Homework 4: Planets and icy satellites

Qu. 1) Water can exist as ice, liquid or vapor. Gravity data suggest that that the outer ~200 km or so of Europa is covered in a material of density ~1 g cm^{-3}, which could be **either** ice **or** liquid water. In addition, the ice can be in different crystalline phases (called ice I, ice II, ice III, etc.) depending upon the temperature and pressure. Basically, high pressure modifies the hydrogen bonds in the ice allowing different crystal structures. The following diagram (Fig. 1) shows you the phases of ice and liquid water that occur at different temperatures and pressures.

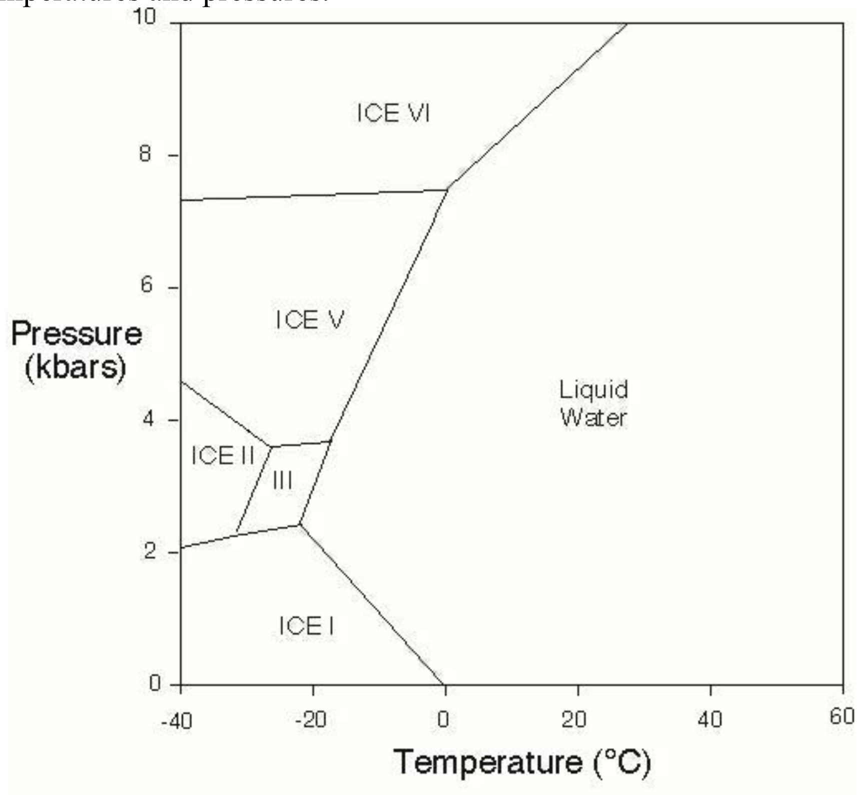

Fig 1: Phases of water

Let us consider applying this phase diagram to the ice shell on Jupiter's moon Europa.

(a) Consider an extreme case: that the ice shell is very thick and extends for most of the 200 km. Examine the diagram and deduce the thickness of the ice-shell at which the ice will change phase from ice I to ice III. Assume that the temperature at the base of the ice shell will be ~250 K. (Hint: Consider the weight of a column and the pressure needed at the base of that column. You may assume that the mean density of the ice I layer is 0.97 g cm^{-3}. Europa's gravity is 1.31 ms^{-2}, which does not change significantly over the depth considered here). [4 points]

(b) Ice I (the ice with which we are commonly familiar) is less dense than liquid water and so floats. However, ice III is denser than liquid water. Suppose the ice I shell thickness reaches that calculated in (a). If water lies beneath Europa's entire ice shell, what do you think will happen to the ice III that begins to form on the underside of the ice I layer? [2 points].

(The full answer to this question would involve calculating heat fluxes and temperature vs. depth. One could imagine that a combination of latent heat release and tidal heating (which is expected to be greatest at the lower boundary of the ice shell) could raise the temperature enough to create liquid water under the ice I layer just at the ice III boundary. The idea is intriguing but some researchers dislike the idea of such a thick ice shell based electric field data, suggesting a conductive layer (salty water) ~45 km depth).

