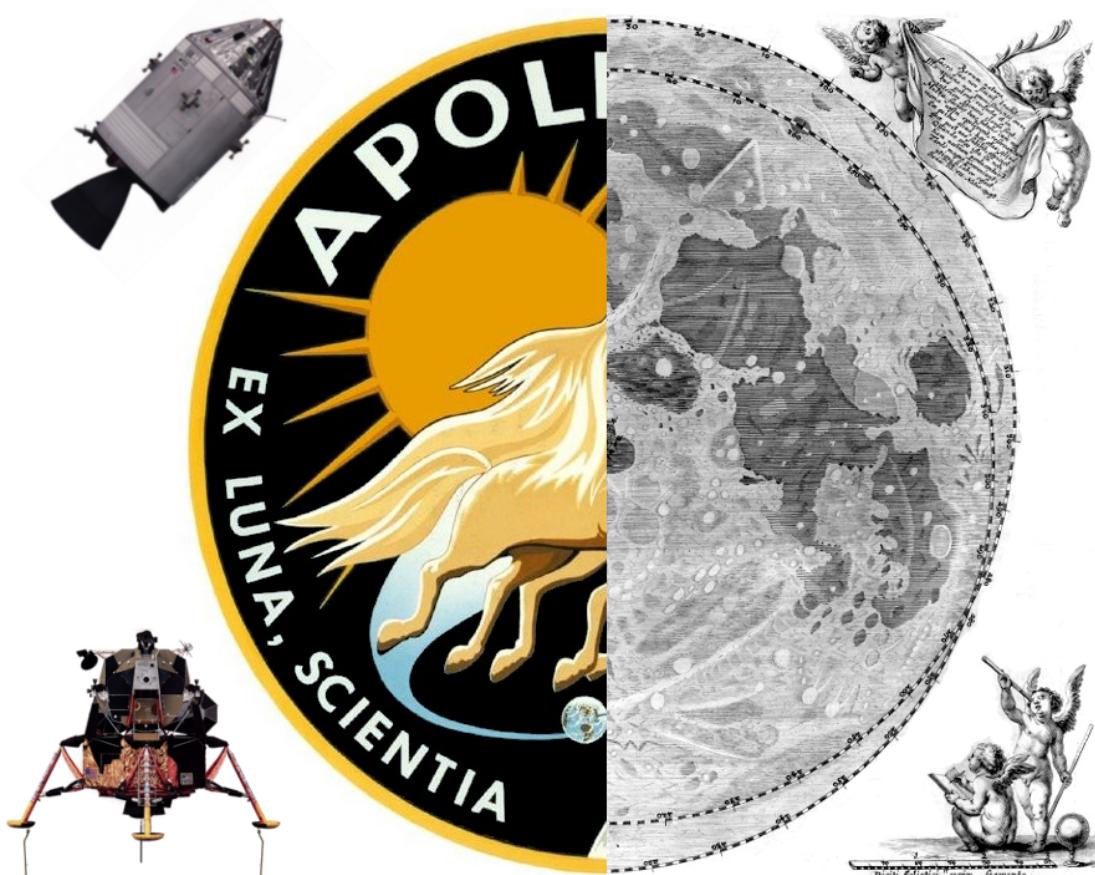


---

# ASTRONOMY 150

## THE PLANETS

---



# Astronomy 150 - Course Pack

Version 2.0

© Toby Smith

This work is licensed under a Creative Commons  
Attribution-NonCommercial-ShareAlike 4.0 International License  
([http://creativecommons.org/licenses/by-nc-sa/4.0/deed.en\\_US](http://creativecommons.org/licenses/by-nc-sa/4.0/deed.en_US))

Unless otherwise credited, the images are copyrighted by NASA or by the author. Cover image from Johannes Hevelius: *Selenographia* (1647) and NASA, montage by TS

The Tranist lab was created by Brett Morris ([bmmorris@uw.edu](mailto:bmmorris@uw.edu)).

This worksheet gives some examples of the types of gravity problems you will see on the midterm and final exams. This is almost the only math you will ever have to do on an exam. Make sure you *really* understand how to do each of these problems. For each of these problems, make sure you show **all** of your work.

**1.** (2 pts) If you were to triple the size of the Earth (Radius =  $3 R_{\oplus}$ ) and triple the mass of the Earth (Mass =  $3 M_{\oplus}$ ), how much would it change the gravity on the Earth (Gravity = ?  $F_{\oplus}$ )?

**2.** (2 pts) If you were to half the size of the Earth (Radius =  $1/2 R_{\oplus}$ ) and double the mass of the Earth (Mass =  $2 M_{\oplus}$ ), how much would it change the gravity on the Earth (Gravity = ?  $F_{\oplus}$ )?

**3.** (2 pts) You have discovered a planet, that is one half the radius of the Earth (Radius =  $1/2 R_{\oplus}$ ) and one half as massive (Mass =  $1/2 M_{\oplus}$ ). How does the gravity on the surface of the planet compare to the Earth?

**4.** (2 pts) You have discovered a planet that has the **same** gravity as the Earth (Gravity =  $1 F_{\oplus}$ ), but is only 1/2 as large (Radius =  $1/2 R_{\oplus}$ ). How would the **mass** of this planet compare to the Earth's?

**5.** (2 pts) You have discovered a planet that has twice the gravity of the Earth (Gravity =  $2 F_{\oplus}$ ), but is only 1/2 as massive (Mass =  $1/2 M_{\oplus}$ ). How would the **size** of this planet compare to the Earth's?

**6.** (2 pts) The gravity of the Moon is about one sixth that of the Earth. For example, an astronaut weighing 180 pounds on the Earth would weigh about 30 pounds on the Moon. If you were to double the distance between the Earth and the Moon, how much would our 180 pound astronaut weigh on the Moon? [Be sure to explain your answer].

For each of the following problems, solve for the unknown value. Make sure to show your work.

7. (2 pts)      Mass =  $4 M_{\oplus}$       Radius =  $2 R_{\oplus}$       Gravity = ?  $F_{\oplus}$

8. (2 pts)      Mass = ?  $M_{\oplus}$       Radius =  $4 R_{\oplus}$       Gravity =  $2 F_{\oplus}$

9. (2 pts)      Mass =  $1/9 M_{\oplus}$       Radius = ?  $R_{\oplus}$       Gravity =  $1 F_{\oplus}$

**10.** (2 pts)      Mass =  $1/3 M_{\oplus}$       Radius =  $2/3 R_{\oplus}$       Gravity = ?  $F_{\oplus}$

**11.** (2 pts)      Mass = ?  $M_{\oplus}$       Radius =  $3/4 R_{\oplus}$       Gravity =  $8/9 F_{\oplus}$

**12.** (2 pts)      Mass =  $1/100 M_{\oplus}$       Radius = ?  $R_{\oplus}$       Gravity =  $1/4 F_{\oplus}$

# Geological Mapping

## Introduction

Few things are as important to explorers as good maps. For a planetary explorer, one of the most important types of maps is a geological map. A geological map shows what types of terrains or rocks one is likely to encounter on a planetary surface, and in what order they were created. Since our ability to go to different planetary surfaces is limited, planetary scientists must do most of their exploring and mapping by studying images from spacecraft. Anybody can look at a pretty picture of a planetary surface and say “That’s Mars”, or “That’s the Moon”. A planetary scientist can take that picture and interpret what is there and reconstruct the history of that surface. Recognizing various landforms on spacecraft images and being able to determine their **relative ages** is an important component of this class.

The identity of the various landforms can be ascertained by comparing known images with what you see (and by asking your TA), while the relative ages of the various features can be determined by using the Principle of Superposition. Nicholas Steno, a seventeenth century physician, is first credited with stating this simple but powerful geological principle. He wrote that “... at the time when the lowest stratum was being formed, none of the upper strata existed.” or in its modern restatement: Young formations overlap old formations.

