**Introduction**

The buoyancy of plates is a relatively simple concept, but it turns out to be very important to understanding some fundamental things about plate tectonics. Why does subduction occur? The answer is because a plate becomes negatively buoyant as the mantle part of the plate cools and becomes denser. This negative buoyancy is perhaps one of the major driving forces of plate tectonics.

The example below shows how Peter Molnar, one of the "inventors" of tectonics, calculates buoyancy as the sum of the buoyancy of the two parts of plates. This analysis, based on Molnar and Gray (1979) gives a force acting on a piece of lithosphere with a surface area of 1 km$^2$, or a 1 km long section of a plate when viewed in cross section.

**Theory**

**Crustal buoyancy**

Recall that the crust has a different composition than the mantle and almost always has a lower density. The buoyant forces that act on it are proportional to the density difference between the crust and the mantle and the thickness as follows:

\[
\text{Crustal buoyancy} = (\rho_{am} - \rho_c) \cdot h_c \cdot g \cdot 10^9,
\]

where $g$ is gravity (m/s$^2$); $\rho_c$ and $\rho_{am}$ are the crust and asthenospheric mantle densities respectively (in kg/m$^3$); and $h_c$ is the crustal thickness (km). The units for buoyancy are in Newtons, but we are interested in buoyancy per square km (this is how 10$^6$ of the 10$^9$ appears; the other 10$^3$ is to convert the crustal thickness from km to m).

**Lithospheric mantle buoyancy**

The mantle lithosphere is generally about the same composition as the underlying asthenosphere, but it is cooler since it has been closer to the surface for millions of years. Since it is cooler, it is slightly denser, but its density varies from top to bottom because the temperature changes (the geothermal gradient in the Earth).
To calculate the buoyancy of the mantle lithosphere, we need to look at the density difference between the lithosphere at each depth and the asthenospheric mantle at those same depths.

A simple way of doing this is to take the temperature difference between the mantle lithosphere and the asthenosphere at the base of the crust, convert that to a density difference, then multiply it by the thickness of the mantle lithosphere and divide the whole mess by 2. This is equivalent to calculating the area of the shaded triangle in Figure 2.

\[
\text{Mantle lithosphere buoyancy} = \frac{\alpha \cdot \rho_{am} \cdot (h_p - h_c) \cdot (T_{am} - T_{bc}) \cdot g \cdot 10^9}{2},
\]

where \( h_c \) is the crustal thickness and \( h_p \) is the total plate thickness; \( T_{am} \) and \( T_{bc} \) are temperatures of the asthenosphere and lithospheric mantle at a base of the crust; \( \alpha \) is the coefficient of thermal expansion. (The \( 10^9 \) factor is again to scale this value to N/km².)
Assignment

Use the equations described above and/or the Excel file called buoyancy.xls to do a few plate buoyancy calculations to provide answers to the following questions. Your answers should consist of a few sentences. (Don’t worry about isostasy in your answers.) Typed responses are preferred.

1. Oceanic plates start out very thin, with almost no mantle attached to them. The plates then increase in thickness as times goes by by adding more and more mantle material to the base of the plate. This addition of material suggests that plate buoyancy will decrease through time. (Note, however, that oceanic crustal thickness and density do not change appreciably after the first million years or less.) There is a graph of this relationship between plate age and thickness in the Excel file.

   a. At what age and thickness does an oceanic plate with a 7 km thick crust become negatively buoyant, i.e. subductable?
   b. How does this age of subductability vary with the thickness of oceanic crust? (Oceanic crust varies between 6 and 8 km thick in most cases.)
   c. What does this age of subductability suggest about controlling factors on the rates of motion for oceanic plates? Keep in mind the average age of subducting crust is 120 my and the average seafloor spreading rate is ~4.5 cm/yr.

2. Some regions in the ocean have seamounts and submarine plateaus that increase the thickness of the basaltic oceanic crust up to 10 to 40 km thick. Under what conditions can these regions be subducted? What might happen if you tried to subduct ocean lithosphere that had a plateau embedded in it?

3. In the Mediterranean, the ocean crust has thin (3 km) to non-existent oceanic crust. When will this be subductable?

4. Can continents be subducted? Use a density of 2.8 g/cm$^3$ for the average crustal density. Allow the plate thickness to vary from 100-350 km, and crustal thickness from 15-60 km. This will allow you to determine the range of conditions under which continents can be subducted.

5. Is it possible to get continental lithosphere with normal crust (30 km thick) and normal plate thickness (200 km) to subduct if it is attached to a length of subducting oceanic lithosphere? What length of oceanic lithosphere and of what age (average) would be needed to subduct a section of continent 150 km long? It may help to recall that the buoyancy calculated by the model is actually buoyancy per unit length (1 km) of plate material. Note: there are some continental rocks in the Alps, Himalayas, and Scandinavian Caledonides that appear to have been temporarily pulled down to depths of 100 km or more.