slip rates times the time period to get stress. Use 'CA_fault_database_slip_rate.mat' to plot the fault slip rates or to use the sources as virtual dislocations for interseismic stressing. To resolve the stress imparted by an earthquake source on each receiver faults given the rake of each fault, use 'CA_fault_database_rake.mat'. If you want to use the receiver faults and choose a common rake, use 'CA_fault_database_noslip.mat'. Note that these are large files and take a long time to run.

New to Coulomb 3.1 relative to Coulomb 3.0:

Merging variable-slip sources to one input file ('merge_input_file' plugin) (Sec. 4.13). Making smoothed seismicity density plots (5.5). User-selected contour intervals (Sec. 6.7 and 7.6). Using the strike/dip/rake/friction slider in the Stress control panel (Sec. 7.2). Active fault files for the western US, Japan, and Turkey (with a readme file references) are now included.

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***Plugin Finder* (plugins are useful tools that are not found in the pull-down menus)**

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Chapter 1

INTRODUCTION

1.1 *Why Coulomb*? The rationale and philosophy of this program

Coulomb is intended both for publication-directed research and for college and graduate school classroom instruction. It is designed to let one calculate static displacements, strains, and stresses caused by fault slip, magmatic intrusion or dike expansion/contraction. The displacements, strains, and stresses can be on calculated at any surface at any depth.

There is now abundant evidence to support the hypothesis that faults interact by the transfer of stress; this is evident on the short time scales of earthquake sequences and aftershocks, and on longer time scales associated with the inter-event time of the largest shocks that occur in a given region. Key review papers include: Harris, R.A. (1998), Introduction to special section: Stress triggers, stress shadows, and implications for seismic hazard, *J. Geophys. Res*., 103, 24,347–24,358; Stein, R.S. (1999), The role of stress transfer in earthquake occurrence, *Nature*, 402, 605–609; King, G.C.P., and M. Cocco (2000), Fault interaction by elastic stress changes: New clues from earthquake sequences, *Adv. Geophys*., 44, 1–36; Freed, A.M. (2005), Earthquake triggering by static, dynamic, and postseismic stress transfer, *Ann. Rev. Earth Planet. Sci*. 33:335–67, doi: 10.1146/annurev.earth.33.092203.122505; Steacy, S., J. Gomberg, and M. Cocco (2005), Introduction to special section: Stress transfer, earthquake triggering, and time-dependent seismic hazard, *J. Geophys. Res*., 110, B05S01, doi:10.1029/2005JB003692. There is also evidence that faults and magmatic systems interact as well, and that static stress changes influence intrusions and eruptions. Undoubtedly, other processes not included in Coulomb are also important, such as dynamic stresses, pore fluid diffusion, and viscoelastic rebound. Further, basins and crustal layering modify the stresses in comparison to the elastic halfspace implemented in Coulomb. Nevertheless, we believe that a simple tool that permits exploration of a key component of earthquake interaction has great value for understanding and discovery.

Coulomb 3.1 is designed to investigate Coulomb stress changes on mapped faults and earthquake nodal planes, and is intended both for publication-directed research and for university teaching and instruction. One can calculate static displacements (on a surface or at GPS stations), strains, and stresses caused by fault slip, magmatic intrusion or dike expansion. Problems such as how an earthquake promotes or inhibits failure on nearby faults, or how fault slip or dike expansion will compress a nearby magma chamber, are germane to Coulomb. Geologic deformation associated with strike-slip faults, normal faults, or fault-bend folds is also a useful application. Calculations are made in an elastic halfspace with uniform isotropic elastic properties following Okada [1992].

We believe that one learns best when one can see the most and can explore alternatives quickly. So the principal feature of Coulomb is ease of input, rapid interactive modification, and intuitive visualization of the results. The program has menus, sub-menus, check-items, and dialogue boxes to ease operation. The internal graphics are suitable for publication, and can be easily imported into illustration or animation programs for further enhancements.

1.2 Hardware/software requirements:

- **Macintosh OSX, Windows PC, or UNIX computer**
  Note: We have not yet tested Coulomb 3.1 on Unix machines or the Vista operating system, but it does run on Intel Mac's.
- **Matlab 7.X or higher is required**. There are a few Matlab functions that work on PCs but not Mac's. Matlab 7.5 is not advised; its full of bugs.
- A color monitor of at least 600 x 400 pixel resolution. A laptop screen (1024 x 768 pixels) is fine.
- A text editor to modify ascii input files, and a spreadsheet to read tab-delimited text files. Some output files are created as .csv (Excel-friendly) files.

1.3 Recommended extras:

- A vector illustration program, such as *Adobe Illustrator*, is strongly recommended.
- When editing input files, we recommend that you use a text editor that allows you to distinguish spaces from tabs, such as *BBEdit* (*BBEdit Lite* is free from http://www.barebones.com/) or *Notepad* on a Windows PC. Regardless of the editor, use a non-kerning (uniform-spacing) font, such as Monaco, so that numbers stay aligned.
- *Google Earth* (which is free)

1.4 User's Guide Alerts

1. **Any words of wisdom in the manual are printed in red!**
2. The images used in the manual to show you what you will see on the screen were captured at low resolution (72 dpi). *But don't worry*: you will save full-resolution vector files.

1.5 Help menu

This can be useful; there is a search command.

1.6 Cover images

The full-page cover page was designed by Serkan Bozkurt (now at Geomatrix Consulting) by importing Coulomb numerical output into ArcGIS. All of the interior cover images were made exclusively from Coulomb 3.1.

1.7 Acknowledgements

We are grateful for generous support by the Office of Foreign Disaster Assistance (OFDA) of the U.S. Agency for International Development (USAID) to code, test, and calibrate Coulomb 3.1. Geoffrey C.P. King's 1995 GEN inspired Coulomb 1.0. We thank many users for testing the functions, finding errors and suggesting improvements.

1.8 Citing Coulomb

Coulomb is intended for teaching and research. If you use Coulomb in research you submit for publication, we ask only that you cite these two papers:

Toda, S., R. S. Stein, K. Richards-Dinger and S. Bozkurt (2005), Forecasting the evolution of seismicity in southern California: Animations built on earthquake stress transfer, *J. Geophys. Res., B05S16, doi:10.1029/2004JB003415.*

Lin, J. and R.S. Stein (*2004*), Stress triggering in thrust and subduction earthquakes, and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults, *J. Geophys. Res., 109, B02303, doi:10.1029/2003JB002607.*

1.9 Some key papers that explain and use Coulomb

Introduction without jargon or math:

Stein, R.S., Earthquake conversations, *Scientific American*, *288 (1)*, 72-79, January 2003. (http://quake.wr.usgs.gov/research/deformation/modeling/refs/ross_refs.html)

Coulomb stress change concepts (for strike-slip faults):

King, G.C.P., R.S. Stein, and J. Lin, Static stress changes and the triggering of earthquakes, *Bull. Seismol. Soc. Amer.*, *84* (3), 935-953, 1994.
(http://quake.wr.usgs.gov/research/deformation/modeling/papers/landers.html)

Coulomb stress concepts (for thrust faults and interaction between thrust and strike-slip faults):

Lin, J., and R.S. Stein, Stress triggering in thrust and subduction earthquakes, and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults, *J. Geophys. Res.*, *109*, B02303, doi:10.1029/2003JB002607, 2004.
(http://quake.usgs.gov/research/deformation/modeling/papers/jlin/lin_stein04.html

Dislocation solution formulae:

Okada, Y., Internal deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Amer.*, *82* (2), 1018-1040, 1992.

Application of Coulomb to seismic hazard:

Toda, S., R.S. Stein, P.A. Reasenberg, and J.H. Dieterich, Stress transferred by the M_w=6.5 Kobe, Japan, shock: Effect on aftershocks and future earthquake probabilities, *J. Geophys. Res.*, *103*, 24,543-24,565, 1998.
(http://quake.usgs.gov/research/deformation/modeling/papers/kobe.html)

Toda, S., and R.S. Stein, Response of the San Andreas fault to the 1983 Coalinga-Nuñez Earthquakes: An application of interaction-based probabilities for Parkfield, *J. Geophys. Res.*, *107*, 10.1029/2001JB000172, 2002.
(http://quake.wr.usgs.gov/research/deformation/modeling/papers/parkfield/parkfield.html)

Toda, S., R. S. Stein, K. Richards-Dinger and S. Bozkurt (2005), Forecasting the evolution of seismicity in southern California: Animations built on earthquake stress transfer, *J. Geophys. Res., B05S16, doi:10.1029/2004JB003415.*
http://quake.wr.usgs.gov/research/deformation/modeling/papers/2005/summaries/landers05JGR.html

Application of Coulomb to dike inflation:

Toda, S., R.S. Stein and T. Sagiya, Evidence from the 2000 Izu Islands swarm that seismicity is governed by stressing rate, *Nature*, 419, 58-61, 2002.
(http://sicarius.wr.usgs.gov)

Application of Coulomb to earthquake-volcano interaction:

Nostro, C., R. S. Stein, M. Cocco, M. E. Belardinelli and W. Marzocchi, Two-way coupling between Vesuvius eruptions and southern Apennine earthquakes (Italy) by elastic stress transfer, *J. Geophys. Res., 103, pp. 24,487-24,504, 1998.*
http://quake.wr.usgs.gov/research/deformation/modeling/papers/nostro.html

Chapter 2

THE KEYS TO THE CITY, AND A QUICK TOUR

2.1 The most important things to know about Coulomb

- **Source *vs.* receiver faults** (*p. 11*)
  Sources have slip and impart stress; receivers do not have slip and receive stress

- **Coulomb failure hypothesis, $Ds_f = Dt_s + m' Ds_n$** (*p. 35*)
  Failure is promoted when the Coulomb stress increases. Ds_f is the change in failure stress on the receiver fault caused by slip on the source fault(s), Dt_s is the change in shear stress (*positive in the direction of receiver fault slip*), Ds_n is change in normal stress (*positive when the receiver fault is unclamped*), and m' is effective fault friction coefficient on the receiver fault.

- **How faults are defined in the input files** (*p. 16*)
  Right-hand rule for start/fin. points, positive dip, rt-lat/reverse or rake/net slip

- **Coulomb stress on specified *vs.* optimally-oriented planes** (*p. 36*)
  assumed slip directions vs regional stress; visualizing slip lines, principal axes

- **Coulomb Figures** (*p. 27*)
  "dead" editable vector *.pdf* files *vs.* "live" matlab 3D *.fig* files that can be spun

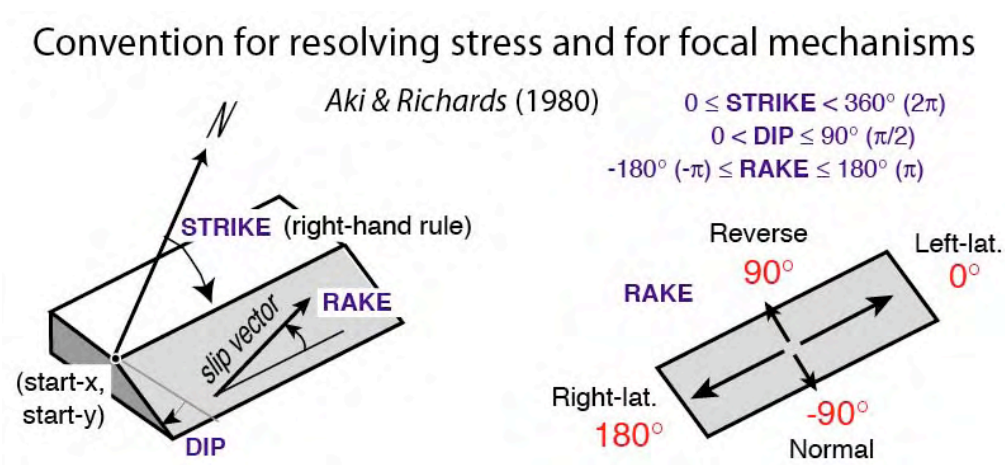
- **'inp' *vs.* 'mat' input files** (*p. 26*)
  .inp is editable text; *.mat* is a binary file, but can include fault and quake overlays

- **Keep an eye on the command window**
  For calculation progress, input/output file names, input source moment, errors

- **Start simple, and add complexity if needed later**
  Even if you have a detailed variable-slip source model, start with idealized faults and develop intuition about the problem. Only then add more realistic detail.

- **For classroom instruction, use Cartesian coordinates unless you want to use overlays**
  Its quicker and easier

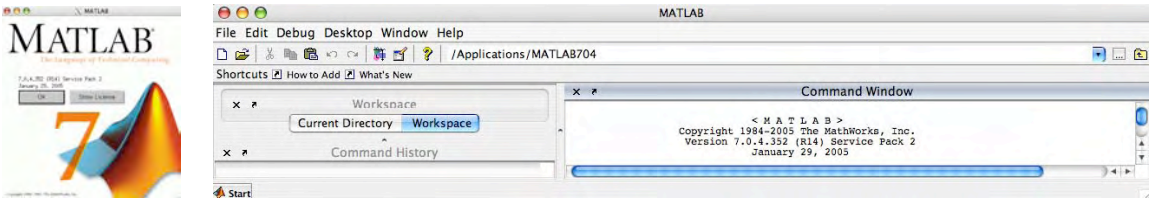
- **How receivers are defined** (*p. 38*)
  Specified faults via Aki-Richards, subdivided receivers, CMTs, and nodal planes:



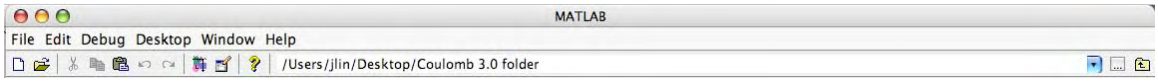
2.2 A quick tour of Coulomb 3.1

Here we just want you to learn the procedure to display and output graphics, and to save the results. We always recommend that you save all your current working documents frequently to prevent lost of files in the event of program crashes.

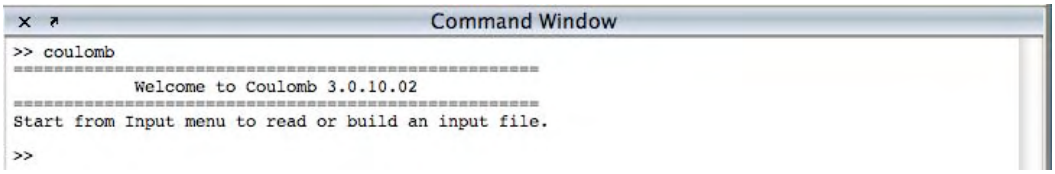
Menus and their pull-down items turn from light white to black as they become options. Here is the procedure to lunch Coulomb:



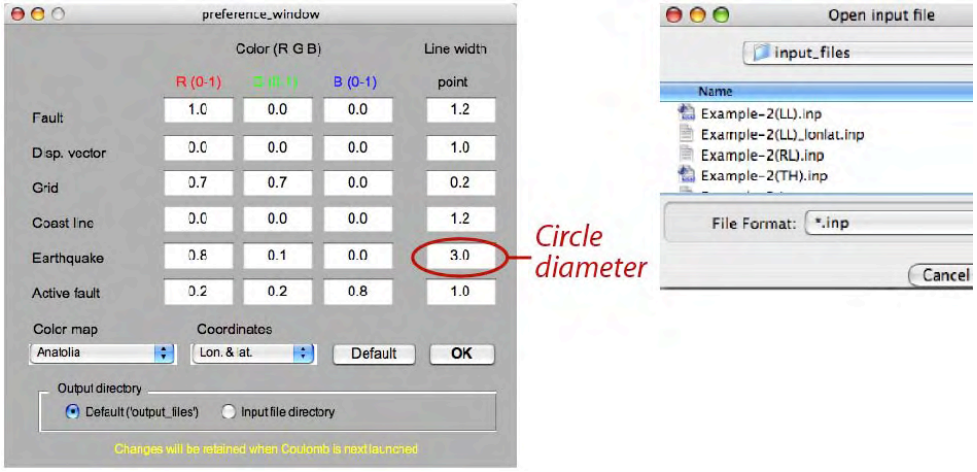
1. Launch Matlab on your computer. In the Matlab menu bar top line, click on the icon enter the path of "Coulomb 3.1 folder" in your computer. For example, in the example shown below, the "Coulomb 3.1 folder" has a path of "/Users/jlin/Desktop/Coulomb 3.1 folder".



2. In the Matlab *Command Window*, type "coulomb". Coulomb will take 30 seconds or so to check the download site and notify you if a newer version is available. **Always migrate to the latest version.**

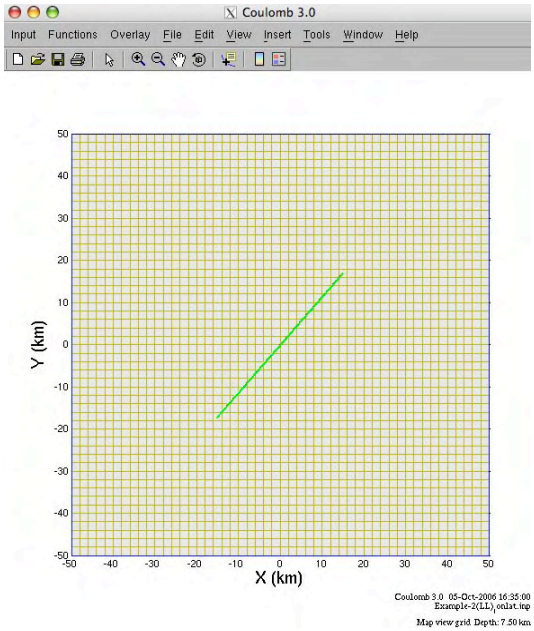


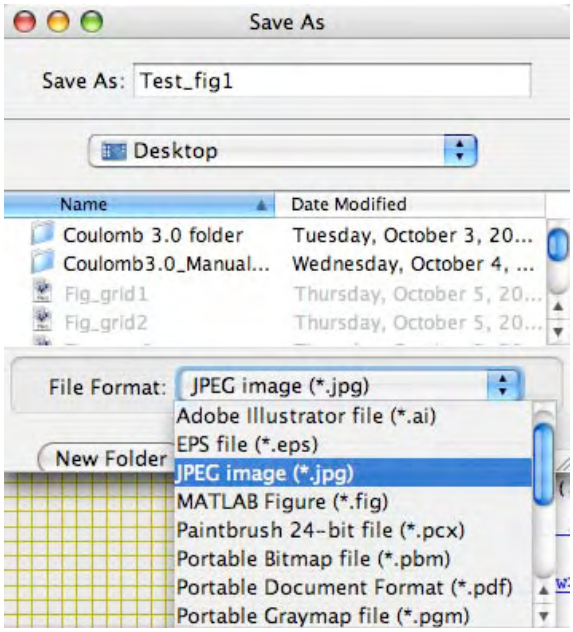
3. Choose **Input** > **Preferences.** Colors, line widths, the 'color map' (the smoothly varying color gradient maps), and the output file folder can all be changed (*below left*). For input files with lat/lon information, you can also choose to plot maps with lat/lon rather than km frame tics. For now, leave them in the default setting.



4. In the pop-up *Coulomb 3.1* window, choose **Input** > **Open existing input file** (*above right*). In the pop-up *Open input file* window, change to sub-directory "input_files". Choose the "Example-2(LL)_lonlat.inp" from the dialog box, then hit <rtrn>. The program will automatically plot the **2D map view** of **the Grid** menu in **Functions**.

5. Once you release the mouse button, the calculation is performed and the program displays the result in the *Coulomb 3.1* window. It's a simple grid with a NE-striking fault in the middle of the grid, as shown below. The bottom right corner also shows the version of the Coulomb program you are using, current date/time, name of the input file you are using, type of calculation for the image, and the calculation depth.





6. Now try, **Functions** > **3D grid**, and play with the zoom and swivel tools. If you want to save this image, choose **File > Save As**. Rename the file in the dialog box, and save it as figure of one of the several types. **Do not use "main_menu_window.fig" as the filename.**

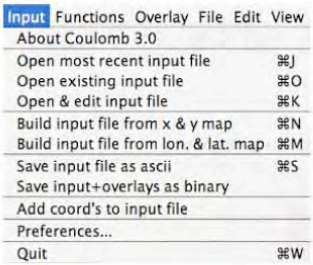
7. You also have the options to **Zoom In**, **Zoom Out**, **Pan**, and **Rotate** your image by clicking on the lower line on the *Column 3.0* menu bar. You can also perform these operations by choosing items in the **Tools** pull-down menu.

8. If you click **Functions** > **Displacements**, in addition to making an image on your *Coulomb 3.1* window, **a numerical output file called "Displacement.cou" will appear in the sub-folder you designated in the Preferences menu**. Similarly, if you click **Functions** > **Stress**, a text output file called "dcff.cou" will be created and can be opened in Excel.

9. To close the *Coulomb 3.1* window, click **Input** > **Quit**. Do not quit out of Matlab if you want to continue with Coulonb. (If you wanted to quit Matlab program, type "exit" in the Matlab *Command Window*.)

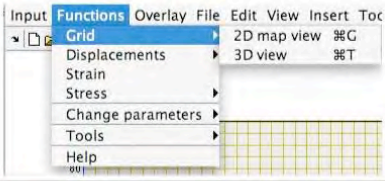
Coulomb Menu Tips

Input



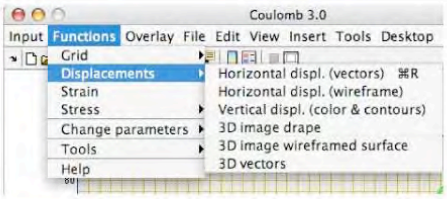
You can use ascii (.inp) or binary (.mat) files as an input file, in input file window you should specify the input file format to make it active.

Functions > Grid

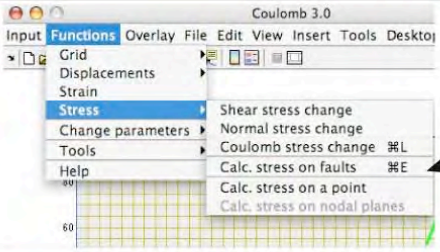


2D Map view is the default first plot for all input files.

Functions > Displacements



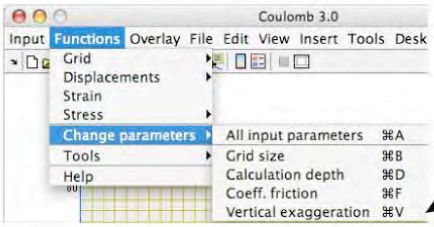
Functions > Stress



Friction Coeficient is 0.4 as a default value.
To modify use Functions > Change parameter > Coeff. friction

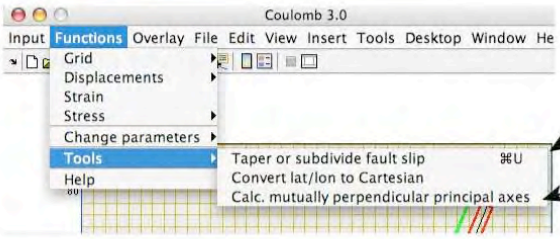
This is stress resolved on a plane in a given rake direction.

Functions > Change Parameters



This is for displacement options

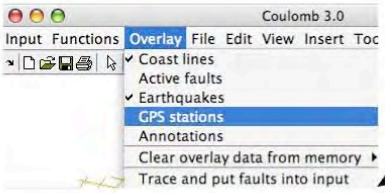
Functions > Tools



These tools permit more realistic simple input files (taper) or variable slip tiles (subdivide).

Used to set regional stress needed for optimally oriented Coloumb stress change plot

Overlay



You must clear overlays before replacing them with new ones
You should save inpu as a .mat file so these overlays are kept.

This option adds input faults by tracing entire faults.

Chapter 3

CONCEPTS, DIMENSIONS AND SIGN CONVENTIONS

This chapter briefly explains the things you must understand to use the software correctly and to avoid meaningless output.

3.1 The crucial concept of source and receiver faults

Source faults have slip, and so they impart stress to the surrounding crust and faults. **Receiver** faults have no slip (slip=0.0 m in the input files). Source and receiver faults otherwise look identical in the input files. The stress imparted by source faults are resolved on the receiver faults through the command **Functions** > **Stress** > **Calc. stress on faults**. Further options for resolving the stress on the receiver fault are controlled by the **Stress on faults control panel**, which automatically appears.

3.2 Calculation procedure

1. Launch Matlab; set the Matlab path to working directory "Coulomb 3.1 folder".
2. Type "coulomb" in Matlab *Command Window*.
3. In *Coulomb 3.1* window menu bar, choose **Input**> **Open existing input file**.
4. In *Coulomb 3.1* window menu bar, choose **Functions** > **Grid, Displacements, Strain,** or **Stress**. Many of these selections trigger requests for additional input, and let you modify the parameters in temporary windows. When you click "Calc. & view", calculations are performed and a new image is displayed.
5. You can perform many operations to the image on the Coulomb 3.1 window, including **Zoom In**, **Zoom Out**, **Pan**, **Rotate 3D**, **Data Cursor**, **Insert Color Bar**, **Insert Color Legend**, etc. You can choose these operations either by clicking the lower menu in the *Coulomb 3.1* window or the **Tools** pull down menu bar. While the graphic plot is open, you **save** this plot.
6. To **print a plot**, save it as a pdf, and then print the small vector file from *Acrobat Reader* or an illustration program. Currently, the **File** > **Print** cmd in Matlab does not work properly.
7. After you have finished all calculations, quit MATLAB.