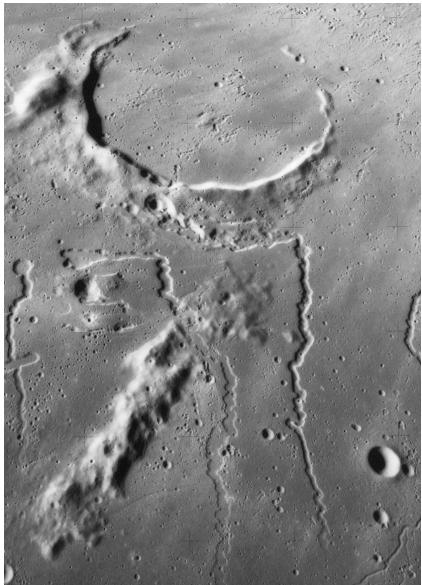
In this lab we will act as planetary scientists and interpret what we see by creating a geological map and writing a description of a selected region of the Moon. Our materials will be the same primary data the Apollo program scientists used when they were first trying to both understand the lunar surface and find interesting landing spots for the Apollo missions. The photographs are from the Lunar Orbiter missions that were flown around the Moon in 1966 and 1967.

## The Lab

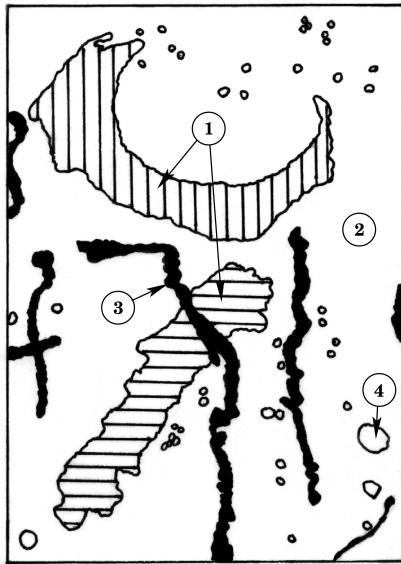
Pick an interesting region on your Lunar Orbiter image. You do not have to map the entire photograph. The region you do pick should have at least 4 different features whose relative ages you can determine. Feel free to pick and label a region with many more features, but not so many that it would take you a week to draw the map.

The pictures on the following page give you some idea as to what we want to do. On the left is an image taken from the command module of Apollo 15. The image is of the area surrounding the ghost crater *Prinz*. On the right is my geological map of the region identifying the different landforms, and labeling my determination of the relative ages for 4 features. You should label the relative ages with numbers, with (1) being the oldest features and (4) being the younger features. At the bottom is the key to the different landforms on my geological map. You do not need to use my shading scheme, colors work really nice.

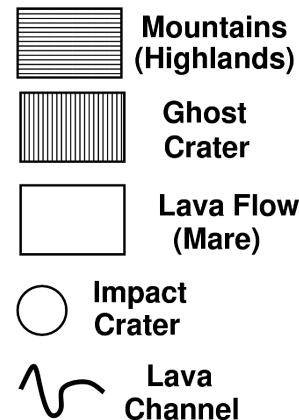
A reader of your map should be able to understand what the various surface features are in the photograph, and in what order they were formed. Often it is not clear what a surface feature is or when it was formed. Be bold and make a guess, we are not going to go the Moon in the near future, so it is hard to tell if you are wrong.



Image



Geological Map



Key

## What to Turn in

Draw your geological map on the next page in the space provided. On the back of that page write a paragraph describing the features you mapped, and answer the questions. Your paragraph should both describe the features and indicate their relative ages. Please refer explicitly to the 4 features you labeled on your map indicating them by number. As an example, here is my paragraph for the above geological map:

"The oldest features in this image are the highland mountains and the ghost crater (1). It is not possible to tell the relative ages of the two features. They may actually be part of the same feature and have the same age. A lava flow (mare surface) fills in much of the image and overlays and abuts the mountains and ghost crater (2). Lava channels overlay the lava flow in numerous places indicating a younger age. In particular one of them (3) cuts across the highland mountains. All of the lava channels seem to have the same relative age since they overlay the same features. Simple impact craters dot the mare surface. A few craters seem to partially cover lava channels, indicating they are younger. One of the impact craters (4) is free of mare and lies on top of the mare surface. It is therefore younger than the mare. This crater and the rest of the impact craters on the mare do not intersect the channels, so their relative ages cannot be determined. My guess is that they are probably younger than the lava channels based on their fresh appearance."

ASTRONOMY 150

GEOLOGICAL MAPPING (20 PTS)

NAME: \_\_\_\_\_

SECTION: \_\_\_\_\_

Geological Map (10 pts)

Map Name: \_\_\_\_\_

**Descriptive Paragraph (6 pts)**

1. (1 pt) What is the oldest feature in your map?
2. (1 pt) What is the youngest feature in your map?
3. (2 pts) What feature covers the largest area in your map?

# Crater Counting on Mars

Impact craters are the dominate landforms on most of the solid surfaces in our solar system. These impact craters have formed on the surfaces over the 4.6 billion years of our solar system. The number of craters on a surface increases with the length of time that surface has been exposed to space. By counting the number of craters in some defined area on a world (determining its **crater density**) and comparing it to the number of craters on a same-sized area on another part of that world, you can determine the **relative ages** of the two surfaces (*e.g.* one area is older than another).

If you want to find out the **absolute age** of the surface you are studying, you need a sample from that surface. Fortunately for us, the Apollo mission brought back lots of rocks from six sites on the Moon. By measuring the ages of rocks from these six sites, and measuring the **crater density** at these sites, we can determine how the **crater density** is related to the **absolute age** at these sites.

In this class, we make the assumption that the cratering rate measured by Apollo on the Moon is typical of the cratering rate in the inner solar system. (*N.B.* This is a **very** important assumption!). We can now extend our measurements of the crater density on the Moon to estimate the ages of various regions on the surface of Mars.

## Crater Density

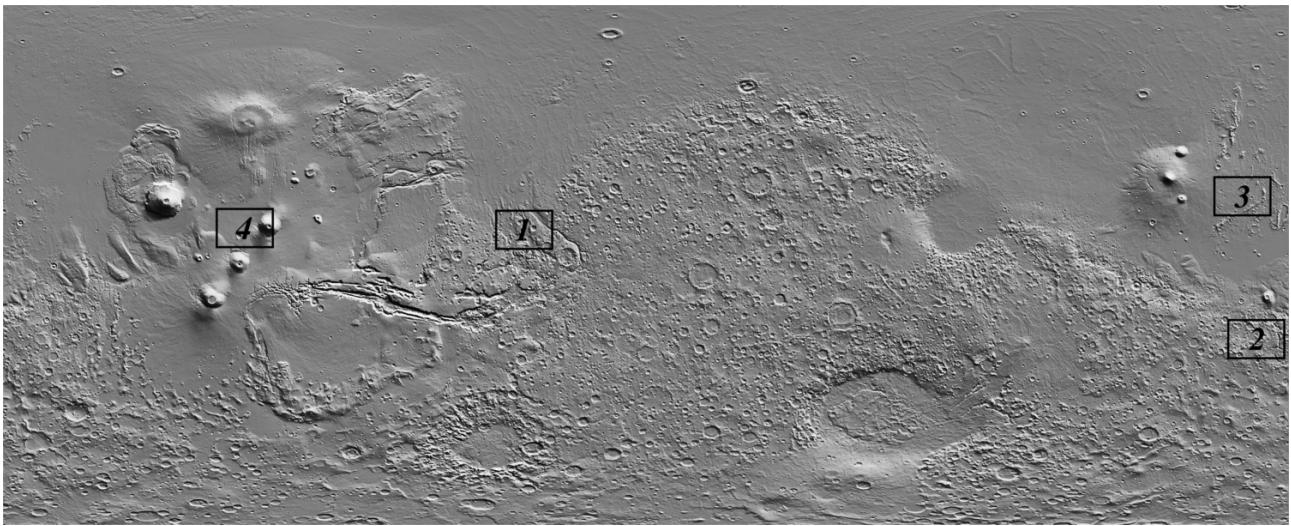
There are many different ways to quantitatively represent the crater density of a surface. One of the most commonly used (and simplest) is to choose an area and count the total number of craters larger than a specific diameter  $D$ . In this simple form, the crater density can be reduced to a single number by choosing a specific diameter and a specific amount of surface area. This allows us to easily compare the crater densities between two surfaces by simply comparing two numbers.

In Astronomy 150, I use the values of 10 km for the crater diameter ( $D$ ) and one million  $\text{km}^2$  for the area. The resulting number is represented as  $N(10)$ , and is read as “the total number of craters that have a diameter equal to or greater than 10 km over one million square km.”

