

Aims

- To improve understanding of elastic deformation from the locked megathrust.
- To practice finding reasonable model parameters from the literature.

In this exercise, you will use MATLAB to construct a model for elastic deformation from a locked megathrust. We will use data from Cascadia (from McCaffrey et al. (2013)) with the crustal block rotation removed, projected along a profile. You will need to select the location for your profile and its azimuth, select the appropriate relative plate velocity, and then adjust the fault model parameters to fit the data.

- 1) Load the MATLAB script `Cascadia_model_template.m`, and then save it under a name you prefer. This will allow you to try multiple profiles without overwriting the values for the first one.

```

18
19
20 % Parameters to choose
21
22 % Profile origin (a point along the trench), azimuth, and width (km)
23
24 - origin_lat = YOU_CHOOSE;
25 - origin_lon = YOU_CHOOSE;
26 - az = YOU_CHOOSE;
27 - profwidth = YOU_CHOOSE;
28
29 % Plate motion rate and azimuth (from McCaffrey et al. (2007), Juan de Fuca
30 % plate relative to crustal blocks
31 % Un-comment the most appropriate of these:
32
33 % Vancouver Island
34 - plate_vel = 46;
35 - plate_az = 54;
36
37 % Oregon-Washington border
38 - plate_vel = 36;
39 - plate_az = 61;
40
41 % Central Oregon
42 - plate_vel = 35;
43 - plate_az = 59;
44
45
46 % Fault model parameters to adjust
47
48 - dip = YOU_CHOOSE; % dip angle
49 - depth = 5; % depth at trench
50 - width = YOU_CHOOSE; % width of locked region along fault plane (km)
51 - locking = YOU_CHOOSE; % locking fraction (0-1)

```

- 2) Next, you need to fill in the values that are marked by “YOU_CHOOSE”. The origin of the profile should be a point on the trench. Use Google Earth to pick it, or else use a figure from a previous paper if you can pick it accurately from there. The azimuth of the profile should be trench-normal direction (pointing roughly east). The easiest way to measure an azimuth is again to use Google Earth. Use

- the “Ruler” tool, and draw a line along the trench. It will give you the heading of that line, and you can add 90 degrees to that (and enter it as azimuth clockwise from north). Choose the most appropriate plate velocity and then try values for the Fault model. When you run the script you will get a plot showing the velocities and model prediction in the trench-normal, trench-parallel, and vertical directions. (Note that there are no data in this data file for the vertical, so only the model prediction is shown.
- 3) Adjust the model parameters until you are happy with the fit. The script calculates the reduced chi-square statistic for the model fit. Ideally, that value should be about 1.0 if the data uncertainties are correct and the model is also a correct linear model (“correct” in the sense that the linear model you are estimating actually captures all of the variation in the data).
 - 4) If you finish one profile, pick another and repeat.

Questions:

- There will be some systematic misfit no matter what you do with your model. What might be the cause?
- For oblique subduction like this, the distance dependence in the trench-normal and trench-parallel components are different. Describe how they are different?

References:

- McCaffrey, R., A. I. Qamar, R. W. King, R. Wells, G. Khazaradze, C. A. Williams, C. W. Stevens, J. J. Vollick, and P. C. Zwick (2007), Fault locking, Block Rotation and Crustal Deformation in the Pacific Northwest, *Geophys. J. Int.*, 169, 1315–1340, doi:10.1111/j.1365–246X.2007.03371.x
- McCaffrey, R., R. W. King, S. J. Payne, and M. Lancaster (2013), Active tectonics of northwestern U.S. inferred from GPS-derived surface velocities, *J. Geophys. Res. Solid Earth*, 118, doi:10.1029/2012JB009473.
- McCrary, P. A., J. L. Blair, F. Waldhauser, and D. H. Oppenheimer (2012), Juan de Fuca slab geometry and its relation to Wadati-Benioff zone seismicity, *J. Geophys. Res.*, 117, B09306, doi:10.1029/2012JB009407.

Aims

- To visualize the displacement field produced by real earthquakes.
- To provide a tool that can be used for many large earthquakes.
- To illustrate why command-line tools and scripting are so useful.