3.3 To change parameters interactively

Most of the settings and parameters can be changed either by modifying an input file using a text editor, or by changing them interactively within Coulomb. Choose **Functions** > **Change parameters**. Parameters changed within the software interactively are transient and will not permanently modify the input file. Every time you select **Input** > **Save input file**, all current selections will be saved in an input file. Change the name of the file if you do not want it overwritten.

3.4 To save, print, or modify a plot

Choose **File** > **Save As…** We recommend you choose **pdf**, a compact vector format. **Rename the file from the default 'main_menu_window.fig' or it will overwrite an important file.** You then print the pdf from *Acrobat Reader*, or from an illustration program if you would like to spruce it up. Currently, the **File** > **Print** command in Matlab does not work properly.

3.5 Coordinates, units, and sign conventions

Coulomb 3.1 calculates in the (x, y, z) Cartesian coordinate system. When the lat/lon of the corner grid points are specified in the input file, it can also plot in lat/lon. In the map view projection on the monitor, x is positive from left to right, y is positive from bottom to top, z is positive upwards for displacement. DEPTH is positive downwards from the Earth's surface. We use the standard *Aki & Richards* (1980, 2002) sign conventions for fault geometry and slip. The units for the input parameters are the following (see Chapters on Input and Output files for more detail):

Input parameters and their dimensions ***(think bars and meters)***

PR1	Poisson's ratio: [dimensionless, 0-1]; 0.25 is typically used
E1	Young's modulus: [bars]; $8x10^5$ bars is typically used
FRIC	Friction coefficient: [dimensionless; 0-1]; 0.4 is often used
Sym	Obsolete legacy from Coulomb 1.0; *ignore it*

Directions, angle, and dip: [degrees; dip must be positive]
Grid and fault positions (x, y): [km]
Depth: [km] downward is positive
Displacements: [m]
Faults: Right-lateral is positive, and reverse slip is positive [m]
Dikes: Opening displacement is positive [m]
Point Source: Inflation is positive [m^3]
Regional stress tensor, S1, S2, S3: positive in compression [bars]

Output parameters and their dimensions

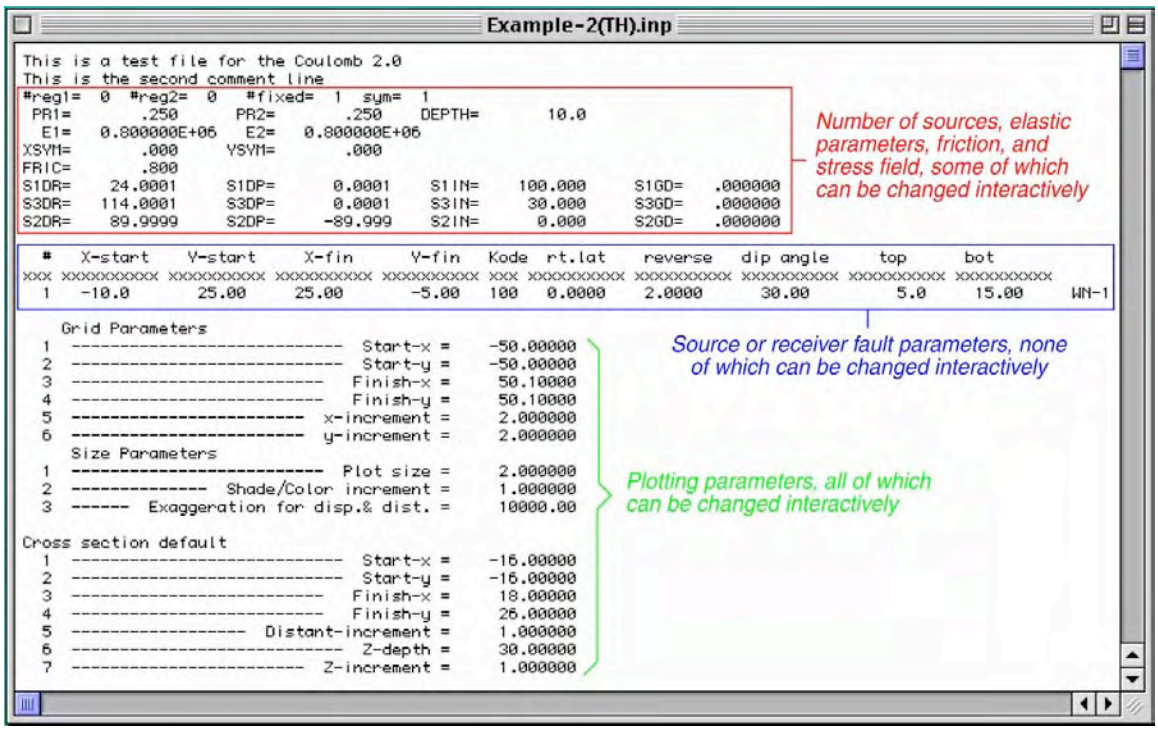
Displacement: [m] North, East, and Up are positive
Shear Strain: [dimensionless] Right-lateral is positive
Principal Strain: [dimensionless] Extension is positive (*tensor notation*)
Dilatational Strain: [dimensionless] Dilatation is positive
Stress: [bars] Right-lateral and unclamping are positive

Shear modulus, *G*. Young's modulus [E] and Poisson's Ratio [PR] are specified in the input file. $G = E/[2(1+PR)]$. So the shear modulus for PR=0.25 and E=$8x10^5$ bars, G=$3.2x10^5$ bars or $3.2x10^{11}$ dyne-cm.

Chapter 4

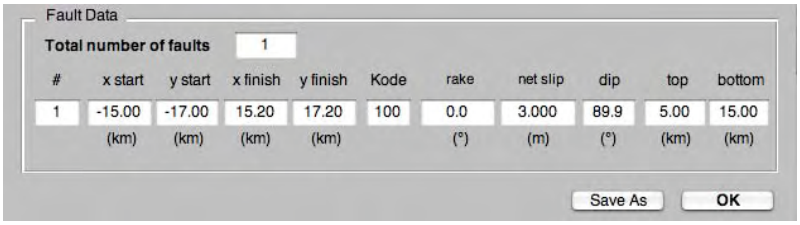
BUILDING INPUT FILES

All Coulomb calculations require input files; some require successive information for which you will be prompted. If an input file is improperly-formatted (e.g., it has tabs, or the number of faults is inconsistent with the '#fixed=', a warning dialog will appear. If it is a text (.inp) file, you must modify the input using text editor. If it is a binary (.mat) file you cannot use it. You can also create an input file interactively or modify an existing file in Coulomb. Open this input file in a text editor:



All **numbers need a decimal point**, except for the line starting "#reg1=" and the first three characters of the source parameters marked '#'. All format statements are shown at the end of this chapter. Right-lateral and reverse slip are reckoned positive (negative values denote left-lateral and normal slip); dip must always be positive. "#reg2=" is an obsolete inheritance from Coulomb 1.0; ignore it.

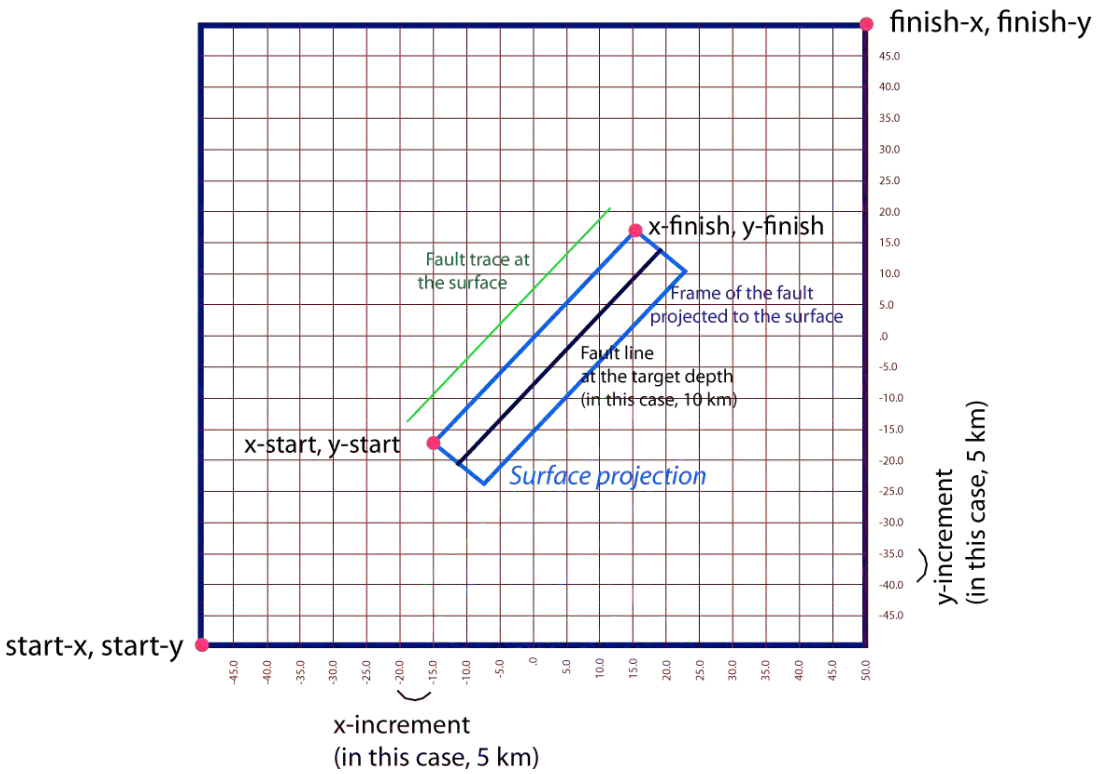
There is an alternate 'rake' input format that specifies **rake (°)** and **net slip (m)**. This permits one to calculate the stress change on receivers (*faults without slip*) in their rake directions, where for example, a left-lat. stress increase would inhibit failure on a right-lateral fault. Try **Input** > **Open & edit input file** > 'Example-2(LL)rake.inp' to see this:



Explanation for grid and fault position

Output graphic (for Data>Old>Example_3.inp)

Map view (Functions > Grid)



Input File

This is **not** a sequence number. It subdivides receiver faults into multiple coplanar receivers. It should be '1' for source faults.

Fault

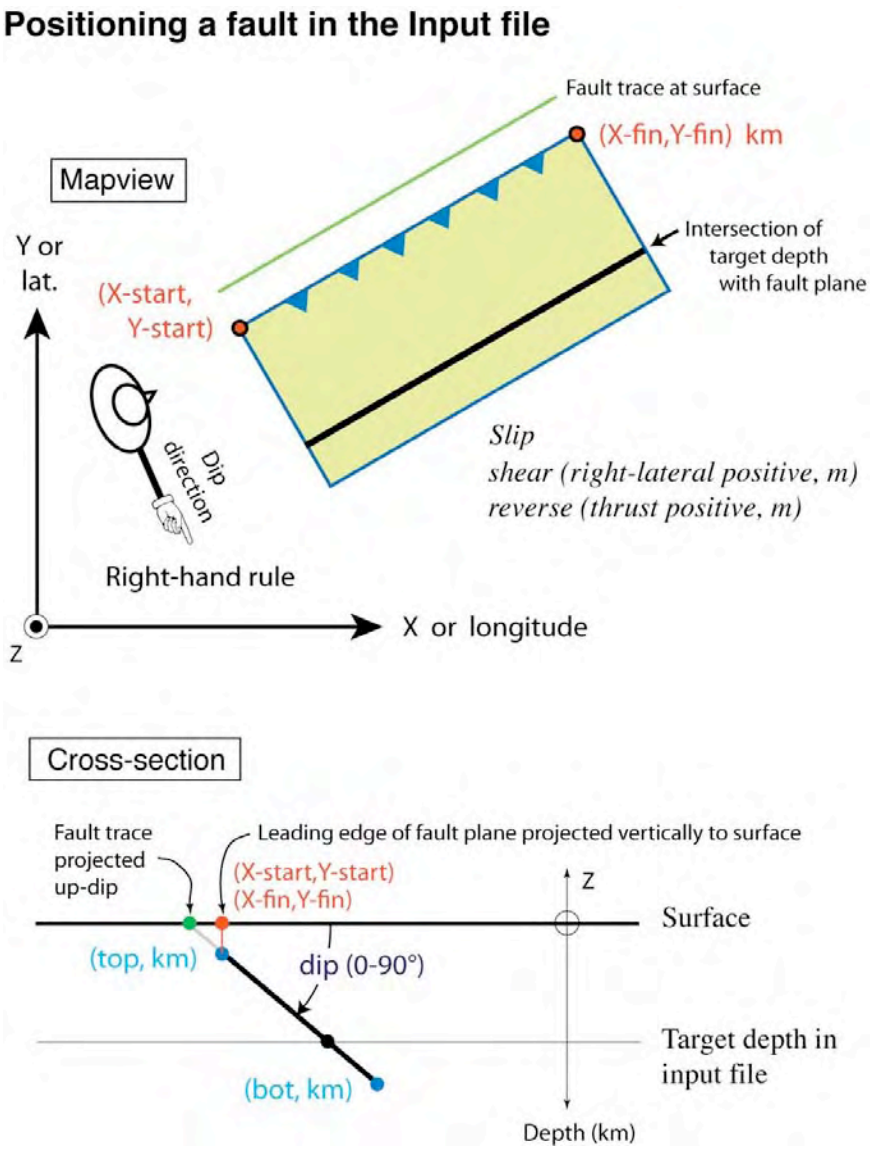
```
  #   X-start    Y-start     X-fin      Y-fin   Kode  rt.lat    reverse   dip angle     top      bot
xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx
  1   -15.1      -17.00     15.20       17.20   100   0.0000    -2.0000     45.0         5.0     15.00     f-1
```

Grid

```
  Grid Parameters
1 ----------------------------  Start-x =    -50.00000
2 ----------------------------  Start-y =    -50.00000
3 --------------------------   Finish-x =     50.10000
4 --------------------------   Finish-y =     50.10000
5 ------------------------  x-increment =     5.000000
6 ------------------------  y-increment =     5.000000
```

4.1 Structure and format for input files

An input file is composed of parameters for the halfspace, regional stress field, source fault positions and slip, receiver fault positions, grid information, graphical representation, and optional cross section and lat/lon information. See the figure, 'Structure and formats of Input file', which annotates the entries. The numbers should be filled within the designated areas with appropriate values. When making or modifying input files, use a non-kerning (uniform-spacing) font, such as Monaco, so that all numbers align under the xxxxxxxx headers.



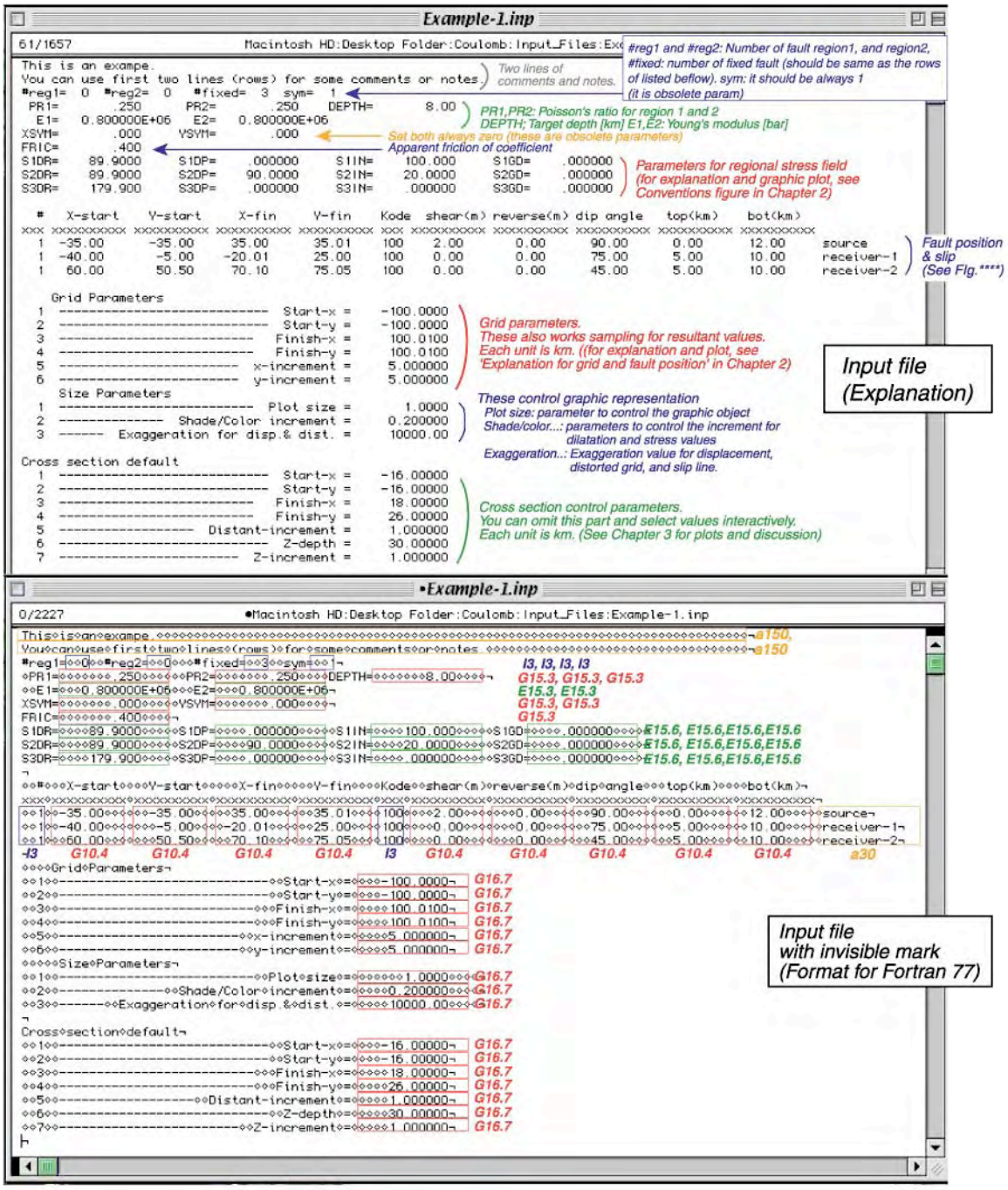
4.2 Working in lat/lon coordinates

Coulomb can read and display lat/lon's if you include the lat/lon of the grid borders and the (0, 0 km) point in the input file, as seen here from 'Example-SFBayArea.inp'

```
Cross section default
  1  ---------------------------  Start-x =    -36.00000
  2  ---------------------------  Start-y =     36.00000
  3  -------------------------   Finish-x =     38.00000
  4  -------------------------   Finish-y =    -36.00000
  5  ------------------  Distant-increment =     1.000000
  6  ---------------------------  Z-depth =     30.00000
  7  ----------------------  Z-increment =     1.000000
     Map infomation
  1  --------------------------- min. lon =    -123.0000
  2  --------------------------- max. lon =    -121.0000
  3  --------------------------- zero lon =    -122.0000
  4  --------------------------- min. lat =      36.0000
  5  --------------------------- max. lat =      38.0000
  6  --------------------------- zero lat =      37.0000
```

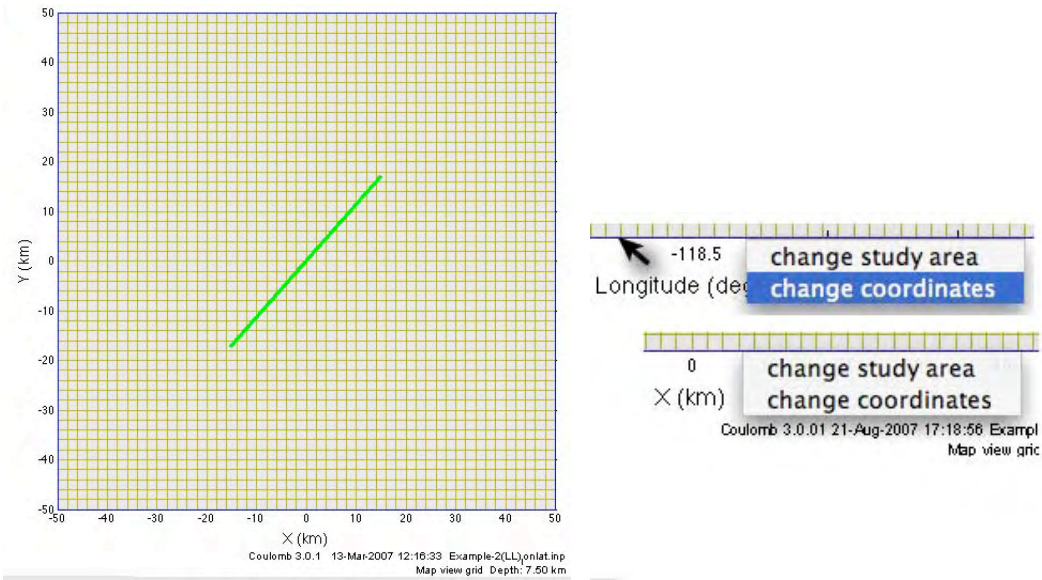
If you have lat/lon information for a source, you can convert it to Coulomb (x, y) input format by selecting **Functions** > **Tools** > **Convert lat/lon to Cartesian**, which brings up a calculator window.

Structure and formats of the Input file

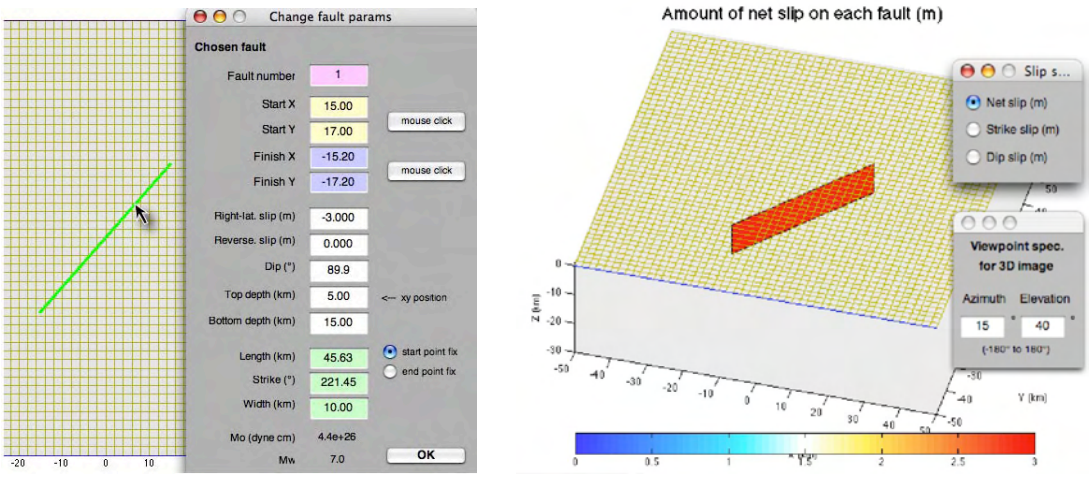


4.3 To open, display and modify existing input file interactively

1. **Input** > **Open existing input file** > Example-2(LL)-lonlat.inp in the "input_files" sub-folder within the "Coulomb 3.1" folder.
2. The graphic on the left below appears in the *Coulomb 3.1* window. You can see the undistorted grid (yellow) and the surface projection of the source fault (green).



3. To show the same plot with lat/lon tic marks, put the cursor on the blue frame and make a right mouse-click (above right). Choose *change coordinates* and make a leftmouse-click. Alternatively, from the menu, **Input** > **Preferences** and change **Coordinates** from *Cartesian* to *Lon. & Lat.*, and click OK.
4. To modify a source or receiver fault, click on the fault with the right mouse click, and it will open the '*change fault params*' window (below left). You can do the same thing to the blue study area border to change the study area boundaries.



4.4 To display the undistorted grid in 3D view

1. Choose **Functions** > **Grid** > **3D view**. The graphic above right appears in the *Coulomb 3.1* window. You can see the undistorted grid in 3D view (yellow) and the fault patches colored by their input slip. You can examine the slip components, change the viewing angle numerically, or with the rotate tool to the right of the 'hand' icon.