Qu. 2) The slow rate of flow (called "creep") of water ice, *r*, is given by the following expression (where *r* would be in units of m/m/sec, i.e., a rate of strain)

$$r \propto \sigma^n \exp\left(\frac{-E_s}{kT}\right)$$

where *T* is temperature, *k* is Boltzmann's constant (1.38×10^{-23} J K-1), E_s (1.1×10^{-19} J) is an activation energy to break hydrogen bonds in the ice , σ is applied stress, and *n* is a constant. The equation shows that the rate of creep is proportional to a temperature-dependent exponential factor.

From this equation, we would expect ice-flow to be very different in the polar regions of the Earth where the temperature is ~273 K compared to ice-flow on outer planet satellites where the temperature is roughly 100 K.

(a) Calculate the following ratio: (rate of creep of ice at 273 K)/(rate of creep at 100 K). [2 points]

(b) If we look at the multi-ring structure around very large ancient craters on the icy surfaces of Callisto and Ganymede, we find that the topography is subdued. The rings are less than ~1 km in height, yet we would expect them to have been much larger when the crater formed. Is this consistent with your answer to part (a). If it is not, what is a reasonable explanation for why the crater rings have heights that are subdued? [3 points]

Qu. 3) What are (a) the Hellas basin and (b) the Tharsis bulge on Mars and when and how did they form? (Use internet/library resources if needed) [6 points]

Qu. 4) A rare and eccentric type of planetary scientist is called a "photogeologist". They pore over spacecraft images of planetary bodies and construct geological histories based on the morphology of geological features. (In my experience, they also tend to wear loud T-shirts and have beards (if male, that is)).
Fig 2(a) is a Voyager 2 picture of Enceladus and Fig 2(b) is an interpretation by a photogeologist. She has divided up the surface into six terrains that are denoted by the letters "ct_1", "cp", etc., which is typically the way that planetary terrain types are labeled. She describes these letter designations as follows:

ct_2 = well-preserved, fairly densely cratered
ct_1 = similar to ct_2 but with flattened craters
cp = cratered plains (with lower crater density than ct1 or ct2)
sp_1 = smooth plains with few craters

sp_2 = smooth plains with no visible craters
rp = ridged plains with no visible craters

For this question, you may need to view the image on a monitor and magnify it.

(a) (i)As far as possible, rank the units in order of relative age. [3 points]

(ii) Roughly how long would you guess is the overall timespan that is sampled by the various geologic units on Enceladus? [1 point]

(b) Examine the boundary between rp and ct_2 or cp, looking at craters on the boundary. What appears to have happened? Is compression of material or extrusion of material suggested? [2 points]

(c) Examine the grooves in the lower left hand corner of the image running from Southwest to Northeast. What does their alignment suggest to you? [2 points]

Qu. 5) Venus probably started out with an inventory of volatile substances (carbon, sulfur, water, etc.) similar to the Earth's. Presumably, Venus had a primordial ocean. If Venus lost its primordial ocean because water vapor was photolyzed and hydrogen escaped to space, a question arises about where all the oxygen went. The surface of Venus is red-colored suggesting the presence of fully oxidized iron (Fe_2O_3 = hematite) and perhaps partially oxidized iron (Fe_3O_4= magnetite). Originally Venus would have had a gray surface characterized by iron in the Fe^{2+} state (FeO), like the Moon. At some point the crust oxidized.