In this exercise, you will use a simple tool `ffaultdisp` written by Sergey Kolesov from Moscow State University, which uses the classic Okada (1985) analytical solution to compute displacements due to dislocations in an elastic halfspace. A nice feature of this program is that it reads a format for the slip distribution in the earthquake that is very close to the format produced by the USGS finite fault models. USGS produces these models for all sufficiently large or important earthquakes, based on teleseismic data. For our example, we are going to work with the 2016 Pedernales, Ecuador earthquake. You can see what USGS provides by checking out the earthquake web page:

<https://earthquake.usgs.gov/earthquakes/eventpage/us20005j32#executive>

I have provided the source code for the program as well as compiled versions for both Mac and Linux. If you have a Windows machine, you will need to run this inside the virtual machine (you can simply download the tutorial zip file inside the VM to get all of the files inside). The file “`ffaultdisp`” in the main directory for this exercise is compiled for a Mac. If you are using Linux, then copy the file from the Linux subdirectory:

```
cp Linux/ffaultdisp .
```

I have provided a script called “`compute displacements`”, which downloads the model parameter file from the USGS. Then it re-formats the file to account for the small format differences, computes the displacements, and generates a figure using GMT. I provide two different versions of the script, one for GMT version 4 and the other for GMT version 5 (look for the text `gmt5` in the filename). Before running it, you need to provide the earthquake ID (see the event page at USGS), and a latitude-longitude box for the plot.

```
set eqid = us20005j32          # Pedernales, Ecuador
set minlon = -90
set maxlon = -75
set minlat = -5
set maxlat = 5
```

All of the scripts are written for the `tcsh` shell and use some standard unix tools.

- 1) Run the script “`compute displacements`”
- 2) Try it again for another earthquake!

Aims

- To improve understanding of how to interpret interferograms.
- To visualize the displacement field produced by a simple magmatic source.
- To gain an appreciation of the uncertainties involved with determining source mechanisms from InSAR data.

In this exercise, you will use Matlab to find the parameters of a simple model of a magma chamber that match real InSAR data at a Peruvian volcano.

- 1) Load and plot the interferogram and UTM position:

```
>> get_started
```

The interferogram is from the European Space Agency Satellites ERS-1/2 and spans 1996-04-25 to 1992-06-02 (3.89 years) and the pixel spacing is 900 m, a 40-fold reduction from the original resolution to speed up modeling. The interferogram shows decrease in the distance between the ground and satellite above Hualca Hualca volcano in southern Peru near the active volcano Sabancaya which erupted in the early 1990's and is taken from Pritchard and Simons (2004). What is the average rate of ground deformation in this time interval? This deformation pattern seems to have stopped between 1996-1998 and a series of earthquakes occurred over the next 17 years (Jay et al., 2015) until the potential magmatic activity resumed in 2015-2016.

- 2) Edit `find_mogi.m` and run it multiple times to find models that you think fit the data – you can use the criteria that is the misfit between the data and model that is in the title of each plot. The model we are using is an axisymmetric point source that is frequently called a “Mogi” model after Mogi (1958) that provides the 3D ground displacements from an inflating or deflating source.

```
>> find_mogi
```

Hints:

- Start by finding the best x and y locations – look at the profiles to see what direction you need to move the source to match the data
- Match the shape of the deformation by changing the depth and ΔV – notice these values trade-off, so look for a range of values that seem to well fit the data.

- 3) Once you have a good estimate of x and y location, you can run

```
>> mogi_loop
```

to plot the misfit as a function of depth and volume change. The title on the plot shows the best fitting values (plotted as a white point). How might you estimate error bounds on these values?

References:

Jay, J. A., F. J. Delgado, J. L. Torres, M. E. Pritchard, O. Macedo, V. Aguilar (2015) Deformation and seismicity near Sabancaya volcano, southern Peru, from 2002-2014, *Geophys. Res. Lett.*, 42, 2780-2788, doi:[10.1002/2015GL063589](https://doi.org/10.1002/2015GL063589)

Mogi, K. (1958), Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them, *Bull. Earthquake Research Inst.*, 36, 99–134.

Pritchard, M. E. and M. Simons (2004) An InSAR-based survey of volcanic deformation in the central Andes. *Geochem. Geophys. Geosys.* 5, 10.1029/2003GC000610.