4.5 Modifying an existing file in a text editor

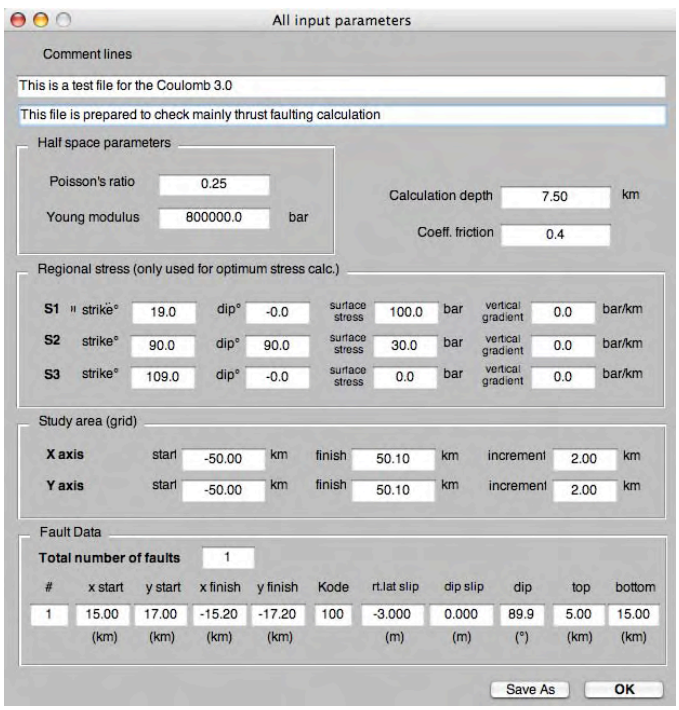
1. Click one of the example files we prepared for tutorials.
2. To duplicate it, type 'd' holding command key (command + D), or drag the icon holding option key.
3. Rename it.
4. Launch an editor and open the file using **File** > **Open** (command + O).
5. Use a non-kerning (uniform-spaced) font, such as Monaco or Courier. Change the numbers you want, checking the units and format. If you want to add source or receiver faults, you

can add a new row. Make sure that the number of the rows (faults) and the number of the fixed faults (#fixed=) in the third row in the input file are the same. Some of the editors have an option to 'show invisibles'. If your editor has the function, make sure that your modified numbers are filled in the properly formatted areas and there are no tabs. A tab will crash the program.

6. Save the file.

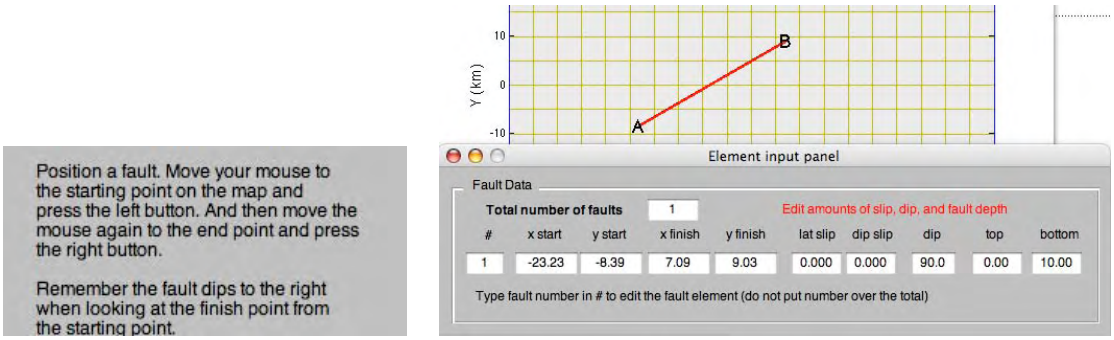
4.6 Editing existing input files within Coulomb (no need to worry about formats)

If you already have an input file prepared, after launching the program the file is read by choosing *Input* > **Open & Edit Input File**. The "input_window" will appear as shown below. You can modify values in the boxes of elastic parameters, regional stress settings (only used for 'Opt.-' stress calculations), Study area (grid), and Fault Data. If the 'Total number of faults' is greater than 1, enter the order number of a specific fault patch that you wish to modify below "#". Then click "OK", properties of that particular source will appear.



4.7 Building an input file from a simple X,Y map

To build an input file from map, you can select from menu **Input** > **Build Input File from x & y Map**. You can add Longitude and Latitude information of your study area by clicking the *Add lon.lat. info* button". We explain how the regional stress is used in Chapter 7, so don't worry about it now.



Note that you must close the above warning message before specifying a fault on the following map. Click "OK" and the fault color will turn to green.

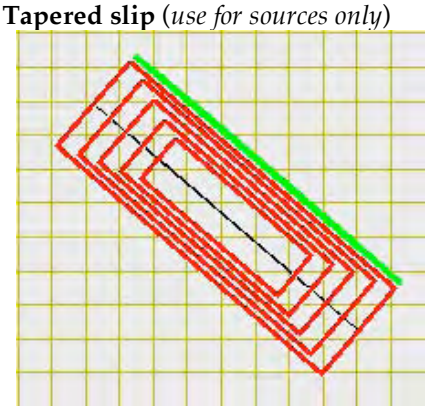
4.8 Tapering the slip on a source fault

To remove unrealistic stress concentrations at the edges of a fault, you can taper the slip automatically in Coulomb. Choose **Input** > **Open an existing file** and choose 'Example-2(TH).inp'. Then choose **Functions** > **Tools** > **Taper or subdivide fault slip**. When the *Element input panel* appears, choose 'Linear tapering'. The tapered slip is built by nested rectangles. Choose 10 km along strike, 5 km down-dip, and 5 nested patches, and hit OK. Save the tapered input file by **Input** > **Save input file as ascii** with a new name, and open it in an editor to see the 5 nested coplanar sources, as shown below.

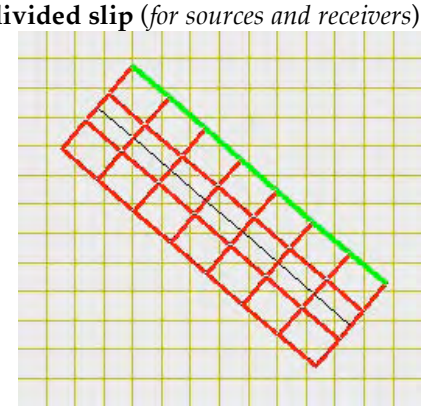
#	X-start	Y-start	X-fin	Y-fin	Kode	rt.lat	reverse	dip angle	top	bot
xxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx
1	-8.6771	22.7019	22.5266	-4.0441	100	0.0000	0.8664	45.0000	0.8839	14.1161
1	-7.3542	20.4039	20.0533	-3.0882	100	0.0000	0.8664	45.0000	1.7678	13.2322
1	-6.0312	18.1058	17.5799	-2.1323	100	0.0000	0.8664	45.0000	2.6517	12.3483
1	-4.7083	15.8077	15.1065	-1.1765	100	0.0000	0.8664	45.0000	3.5355	11.4645
1	-3.3854	13.5096	12.6332	-0.2206	100	0.0000	0.8664	45.0000	4.4194	10.5806

Notice that the patches get successively smaller on down the list, and that each patch has the same slip. The seismic moment (summed slip x area of each patch) of the tapered source is identical to that of the original uniform-slip input file. The larger the number of patches, the smoother the stress but the longer Coulomb needs to calculate.

Tapered slip (*use for sources only*)



Subdivided slip (*for sources and receivers*)



4.9 The seismic moment is calculated every time an input file is loaded

Every time you launch an input file, it calculates the total seismic moment of the sources in the input file, using the fault area, slip, Young's modulus, E, and Poisson's ratio, PR, from the input file. The seismic moment (in dyne-cm) and the equivalent M_w appears in the *Matlab window*:

```
-----------------------------------------------------
User selected/Users/Toda/AFRC project IV/coulomb30/input_files/Example-1.inp
   No lat. & lon. information is included in the input file.
   Total seismic moment = 7.60e+26 dyne cm (Mw = 7.19)
---> To calculate deformation, select one of the submenus from 'Functions'.
```

So, if you want to the seismic moment of individual sources, remove the others from the input file. The tapered fault will always have the same moment as its untapered version.

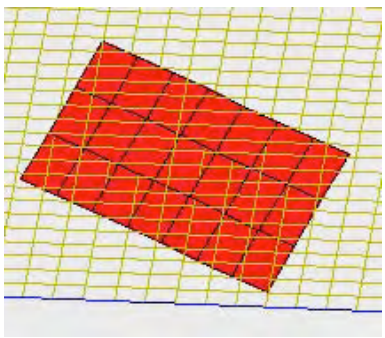
4.10 Sub-dividing or 'tiling' the slip on a fault

Many large sources have variable slip models with numerous small patches of slip. You might also want to subdivide a receiver fault so that you can assess the variations in stress imparted by a nearby earthquake. As you did before, choose **Input** > **Open an existing file** and choose 'Example-2(TH).inp'. Then choose **Functions** > **Tools** > **Taper or subdivide fault slip**. This time, when the *Element input panel* appears, click on 'Splitting'. Now choose a 7 x 3 patch subdivision,

and hit OK, and you will see the picture above right. Save the tiled input file by **Input** > **Save input file as ascii** with a new name, and open it in an editor to see the 21 adjacent coplanar sources, all with the same slip as the initial input file. You can now change the slip on each patch. The input folder contains two examples of these (the 1992 M=7.3 Landers, California, and 1995 M=6.9 Kobe, Japan, shocks).

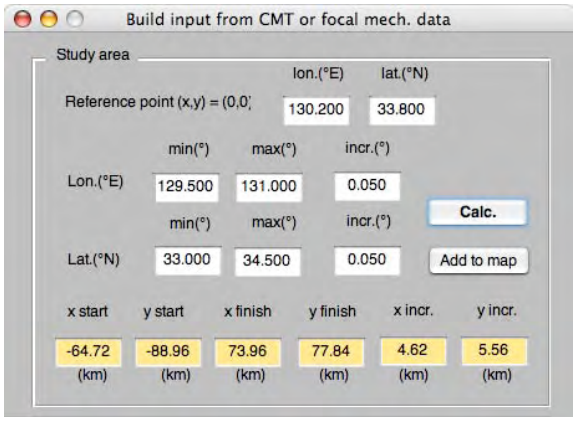
#	X-start	Y-start	X-fin	Y-fin	Kode	rt.lat	reverse	dip angle	top	bot
xxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx
1	-10.0000	25.0000	-5.0000	20.7143	100	0.0000	2.0000	45.0000	0.0000	5.0000
1	-13.2540	21.2037	-8.2540	16.9180	100	0.0000	2.0000	45.0000	5.0000	10.0000
1	-16.5079	17.4074	-11.5079	13.1217	100	0.0000	2.0000	45.0000	10.0000	15.0000
1	-5.0000	20.7143	0.0000	16.4286	100	0.0000	2.0000	45.0000	0.0000	5.0000
1	-8.2540	16.9180	-3.2540	12.6323	100	0.0000	2.0000	45.0000	5.0000	10.0000
1	-11.5079	13.1217	-6.5079	8.8360	100	0.0000	2.0000	45.0000	10.0000	15.0000
1	0.0000	16.4286	5.0000	12.1429	100	0.0000	2.0000	45.0000	0.0000	5.0000
1	-3.2540	12.6323	1.7460	8.3466	100	0.0000	2.0000	45.0000	5.0000	10.0000
1	-6.5079	8.8360	-1.5079	4.5503	100	0.0000	2.0000	45.0000	10.0000	15.0000
1	5.0000	12.1429	10.0000	7.8571	100	0.0000	2.0000	45.0000	0.0000	5.0000
1	1.7460	8.3466	6.7460	4.0609	100	0.0000	2.0000	45.0000	5.0000	10.0000
1	-1.5079	4.5503	3.4921	0.2646	100	0.0000	2.0000	45.0000	10.0000	15.0000
1	10.0000	7.8571	15.0000	3.5714	100	0.0000	2.0000	45.0000	0.0000	5.0000
1	6.7460	4.0609	11.7460	-0.2249	100	0.0000	2.0000	45.0000	5.0000	10.0000
1	3.4921	0.2646	8.4921	-4.0211	100	0.0000	2.0000	45.0000	10.0000	15.0000
1	15.0000	3.5714	20.0000	-0.7143	100	0.0000	2.0000	45.0000	0.0000	5.0000
1	11.7460	-0.2249	16.7460	-4.5106	100	0.0000	2.0000	45.0000	5.0000	10.0000
1	8.4921	-4.0211	13.4921	-8.3069	100	0.0000	2.0000	45.0000	10.0000	15.0000
1	20.0000	-0.7143	25.0000	-5.0000	100	0.0000	2.0000	45.0000	0.0000	5.0000
1	16.7460	-4.5106	21.7460	-8.7963	100	0.0000	2.0000	45.0000	5.0000	10.0000
1	13.4921	-8.3069	18.4921	-12.5926	100	0.0000	2.0000	45.0000	10.0000	15.0000

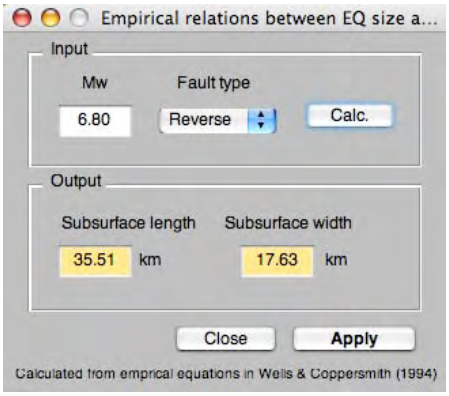
If you are tapering or subdividing a vertical fault, you can still see the nested or tiled patches by choosing **Functions** > **Grid** > **3D view**. Then you can use the swivel tool to view it on its side. 3D view is also valuable because the patches are colored by their slip, rather than being translucent.

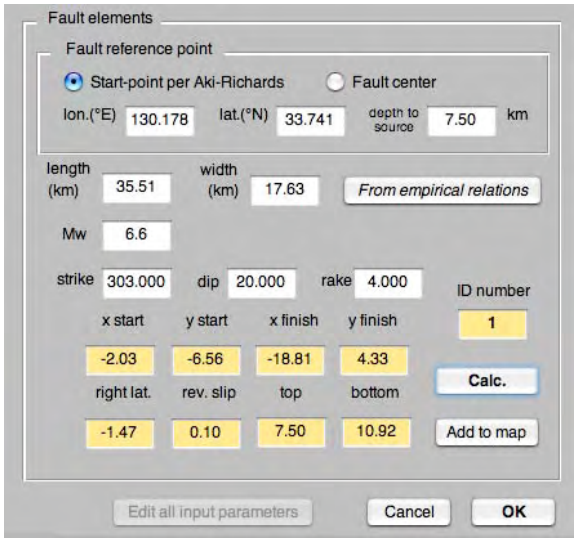
Subdivided fault in 3D view  **Use** **swivel tool in menu**

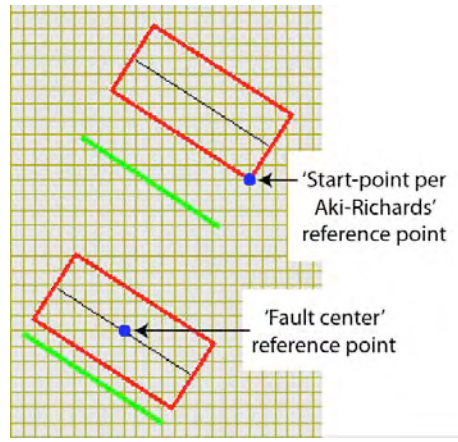
4.11 Making realistically-scaled source faults from CMT or focal mechanism data

1. Choose **Input** > **Build input file from lon. & lat. map**. *The Map positions to Cartesian positions* calculator will appear:









2. Press 'Calc.' in the 'Study area' box (*above*) to calculate boundaries and grid increments of the study area (the yellow fields). Then hit 'Add to map' to apply changes to Coulomb window, which will create the grid.

3. To create the source fault from the CMT information, drop down to the 'Fault element' box (*above left*). You can choose the 'Fault center' (this is the geometrical center of the rectangle, so make sure the top of the fault is at or below the ground surface), or the 'Start-point per Aki-Richards' (this is the Coulomb start-x, start-y position), and then input the M_w, strike, dip, and rake from a CMT file. In this example, just change M_w to 6.8 and change the dip to 20°.

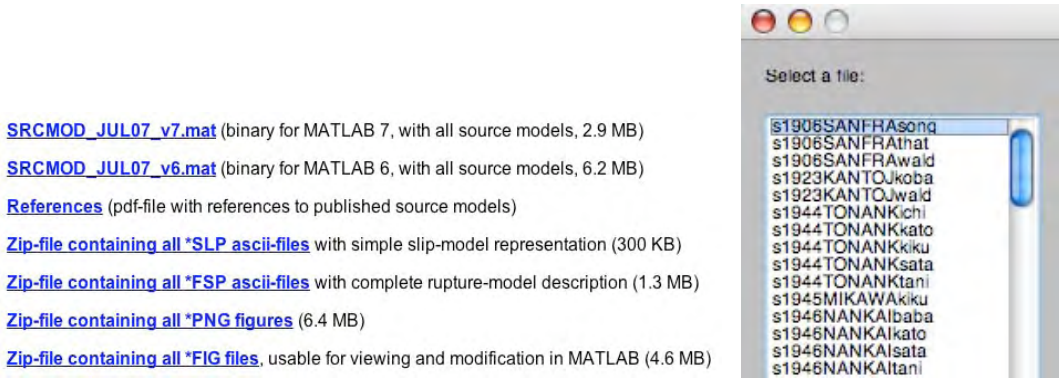
4. If you would like to use empirical magnitude-area relations to estimate appropriate fault lengths and widths, press the 'From empirical relations' button, and the 'empirical relations…' box will appear (*above right*). Choose the type of fault (here, reverse) and hit 'Calc.' To accept the length and width values, hit the 'Apply' button, and then close the 'empirical relations' window. You will see 'length' and 'width' information changed in the Fault elements box. Notice, however, that these relations permit the fault width in large strike-slip events to get too deep.

5. Now press 'Calc.' in the Fault element window to calculate fault position, and press 'Add to map' to apply the fault to the coulomb window. A portion of the resulting map is shown above at right. Notice that the blue dot is the fault reference point you selected. To save the input file you just created, choose 'Save input file as ascii' in the Input menu, and name it. You can replace the comment lines to the file.

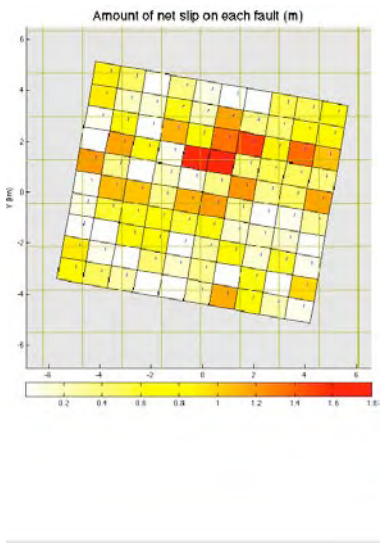
4.12 Converting online variable-slip coseismic models to Coulomb input files

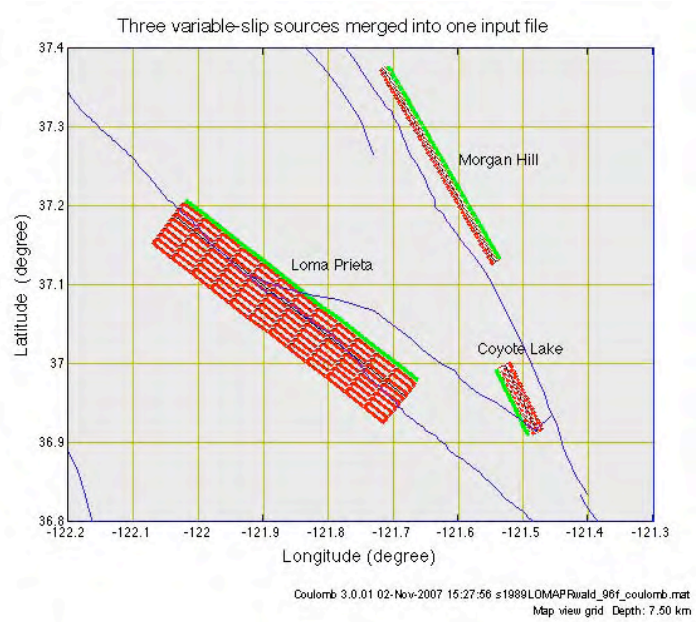
Martin Mai (ETH Zurich) has built the outstanding SRCMOD database of over 150 variable-slip input files from the literature, which can be read in as Coulomb input files. Bear in mind that these files can have hundreds to thousands of slip patches are so calculations, particularly '3D view' and 'calc. slip on faults', can be very slow.

1. Go to **http://www.seismo.ethz.ch/srcmod/** and click on 'Downloads'. Then download the most recent .mat file for Matlab 7 (*the top file below left*) to the Coulomb30 folder. Make sure you *Save as* a binary '.mat' file, not a '.txt' file.



2. In the Matlab command window, type the plugin '**srcmod2coulomb**'. You will then see the file selection window (*above right*). The selected file will automatically be saved into the input file folder as an .mat input file. The file name will also indicate the number of sources ('_100f_' means 100 slip patches). *Warning*: A large number of patches demands much more calculation time.
3. Then, **Input** > **Open existing input file** > **Grid** >**3D view**. The example below left is 's1987WHITTIhart_100f_coulomb.mat', the 1987 M_w=6 Whittier Narrows shock:





4.13 Merging several variable-slip models to one input file ('merge_input_file' plugin)

Sometimes you will want to take many variable-slip input files for nearby earthquakes and merge them into one .mat input file. Here's how you do it:

1. Open an existing input file. Type 'merge_input_file' into the Matlab command window. You are then requested to choose the second input file. This process is repeated until you have included all files that you want.
2. Save the combined file with any name you would like. In the example above right, we used the Overlay > Annotation tool to add the quake names to the map. They will be preserved in the .mat file, although you need to uncheck and recheck them when you next plot the file (a Matlab bug).

Chapter 5

EARTHQUAKE, FAULT, AND COASTLINE OVERLAYS

5.1 Overlays (coastlines, active fault traces, seismicity)

1. It is often enormously valuable to plot your map with lat/lon tic marks and overlay geographic or seismic catalog information. This is easy to do as long as the input file (.inp or .mat) has lat/lon information which is the last item in the input file, such as

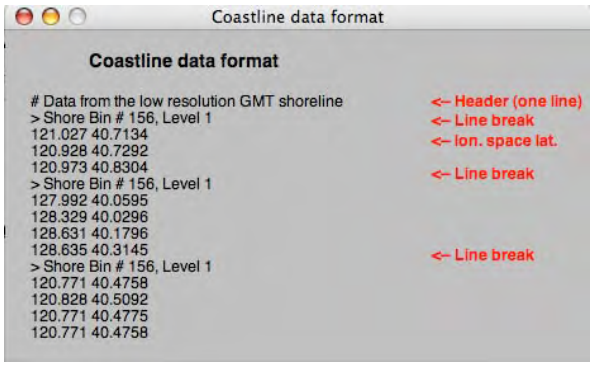
```
  Map infomation
1 ---------------------------- min. lon =    -123.0000
2 ---------------------------- max. lon =    -121.0000
3 ---------------------------- zero lon =    -122.0000
4 ---------------------------- min. lat =      36.0000
5 ---------------------------- max. lat =      38.0000
6 ---------------------------- zero lat =      37.0000
```

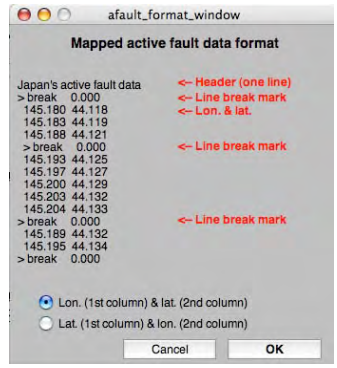
   To plot with lat/lon tic marks, **Input** > **Preferences** > **Coordinates** > **lon. & lat.** and then launch the input file. (If you do not have this information, you can calculate it using the Coulomb tools: **Functions** > **Tools** > **Convert lat/lon to Cartesian**, which opens a calculator window that will create your input file for you.)

2. **Use of the National Geophysical Data Center Coastline Extractor**. Go to **http://www.ngdc.noaa.gov/mgg_coastline/** and input the boundary coordinates, or 'use Java Map for lat/lon', zooming in as needed. We recommend the Medium Resolution (1:70,000) Coastline database. Select the Matlab Format, choose no compression, and preview it with a GMT plot. Hit the 'SUBMIT' button. Save the resulting '.dat' file in the Coulomb 'coastline_data' folder, and rename it if you like.