## Data

The data we will use in this lab come from the Mars Global Surveyor spacecraft. The Mars Global Surveyor was a global mapping mission that examined the entire planet from September of 1997 to January 2007. The images we will use come from the atlas of the surface compiled by Mars Global Surveyor and published in 2002:

[http://www.msss.com/mars\\_images/moc/moc\\_atlas/](http://www.msss.com/mars_images/moc/moc_atlas/)



## Procedure

In this lab, we will be investigating four regions on the surface of Mars, that span the history of the planet. Each of the four regions are divided into 6 smaller regions that each have a surface area of  $87,838 \text{ km}^2$ . The total area of the 6 small regions is  $527,028 \text{ km}^2$ .

At the upper right, and lower left corner of the images is a black dot that represents the size of a 10 km craters on the image. Use this as a guide to determine the size if the craters on the image.

Follow these steps for each of the four images:

- Count the total number of craters larger than 10 km in each of the panels and record that number in the column labeled “N(10) in Image” in the corresponding data table. Work from the upper left panel to the lower right panel.
- Since each panel have an area of  $87,838 \text{ km}^2$  you need to multiply the number of crater we counted by 11.4 to find the number of craters in  $1,000,000 \text{ km}^2$  ( $1,000,000 / 87,838 = 11.4$ ). Record this number in the next column.
- Now that you know that value of N(10), use the lunar surface calibrated graph on the back of the data table page to determine the age of each panel in the image. Record this age in the last column. If you can not determine the age, record a 0 for the age.
- Add up the total number of craters you counted in the six panels and record this number in the first column of the last row of the data table.
- Multiply the total number of craters by 1.9 to get the value of N(10) for area covered by all six panels ( $1,000,000 / 527,028 = 1.9$ ). Record this number in the second column of the last row.
- Use the calibrated graph to determine the age of the whole image and record this number in the last cell.

ASTRONOMY 150  
CRATER COUNTING (42 PTS)

NAME: \_\_\_\_\_

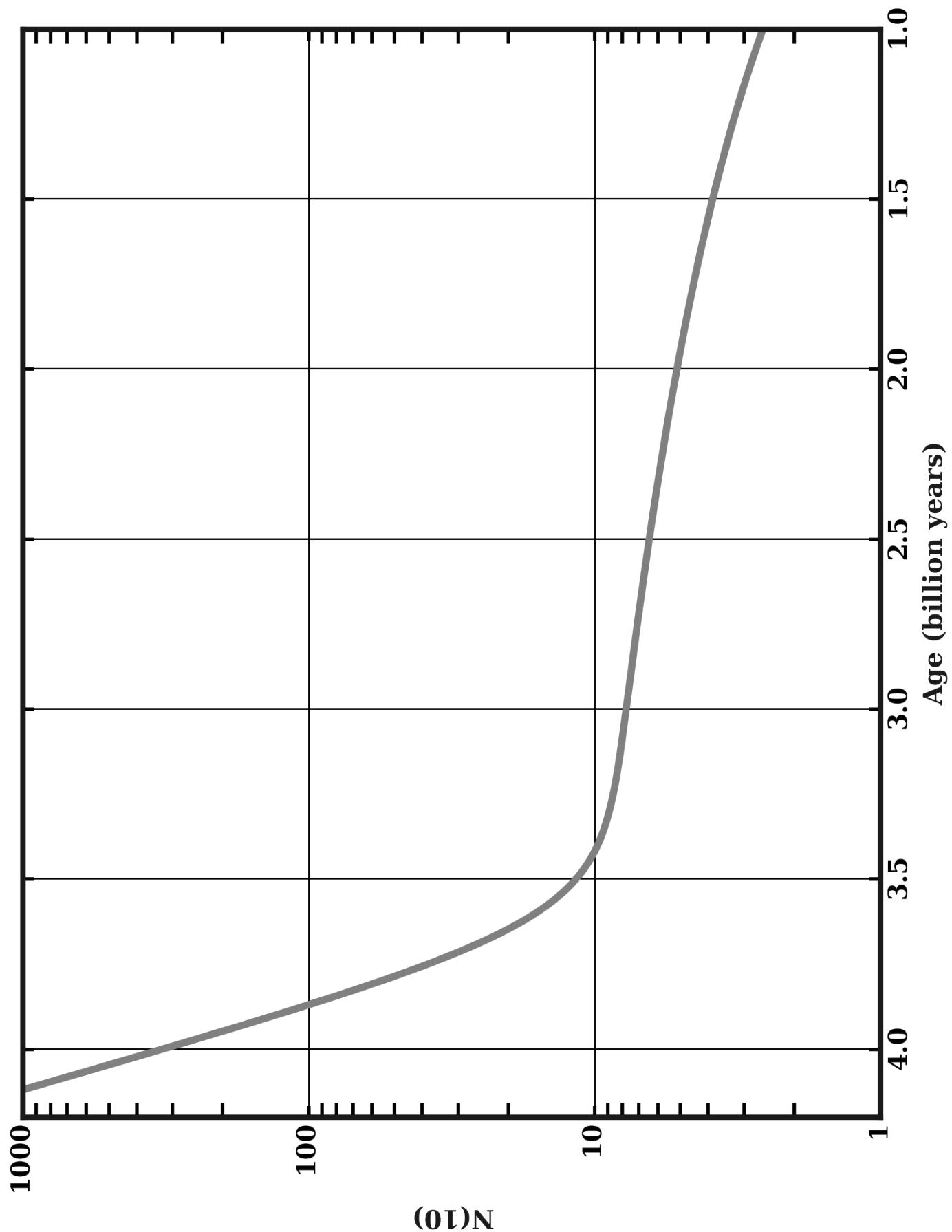
SECTION: \_\_\_\_\_

Region 1			
Panel	N(10) in Image	N(10) in $10^6 \text{ km}^2$	Age Billion yrs
1			
2			
3			
4			
5			
6			
Total			

Region 2			
Panel	N(10) in Image	N(10) in $10^6 \text{ km}^2$	Age Billion yrs
1			
2			
3			
4			
5			
6			
Total			

Region 3			
Panel	N(10) in Image	N(10) in $10^6 \text{ km}^2$	Age Billion yrs
1			
2			
3			
4			
5			
6			
Total			

Region 4			
Panel	N(10) in Image	N(10) in $10^6 \text{ km}^2$	Age Billion yrs
1			
2			
3			
4			
5			
6			
Total			