Suppose the endpoint of FeO oxidation in the crust was predominantly Fe_3O_4 (magnetite). For a rough calculation, let us assume that the crust was oxidized to 30 km depth (a reasonable depth for "tectonic mixing") and started out with 10% (by mass) FeO that all got oxidized to magnetite via:

$$3FeO + 0.5O_2 = Fe_3O_4$$

(a) Calculate how much oxygen (in kg of O per square meter) the crust would absorb in this case. [4 points]

(b) Given that the mean radius of Venus is 6052 km, what is the total mass (in kg) of oxygen absorbed by the crust in this scenario? [1 point]

(c) The oxygen in your answer to (b) would have been derived from splitting liquid water. Given you answer in (b), calculate how much water gave rise to the oxygen taken up by the crust. [2 points]

(d) How deep would this amount of water be if spread all around the surface of primordial Venus? [1 point]

(e) The mass of Earth's oceans is 1.4×10^{21} kg. How much, as a fraction of the Earth's oceans, is your answer in (c). [1 point]

A similar calculation, assuming hematite as the end-point of FeO oxidation rather than magnetite, suggests that the crust would absorb 1/3 of an Earth ocean. Perhaps at some point in Venusian history the crust was saturated with oxygen so that O_2 began to accumulate in the atmosphere to significant concentrations and oxygen was lost to space by non-thermal processes. A similar fate may await the Earth in several billion years time when it loses its oceans as the Sun warms up. Some people speculate that a few hundred bar pressure of O_2 may then accumulate in Earth's atmosphere after the accessible crust becomes saturated with oxygen.

[Data: assume the density of Venus crust is ~2500 kg m^{-3}; density of water = 1000 kg m^{-3}; take atomic masses: Fe = 56g/mole, O = 16g/mole; molar mass of water = 18g/mole]