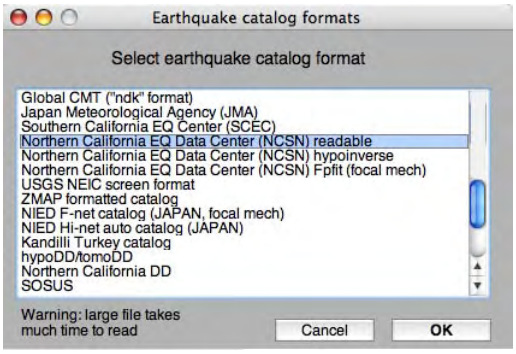
5.2 How to use overlays in 2D and 3D plots

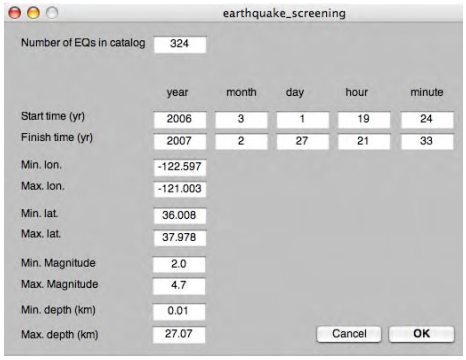
1. Launch 'Example-SFBayArea.inp'. Now, **Overlay** > **Coastlines**. Open the 'coastline data' folder in the Coulomb30 folder, and select 'california_coastline_di_neg.dat'. The 'di' refers to intermediate resolution, there is also a high resolution 'dh' file in the folder. Answer the pop-up question, 'no'. Some datasets treat western longitudes as negative; others do not. The coastline will appear on your plot. Now try, **Overlay** > **Active faults.** (You could load folds or roads or anything you like; the formats are explained in a pop-up window). Choose 'California faults_longlat_dat'. It's a large file but shortly will plot on your map. The *Coastline* and *active fault data format windows* are shown below:





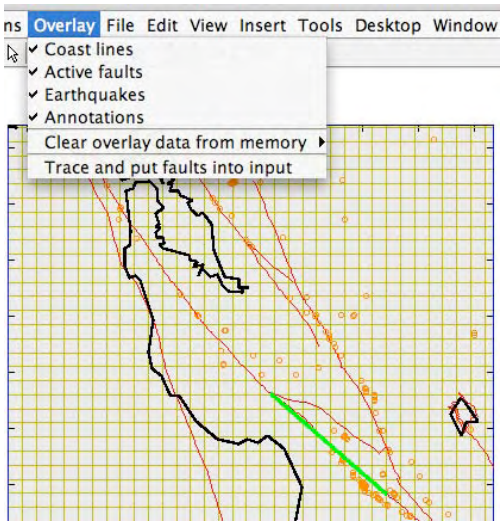
2. Now choose **Overlay** > **Earthquakes**, and choose the'(NCSN) readable' format in the *Earthquake catalog formats* menu below left. Then select the 'readable' format of the actual data file in the data folder. It is only important that the format chosen matches the format of the dataset you are opening. Fourteen formats are supported by Coulomb from global data, the U.S., Japan, and Turkey, and we plan to add more.





An *Earthquake_screening* window (shown above right) will appear that lets you filter the time, location, depth, and magnitude of earthquakes you would like to plot. It if is a large catalog, this can take time.

3. For this exercise, just click 'OK' to plot all 324 earthquakes that occurred in the grid are defined in the input file, and you should see the image below. The default colors appear below, but the colors of all overlays are controlled in the Preferences panel.



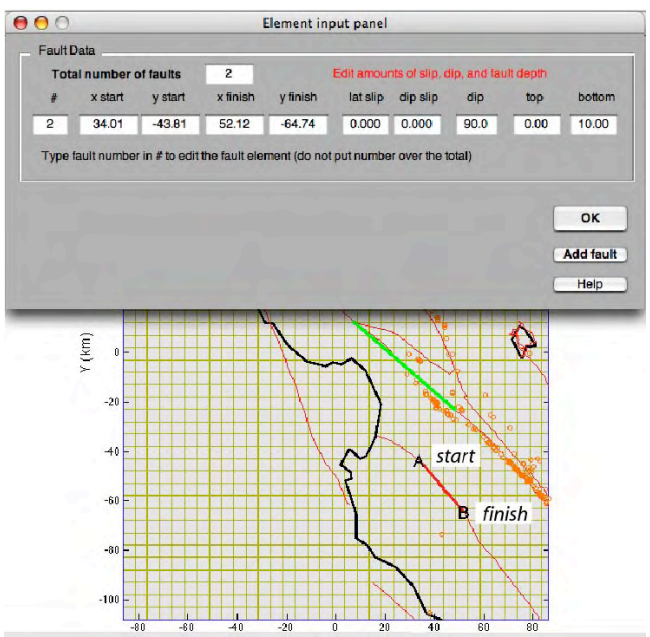
You can remove any overlay by **Overlay** > **Clear overlay from memory**, if you want to use a different dataset instead, or you can toggle on/off any overlay by unchecking it.

4. Save an input file with all of the overlays by **Input** > **Save Input + Overlays as .mat**. Name it uniquely. This will create a compact binary file that you can use in the future—a great time savings—although it cannot be epened in an editor.

5.3 Adding source or receiver faults by tracing active faults (or folds)

1. It is very fast and easy to build source or receiver faults by tracing the active faults on the map. Starting from where you left off in the previous exercise, **Overlay** > **Trace and put faults into input**. Instructions pop up to remind you that you use your left mouse button for the **Start** end of the fault and your right mouse button for the **Finish** end. Remember that the right-hand rule means that for non-vertical sources, the Start-Finish order determines which direction it dips: the fault dips to the right when you are looking toward the Finish from the Start (see the all-important Aki-Richards convention diagram in Chapter 4).

The *Element input panel* appears (see below) with the Start-Finish coordinates you moused on the map. Now, add the slip and top/bottom depth and hit 'OK'. Remember that if the fault is non-vertical and blind, it will be offset from the trace as a function of its dip and upper depth (refer to the 'Map Positioning' figure in Chapter 4 to see this). The new fault appears in red (below); when you hit OK, it turns green to indicate it is now the trace of a source or receiver. If you save the input file, the new source or receivers will be included. **A** corresponds to Start, and **B** corresponds to Finish.



5.4 Making 3D source and seismicity figures that you can spin and roll

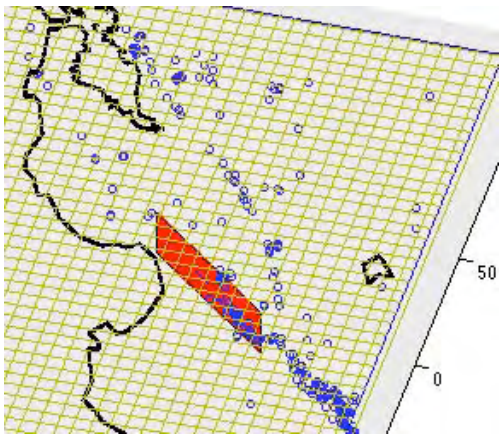
Matlab lets you create very compact 'figure' files that can be manipulated in 3D to see, for example, if your coseismic source fault is properly located with respect to its aftershocks.

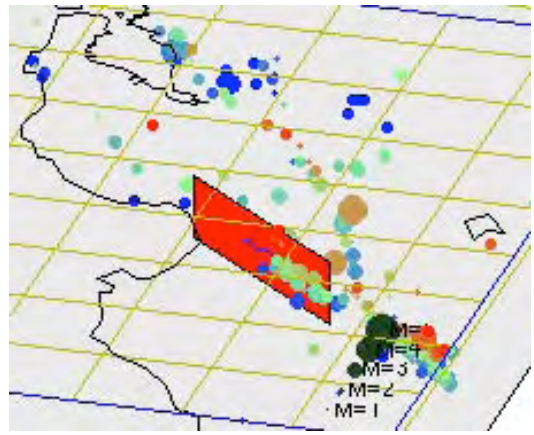
1. **Input** > **Preferences** > **Cartesian**. Open an input file, add the coastline and earthquake catalog overlays. Now, **Functions** > **Grid** > **3D view** (*see below left*).
2. Switch to the Matlab *command window*, and type the plug-in, '**earthquake_plot3**'. You will asked on screen if you would like the earthquake magnitude scaled by circle size and depth scaled by color (choose Y); circles or filled disks (choose N).
3. You can use the tool to blow up the area of interest, but the file will still contain the full data. Now use the to spin and roll the view. A portion is shown below, at right.

With this tool selected, a right mouse-click lets you to reset to a regular map, side, or depth view. The source slip is scaled by its color.

4. *If you are using a PC*, you can save this file and re-open it later. **File > Save as** > 'yourname.fig.' Its an amazingly small file.
5. If you simply double-click on this figure, it opens in Matlab (not Coulomb) and can again be maninpulated. Matlab has yet to implement this feature on Mac's.

3D view in Grid **using 'earthquake_plot3' plugin**

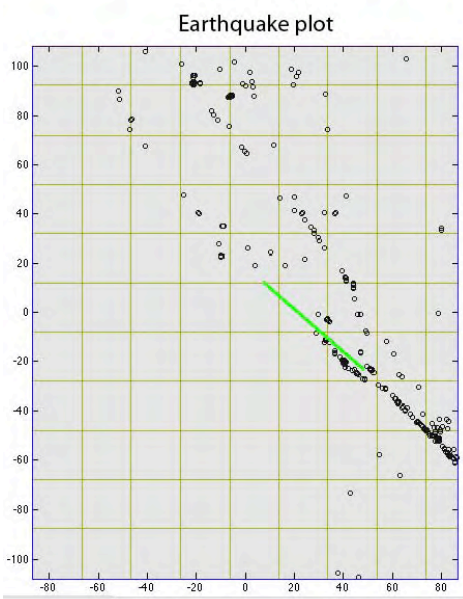


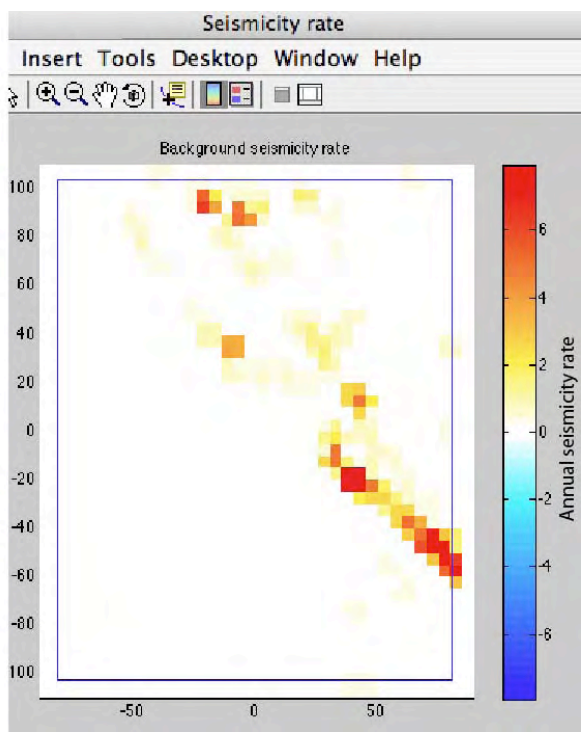


5.5 Making smoothed seismicity density plots

Rather than showing earthquakes, you might want to plot seismicity density smoothed over some radius. This can be accomplished by plotting an earthquake catalog in a 2d Grid view, and then typing in the plugin, 'smoothed_background'. You will choose a smoothing radius, and it will plot the seismicity density over a box reduced in size to the original so that the smoothing kernal can use all cells, as shown below.

Use of the plugin, 'smoothed_background'





Chapter 6

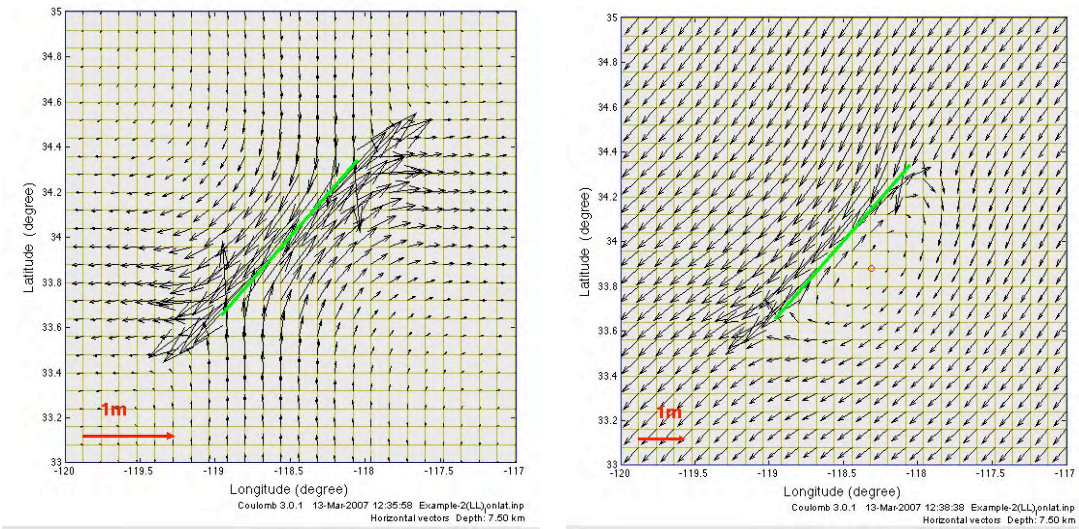
DEFORMATION, GPS DISPLACEMENT AND STRAIN

Here we guide you in calculating deformation caused by an earthquake and display the results graphically.

6.1 To display horizontal displacement vectors

1. **Input** > **Preferences** and change **Coordinates** from *Cartesian* to *Lon. & Lat*. **Input** > **Open existing input file** > 'Example-2(LL)-lonlat.inp'. Then, **Functions** > **Displacements** > **Horizontal displ. (vectors).** You will see a dense vector image in the *Coulomb 3.1* window. To plot fewer vectors, **Functions** > **Change parameters** > **Grid size**, and change it from 0.06° x 0.04° to 0.12° x 0.08°, and hit OK. Now repeat **Functions** > **Displacements** > **Horizontal displ. (vectors).** After you've seen the plot, return the coordinate system to (x, y) by **Input** > **Preferences** and change **Coordinates** from *Lon. & Lat.* to *Cartesian*, and click OK.

No reference point **Reference point by mouse click**



2. *To change vector scale and reference frame*: In the *Displacement control panel*, either move the slider (which rescales the vectors on the fly) or type in a number (try 10,000) in the text field (these means the vector scale is 10,000 x the distance scale). Then click on *Fixed point*, hit the *Mouse click* button and click on a point to the SE of the fault, and hit "Calc. & view." You should now see a plot like that above right, with the reference point indicated by a red circle.

3. *Numerical output files are created every time you make a run*. Every time when you click "Cal. & View" in the *Displacement control panel*, a text output file called "Displacement.cou" will be created or updated and saved in a sub-folder called "Output files" within the "Coulomb 3.1 folder". When you want to save your latest runs, remember to rename the "Displacement.cou" file; otherwise it will be overwritten by your next displacement calculations. Below left is an excerpt of a "Displacement.cou" text output file.

Coordinates **Displacements**

Displacement.cou

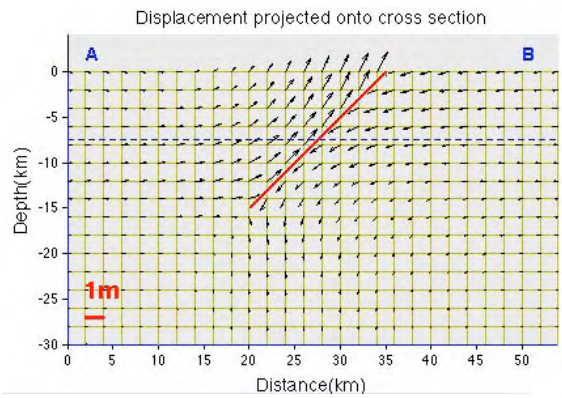
Input file selected: Example-2(LL)_lonlat.inp

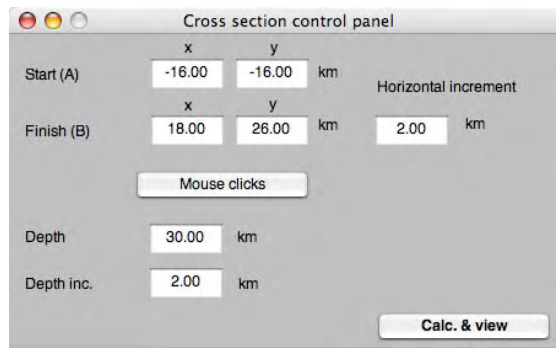
x (km)	y (km)	z (km)	UX (m)	UY (m)	UZ (m)
-50.00000000	-50.00000000	-7.50000000	-0.01714258	0.00551020	-0.00152591
-50.00000000	-48.00000000	-7.50000000	-0.01969615	0.00407689	-0.00206484
-50.00000000	-46.00000000	-7.50000000	-0.02256910	0.00253268	-0.00263662
-50.00000000	-44.00000000	-7.50000000	-0.02578451	0.00089117	-0.00323851

```
Cross section default
  1  ----------------------------  Start-x =    -36.00000
  2  ----------------------------  Start-y =     36.00000
  3  --------------------------   Finish-x =     38.00000
  4  --------------------------   Finish-y =    -36.00000
  5  ------------------ Distant-increment =      1.000000
  6  ----------------------------  Z-depth =     30.00000
  7  ------------------------  Z-increment =      1.000000
```

4. *Change sampling depth of calculation:* In the *Displacement control panel*, type your desired value after "Depth". Most often for displacements, one sets DEPTH to 0.0 to compare the results to geodetic data.

5. *Make a displacement cross-section:* Choose **Input** > **Open existing input file** > Example-2(TH).inp. Next, **Functions** > **Displacements** > **Horizontal displ (vectors).** In the *Displacement control panel*, choose "Cross section". Change the increments to 2 km by 2 km. This is a reverse fault; the dashed blue line in the plot below is the depth of the vectors in the map view plot. The cross-section line was included in the input file (this optional information is shown above right). You can change the cross-section line interactively in the *Cross section control panel*. Use the **left mouse button** to click the start (A) point, and the **right mouse button** to click the end (B) point, and make sure that the starting point is **to the left** of the ending point. If you do not have a two-button mouse, use ctrl+click for the right button. To save the changes, choose **Input** > **Save input file as ascii** with a new file name.





For displacement plots, the dip of the cross section is always vertical. Within the *Cross section window*, you can chose items on the menu bars to **Zoom In**, **Zoom Out**, **Pan**, and **3D Rotate**.

6.2 To display observed and modelled GPS vectors

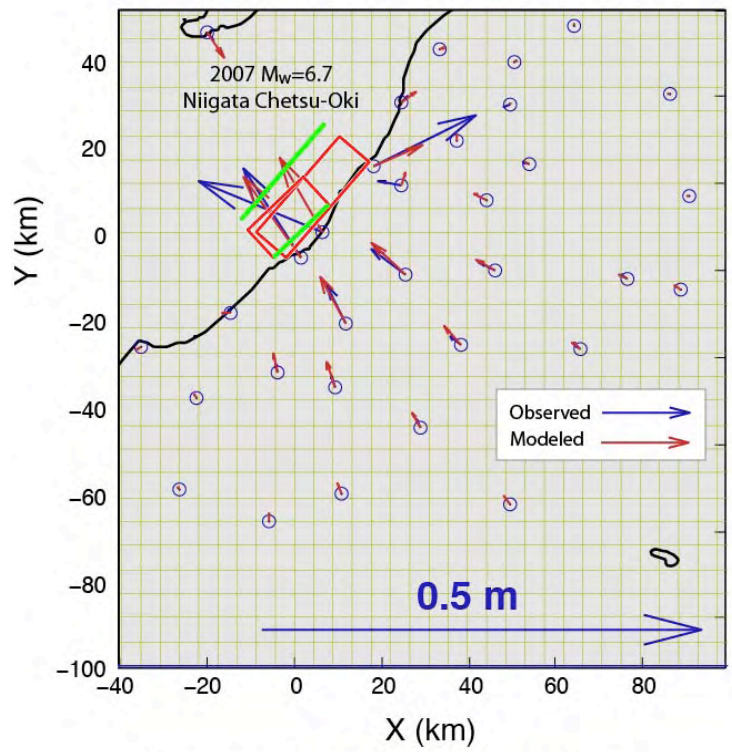
1. You can create a GPS file with five columns: lon.°, lat.°, dx, dy, dz (m), in space delimited format. If easier, prepare the file in Excel and then save as 'Formatted text (space delimited)'. An example of the format is shown below. Also, see 'gps_example.dat' in the GPS_data folder.

```
Lon.      Lat.    Easting(m) Northing(m) Upwarding(m)
-------- -------- -------- -------- --------
138.5744  37.3977  -.14310  0.0597   0.000
138.5164  37.3485  -.06670  0.1019   0.000
138.7069  37.5358   .11680  0.0597   0.000
138.7900  37.3113  -0.0404  0.0301   0.000
138.7805  37.6675   0.0054  0.0073   0.000
```

2. After you have plotted a figure, choose **Overlay** > **GPS stations**, and select the file you created. If you did not set 'Depth' in the input file to zero, choose **Functions** > **Change Parameters** > **Calculation depth**. If the input file has a source fault, you will see a plot like the one below for the observed and modelled vectors (no error ellipses; the circles mark the stations) and a meter scale bar. Here we saved the file as a pdf and added the legend in Illustrator.

3. To output a numerical file of the observed and modelled displacements, follow the instructions in the command window (reproduced below). The GPS_DATA file can be opened in Excel for further calculations of residuals.

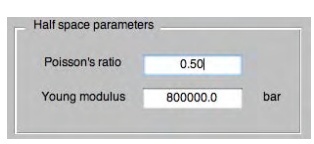
```
----- GPS data -----
User selected/Users/ross/Desktop/coulomb30/GPS_data/niigata2007.dat
GPS_output.csv is saved in /Users/ross/Desktop/coulomb30/output_files

 * To save the GPS data as binary, use the following command
 * in the Command Window.
 * save filename GPS_DATA (e.g., save mygps.mat GPS_DATA)
 * To read the .mat formatted GPS data, use 'File -> Open...' menu later.
```



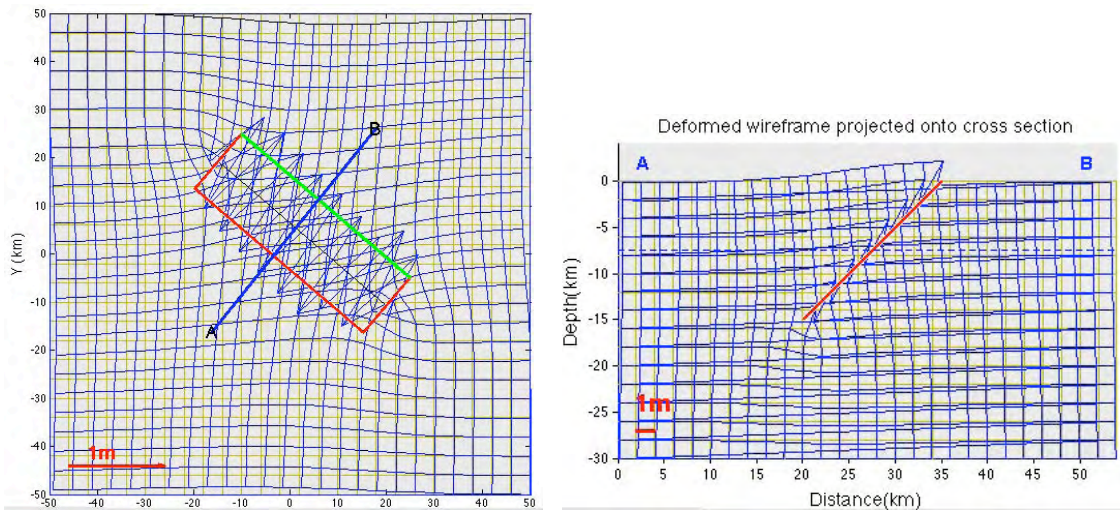
Coulomb 3.0.08.06 06–Aug–2007 16:23:37 2007 Niigata.mat

6.3 To display crustal deformation as wireframe images

1. Using Example-2(TH).inp, Choose **Functions** > **Displacements** > **Horizontal displ. (wireframe).** The undistorted grid is in yellow and the distorted grid in blue. For a cross-section, use the default cross-section line, but change the horizontal and depth increments to 2 km in the *Cross section control panel* to see the images below. These cross-sections conserve area (they are 'retrodeformable' in geological jargon) if you set Possion's ratio to 0.5 by **Functions** > **Change Parameters** >**All input parameters**:



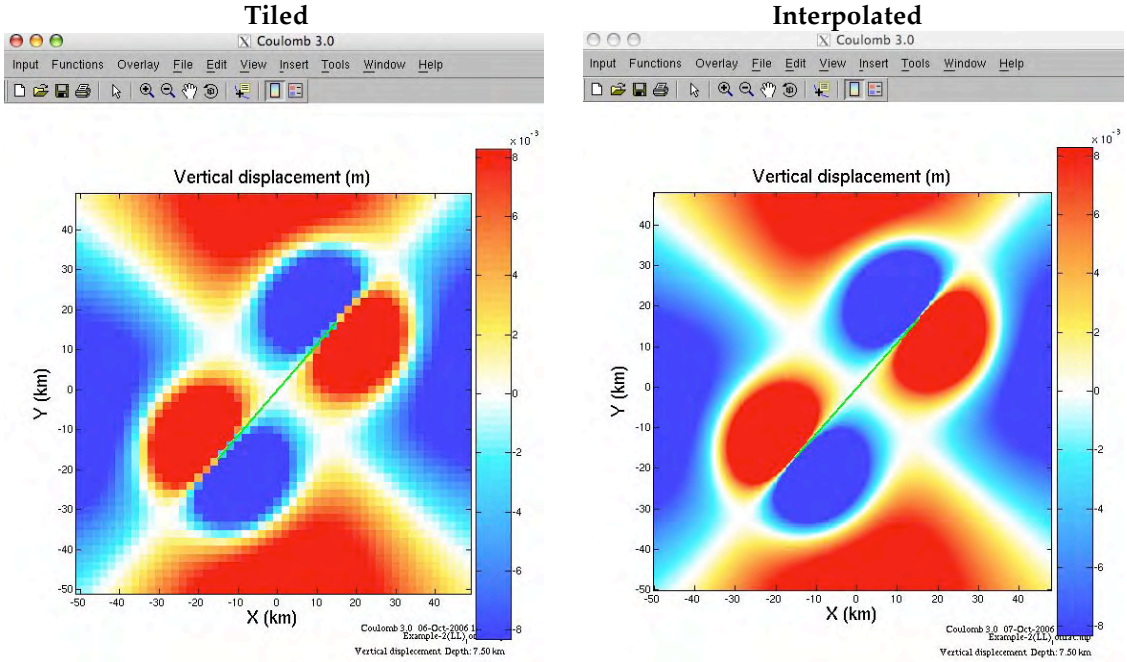
2. The wireframe cross-sections are useful to illustrate deformed strata associated with thrust and normal faults and ramp-thrusts. You can pop them into Illustrator and color the layering so it appears like strata.