## Questions

**1** (2 pts) Calculate the age of Region 2 if you removed **ten** 10 km crater from the image?

**2** (1 pts) What is the difference from the original age you determined?

**3** (2 pts) Calculate the age of Region 4 if you removed **one** 10 km crater from the image?

**4** (1 pts) What is the difference from the original age you determined?

**5** (4 pts) Explain why it is difficult to accurately determine the age of a young surface (age < 2 billion years).

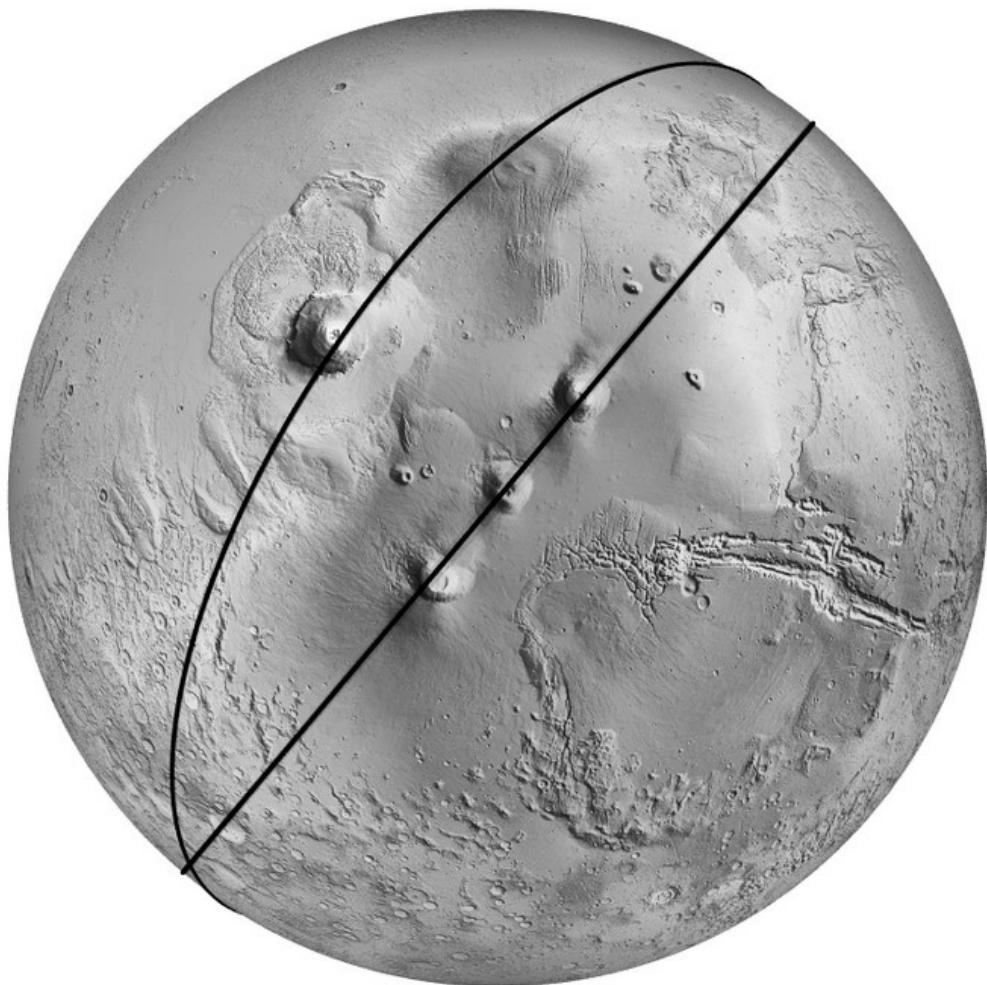
**6** (4 pts) Explain why it is difficult to accurately determine the age of a very small surface (Area < 100 km<sup>2</sup>).

**7** (4 pts) If the Earth was cratered at the same rate as the Moon and Mars, how many craters larger than 10 km should North America have (Area = 25 million km<sup>2</sup>) if it is about 1 billion years old?

**8** (2 pts) Currently the state of Washington has zero 10 km impact craters. What happened to them?

## Mars Plate Tectonics

One of the reasons I gave in class for the very large scale of the volcanoes on Mars was the lack of plate tectonics on Mars. I showed how, on the Earth, the Hawaiian islands never grow to Mars proportions due to plate tectonics dragging the islands off of the volcanic hotspot. Well, some scientist now argue that Mars **did** have plate tectonics in the past. One of the pieces of evidence that they point to is that the large Tharsis volcanoes lie along great circles. The most obvious of these is the lineup of the three huge volcanoes Arisa, Pavonis and Ascraeus Mons and maybe Uranius Patera (see image below). It can also be argued that Olympus Mons and Alba Planitia lineup. The idea is that these volcanoes have been dragged to the northwest (upper right in the image) over a hotspot by plate tectonics. One of the great things about theories in science is that they are testable. If they are not testable, they are not science. This does not mean that the tests of a theory have to be easy, or can be done with current technology. One idea for a test of the plate tectonic theory could involve looking at the **ages** of the individual volcanoes.

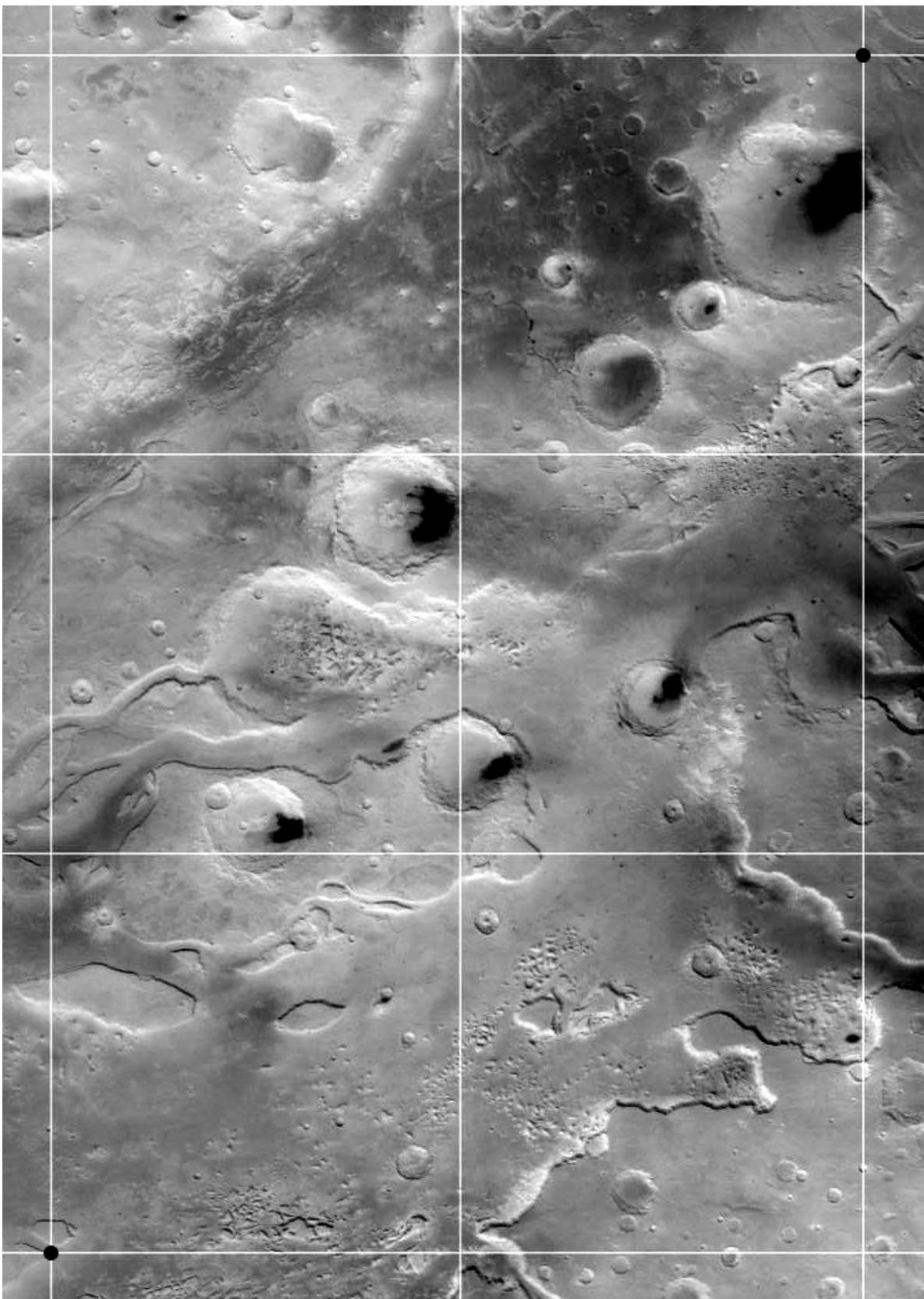


**9** (4 pts) Using the image and volcanoes on the front, explain how the age of each of the volcanoes differs in the plate tectonic model compared to a model where there was no plate tectonics on Mars?