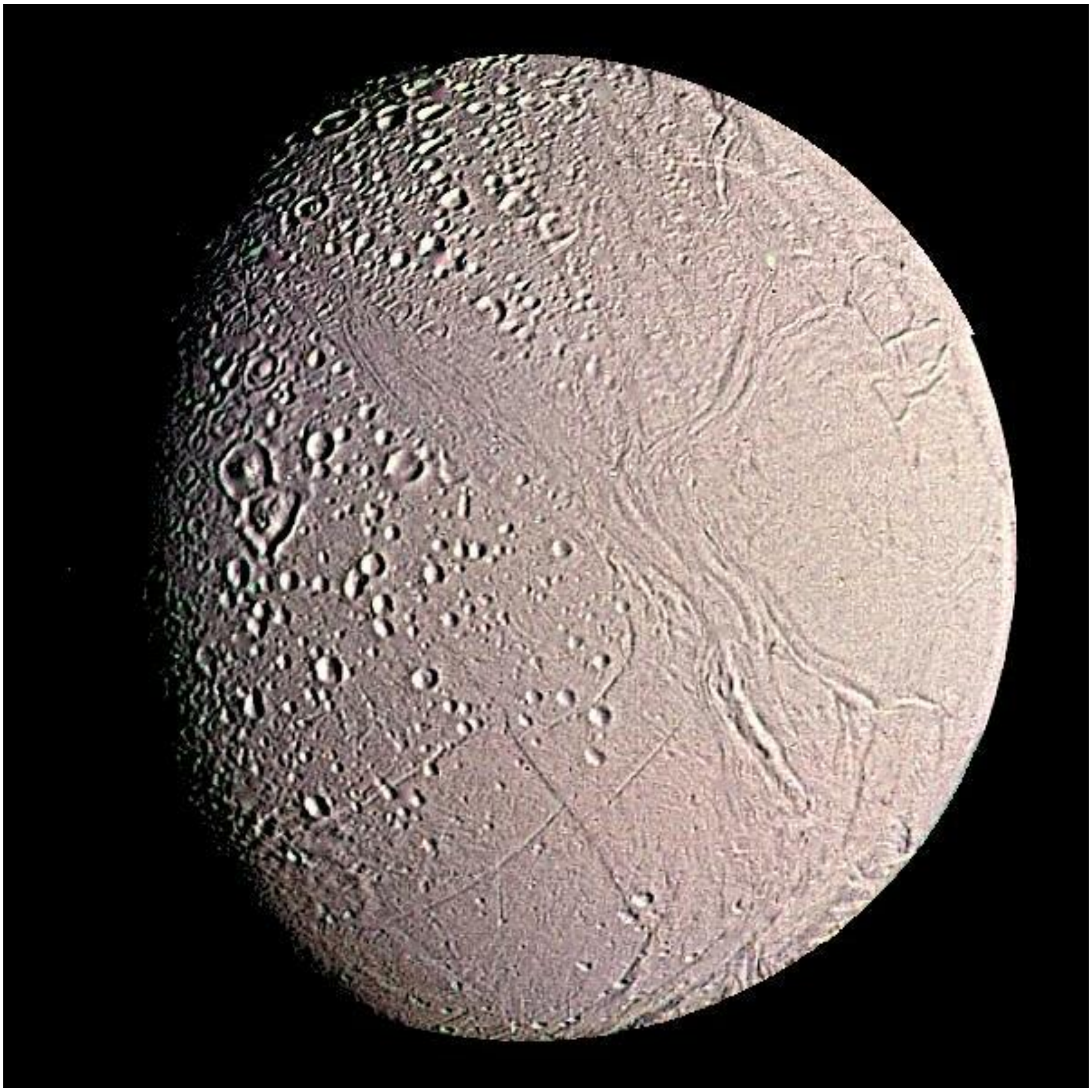

FIG 2(a) Voyager 2 picture of Enceladus. This is the brightest satellite in the Solar System (in terms of albedo) and so has been contrast enhanced.

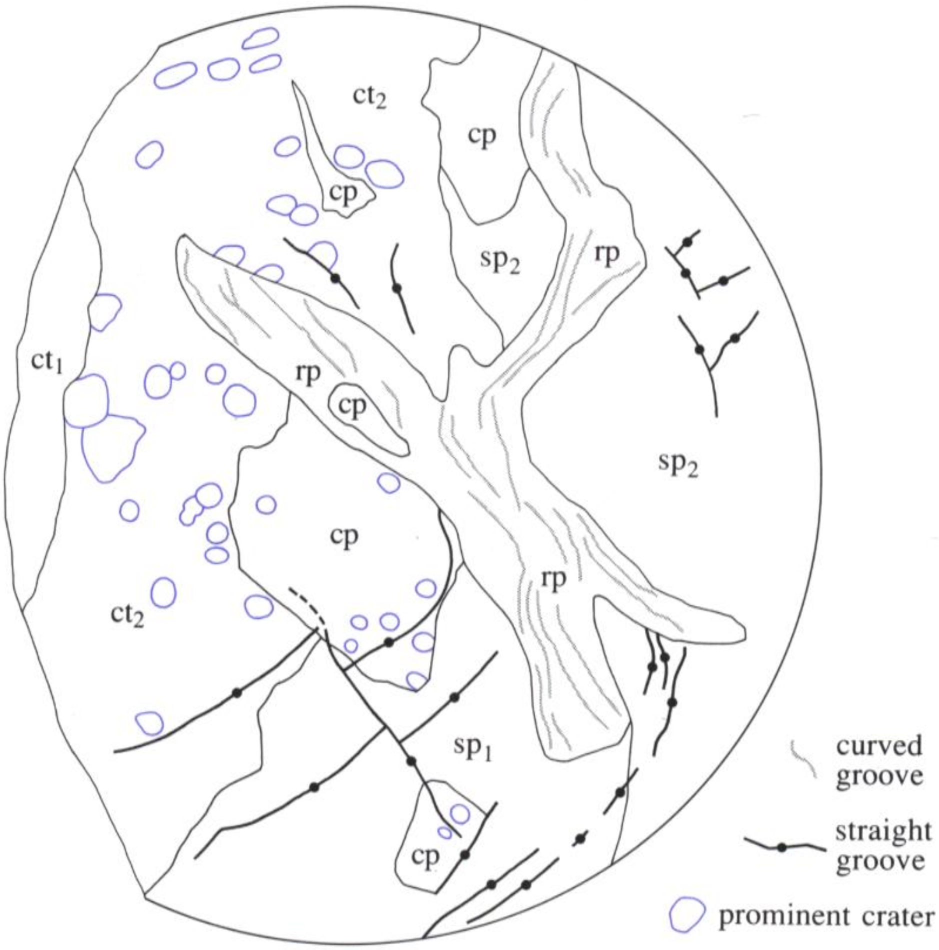

FIG 2(b) Geologic map.