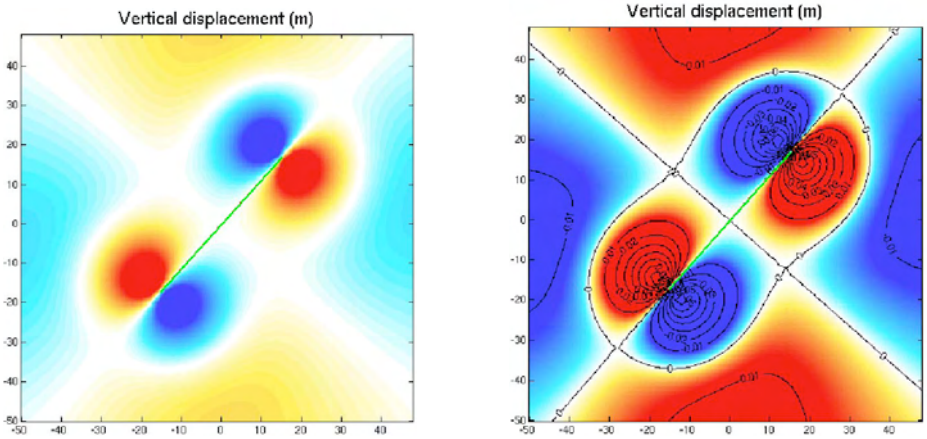
6.4 To display the vertical displacement by color gradients and contours

1. Choose **Input** > **Open an existing file** 'Example-2(LL)-latlon.inp'; then **Functions** > **Displacements** > **Vertical displ. (color & contours).** You will see the following left image in the *Coulomb 3.1* window.

Tiled **Interpolated**



2. *Data smoothing and color scale options:* In the *Vertical displ. control panel*, you can choose either Mosaic, i.e., un-interpolated data (left image shown above) or Interp., i.e., interpolated (right image shown above). *Color saturation:* You can adjust color scale by moving the slider bar under "Color saturation" or type the value in the box, hit return, and then click 'Calc. & View" in the Displacement control panel (below left).



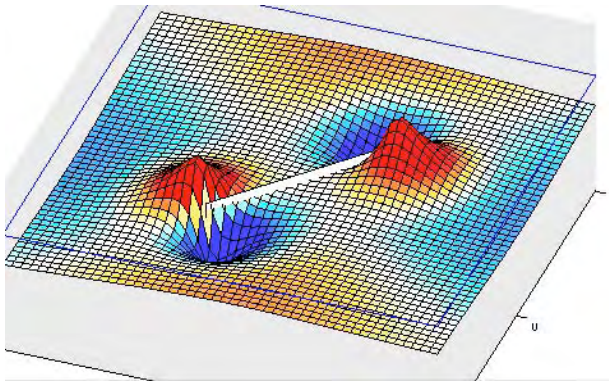
3. *Contours:* In the *Displacement control panel*, choose "Contours" and click "Calc. & View". Contours showing vertical displacements are superimposed on the color image (image above right). You can choose the contour interval.

4. *Cross section*: Choose "Cross section" *in the Displacement control panel*. The methods of making cross sections are similar to those described in previous sections.

6.5 To display the vertical displacement as a 3D image drape

1. Choose **Functions** > **Displacements** > **3D image drape.** The color scale is controlled by the parameter in your input file.

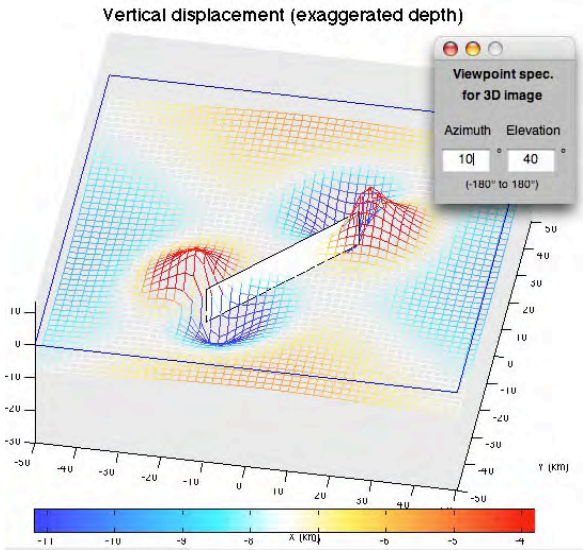
2. To control the amount of vertical exaggeration (the "m" factor in the screen images), choose **Functions** > **Change parameters** > **Vertical**, and you will see a pop-up *Vertical exaggeration* window, in which you can change vertical exaggeration by entering a new value and then clicking "OK".



3. In the *Coulomb 3.1* window, you can use options of **Zoom In**, **Zoom Out**, **Pan**, **3D Rotate**, **Insert/Remove ColorBar**, and **Insert/Remove Legend**, as described in previous sections.

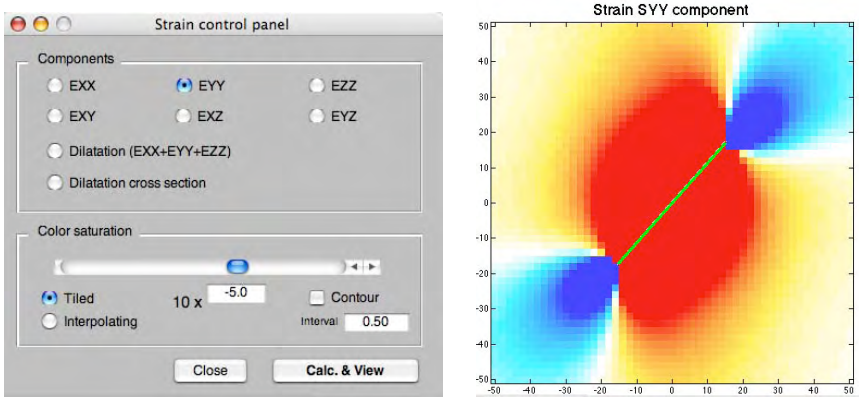
6.6 To display the vertical displacement as 3D image wireframed surface

1. Choose **Functions** > **Displacements** > **3D image wireframed surface.** The color scale is controlled by the parameter in your input file.
2. You can use options of **Zoom In**, **Zoom Out**, **Pan**, **3D Rotate**, **Insert/Remove ColorBar**, and **Insert/Remove Legend**, as described in previous sections. Now try changing the vertical exaggeration by choosing **Functions** > **Change parameters** > **Vertical exaggeration** > 8000. Then, again choose **Functions** > **Displacements** > **3D image wireframed surface**. Now change the azimuth to 10° and Elevation to 40° in the *Viewpoint window* by hitting tab after each number and the screen will redraw:



6.7 To display any component of the strain field

1. Choose **Functions** > **Strain.** A Strain control panel will appear (below right).



2. In the Strain control panel, choose the type of strain you want to calculate. For example, choose *Eyy* and you will see the image above right.

3. *Numerical output files*. Every time you click "Cal. & View" in the *Strain control panel*, an output file called "dilatation_section.cou" will be created or updated. When you want to save your latest runs, remember to rename the "dilatation_section.cou" file within the "output files" sub-folder; otherwise it will be written over by your future displacement calculations. Here is an example of "dilatation_section.cou" output file:

dilatation_section.cou

Input file selected: Example-2(LL)_lonlat.inp

x (km)	y (km)	z (km)	dilatation(ex+ey+ez) (-)	dilatation (-)	dilatation (-)
-36.0000000000000000	36.0000000000000000	-0.0000000000000000	0.0000001666026758	0.0000001666026758	0.0000001666026758
-36.0000000000000000	36.0000000000000000	1.0000000000000000	0.0000001641860500	0.0000001641860500	0.0000001641860500
-36.0000000000000000	36.0000000000000000	2.0000000000000000	0.0000001616694448	0.0000001616694448	0.0000001616694448
-36.0000000000000000	36.0000000000000000	3.0000000000000000	0.0000001590625171	0.0000001590625171	0.0000001590625171

4. By choosing parameters in the *Strain control panel*, you have the options to switch between the tiled versus interpolated data grid, change color saturation, and contours, as explained in previous sections.

Chapter 7

COULOMB STRESS CALCULATIONS

Here we calculate static stress changes caused by the displacement of a fault or dike or point source (we refer to these as 'source faults'), derived from the strain field shown in previous sections. We resolve the shear and normal components of the stress change on grid node points or on specified 'receiver' fault planes. Receiver faults are planes with specified strike, dip, and rake, on which the stress changes caused by the source faults are resolved. The shear stress change (an increase or decrease) is dependent on the position, geometry, and slip of the source fault, and on the position and geometry of the receiver fault geometry (including its rake). The normal stress change (clamping or unclamping) alone is independent of the receiver fault rake.

We use the Coulomb failure criterion, $\Delta\sigma_f = \Delta t_s + \mu' \Delta \sigma_n$, in which failure is hypothesized to be promoted when the Coulomb stress change is positive. Here, $\Delta\sigma_f$ is the change in failure stress on the receiver fault caused by slip on the source fault(s), Δt_s is the change in shear stress (reckoned positive when sheared in the direction of fault slip), $\Delta \sigma_n$ is change in normal stress (positive in unclamping of the fault), and μ' is effective coefficient of friction on the fault.

We'll explore three kinds of receiver faults: (1) receiver faults listed in the input file with no slip, (2) focal mechanism files, and (3) faults optimally-oriented for failure. Their optimal orientations are a function of the regional stress, the stress change associated with the source fault, and the assumed friction coefficient.

On the following page are Figures 2 and 3 from *King et al.* [1994], which graphically present the Coulomb stress change resolved on vertical strike-slip faults parallel to the source fault (Fig. 2a); and resolved on optimally oriented planes (Fig. 2b) for a given regional uniaxial compression and friction coefficient. In Figure 3, the influence of the regional stress magnitude is seen on the orientation of the optimal planes, and on the stress change resolved on these planes. These figures were made in a primordial version of Coulomb.

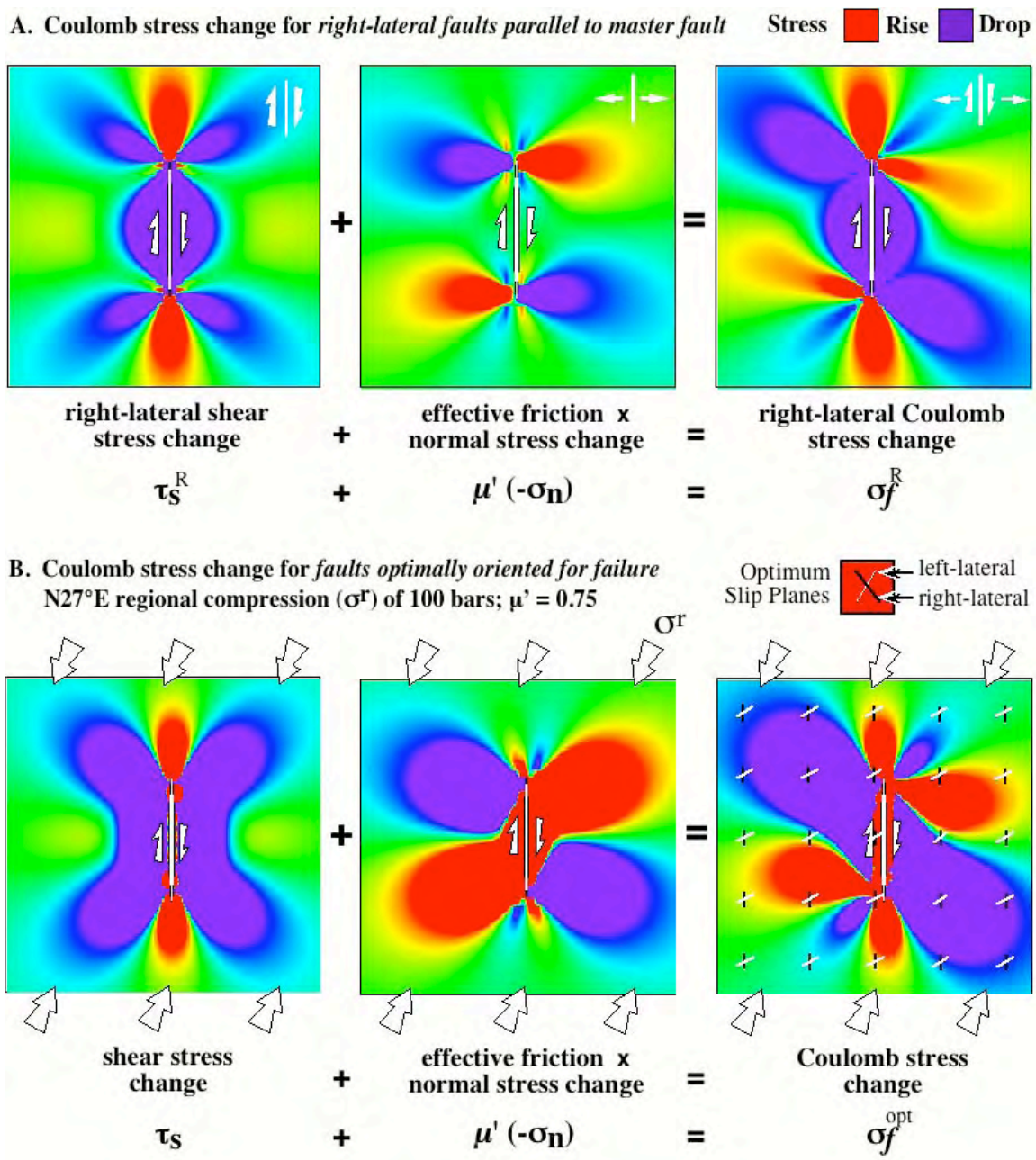
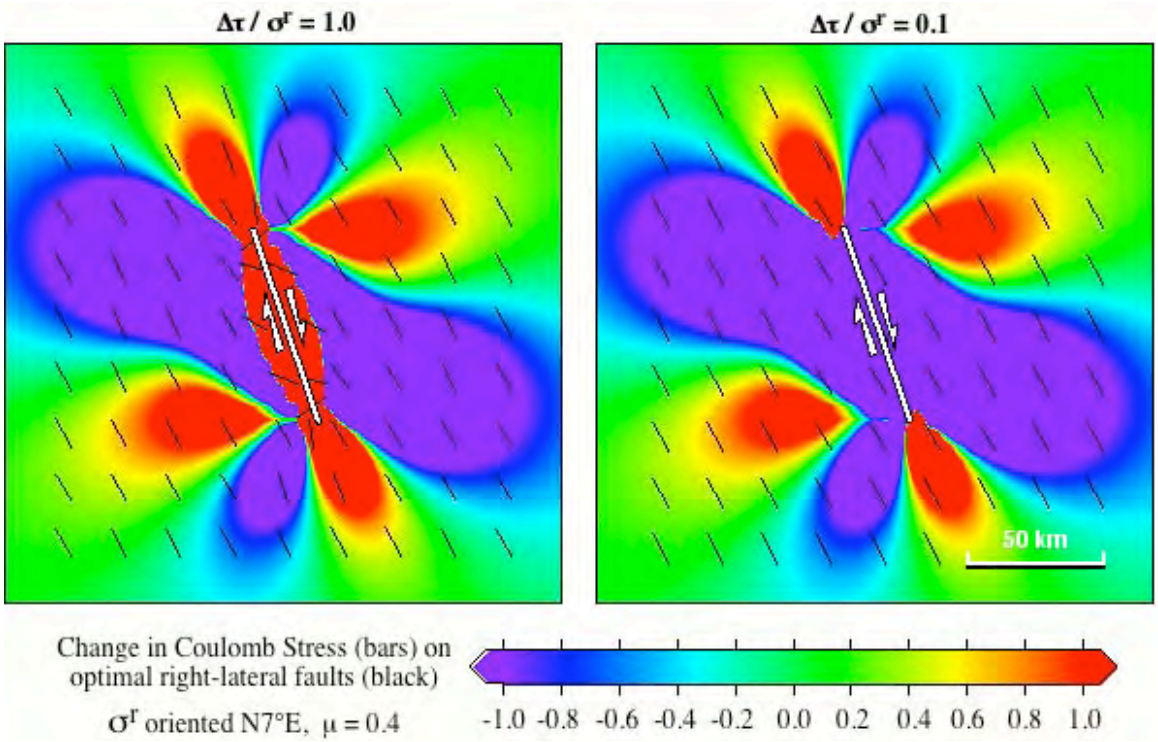


Illustration of the Coulomb stress change (Fig. 2 from King et al [1994]). The panels show a map view of a vertical strike-slip fault embedded in an elastic halfspace, with imposed slip that tapers toward the fault ends. Stress changes are depicted by graded colors; green represents no change in stress. (A) Graphical presentation of equation 8 of King et al (1994), a "specified fault" calculation. (B) Graphical presentation of equation 13 of King et al (1994), for optimally-oriented strike-slip ("opt strike-slip") faults.

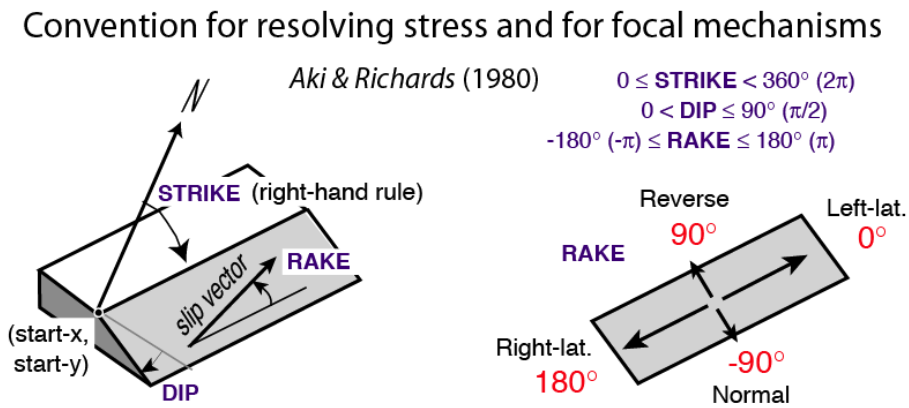


Dependence of the Coulomb stress change on the regional stress magnitude, σ^r, for a given earthquake stress drop, $\Delta\tau$ (Fig. 3 from *King et al.* [1994]). If the earthquake relieves all of the regional stress (*left panel*), resulting optimum slip planes rotate near the fault. If the regional deviatoric stress is much larger than the earthquake stress drop (*right panel*), the orientations of the optimum slip planes are more limited, and regions of increased Coulomb stress diminish in size and become more isolated from the source fault. In this and subsequent plots, the maximum and minimum stress changes exceed the plotted color bar range (in other words, the scale is saturated).

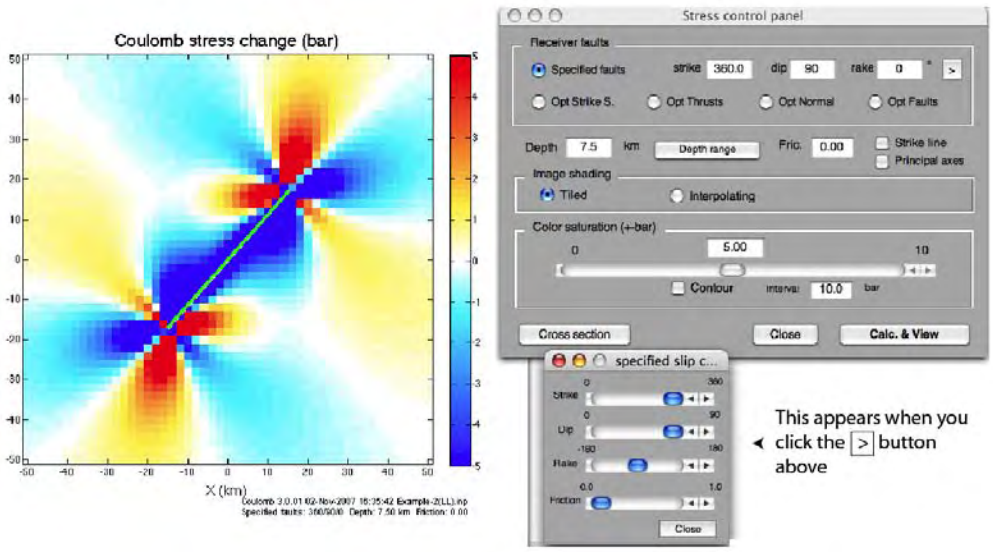
7.1 Coulomb stress change on specified receiver faults ('Specified faults')

This is the simplest calculation, and is widely used by researchers. To resolve the stress, you need to specify the fault strike, dip, and rake of the receiver planes following the *Aki & Richards* convention, shown graphically in the next page of this manual.

1. Launch Matlab/Coulomb 3.1.
2. Choose **Input** > **Open existing input file**. Then in the *Open input file* window, choose the "input_files" sub-folder within the "Coulomb 3.1" folder, and select "Example-2(LL)-lonlat.inp"
3. Choose **Functions** > **Stress** > **Coulomb stress change**.
4. You will see the pop-up *Stress control panel*.
5. To calculate stress changes on specified receiver fault planes, click "Specified faults". Coulomb averages the information on all input fault patches listed in the input file and puts the values in the boxes, but you can change them. Strike, dip, and rake are defined following the conventions of Aki & Richards (1980, 2002):



For practice, choose a strike/dip/rake of 360°/90°/0°, change the friction coefficient to 0.0, set the stress-change color saturation to ±5 bars, and hit 'Calc. & View'.



The Coulomb stress changes default using our "Anatolia" color scheme. Other schemes ("Rainbow" or "Black & White") can be changed by pulling down the **Input** > **Preferences** menu bar and clicking on "Color Map". Then re-run the input file.

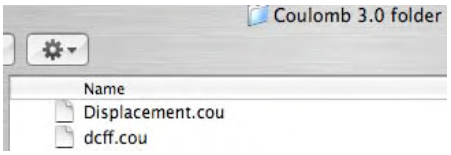
7.2 Using the strike/dip/rake/friction slider (Specified slip control panel)

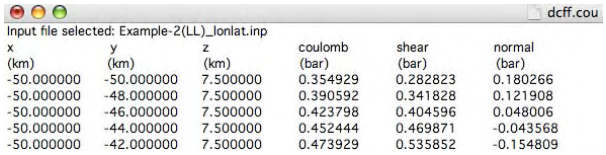
To vary these parameters on the fly, hit the > button in the Stress control panel, and the Specified slip control panel pops up (*see it above*). Slide the balls to explore how the stress pattern changes.

7.3 Saving the graphic and numerical output of stress calculations

To save this graphic, **File** > **Save As…** > choose a .pdf format and rename it; its only 40 kb but is a full vector image. **Stress change is calculated in the *lower left corner* of each grid square at the target depth specified in the input file.** Calculated values of stress change may saturate (exceed the plotted range), so experiment with the slider to see more subtle features. The stress-scale legend is to the right of the plot.

Every time you click "Cal. & View" in the *Stress control panel*, a numerical output file called "dcff.cou" will be created or updated and saved in a sub-folder you designate in the **Preferences** menu. Remember to rename "dcff.cou" if you want to save the numerical file; otherwise they will be overwritten.