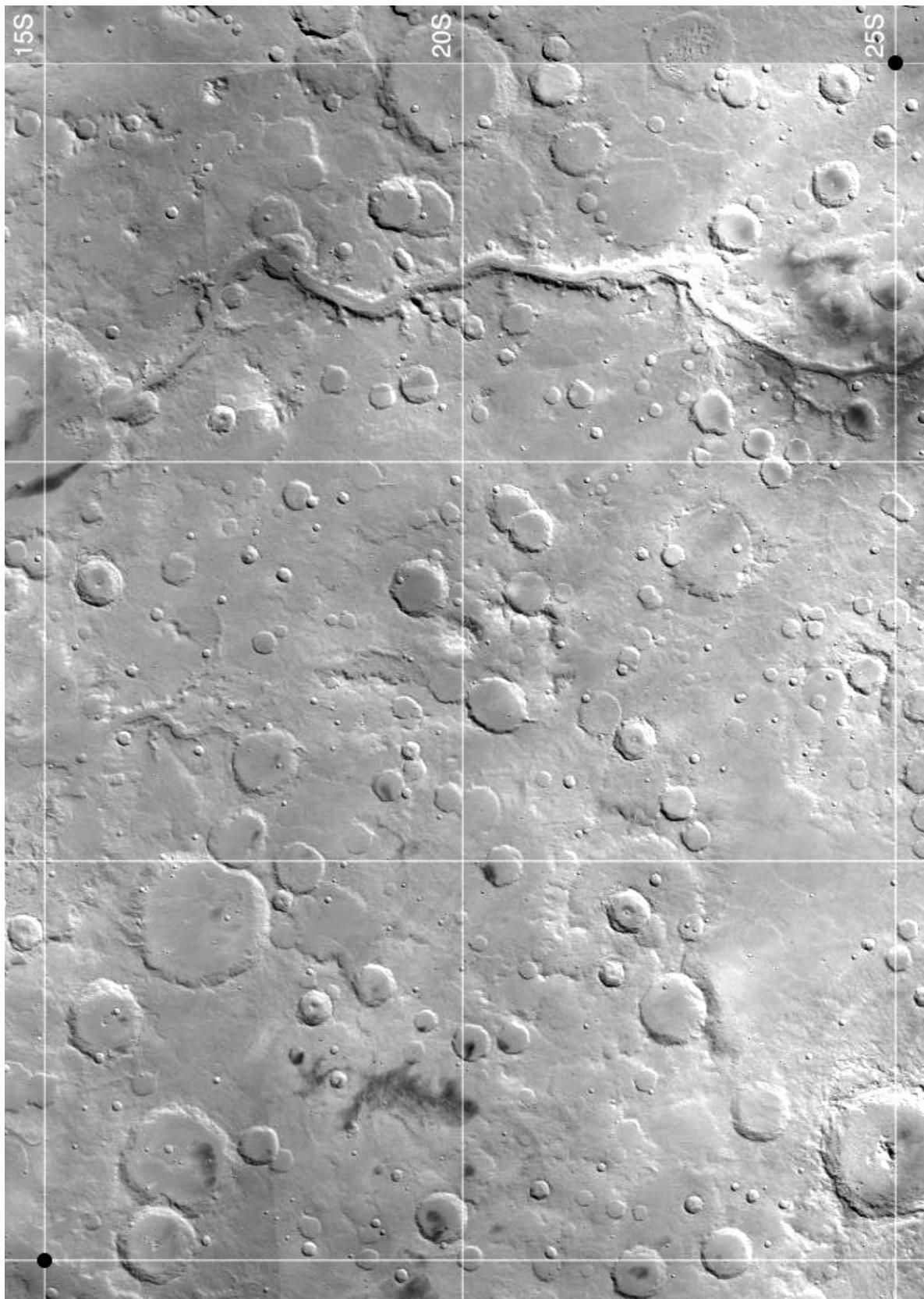
**10** (4 pts) How accurate would your age determination for the volcanoes if you used crater counting to determine their ages?

**11** (2 pts) The difference in age of the individual Hawaiian islands is about 1 million years. Could you determine this age difference using crater counting?

**12** (2 pts) If you were not limited by current technology, what would be the **best** way to determine the age of the Martian volcanoes?



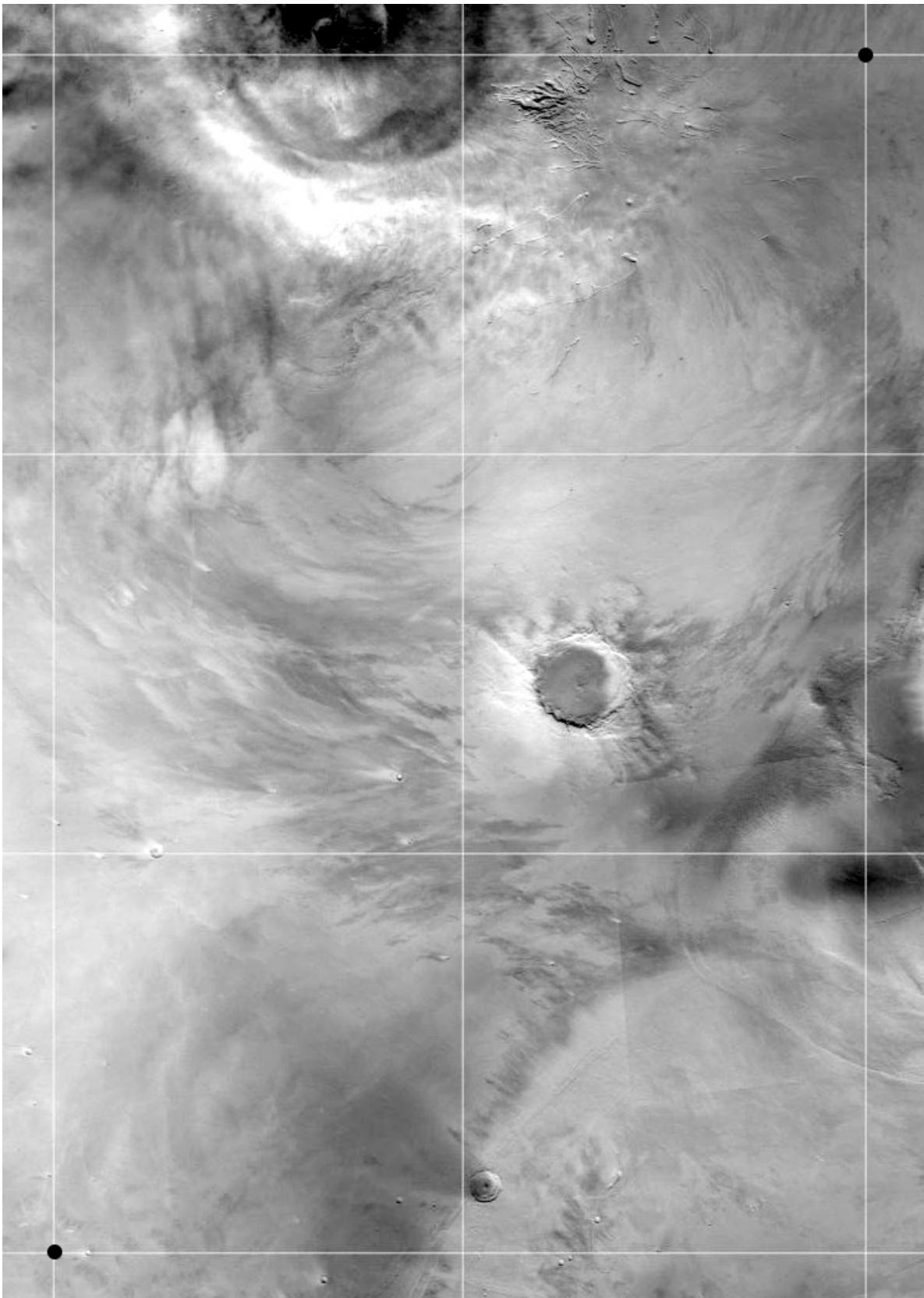
Region 1



Region 2



**Region 3**



Region 4

# Atmospheric Escape

The ability of a planet to hold onto an atmosphere depends mainly on just two factors: **Temperature** and **Gravity**. The temperature of a planet is important because it is really just a measure of how fast, on average, the molecules of gas in the atmosphere are moving around. The higher the temperature, the faster the molecules are moving. The gravity of a planet is important because it determines the escape velocity of a planet. Any object with a velocity greater than the escape velocity will escape the gravitational pull of the planet.

The gravity of a planet is determined by its mass and radius. A planet with a stronger gravitational pull will have a higher escape velocity. The table to the right lists the escape velocities and distances for a few worlds in our solar system.

Planet	V <sub>escape</sub> (m/s)	Dist (AU)
Jupiter	59,500	5.2
Earth	11,200	1.0
Mars	5,000	1.5
Moon	2,300	1.0
Ceres	510	2.8

The temperature of a planet is determined mainly by its distance from the Sun. The table below shows the temperature a planet would have at various distances from the Sun.

