Geodynamics 5690/6690: Exercises 2 Due 3 May (5pm)
Show all work; write clearly (Full sentences! Well-structured paragraphs!) in developing equations and discussing results.

(1) Which of the following are responsible for topographic elevation variations in the western United States?
(a) Temperature variations within the lithospheric thermal boundary layer
(b) Variations in thickness of a buoyant crust
(c) Variations in rock-types found within the crustal column
(d) Temperature variations within the convecting asthenosphere
(e) Surface processes (including erosion, faulting and volcanic construction) and their isostatic response

(2) Early in the semester, we read a paper by Kellogg et al. (1998) postulating two-layer mantle convection in which the deeper layer was a thin, compositionally-distinct zone at the bottom of the mantle (in what are now called Large Low Shear Velocity Provinces, or LLSVPs).

(a) Describe at least three hypotheses for the origin of LLSVPs.

(b) Kellogg and other papers we discussed in class listed more than five observations supporting incomplete mixing of the mantle. Describe at least three of these observations, and for each one, discuss how it is or is not consistent with each of the three hypotheses you listed in part a.

(c) Given the observations, which hypothesis do you find most plausible and why?

(3) Early seismic studies of the Sierra Nevada mountain range in California found no evidence for an isostatic “crustal root” that researchers expected to find (and partially wrote their proposals based on finding). Assuming a topographic amplitude of 3000 m, a regional effective elastic thickness of 15 km, ρ_c = 2670 kg/m^3, and ρ_m = 3350 kg/m^3:

(a) Assume that the ~100 km width of the range represents half the wavelength of sinusoidal flexural loading and response. What would be the amplitude of Moho deflection expected if the range is a surface load? (Remember: The final surface topography is the surface load ***plus*** the flexure.) What should the amplitude of Moho deflection be if the topography is a flexural response to loading at the Moho?

(b) Now assume that the ~400 km length of the range is half the wavelength of loading and response. What would the Moho deflection be in that case if it is a surface load? What would it be if it is a subsurface load?

(c) The Sierra Nevada is two-dimensional, and we have discussed in class how 2D wavenumber is represented as a 1D k. What is the correct wavelength in this case, and what are the Moho deflections for surface and subsurface loading?

(d) Now look at the Moho deflection under the Sierra Nevada measured in more recent analyses by Lowry & Pérez-Gussinyé (Nature 2011). How does this compare to your calculations? What other dynamics are going on here that we've discussed in class, and how might that affect your interpretation?

(4) Most models of lake and postglacial rebound assume Maxwell (linear) viscoelasticity in a 1D Earth with just a few layers having uniform viscosity. For example, Karow & Hampel (Int J Earth Sci 2010) modeled effects of Bonneville rebound on Wasatch fault strain using an Earth model with lower-crustal viscosity (15-30 km depth) of 10^{22} Pa s, upper mantle viscosity (30-100 km depth) of 10^{18} Pa s, and asthenospheric viscosity (> 100 km) 10^{17} Pa s (based on results of earlier models that had parameterized layer thicknesses and viscosities by fitting the observed shoreline uplift).

(a) Karow & Hampel (2010) infer that their 10^{18} Pa s upper mantle layer corresponds to the mantle lithosphere, because Zandt et al. (1995) teleseismic data suggest a base of lithosphere at ~60-70 km (similar to Levander & Miller, 2012) and basaltic melts originate at similar depths. How do each of these observations relate to the various definitions of "lithosphere" that we have discussed in class (hint: go back to the beginning!), and more specifically how do these other definitions relate to the rheological definition of lithosphere?

(b) The Moho temperature under Bonneville (Schutt et al., 2018) averages about 700°C at ~31 km depth. Using the dislocation creep power law parameters given below (from Bürgmann & Dresen, 2008), and assuming a water fugacity of 5800 Pa (the approximate saturation fugacity for olivine at that depth), first calculate the flow yield strength that crustal and mantle rocks should have given an assumed strain rate of 10^{-15} s^{-1}; then calculate the strain rates that would be required (for both wet and dry rocks) to get an effective viscosity ($\eta_{eff} = \Delta\sigma/2\dot{\varepsilon}$) of 10^{22} in the lower crust and 10^{18} in the mantle:

	Pre-exponential coefficient A	Water fugacity exponent r	Exponent n	Activation energy Q	Activation volume V
wet anorthite	1.58	1	3	3.45×10^{5}	3.8×10^{-5}
dry anorthite	5.01×10^{12}	0	3	6.41×10^{5}	2.4×10^{-5}
wet olivine	1.58×10^{3}	1.2	3.5	5.2×10^{5}	2.2×10^{-5}
dry olivine	10^{5}	0	3.5	5.3×10^{5}	1.8×10^{-5}

(Hint: If you aren't sure of your calculations, you'll be able to check them by comparing to yield strengths that you can calculate using computer codes you'll use to answer questions 5 & 6!). Assume a mean crustal density of 2800 kg/m^3; the grain-size exponent m for dislocation creep is zero; and the units of A will yield $\Delta\sigma$ in MPa (so multiply by 10^6 to get mks units of Pa). Typical surface strain rates are in the range 10^{-14} to 10^{-16} and strain rates at the Moho may be several orders of magnitude higher. What does this imply about the viscosities assumed in Karow & Hampel?

(c) The viscosity structure in Karow & Hampel was chosen based on earlier viscoelastic modeling of uplifted Bonneville shorelines. Think carefully about the modeling results in Willett et al. (1985) and the materials we discussed in class on the relationship of T_e to rheology. What limitations might one expect in estimating viscosities of a four-layer model from the forward modeling of uplifted shorelines as the response of a four-layer Earth with uniform viscosity in each layer? Hint: Nakiboglu & Lambeck (JGR 1983) discuss this also in an early paper modeling Bonneville rebound.

For exercise (5), you will need to run a fortran code that I have created for you and placed in the course Canvas website (under the "Files" heading). This exercise will be easiest to do if you use a Mac computer with Matlab installed (it should be possible to compile and run the code on other operating systems also, but I will only give instructions for Mac unix here). You'll need to open a terminal in order to run and/or compile the codes. If the zip file linked to these exercises did not automatically unpack you can go to the directory where you put it (e.g.,

```
cd Desktop/
```

and unzip by command:

```
unzip G5690.zip
cd G5690
```

If your Mac OS is the same as mine you may be able to run the executables that are already in that directory & I would try that first:

```
./YSE_Plot
```

If the executable is not compatible with your OS, then

```
cd Source/
sh fcomp.sh
cd ../
```

and if you have gfortran on your machine as your fortran compiler, you should be ready to go. (If not, you may need to edit fcomp.sh and replace "gfortran" with "gcc" or whatever your fortran compiler is). Output files from these codes can be plotted in Matlab using

```
YSE_Plot
```

with output figures printed to a file in png format. (GMT shellscripts to do plotting are also included in the directory, but they are written in GMT v4.5, which is not commonly used anymore).

(5) Use the code YSE_Plot to model geotherms, yield strength envelopes, effective viscosity and T_e.

(a) First, use the geotherm parameters derived for Exercise 1 question 5d to specify a geotherm. (You can use the parameters I specified in the Key posted on the website to match observations of the Moho temperature and surface heat flow.) Effective elastic thickness in the Bonneville region is about 10 km, while in the Wyoming craton it's nearer 90 km. Which (if any) rheological layering combinations most closely match these two cases if you use the geotherms for these regions that match the observations? Plot the corresponding yield strength envelopes for each location using YSE_Plot in Matlab. Do these match what you might expect to see for this region?

(b) YSE_Plot also creates a file called EffVisc.zh containing the effective viscosity for a given yield strength envelope. Run the code once using your preferred Basin & Range parameters and rename that file to call it EffVisc_BR.zh; then run it again with Colorado Plateau parameters and rename the output EffVisc_CP.zh. Then you can use Visco in Matlab to plot viscosity with depth for both locations. Does the Bonneville region viscosity match that modeled by Karow & Hampel based on earlier rebound studies, if you use the suggested strain rate? Note the strength and viscosity calculations used here depend on the assumed strain rate. Is a constant strain rate a reasonable approximation to make? How does it change if you change the strain rate? What does that imply about the rebound process?

(6) Based on the results of these calculations, what can you infer about controls on deformation processes in the western United States?