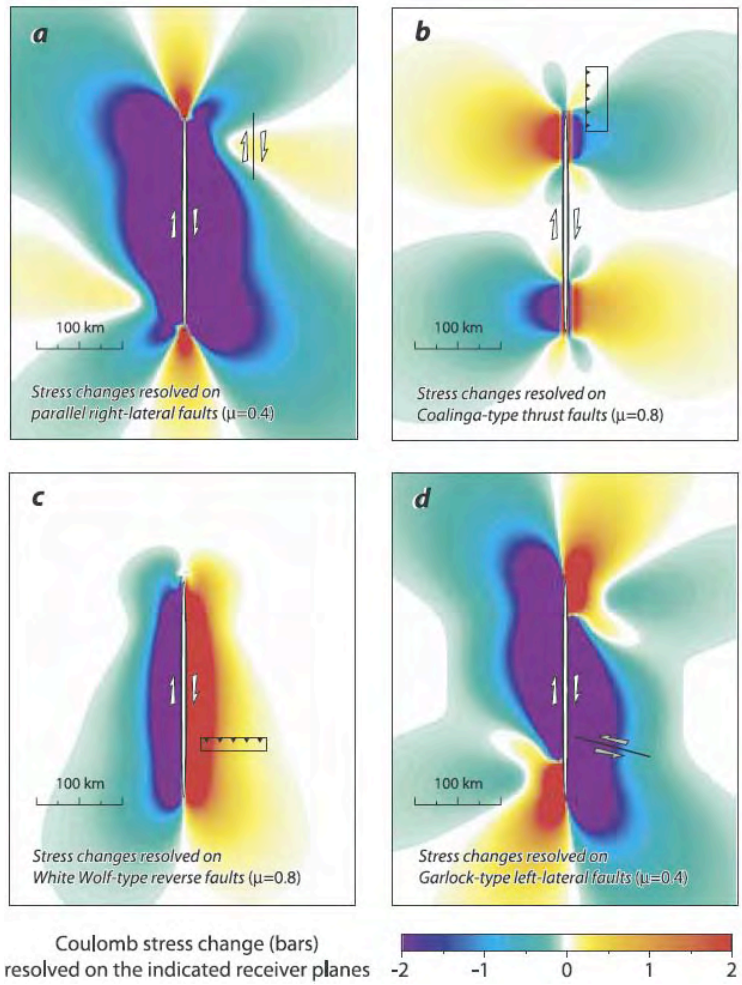




x (km)	y (km)	z (km)	coulomb (bar)	shear (bar)	normal (bar)
-50.000000	-50.000000	7.500000	0.354929	0.282823	0.180266
-50.000000	-48.000000	7.500000	0.390592	0.341828	0.121908
-50.000000	-46.000000	7.500000	0.423798	0.404596	0.048006
-50.000000	-44.000000	7.500000	0.452444	0.469871	-0.043568
-50.000000	-42.000000	7.500000	0.473929	0.535852	-0.154809

7.4 The importance of the receiver fault geometry in Coulomb modeling

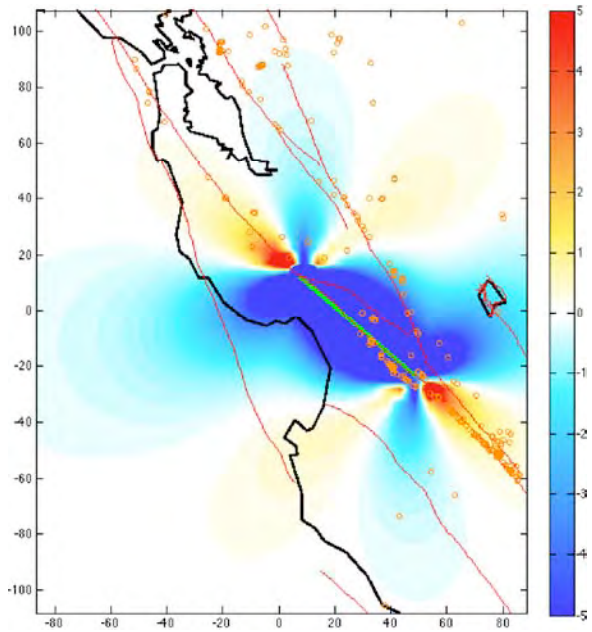
In the figure below, from *Lin & Stein* (JGR, 2004), the source is an idealized M~7.9 right-lateral southern San Andreas rupture. The most familiar stress pattern is the case of source and receiver faults with the same strike, dip and rake (**a**). But look how strongly the pattern changes when the receiver faults are nearby thrusts (**b-c**) or left-lateral faults (**d**). Thus, a stress shadow for one receiver may be a stress trigger zone for another receiver fault. Note also that we tend to assume a high coefficient of friction (~0.8) for continental thrust faults, moderate friction (0.4) for strike-slip or unknown faults, and very low friction (>0.2) for major transforms, such as the San Andreas.

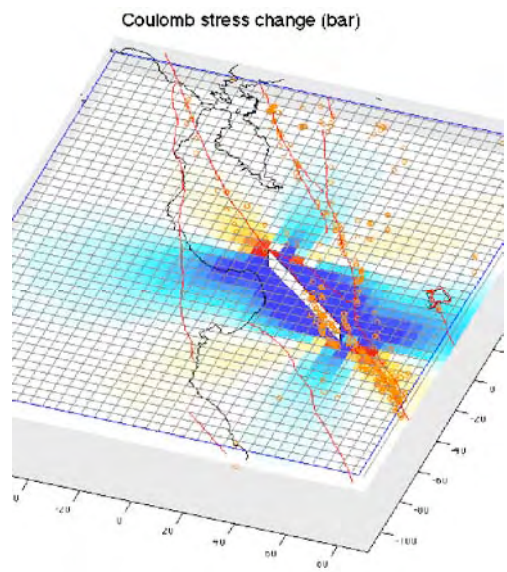


7.5 Adding Coulomb stress to an overlay plot and viewing it in 3D

1. Launch 'Example-SFBayArea.inp'. **Overlay** > **Coastlines**. Open the 'coastline data' folder in the Coulomb30 folder, and select 'california_coastline_di_neg.dat' Answer the pop-up question, 'no' (some datasets treat western longitudes as negative; others do not). Now, **Overlay** > **Active faults.** Choose 'California faults_longlat_dat'.

2. You can now add any kind of stress changes to this plot without losing any of the overlays. Just hit **Functions** > **Stress** > **Coulomb stress change**, and select a stress component and option, and you will see a map view image such as that below left.



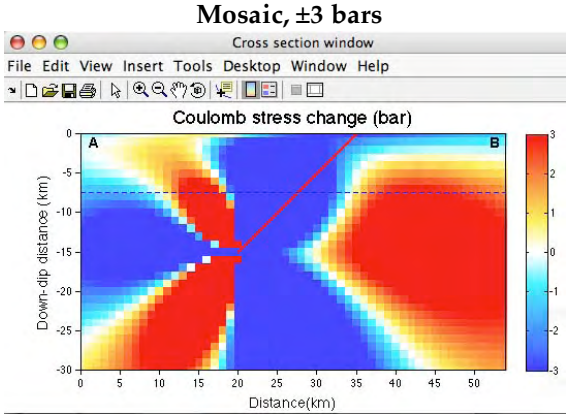


3. After completing any Coulomb stress calculation made over the grid, such as **Coulomb stress change**, **Shear stress change**, or **Normal stress change**, just return to the MATLAB window and type in "**coulomb_3d_view**". This calls a *plugin* (which can be found in the plugin folder in Coulomb30 folder). It executes a 3D view that you can manipulate and save as a pdf file, such as that above right.

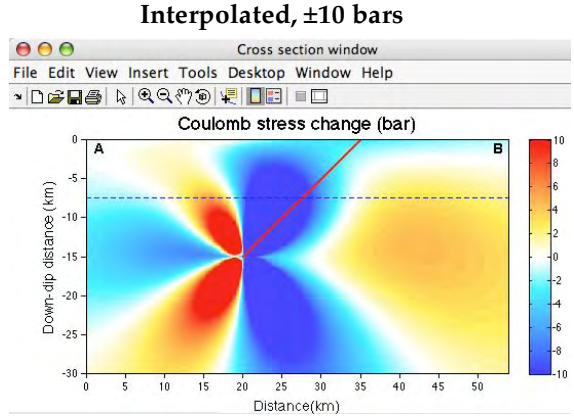
7.6 Coulomb stress cross-sections

1. Choose **Input** > **Open existing input file** > Example-2(TH).inp. Next, choose **Functions** > **Stress** > **Coulomb stress change.** Change the color saturation to 3.0 bars, and hit 'Calc. & View' in the *Stress control panel*. After the mapview plot appears, hit the *Cross section* button on the *Stress control panel*, which displays the cross section parameters from your input file (left plot below). Click "Calc. & View" and you will see the image below left. Now change the saturation to ±10 bars and chose interpolated shading, and hit "Calc. & View" again (right panel below).

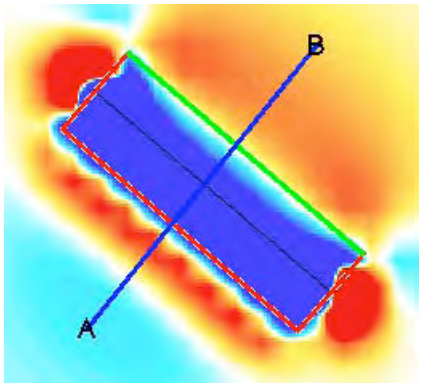
Mosaic, ±3 bars

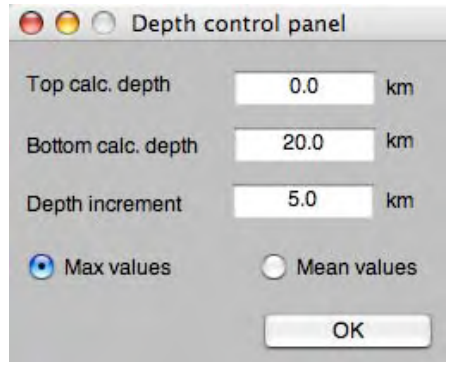


Interpolated, ±10 bars



2. When building a cross-section, the "Start (A)" point should always be on the **left side** of the "Finish (B)" point (see below right). You can overlay seismicity in cross-sections if you first plot the mapview with earthquakes and then make the section. The default setting plots seismicity within ±20 km of the section line. To change this, print EQPICK_WIDTH=5 for ±5 km, etc, in the command window.

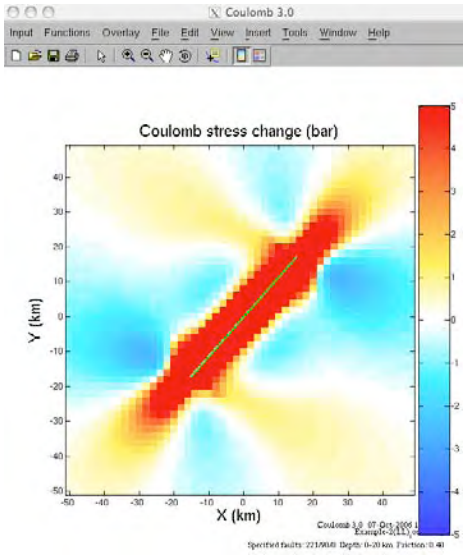




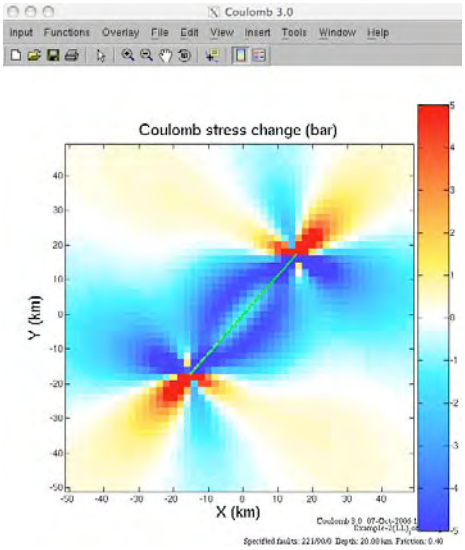
3. You can also change the dip angle of the cross section by entering a new value in the "Dip" box in the above panel. The blue dashed line is the depth at which stress was sampled in the map view. The red line is the intersection of the fault plane with the cross-section line. These can be seen in map view, which has a blue cross-section line, a red fault perimeter, a green line where the fault projects to the ground surface, and a black line where the fault intersects the depth at which stress is being sampled. You can change the depth, and many other parameters, in the *Stress control panel*.

4. You can calculate the maximum or mean values of Coulomb stress changes between various depth ranges. Click "**Depth range**" and then "Cal. & View" in the Stress control panel, you will see Depth control panel. In the *Depth control panel*, enter depths of the top and bottom surfaces, as well as the depth increment, for which you want to perform the comparisons. You can calculate either "Maximum values" of Coulomb stress changes over the given depth range (below left), or the "Mean values" over the range (below, right). The numerical output file shows the maximum value at each grid point. The maps below were made using the left-lateral strike-slip fault input file, Example-2(LL)-lonlat.inp.

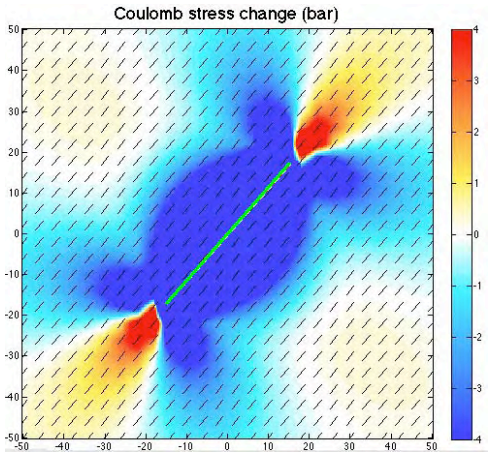
Max stress change over a depth range

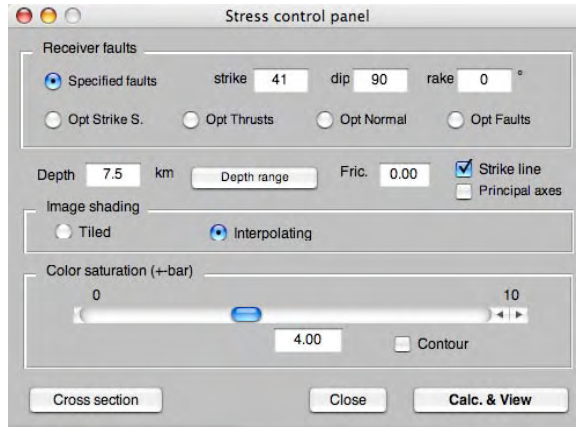


Mean stress change over a depth range



5. You can plot the orientation of the 'specified fault' strike in map view. Choose **Input** > **Open existing input file** > Example-2(LL).inp. Next, choose **Functions** > **Stress** > **Coulomb stress change.** Check the "Strike line" box in the *Stress control panel*, and for practice, change friction to 0.0, shading to interpolatedand then "Calc. & View", resulting in the following image on the left. Notice that the lines strike 41° as specified. Stresses and slip lines are plotted on the lower left corner of each grid box.



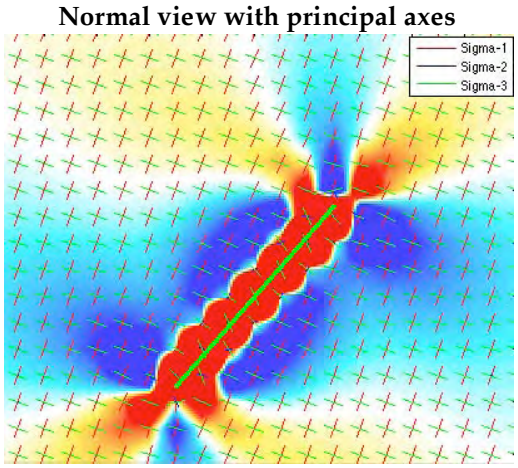


7.7 To display the principal stress axes rotated by the earthquake stress change

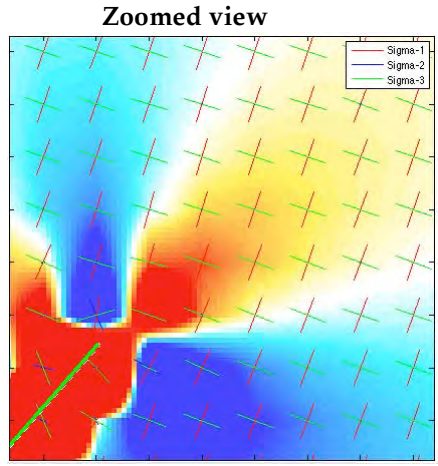
Coulomb makes the tensor addition of the earthquake stress change, which diminishes with distance from the source fault, and the regional stress, which is assumed uniform, to calculate the total principal stress axes. Once the total principal stress axes are determined, Coulomb uses this and the assumed friction coefficient to determine the optimum planes.

Choose **Input** > **Open existing input file** > Example-2(LL).inp. Then, **Functions** > **Change parameters > Grid**, and change the grid to 5.0 x 5.0 km so the axes are not too crowded (this is not a requirement; you can choose *any* grid spacing of interest). Now, **Functions** > **Stress** > **Coulomb stress change**. In the pop-up *Stress control panel*, choose "Opt. Strike S.", "Principal Stress", and "Interpolating", and click "Calc. & View". You will see the image on left below. Using **Tools** > **Zoom In**, you will see the right image below.

Normal view with principal axes



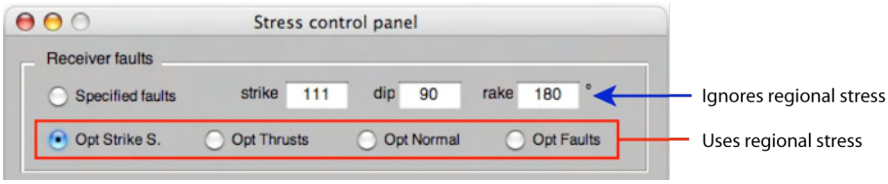
Zoomed view



The axes are not scaled by their stress magnitudes, since too many would be invisible. Notice that the axes rotate in 3D, not just in the horizontal plane, and so $\square_3$ deviates from being vertical close to the source, as a result of the stress changes imparted by the earthquake. This means that $\square_3$ can be seen in the lower left corner of the zoomed image.

7.8 Using the regional or 'tectonic' stress in optimally-oriented stress calculations

The regional stress is used only when you choose **Functions** > **Stress** > **Coulomb stress changes** *AND* choose one of the optimally-oriented ("**Opt.**") stress changes in the **Stress control panel**. Otherwise the regional stresses are ignored (see below). See *King et al* (BSSA, 1994) for more on this topic.

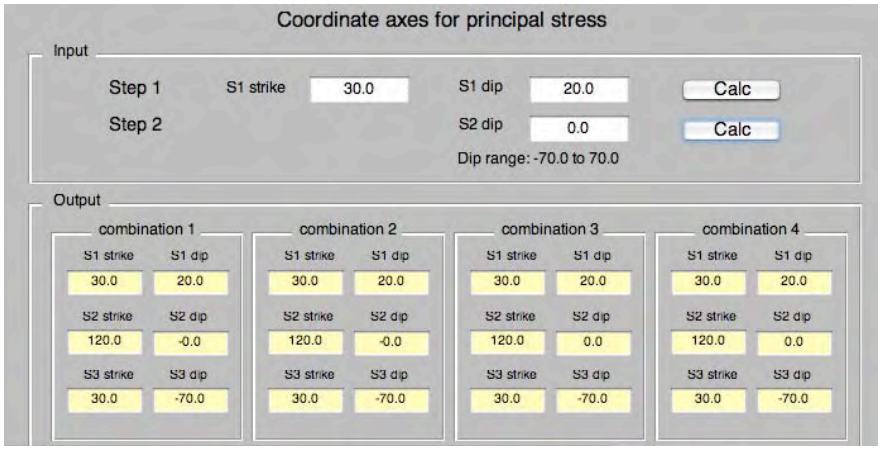


1. All of the example input files contain simple regional stress fields. The sign convention for S1, S2, and S3 is positive in compression [bars]. Although you can assign axes that are neither horizontal nor vertical (in other words, they plunge at angles other than 0° and 90°), and you can assign a vertical gradient in the stress axes, such that the stress magnitude increases (or decreases) with depth, we advise you to keep it simple. We almost always make the greatest principal stress, S1, horizontal and about 100 bars, and the intermediate principal stress about 0 bars.
2. A reasonable regional stress must promote slip on all the faults in your area. You can use the P and T axes from focal mechanisms of earthquakes off the main faults, hydrofrac or borehole breakout information, and fault striae inversions to assess the strike of the greatest and least principal axes. The World Stress Map (http://www-wsm.physik.uni-karlsruhe.de/) may also be useful for this purpose. But most important, ask yourself if the stress tensor you are proposing is consistent with the fault types and orientations in the area of study.
3. You can build principal stress axes (which must be mutually perpendicular) by selecting **Functions** > **Tools** > **Principal axis calculator**. You can also visualize the principal axes by **Functions** > **Stress** > **Coulomb stress change**, and then by checking **'Principal axes'** in the pop-up *Stress control panel*.

7.9 To display Coulomb stress changes on the optimally oriented strike-slip, thrust, and normal faults (with the fault dip fixed) in map view

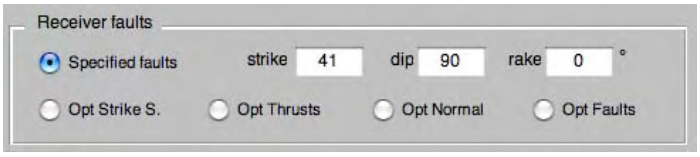
"Optimally-oriented" planes are those oriented such that the Coulomb stress change resolved on them is most positive (in our plots, most red). Here one assumes that aftershocks have a range of orientations, and will be most abundant at the depth, location and with the geometry that most promotes failure. So at every point on our grid, we find the receiver plane along which the resolved Coulomb stress change is most positive. If the regional stress were zero, there would be a positive Coulomb stress change on some plane everywhere. But at large distances from a source fault, the earthquake stress change will be much smaller than the regional stress, so the planes rotate very little.

1. Choose **Input** > **Open existing input file**> "Example-2(LL).inp". To calculate optimally oriented faults, one must specify the regional (sometimes called, tectonic) stress field in the input file. "Example-2(LL).inp" contains a sample 3D regional stress field. If you use your own input file, make sure the regional stress tensor is properly defined. To make sure that the directions of your regional stress axes are geometrically compatible (i.e., orthogonal to each other), choose **Functions > Tools > Principal axes calculator**. You will see a pop-up *Coordinate axes for principal stress* window (below).

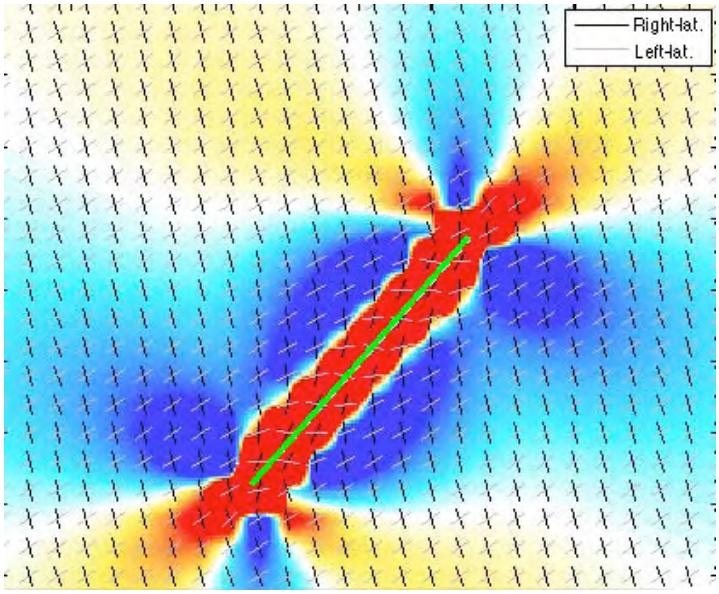


To check the compatibility of regional stress axes, first enter the strike and dip (plunge) of the greatest principal axis, S1 strike and S1 dip. Click "Calc". Then enter the dip of the intermediate principal stress axis ("S2 dip"), which should stay within the shown permissible range of values ("Dip range") to ensure that three principal axes are mutually perpendicular, which is obligatory. Click "Calc" again, and you will see four sets of combinations for the three principal axes, all of which are consistent with the entered values.