Distance (AU)	0.5	1	2	4	6	8
Temperature (K)	566	400	283	200	163	141

The speed of a molecule of gas in an atmosphere depends on its temperature and on its mass. A heavier molecule moves slower than a light molecule at the same temperature. The mass of a molecule is measured in atomic mass units [amu]. On the back of this page is a copy of the periodic table. The mass of each element is given as the number at the bottom of each box. To find the mass of a molecule, just add up the masses of each element.

A few molecules and their masses are given in the table to the right.

Name	Symbol	Mass
Hydrogen	H <sub>2</sub>	2
Methane	CH <sub>4</sub>	16
Ammonia	NH <sub>3</sub>	17
Water	H <sub>2</sub> O	18
Nitrogen	N <sub>2</sub>	28
Argon	Ar	40
Carbon	CO <sub>2</sub>	44
Dioxide		

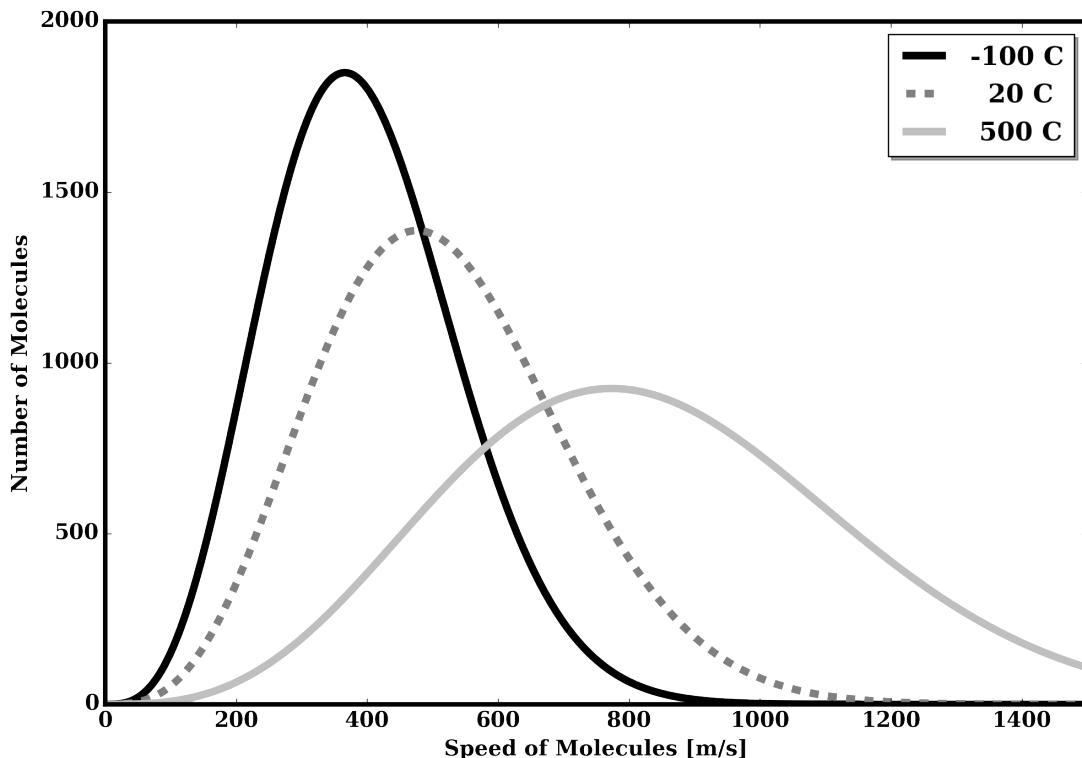
The speed of a molecule of gas can be determined from the equation:

$$\text{Velocity (m/s)} = 157 \sqrt{\frac{\text{Temperature}}{\text{molecule mass}}}$$

## Temperature and Speed

The speed that you calculated in the last equation can be thought of as the average speed of a molecule in a gas at a given temperature. In reality, at a given temperature, the speed of molecules in a gas have a wide range.

The plot below shows the distribution of the speeds of molecules at different temperatures. The distribution is called the Maxwell distribution. Notice that at even low temperatures, there are *some* molecules that have very high speeds.



## Holding on to an atmosphere

A “rule of thumb” in planetary science is that a planet can hold onto a gas for the age of the solar system if the velocity of the gas is less than one sixth the escape velocity of the planet:

$$V_{gas} < \frac{1}{6} V_{escape}$$

For example, the escape velocity of Earth is 11,200 m/s.  $1/6 \times 11,200 = 1,867$  m/s, so the Earth can hold onto any gas with a speed less than 1,867 m/s.

Please show all of your work, including units.

**1** (2 pts) What is the velocity of a **hydrogen** molecule at 1 AU?

**2** (4 pts) Can the Earth hold onto an atmosphere of **hydrogen**? Explain why or why not.

**3** (4 pts) Can the Earth hold onto an atmosphere of **nitrogen**? Explain why or why not.

**4** (4 pts) Estimate how far our Moon would have to be from the Sun before it would be cool enough to retain a **nitrogen** atmosphere.

**5** (4 pts) What gasses from the table on the first page could Mars hold onto?

**6** (4 pts) What gasses from the table on the first page could Ceres hold onto?

**7** (4 pts) Could Jupiter hold onto an atmosphere of Hydrogen molecules if you moved it to 0.5 AU from the Sun?

## Calibration

1. Each spectrometer is numbered. Since the readings of every spectrometer are different, make sure you use the same spectrometer each time you collect data.
2. **Spectrometer Number** =
3. Set the spectrometer on a flat surface so that no light is allowed in. Do not press any of the buttons. Notice that the detector does not read zero; rather, it reads a small number. This is called the **dark current**. Write this number in the box below.  
**Dark Current** =
5. Set the spectrometer on a flat piece of paper. Press the 600 nm button. Notice that the number you get is different from any other person in the room. This is the instrumental or **raw** number. This number depends on the particular spectrometer you are using, so is not very useful.
6. Next we need to calibrate our spectrometer so that the numbers have some meaning independent of the particular spectrometer we are using. Luckily, photographers also need to do the same type of calibration, so they have made a standard gray card that reflects 18% of the light at all wavelength.
7. Position your reflectance spectrometer flat on the gray card. Turn on the lights one at a time and hold down the button until the numbers in the display stabilize. Record the number on the display in the first column of the **Calibration Table** on the next page.
8. This is not the actual amount of light being reflected by the gray card — remember the dark current. To determine the actual amount of light being reflected by the gray card, subtract the dark offset from each measurement and record the result in the second column.
9. Next we want to find out how much light each of the bulbs is actually emitting (and thus to figure out how much light our samples are reflecting). But we know that the gray card reflects 18% (or 0.18) of the light hitting it, so we can use our previous measurements to calculate this:
10. **Light reflected by gray card** =  $0.18 \times$  **Light emitted from bulb**
11. Therefore, the light emitted is the measurement in the second column divided by 0.18. Record your calculations in the third column.

## Collecting Data

- Now place a green leaf on a foam card, and place the spectrometer on top of the leaf. Measure the reflectance of green leaf at each of the wavelengths.
- In the first column of the **Data Table**, record the raw instrumental numbers (raw).
- In the second column of the data table (refl):
  - Take the number from the first column, subtract the dark current.
  - Divide this value by the amount of light the bulb is actually emitting (you calculated this in the last column of **Calibration Table**).
  - The numbers in the “refl” column should be between 0.0 (*i.e.* reflecting no light) to 1.0 (reflecting all the light).
  - Plot your results and connect the points.
- Now observe the rock samples. Calculate their reflectance at each wavelength using the procedure above, and record them in the table. Plot your results on the same graph. Please use a different symbol, color, or line style to distinguish each of the lines on your plot.

## Calibration Table - Grey Card

	Raw Instrumental Number	Remove Dark Current (Raw - Dark)	Amount of Light Emitted by Bulb (Raw - Dark) / 0.18
470 nm			
525 nm			
560 nm			
585 nm			
600 nm			
645 nm			
700 nm			
735 nm			
810 nm			
880 nm			
940 nm			

## Data Table

	Green Leaf (raw)	Green Leaf (refl)	Basalt (raw)	Basalt (refl)	Olivine (raw)	Olivine (refl)	Anorth (raw)	Anorth (refl)
470 nm								
525 nm								
560 nm								
585 nm								
600 nm								
645 nm								
700 nm								
735 nm								
810 nm								
880 nm								
940 nm								

When you take an image with a camera, the film records an image of the entire visible spectrum. Most cameras on spacecraft take images of only a small chunk of the spectra and range far beyond the visible part. To take images of just a piece of the spectrum, filters are placed in front of the camera. Two such filters are indicated by the cross-hatched regions labeled “1” and “2” on your graph.