2. Choose **Functions** > **Stress** > **Coulomb stress change**. You will see the following in the pop-up *Stress control panel*:



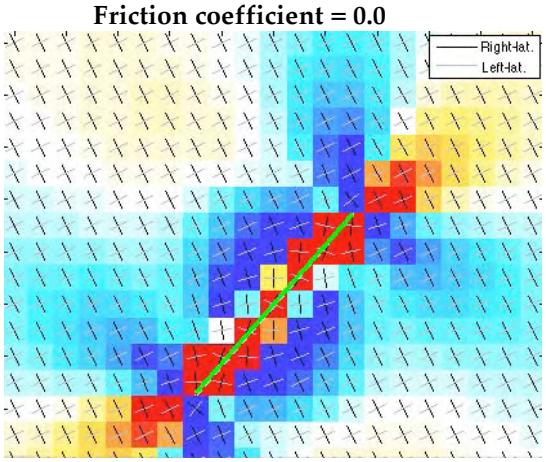
In *Stress control panel*, the alternatives are "Opt Thrusts", "Opt Normal", and "Opt Faults". 'Opt fault' is an exceedingly slow grid search over the entire focal sphere for the receiver planes at every grid point, and so you need patience in waiting for the completing of the calculation. Here, choose "Opt Strike S." and click on *Strike lines*; then click "Calc. & View" and you will see this in the interior of the plot:



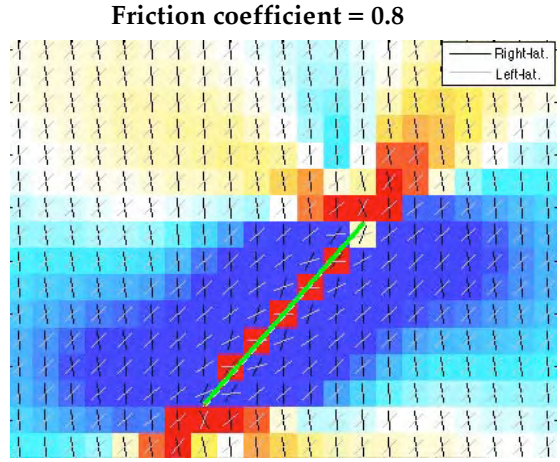
3. **Explanation of the Slip lines**. For the "Opt Strike S." option, the receiver faults dip vertically and their strikes are a function of S1 (α_1) and the friction coefficient μ (FRIC in Coulomb). The right-lateral and left-lateral optimum planes are plotted at every grid point. Their internal angle is a function only of the friction coefficient; they are orthogonal for zero friction and acute for high friction. You can see large rotations of these planes very close to the source fault, because the earthquake stress change is about as large as a the assumed regional stress, ~100 bars. Far from the source, the slip lines are parallel and their orientation is a function of the regional stress in the input file, because at these distances from the source, the earthquake stress changes are negligible. For the thrust and normal faults, their dip is a function of the friction coefficient, and their strike is perpendicular to S1 (α_1) and S3 (α_3), respectively. The relationship of the angle, β between S1 and the dip (for strike-slip faults) or strike (for dip-slip faults) is **tan 2β = 1/FRIC**. See King et al. [1994], which can be accessed online from the Coulomb web site at
http://quake.wr.usgs.gov/research/deformation/modeling/papers/landers.html

4. For a friction coefficient of zero, the optimum planes would be orthogonal and we could compare them to aftershock focal mechanisms unambiguously. Try checking this by selecting **Functions** > **Change parameters > Coeff. Friction.** In the pop-up *Coeff. Friction* window, type 0.0 and click "OK". Then, **Functions** > **Change parameters > Grid**, and change the grid to 5.0 x 5.0. (For normal and thrust planes, the strike for the two planes is the same and their dip is a function of the friction coefficient). Then hit **Functions** > **Stress** > **Coulomb stress change**. In the *Stress control panel*, check 'Opt. Strike S.', and 'Strike line'. An excerpt is shown below left. Repeat the process and in the *Stress control panel*, change the friction to 0.8 and hit the tab. You'll see the image on the right.

Friction coefficient = 0.0

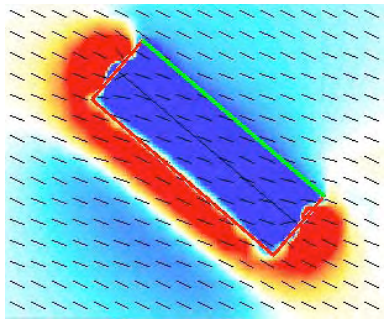


Friction coefficient = 0.8



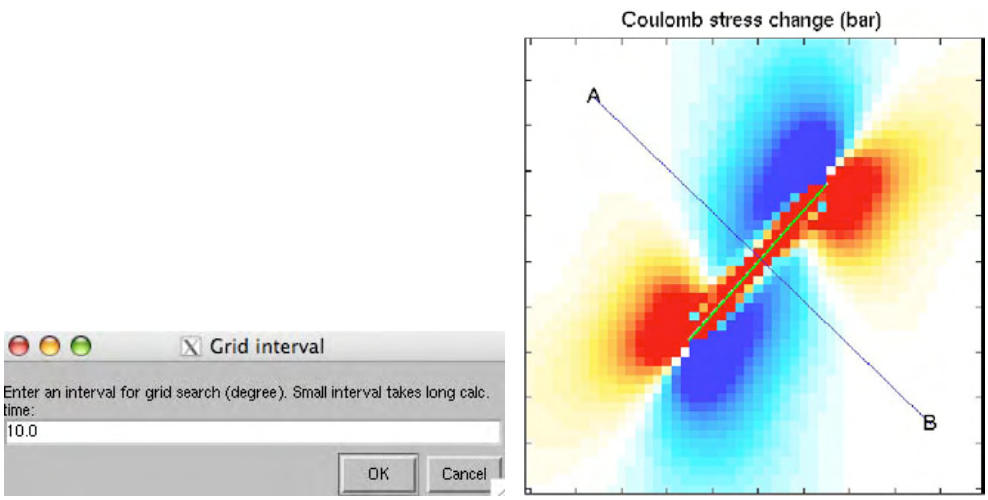
The stress changes are larger and more asymmetrical about the fault plane for high friction, and the rotation of the optimal planes near the source fault are a little greater. These aspects are discussed in King et al [BSSA, 1994].

5. Strike lines for optimally-oriented thrust faults. Choose **Input** > **Open an existing file** and choose 'Example-2(TH).inp'. Then choose **Functions** > **Stress** > **Coulomb stress change**. In the *Stress control panel*, check 'Opt. thrusts', 'Strike line', and 'Tiled' image shading, and hit 'Calc. & View'. You will see an image like this:



Here the two strike lines are parallel to the mapview (they would not be so in cross-section), so only one is visible. The rotations are greatest in the deep red and blue areas, where the stress change is large relative to the assumed regional stress. In this example, the fault is not quite orthogonal to the assumed regional stress.

6. In addition to "Opt Strike S.", Opt Thrust", and "Opt Normals", you can also calculate optimally-oriented receiver faults on which Coulomb stress is maximum while not restricting fault types. Click "Opt Faults" and "Calc. & View" in the Stress control panel. You will see the following pop-up window:



You are requested to enter interval of grid research (°) in the *Grid interval window*. Small intervals take time to calculate. We recommend interval of 10° or greater, at least until you've settled on all the parameters you want to use.

7.10 To resolve stress changes on receiver faults ('Calc. stress on faults')

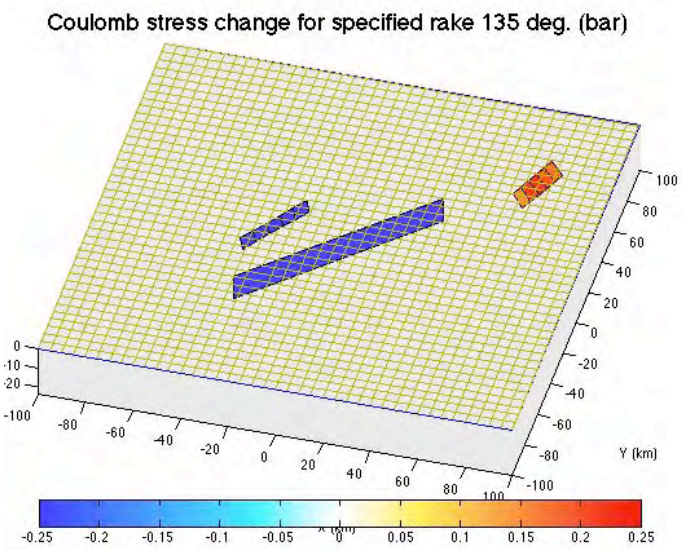
This is perhaps the simplest Coulomb calculation, and is widely used in research. The regional stress information is not used, regardless of whether it is included in the input file. Coulomb permits one to show the resolved stresses graphically and output the numerical results.

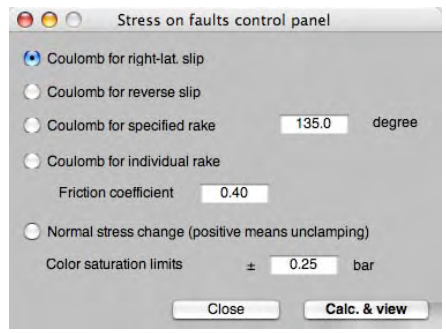
1. Open 'Example-1.inp' in an editor; notice that there is a source fault with slip, and two receiver faults (called receivers because they lack slip). These two faults are automatically broken up in to 5 patches by placing the number '5' in the '#' column. This permits a stress calculation at the center of each patch on a plane. This is much easier and faster than inputting 10 receiver faults.

#	X-start	Y-start	X-fin	Y-fin	Kode	shear(m)	reverse(m)	dip angle	top(km)	bot(km)	
xxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	
1	-35.00	-35.01	35.00	35.01	100	2.00	0.00	90.00	0.00	12.00	source test
5	-40.00	-5.01	-20.01	25.00	100	0.00	0.00	75.00	5.00	10.00	receiver-1
5	60.00	50.50	70.10	75.05	100	0.00	0.00	45.00	5.00	10.00	receiver-2

This creates 5 evenly-distributed along-strike patches on which the stress imparted by the source fault is resolved

2. Now, **Input** > Example-1.inp; **Functions** > **Stress** > **Calc. stress on faults**. A *Stress on faults* control panel will open to let you choose the stress component that you would like to resolve on the faults. A specified uniform rake of 135° was used in the plot below, with the (blue) stress drop on the source fault and one of the receiver faults, and the (red) stress increase on the other receiver patches, which varies along strike.





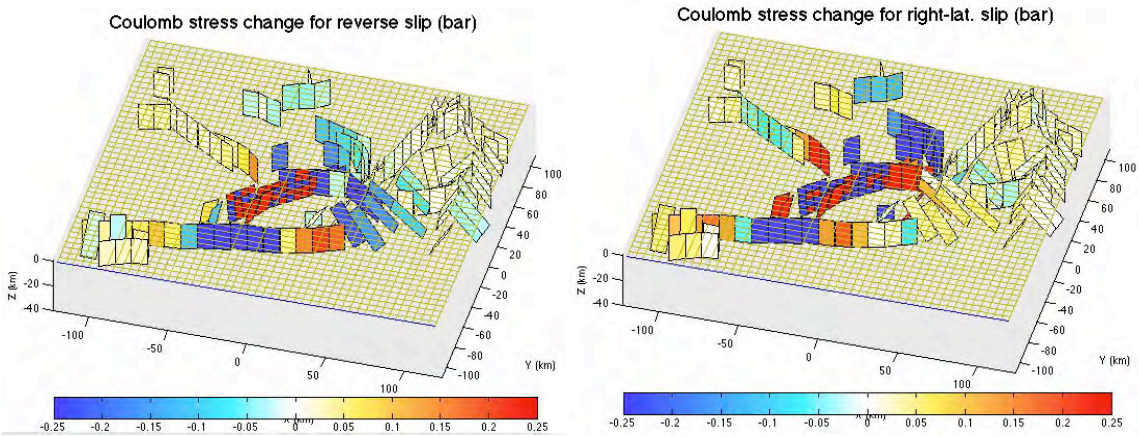
3. If your input file used the (rake, net slip) format rather than the (rt.lat. slip, reverse slip) format, then you could use the 'Coulomb for individual rake' option. To switch how the input file is interpreted, it searches for the word, "rake", so don't misspell it. In the input folder, the full 1400-patch California Reference Database is included in various formats. 'CA-fault-database-rake.inp' (and 'CA-fault-database-rake.mat') are formatted by rake for this purpose. Because it is a large file, it takes time to calculate. Here are the first two sources in the database input file, with the right-lateral (rake rake=180°) Green Valley reverse (rake=90°) Mount Diablo thrust faults:

```
  #   X-start    Y-start     X-fin      Y-fin   Kode   rake     net slip    dip angle     top       bot
xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx
  1  -181.8571   115.5202  -187.3601   139.9612 100   180.0000     0.0000    90.0000     0.0000    14.0000    #Green Valley (So)
  1  -160.3110    81.1833  -178.9410    97.5293 100    90.0000     0.0000    38.0000     8.0000    16.0000    #Mount Diablo Thrust
```

4. You can also use a subset and plot it, since all the faults have their associated names. Remember to make sure the '#fixed=' in the third line of the input file is changed to reflect the number of faults in the input file ('#fixed=faults+receivers).

5. A more complex case is represented for the 1995 Kobe earthquake. Both a uniform-slip and variable slip source model input files are included in the input file folder, in addition to about 50 surrounding faults with various orientations and dips. **Input** > **Preferences** > *Cartesian*; then **Input** > 'Kobe-uniform-slip.inp'; then **Functions** > **Stress** > **Calc. stress on faults.** Note that a numerical output file is created each time you make a **Calc. stress on faults** run, which is very useful for further analysis. Two stress components are shown below. Experiment with different viewing angles and azimuths using the numerical input window; using the rotation tool with files this large is difficult due to the time lag.

Stress from the 1995 Kobe variable-slip model resolved on surrounding faults

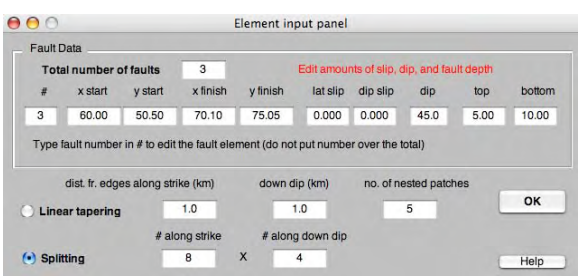


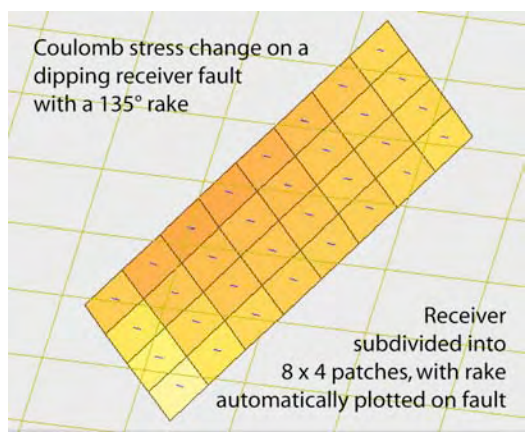
Notice that on the Kobe rupture itself, there are both red and blue patches. The Coulomb stress change is not uniformly negative (blue) because of the irregular coseismic slip which leaves spikes of stress increase, the presumed sites of along-fault aftershocks.

7.11 Calculating stress change on a subdivided (tiled) receiver fault

Often one would like to determine the distribution of Coulomb stress change on a large receiver fault. This can be easily done and visualized in Coulomb 3.1.

1. Open 'Example-1.inp' in a text editor and change the '5' in the # column for 'receiver-2' to 1, so it's now a single patch. Then launch 'Example-1.inp' in Coulomb. **Functions** > **Tools** > **Taper or subdivide fault slip**, type fault 3 in the fault # box, and split the source into 8 x 4 patches, and hit OK (*below left*). So now you have subdivided it into 32 patches.





2. **Functions** > **Stress** > **Calculate stress on faults**. You can zoom in and spin the view, as shown above right. The Coulomb stress change is colored and the rake vectors are plotted in blue. You can change the rake in the *Stress on faults* control panel.

Chapter 8

ADVANCED STRESS FEATURES AND MAGMATIC SOURCES

At this point we assume that you are now familiar with the typical steps and menu options in Coulomb, and our instructions will be more abbreviated, but still accurate.

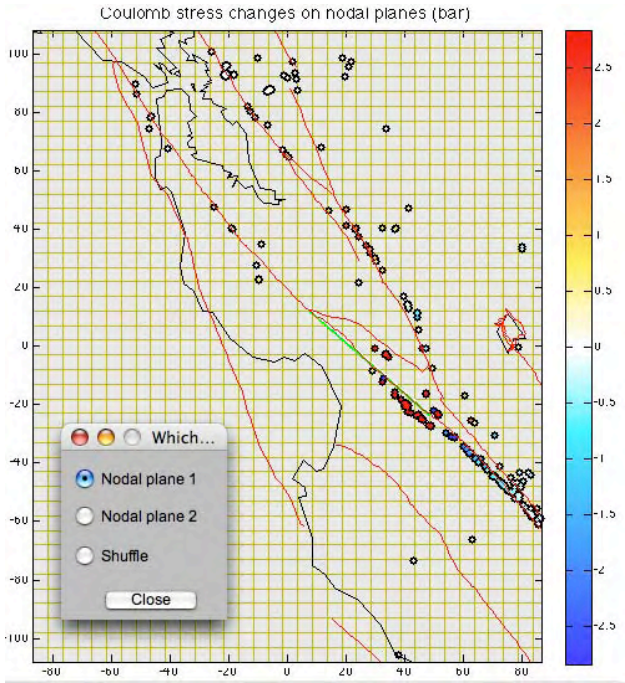
8.1 Coulomb stress changes resolved on earthquake nodal planes

1. If there is focal mechanism information available, you may want to test whether the fault plane associated with each earthquake was brought closer to Coulomb failure. This is presumably a more stringent test than determining if earthquakes occurred in the red regions, although typically only the fraction of the catalog contains reliable focal mechanisms.

   If the friction were 0, this would be a straight-forward test because the shear stress change on the orthogonal nodal planes is identical (eg., *Parsons*, JGR, 2002). But for non-zero friction, the optimum Coulomb planes are not orthogonal, and so they will be different. In fact, one plane may have a stress increase and the other a decrease. You can sometimes identify the fault plane based on independent information, and there are published approaches others have taken, such as comparing the percentage of stress increases on seismicity in the region before and after a mainshock (*Hardebeck et al*, JGR, 1998; *Ma et al*, JGR, 2005), or by using seismicity alignments (*Seeber & Armbruster*, Nature, 2000).

2. Using the same 'Example-SFBayArea.inp' you used in the last section, **Overlay** > **Clear overlay data from memory** > **Clear earthquake data** (because the file used did not contain focal mechanisms). Now, **Overlay** > **Earthquakes** > In the *Earthquake catalog formats* window, select 'NCSN fpfit (focal mech)', and then choose the dataset with this name from the folder. Earthquake circles plot on the map.

3. **Functions** > **Stress** > **Calc. stress on nodal planes**. A window appears to ask you which set (Nodal set 1 or set 2, which are usually arbitrarily ordered in a catalog, or Shuffle—random selection of set 1 or 2). It will assign colors to each earthquake according to how much the nodal planes were brought closer to or farther from failure. You should see this plot:

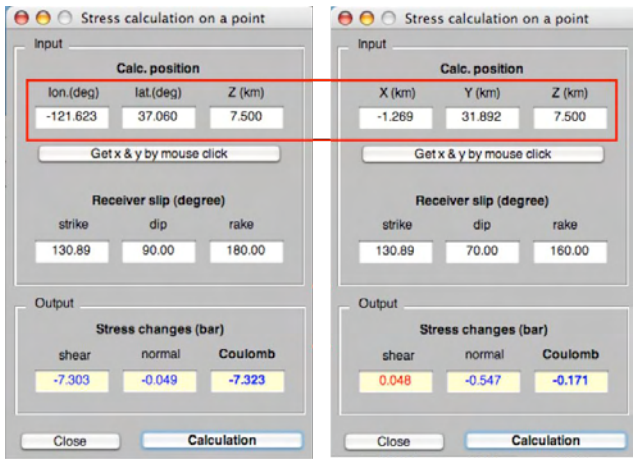


You can plot each set (Nodal plane 1 or Nodal plane 2) separately, shuffle them randomly, or you can edit the catalog in an editor to make set 1 the likely fault planes.

8.2 Coulomb stress at a point, from lat/lon, x/y, or a mouse click

Sometimes you want to probe the calculated stress changes at a given point, rather than over a regular grid or on receiver faults. This is easy to do in Coulomb by using the mouse or by entering a lat/lon or UTM coordinates.

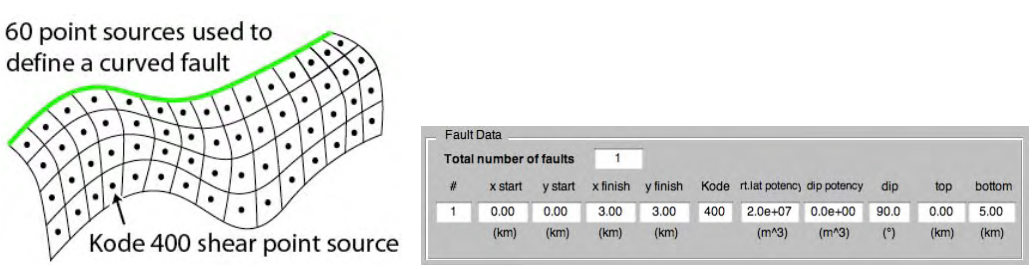
1. **Functions** > **Stress** > **Calc. stress at a point**. A *Stress calculation on a point* window pops up. You can enter the coordinates and depth of interest, and you can also enter the receiver fault geometry. The output is numerical, and appears in the Output window, with blue numbers when negative and red when positive (see below).



2. When using the **Calc. stress at a point** option, you can change the assumed friction coeffient in the same manner that you can for other stress calculations, by choosing **Functions** > **Change parameters** > **Change Coefficient fric.**, and entering the new number. If you want to use x/y values, change to Cartesian coordinates in the **Preferences** menu. Then return to the **Calc. stress at a point** selection and use the *Stress calculation on a point* window. The lat/lon vs. Cartesian options are highlighted above in the red box.

8.3 Point shear sources for small quakes or curved faults (Kode 400)

1. If you specify Kode 400 rather than 100 in the input file, Coulomb will interpret it as a point source with rt.-lateral and reverse slip components. The location of the point source is defined by the rectangle in the input file. The point is located at the center of the rectangle: the midpoint of the start and end positions, and at the mid-depth of the top and bottom positions. The plane defined by this geometry is used for strike and dip of the point source. This is a simple way to represent small shocks.
2. Another use of Kode 400 sources is if you have a very crenulated or curved fault, the overlap and underlap of the rectangles can be avoided by making a mesh of point sources (*shown schematically below left*). But this is demanding, and don't sample the stress closer to the fault than the point spacing, or you will see numerical noise.



3. We provide an input file with a single point source, 'Example-Kode400.inp'. Note that the rt.-lateral and reverse units are in potency (m^3), not in slip (m), since a point has no area (see above right, from **open & edit input file**). Potency, also called the 'geometric moment,' is the seismic moment/G, where G is the shear modulus (see boxed equation in Chapter 3 to calculate G from E and PR).

8.4 Crack opening or closing (Tensile Kode 200 and 300 sources)

Many magmatic intrusion problems involve a tabular body, such as dike or sill, undergoing expansion or contraction. Here we introduce the deformation and stress change caused by a tensile component of displacement, such as the opening or closing of a tabular or crack-like body, using the equations of *Okada* [1992]. For simplicity, the input file format for the Coulomb has only two slip components, labelled 'rt.lat' and 'reverse'. So, when you change the Kode of the source to 200 or 300, the first of these slip components takes on a tensile-displacement interpretation by the program, as described below.

1. **Kode 200 permits tensile (opening) slip and strike-slip to be input**. Put lateral slip in the 'rt.lat.' column and tensile slip in the 'reverse' column (*dike opening is positive*; unit = meters), 'Example-6(200Kode).inp'. Here's how a Kode 200 source appears in the **Functions** > **Open & edit input file** window,

Fault Data

Total number of faults: 1

#	x start	y start	x finish	y finish	Kode	lat slip	tensile open	dip	top	bottom
1	0.10	-20.00	0.10	20.00	200	0.000	1.000	90.0	5.00	15.00
	(km)	(km)	(km)	(km)		(m)	(m)	(°)	(km)	(km)

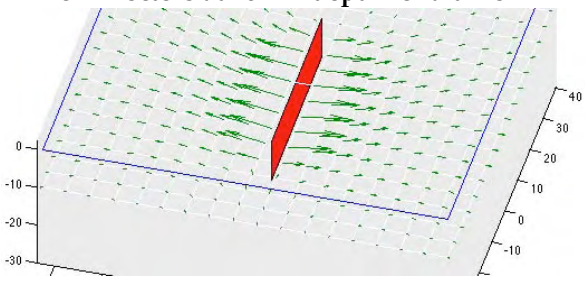
2. **Kode 300 permits tensile (opening) slip and dip-slip to be input**. For Kode 300, put tensile slip in the 'rt.lat.' column (again, dike opening is positive), and put reverse slip in the 'reverse' column.
3. If the element has three components of slip (strike-slip, dip-slip, and tensile-slip), you can accomplish this by including both Kode 200 and a Kode 300 sources in the input file as shown in the file below, 'Example-7(200-300kode).inp'. To the right of the 'bot' values you can add comments that help you keep track of the source or receiver name; this is true for all .inp files.

Example-7(200-300kode).inp

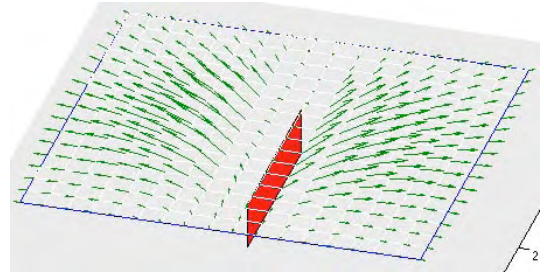
```
This is a test file for the Coulomb 2.0
These two co-located tensile/shear-slip sources enable strike-slip, dip-slip, and opening to be imposed simultaneously
#reg1=  0  #reg2=  0   #fixed=  2  sym=  1
 PR1=       .250      PR2=       .250    DEPTH=        15.
  E1=   0.800000E+06   E2=   0.800000E+06
XSYM=       .000      YSYM=       .000
FRIC=       .000
S1DR=    19.0001     S1DP=     -0.0001    S1IN=    100.000     S1GD=   .000000
S3DR=    89.9999     S3DP=      89.999    S3IN=     30.000     S3GD=   .000000
S2DR=   109.0001     S2DP=     -0.0001    S2IN=      0.000     S2GD=   .000000

  #   X-start    Y-start     X-fin      Y-fin   Kode  rt.lat    reverse   dip angle     top      bot
xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx
  1   -15.1      -17.00     15.20      17.20   200   2.0000    1.0000      60.00        5.0     25.00   rt-lat + open
  1   -15.1      -17.00     15.20      17.20   300   1.0000    2.0000      60.00        5.0     25.00   open + reverse
```

4. Define the dike geometry (endpoints, dip, and top/bottom depth) as you do for faults. Unfortunately, the way we define sources and receivers does not permit one to put in a strictly horizontal plane, since the top and bottom depths would be identical, but you can put a tiny dip (~1°), and it will work fine.
5. Uniform opening or closing of a dike is likely to be unrealistic. Just as you can for faults, you can taper the displacement toward the edges by **Functions** > **Tools** > **Taper**.
6. Select the file, Example-8(dike).inp, and then choose **Functions** > **Displacements** > **3D Vectors**. You will get the image shown on the left. Now, **Functions** > **Change Parameters** > **Vertical Exaggeration** > 25000, and change **Calculation depth** to the surface (0.0 km). You will get the image on the right. Experiment with view angles.

3D Vectors at 10 km depth for a dike

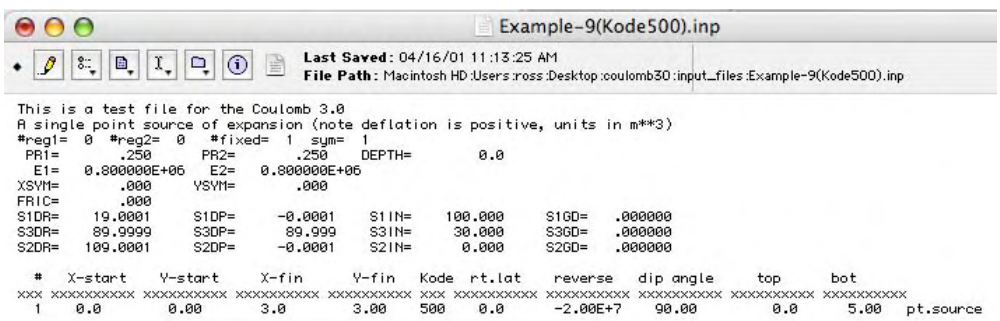


3D Vectors at the free surface



8.5 Point source of deflation or inflation (Kode 500)

We have implemented the formula of Okada (BSSA, 1992) for a buried point source of expansion or contraction. Of course, the calculated stress changes very close to such a point source are infinite and are thus unreliable, but at larger distances, this source is useful for magmatic intrusion problems, such as studying how an intrusion event may bring other faults or dikes closer to failure. An example of this is *Nostro et al.*, Two-way coupling between Vesuvius eruptions and southern Apennine earthquakes by elastic stress transfer, *JGR*, *103*, 24,487-24,504, 1998, which is on our web site at http://quake.usgs.gov/research/deformation/modeling/papers/nostro.html. As with the dike or sill source, we have created two kodes for mixed volumetric and shear displacements.



Example-9(Kode500).inp

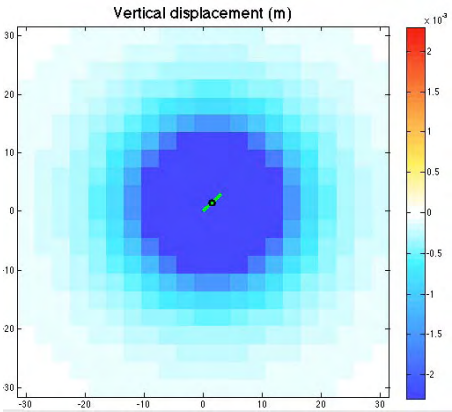
Last Saved: 04/16/01 11:13:25 AM
File Path: Macintosh HD:Users:ross:Desktop:coulomb30:input_files:Example-9(Kode500).inp

```
This is a test file for the Coulomb 3.0
A single point source of expansion (note deflation is positive, units in m**3)
#reg1=  0  #reg2=  0   #fixed=  1  sym=  1
 PR1=       .250      PR2=       .250    DEPTH=        0.0
  E1=   0.800000E+06   E2=   0.800000E+06
XSVM=        .000     YSVM=        .000
FRIC=        .000
S1DR=     19.0001     S1DP=     -0.0001    S1IN=    100.000     S1GD=    .000000
S3DR=     89.9999     S3DP=      89.999    S3IN=     30.000     S3GD=    .000000
S2DR=    109.0001     S2DP=     -0.0001    S2IN=      0.000     S2GD=    .000000

  #   X-start    Y-start    X-fin      Y-fin    Kode  rt.lat    reverse   dip angle     top      bot
xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx xxxxxxxxxx
  1    0.0        0.00       3.0        3.00    500    0.0      -2.00E+7    90.00        0.0      5.00   pt.source
```

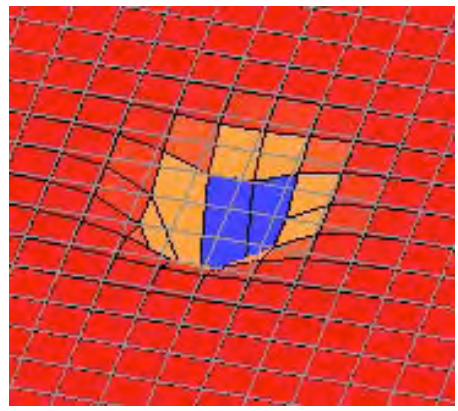
1. The unit for deflation or inflation is potency (m^3), the volume change associated with the evacuation or expansion of a spherical magma chamber. **Expansion is positive**. Potency, also called the 'geometric moment,' is equivalent to the seismic moment/G, where G is the shear modulus. As discussed previously (*see boxed equation in Chapter 3*), in Coulomb one inputs Young's modulus (E) and Poisson's ratio (PR), from which G can be computed. The units for the strike or dip slip is meters, as usual. One designates the source as Kode 500.
2. **Kode 500** permits both a dike and point source of expansion to be input. Put the tensile opening in the first ('rt-lat.') column (units are m^3; right-lateral is positive), and put the point source in the 'reverse' column (units are m^3; expansion is positive).
3. The location of the point source is defined by a plane in the input file. The point is located at the midpoint of the start and end positions, and at the midpoint of the top and bottom positions. The plane defined by this geometry is used for the dike opening. So if you only calculate the point-source expansion, the length and width of the plane are unimportant; only if you also want to consider opening or closing of the planar dike do these dimensions get used in the calculation. The point source is indicated graphic output files as a small black circle.

The following figure was made using 'Example-9(Kode500).inp' with two different **Displacement** options selected. The surface projection of the dike is the short green line.

Vertical displ. (color & contours)

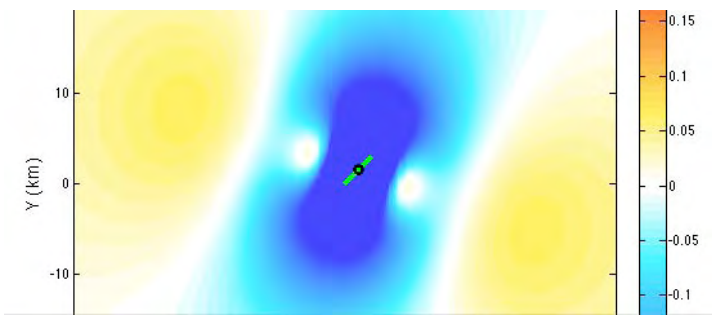


3D image drape



In the example below, we have chosen **Stress** > **Coulomb stress change** > Opt Normal with a 1 x 1 km grid, friction=0.8, depth of 8 km, and color saturation of ±0.25 bars:

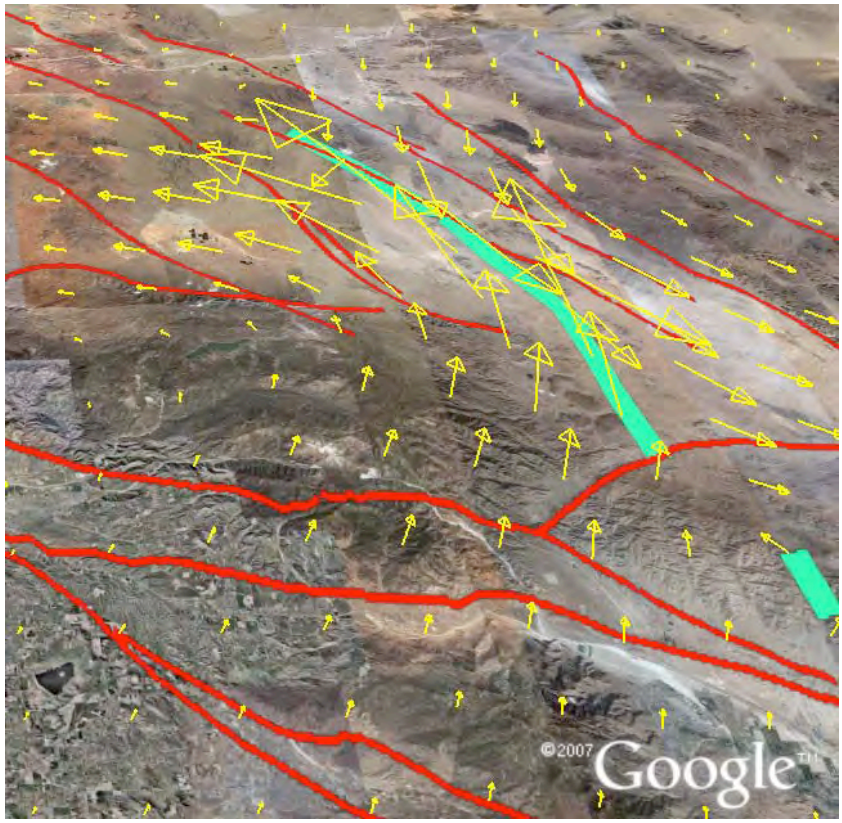
Coulomb stress change (bars) on optimally oriented normal faults



8.6 Displaying Coulomb Displacement, Stress and Overlay graphics in *Google Earth*

Google Earth offers wonderful opportunities to drape Coulomb files on satellite images and DEMs. You need to download and install *Google Earth* on your computer before following these steps. In addition to this, you will need *Adobe Illustrator* or any reasonable graphic application.

1. Make sure that you have selected the *lon. & lat.* **Coordinate** option in the **Preferences** menu.
2. Run any horizontal displacement function, such as **Horizontal displ. (vectors)** or **Horizontal displ. (wireframe).** Add the **Overlay** options that you would like in the plot. When the final plot appears in the Coulomb 3.1 window, type "**coulomb2googleearth**" in the MATLAB command window, and hit return. You will get messages in the command window once files are saved. Then, you can drag the kml files onto the *Google Earth* icon on your computer dock or desktop, or you can open the files from the *Google Earth* menu.

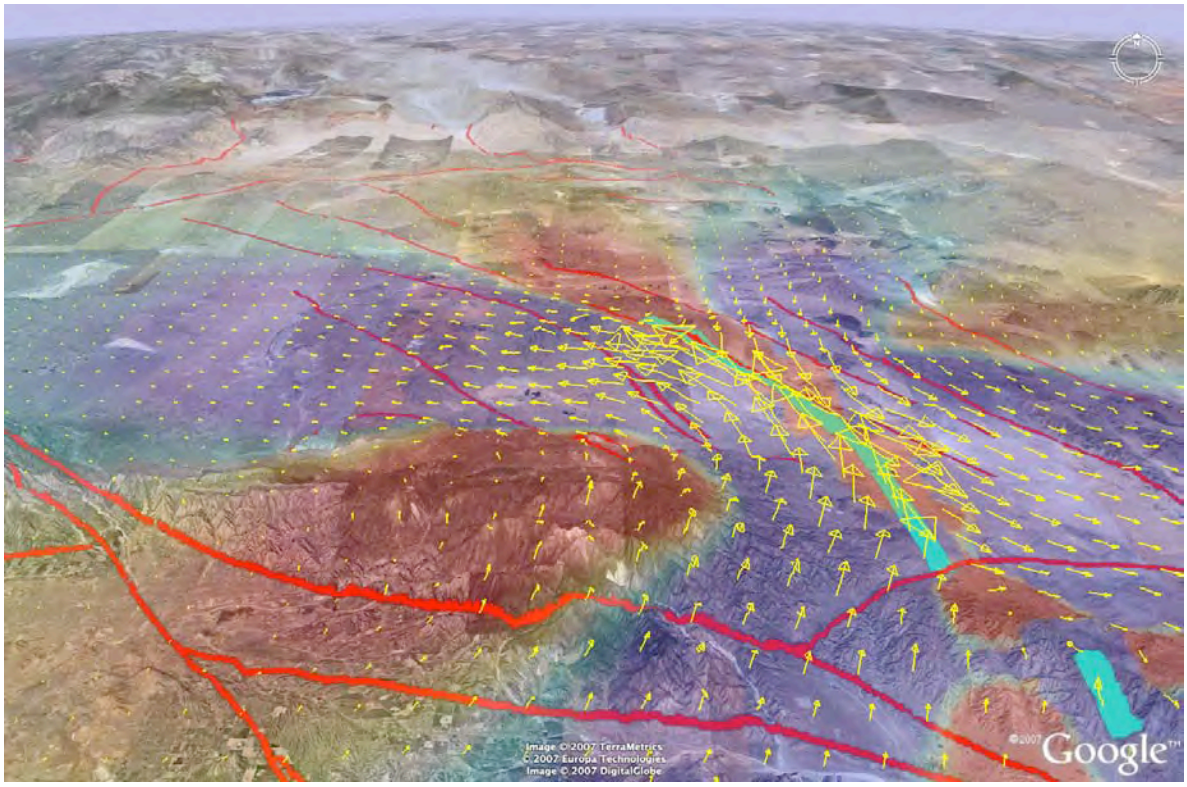


This file was made using the input file, 'Landers-uniform-slip.inp' and **Displacement** > **Horizontal Displ. (Vectors)**.

3. For color gradient images such as are created in the **Coulomb stress change**, **Shear stress change**, **Normal stress change** options, or the **Vertical displacement (color)** options **File** > **Save As... pdf** using the commands, renaming them.
4. Open the .pdf files in Illustrator or the graphics software you are using, and remove all the text and lines, and keep only the color (raster) image. Save the color image as .**jpeg** file, and name it "coulombmap.jpeg" in the Coulomb directory.
5. Type "**coulomb2googleearth**" in the command window. This calls a script that is run by Coulomb; this is not a feature of the normal pull-down menus. You will get the overlay kml file.

```
>> coulomb2googleearth
Calculating... Please wait...
  -> 'coulomb_study_area_box.kml' is saved in the current directory.
  -> 'coulomb_source_fault_plot.kml' is saved in the current directory.
Done!
>>
```

Start



In the plot above, a Coulomb stress change image was added. The DEM exaggeration (3:1) was maximized in *Google Earth* with an oblique viewing angle from the south. *Google Earth* also lets you control the translucency of the jpeg.

6. The full plugin script can be found in the plugins folder in the Coulomb30 folder:

coulomb2googleearth.m

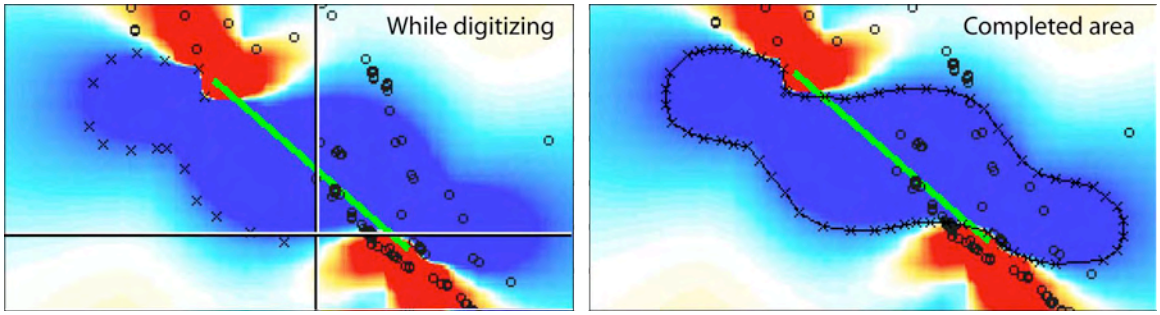
```
% coulomb2googleearth
%
% This script converts coulomb calculation results into .kml format for
% plotting onto Google Earth, using global variables saved in the MATLAB
% console.
% To convert MATLAB data into Google Earth kml file, 'Matlab2GoogleEarth
% Toolbox' developed by Scott Davis (see MATLAB Central) is implemented.
% We really appreciate his code.
%
% === OUTPUT FILE ================
%   'coulomb_displacement.kml'
%   'coulomb_source_fault_plot.kml'
%   'coulomb_afault_plot.kml'
%
% Copyright: Shinji Toda, January 30, 2007
```

8.7 Digitize Polygon Function (to select and create a lat/lon file of any area, such as a Coulomb stress-change or deformation contour)

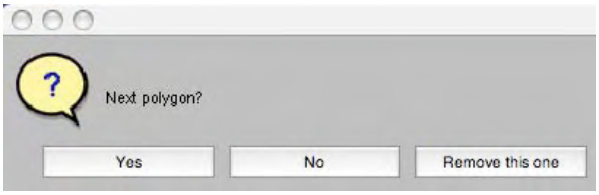
The *Digitize Polygon* function is useful for comparing a zone of Coulomb stress change or deformation with aftershocks or the seismicity rate change as calculated from the independent Matlab program, ZMAP.

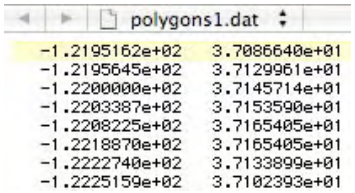
1. Make sure that you have selected the *lon. & lat.* **Coordinate** option in the **Preferences** menu.
2. Run any map view function (not 3D) in Coulomb, and then type "digitize_polygon" in the MATLAB command window, and hit return. In the example below, we have used the input

file, 'Example-SFBayArea.inp' and selected a Coulomb mapview. Below we have digitized the -3 bar contour.



3. The mouse becomes a digitizing cursor in the Coulomb main window. You will see a large "+" over the map (*above right*). To digitize, make multiple left-button clicks to circumscribe an area. Finalize and close the area by using a right-button click; the graphic will then show the completed area (*above right*). A window (*left below*) asks if you intend to digitize multiple areas; hit 'no' if this is it. The digitized file is saved in the "coulomb" folder. The first 8 lines of the file, 'polygons1.dat' is shown below at right; notice it is in lat/lon coord's with the convention that western longitudes are negative.





4. In ZMAP, you can move the file to the ZMAP folder and then read it from the area selection function.
5. The ZMAP software, by Prof. Stefan Wiemer at ETH Zurich, is available on http://www.earthquake.ethz.ch/software/zmap

Chapter 9

NUMERICAL OUTPUT FILES

In addition to Coulomb's internal graphics, you may want to analyse or plot the underlying numerical output, so all Coulomb graphics calculations produce a numerical output file with useful headers. These can be opened in Excel or brought into a rasterizing program for replotting.

9.1 Map view displacement output file

Every time when you click "Cal. & View" in the *Displacement control panel*, a text output file called "Displacement.cou" will be created or updated and saved in the sub-folder you designated in the Coulomb preferences menu (the default is 'output_files'). When you want to save your latest runs, remember to rename the "Displacement.cou" file within the "Output files" sub-folder; otherwise it will be overwritten by your future calculations. Here is an example of "Displacement.cou" text output file.

Displacement.cou

Input file selected: Example-2(LL)_lonlat.inp

x	y	z	UX	UY	UZ
(km)	(km)	(km)	(m)	(m)	(m)
-50.00000000	-50.00000000	-7.50000000	-0.01714258	0.00551020	-0.00152591
-50.00000000	-48.00000000	-7.50000000	-0.01969615	0.00407689	-0.00206484
-50.00000000	-46.00000000	-7.50000000	-0.02256910	0.00253268	-0.00263662
-50.00000000	-44.00000000	-7.50000000	-0.02578451	0.00089117	-0.00323851

9.2 Map view strain output file

Every time when you click "Cal. & View" in the *Strain control panel*, a text output file called "strain.cou" will be created or updated and saved in a sub-folder called "output files" within the "Coulomb 3.1 folder". When you want to save your latest runs, remember to rename the "strain.cou" file within the "output files" sub-folder; otherwise it will be written over by your future displacement calculations. Following is an example of "strain.cou" text output file.

Input file selected: Example-2(LL)_lonlat.inp

x	y	z	dilatation(ex+ey+ez)	dilatation	dilatation
(km)	(km)	(km)	(-)	(-)	(-)
-36.0000000000000000	36.0000000000000000	-0.0000000000000000	0.0000001666026758	0.0000001666026758	0.0000001666026758
-36.0000000000000000	36.0000000000000000	1.0000000000000000	0.0000001641860500	0.0000001641860500	0.0000001641860500
-36.0000000000000000	36.0000000000000000	2.0000000000000000	0.0000001616694448	0.0000001616694448	0.0000001616694448
-36.0000000000000000	36.0000000000000000	3.0000000000000000	0.0000001590625171	0.0000001590625171	0.0000001590625171

9.3 Cross-section dilatation output file

When you click "Cal. & View" in the *Strain control panel*, and have selected the 'Dilatation cross section' option, a text output file called "dilatation_section.cou" will be created or updated and saved in the sub-folder.

9.4 Map view Coulomb stress output file

Every time when you click "Cal. & View" in the *Stress control panel*, a text output file called "dcff.cou" will be created or updated and saved. 'Dcff' is an abbreviation for the change in the Coulomb failure function. When you want to save your latest runs, remember to rename the "dcff.cou" file within the "Output files" sub-folder ; otherwise it will be written over by your future calculations. Following is an example of "dcff.cou" text output file.

dcff.cou

Input file selected: Example-2(LL)_lonlat.inp

x	y	z	coulomb	shear	normal
(km)	(km)	(km)	(bar)	(bar)	(bar)
-50.000000	-50.000000	7.500000	0.354929	0.282823	0.180266
-50.000000	-48.000000	7.500000	0.390592	0.341828	0.121908
-50.000000	-46.000000	7.500000	0.423798	0.404596	0.048006
-50.000000	-44.000000	7.500000	0.452444	0.469871	-0.043568
-50.000000	-42.000000	7.500000	0.473929	0.535852	-0.154809

9.5 Cross-section Coulomb stress output file

Every time when you click "Calc. & View" in the *Cross section* control panel, a text output file called "dcff_section.cou" will be created or updated. Remember to rename it if you want to save the latest cross section run since "dcff_section.cou" will be overwritten. The following is an example of "dcff_section.cou" text output file.

dcff_section.cou

Input file selected: Example-2(LL)_lonlat.inp

x (km)	y (km)	z (km)	coulomb (bar)	shear (bar)	normal (bar)
-36.000000	36.000000	-0.000000	0.440732	0.332070	0.271655
-36.000000	36.000000	1.000000	0.440016	0.332287	0.269323
-36.000000	36.000000	2.000000	0.438220	0.331613	0.266516
-36.000000	36.000000	3.000000	0.435482	0.330172	0.263275
-36.000000	36.000000	4.000000	0.431935	0.328079	0.259642

9.6 Element Conditions stress output file for 'Calc. stress on faults' option

Every time when you select 'Calc. stress on faults', Coulomb produces a 'Element_conditions.csv' file with the results in tabular form. It includes not only the specified rake you selected for the calculation, but also the maximum (most positive) Coulomb stress change and the associated rake for this maxima.

Element_conditions.csv

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Fault	X-cent	Y-cen	Z-cen	length	strike	dip	lat-slip	dip-slip	sig-right	sig_rev	normal	coul-right	coul-rev	opt-rake	opt-coul	spec-rake	spec-coul	nt-rake	rake-coul
2	#	(km)	(km)	(km)	(km)	(km)	(deg)	(m)	(m)	(bar)	(bar)	(bar)	(bar)	(bar)	(deg)	(bar)	(deg)	(bar)	(deg)	(bar)
3	1	0.0	0.0	6.0	99.01	45	90	2	0	-23.39	0.00	0.00	-23.39	0.00	0	23.39	135	-16.54	0	-16.54
4	2	-37.4	-2.4	7.5	7.212	33.7	75	0	0	-1.93	0.08	1.64	-1.28	0.74	2.5	2.59	135	-0.65	0	-0.65
5	2	-33.4	3.6	7.5	7.212	33.7	75	0	0	-2.12	0.02	1.23	-1.62	0.52	0.6	2.61	135	-0.99	0	-0.99
6	2	-29.4	9.6	7.5	7.212	33.7	75	0	0	-2.10	-0.02	1.02	-1.69	0.39	-0.5	2.51	135	-1.09	0	-1.09