**1** (2 pts) List the four samples from brightest to darkest as seen through filter #1:

**2** (2 pts) List the four samples from brightest to darkest as seen through filter #2:

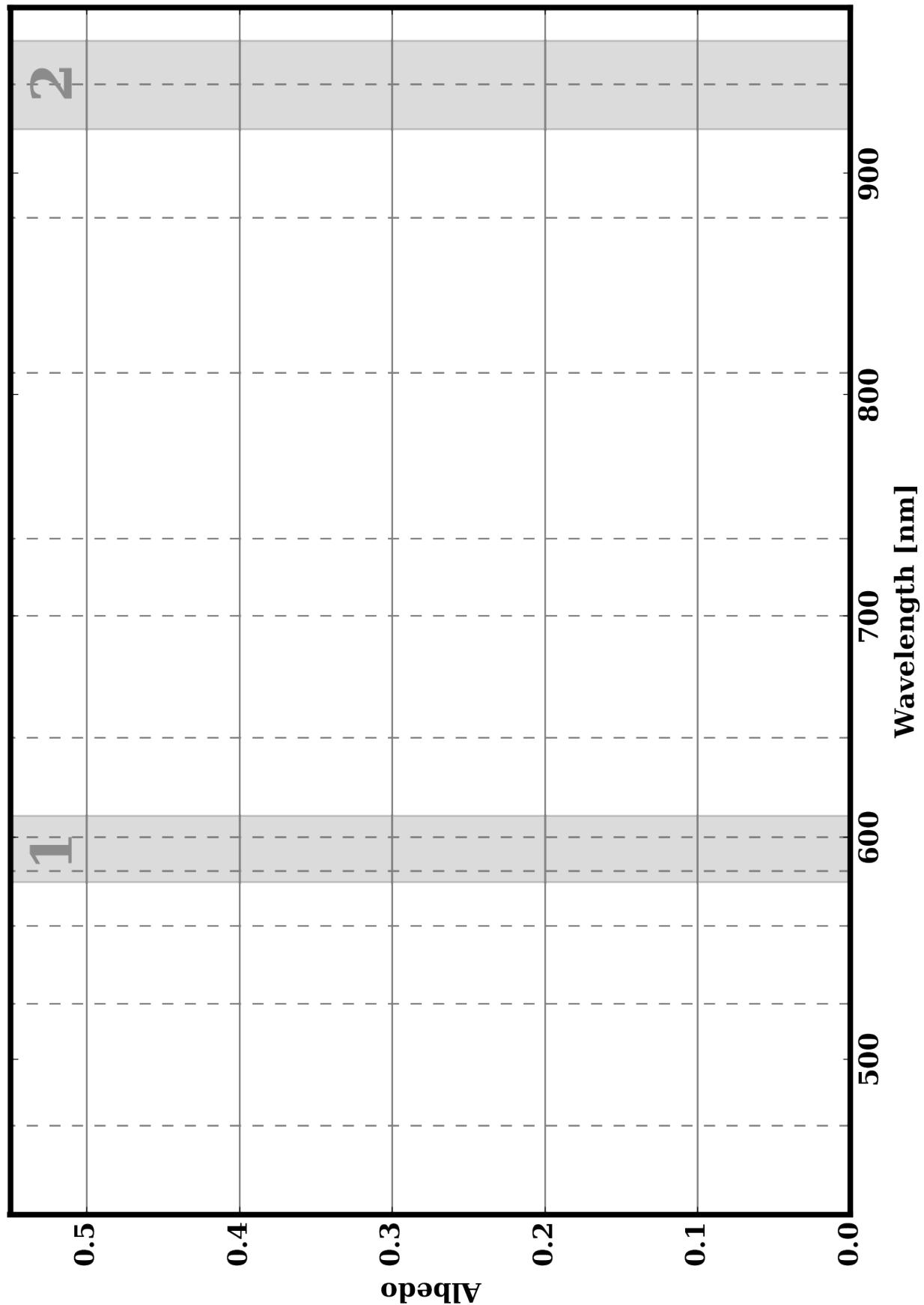
Assume that you *only* have data from filters #1 and #2. For the following four questions comment on the appearance of the sample in **both** filters.

**3** (2 pts) How could you distinguish Anorthosite from Basalt?

**4** (2 pts) How could you distinguish Olivine from Basalt?

**5** (2 pts) How could you distinguish Basalt from a Leaf?

**6** (2 pts) How could you distinguish Anorthosite from a Leaf?



## Other Worlds

Of course the surfaces of worlds in our solar system are rarely composed of pure basalt, or olivine, or anorthosite. Mostly, they are combination of lots different material, so their reflectance spectra are usually a complicated mess. Actually determining the types and amounts of materials is quite an art. Here is a simple example. The table on the right is data from the two different surfaces made up of the materials you measured the reflectance spectra of in this lab.

Plot and label the data from this table on your data graph. The plot is getting crowded, so try to be neat!

Wavelength (nm)	Surface A (refl)	Surface 2 (refl)
470	0.27	0.08
525	0.37	0.12
560	0.38	0.12
585	0.39	0.12
600	0.39	0.11
645	0.33	0.09
700	0.32	0.11
735	0.35	0.17
810	0.22	0.20
880	0.17	0.19
940	0.16	0.18

**7** (2 pts) What is the most likely composition of Surface A?

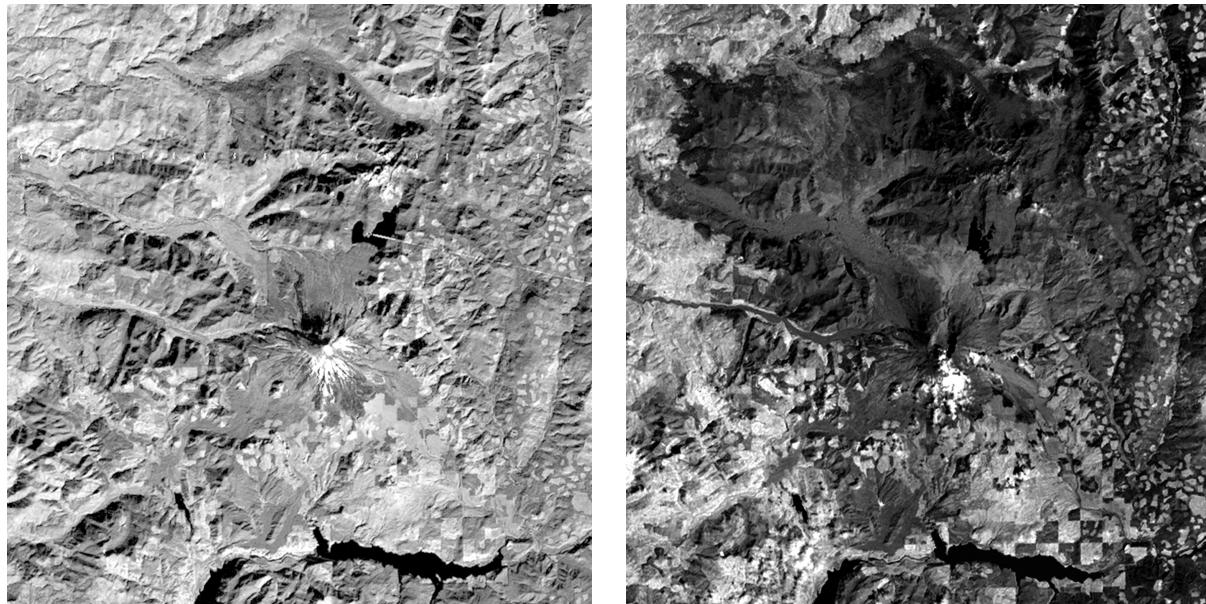
**8** (2 pts) What is the most likely composition of Surface 2?

**9** (4 pts) Now assume that you could only image the two surfaces though filters #1 and #2. Discuss if it would be possible to determine the composition of the surfaces.

## Reflectance Spectroscopy Using Landsat Images - Remote Sensing

**Landsat** are a series of Earth-observation satellites that have fundamentally changed how we look at our world. The first Landsat was launched in July of 1972 and the seventh in the series was launched April 15, 1999. The Landsat satellites image Earth at many different wavelengths, including wavelengths in the infrared. They are essentially orbiting reflectance spectrometers.

Below are two images of Mount St. Helens that were taken by the Landsat satellite through a filter that closely corresponds to our Filter #2. the peak of Mount St. Helens is the dark object near the center of the left edge of each image. The image on the left was taken in 1973 and the image on the right was taken in 1983. Mount St. Helens erupted on May 18, 1980. It is easy to see the dramatic change between the pre- and post-eruption images.



**10** (2 pts) In the 1973 image, Mount St. Helens is surrounded by material that is bright in Filter #2. Based on the data we collected, what is this material?

**11** (2 pts) In the 1983 image, Mount St. Helens is surrounded by material that is darker in Filter #2. Based on the data we collected, what is this material?

**12** (2 pts) Explain the reason for the change.

**13** (4 pts) Assume it was possible to take a similar Landsat image of the city of Seattle 200 years ago. Describe **how** that image would look different from one taken today, and **explain** the reason for this difference.

October 29, 2015

TA's Name & Section (2 pts): \_\_\_\_\_

---

**14** (2 pts) Which of the following ages most closely matches the typical age of a lunar basalt?

- (a) 4.5 Billion yrs
- (b) 4.0 Billion yrs
- (c) 3.8 Billion yrs
- (d) 3.5 Billion yrs
- (e) 500 Million yrs
- (f) 100 Million yrs
- (g) 10 Million yrs
- (h) 1 Million yrs

**15** (2 pts) Which of the following ages most closely matches the age of the Caloris impact basin on Mercury?

- (a) 4.5 Billion yrs
- (b) 4.0 Billion yrs
- (c) 3.8 Billion yrs
- (d) 3.5 Billion yrs
- (e) 500 Million yrs
- (f) 100 Million yrs
- (g) 10 Million yrs
- (h) 1 Million yrs

**16** (2 pts) Which of the following ages most closely matches the age of the Solar system?

- (a) 4.5 Billion yrs
- (b) 4.0 Billion yrs
- (c) 3.8 Billion yrs
- (d) 3.5 Billion yrs
- (e) 500 Million yrs
- (f) 100 Million yrs
- (g) 10 Million yrs
- (h) 1 Million yrs

**17** (2 pts) Which of the following ages most closely matches the age of the dinosaurs?

- (a) 4.5 Billion yrs
- (b) 4.0 Billion yrs
- (c) 3.8 Billion yrs
- (d) 3.5 Billion yrs
- (e) 500 Million yrs
- (f) 100 Million yrs
- (g) 10 Million yrs
- (h) 1 Million yrs

**18** (2 pts) Which of the following ages most closely matches the typical age of the surface of Venus?

- (a) 4.5 Billion yrs
- (b) 4.0 Billion yrs
- (c) 3.8 Billion yrs
- (d) 3.5 Billion yrs
- (e) 500 Million yrs
- (f) 100 Million yrs
- (g) 10 Million yrs
- (h) 1 Million yrs

**19** (2 pts) Which of the following ages most closely matches the age of the Big Island of Hawaii?

- (a) 4.5 Billion yrs
- (b) 4.0 Billion yrs
- (c) 3.8 Billion yrs
- (d) 3.5 Billion yrs
- (e) 500 Million yrs
- (f) 100 Million yrs
- (g) 10 Million yrs
- (h) 1 Million yrs

**20** (8 pts) Describe two pieces of evidence that show that the Moon was formed in a very high-energy (hot) event.

For each of the worlds below, describe the **most important** process that is **currently** modifying the surface of the world.

**21** (2 pts) The Earth:

**22** (2 pts) The Moon:

**23** (2 pts) Mars:

**24** (2 pts) Venus:

**25** (8 pts) I said in class: “To learn the history of a world, you have to dig.” Explain what that means.

**26** (8 pts) Explain two reasons why crater counting is a lousy way to determine the age of the Hawaiian islands.

Assume you have discovered a new world in our Solar system, and it has the following properties:

Mass =  $8 M_{\oplus}$

Radius =  $2 R_{\oplus}$

Density =  $4.0 \text{ g/cm}^3$

Moment-of-Inertia = 0.30

Distance from Sun = 1.1 AU

**27** (8 pts) How does the gravity on this world compare to the gravity on the Earth? Make sure to show your work.

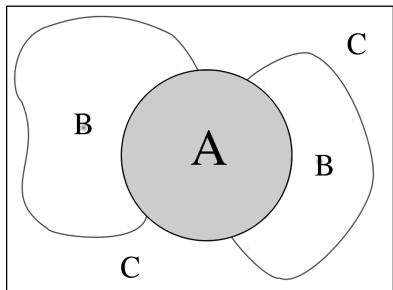
**28** (8 pts) Explain why it would be *very unlikely* to find a 30-kilometer-high volcano on this world.

**29** (2 pts) True or False: This world has a uniform composition, from crust to core.

**30** (8 pts) Explain why this world would most likely still be geologically active today.

**31** (8 pts) Explain why it is likely that this world would have a substantial atmosphere.

**32** (2 pts) What type of rock would be most common on the geologically active surface of this world?



On the left is a geological map of a region on a world.

The region labeled **A** is a very large impact basin, the region labeled **B** has a crater density of  $N(10) = 9$ , and the region labeled **C** has a crater density of  $N(10) = 421$ .

**33** (4 pts) What does it mean if a surface has a crater density of  $N(10) = 9$ ?

**34** (4 pts) According to the data in the map, what is the order of formation of the three regions (from oldest to youngest)?

**35** (10 pts) Explain why this geological map is probably completely wrong. (Clue: look at the implied ages)

**1** (6 pts) Explain why you cannot find a 4.2-billion-year-old piece of basalt that was formed on the Earth.

**2** (6 pts) Describe the surface of the most likely place, in the solar system, to find a piece of 4.2-billion-year-old basalt today.

**3** (2 pts) Which of the following materials is most common in the solar system?

- (a) Iron metal
- (b) Methane ice
- (c) Silicate rock
- (d) Water ice

**4** (8 pts) Explain why the Moon is not subject to tidal heating.

**5** (8 pts) Explain why the surfaces of Kuiper belt objects (including Pluto and Triton) are dark red.

**6** (2 pts) Which of the following materials is the most volatile?

- (a) Iron metal
- (b) Methane ice
- (c) Silicate rock
- (d) Water ice

**7** (6 pts) Explain what is meant by the statement: *Methane ice is more volatile than water ice.*

**8** (8 pts) Explain why you would expect the parent body of a carbonaceous chondrite to be more volatile-rich than the parent body of an ordinary chondrite.

**9** (2 pts) Which of the following materials is most common in the rings of Saturn?

- (a) Iron metal
- (b) Methane ice
- (c) Silicate rock
- (d) Water ice

**10** (8 pts) Explain why an ice-rich surface could have a different crater population than a rock-rich surface, even if they were the same age.

**11** (8 pts) Explain why accretion is very slow in the Kuiper belt.

**12** (2 pts) Which of the following materials has the highest density?

- (a) Iron metal
- (b) Methane ice
- (c) Silicate rock
- (d) Water ice

**13** (8 pts) Explain why the atmosphere of Titan is composed of nitrogen and methane while the most common material on Titan's surface is water ice.

**14** (8 pts) In the space below, sketch the **visible** reflectance spectra of the surface of a small world (< 100 km) that formed at a distance of 20 AU.

**15** (2 pts) Which of the following materials is most common on Jupiter's tidally heated satellite Io?

- (a) Iron metal
- (b) Methane ice
- (c) Silicate rock
- (d) Water ice

**16** (8 pts) Describe how you can determine the size (radius) of an exoplanet.

**17** (6 pts) The permanently shadowed craters on the poles of the Moon contain traces of volatile water-ice. This water-ice certainly did not form there. Explain how it got there.

**18** (2 pts) Which of the following materials is most common on the surface of Pluto?

- (a) Iron metal
- (b) Methane ice
- (c) Silicate rock
- (d) Water ice