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## 12 Introduction to the Geology of the Terrestrial Planets

### 12.1 Introduction

There are two main families of planets in our solar system: the Terrestrial planets (Earth, Mercury, Venus, and Mars), and the Jovian Planets (Jupiter, Saturn, Uranus, and Neptune). The terrestrial planets are rocky planets that have properties similar to that of the Earth. While the Jovian planets are giant balls of gas. Table 12.1 summarizes the main properties of the planets in our solar system (Pluto is an oddball planet that does not fall into either categories, sharing many properties with the “Kuiper belt” objects discussed in the “Comet Lab”).

Table 12.1: The Properties of the Planets

Planet	Mass (Earth Masses)	Radius (Earth Radii)	Density gm/cm <sup>3</sup>
Mercury	0.055	0.38	5.5
Venus	0.815	0.95	5.2
Earth	1.000	1.00	5.5
Mars	0.107	0.53	3.9
Jupiter	318	10.8	1.4
Saturn	95	9.0	0.7
Uranus	14.5	3.93	1.3
Neptune	17.2	3.87	1.6
Pluto	0.002	0.178	2.1

It is clear from Table 12.1 that the nine planets in our solar system span a considerable range in sizes and masses. For example, the Earth has 18 times the mass of Mercury, while Jupiter has 318 times the mass of the Earth. But the separation of the planets into Terrestrial and Jovian is not based on their masses or physical sizes, it is based on their densities (the last column in the table). What is density? Density is simply the mass of an object divided by its volume:  $M/V$ . In the metric system, the density of water is set to 1.00 gm/cm<sup>3</sup>. Densities for some materials you are familiar with can be found in Table 12.2.

If we examine the first table we see that the terrestrial planets all have higher densities than the Jovian planets. Mercury, Venus and Earth have densities above 5 gm/cm<sup>3</sup>, while Mars has a slightly lower density ( $\sim 4$  gm/cm<sup>3</sup>). The Jovian planets have densities very close to that of water—in fact, the mean density of Saturn is lower than that of water! The density of a planet gives us clues about its composition. If we look at the table of densities for

Table 12.2: The Densities of Common Materials

Element or Molecule	Density gm/cm <sup>3</sup>	Element	Density gm/cm <sup>3</sup>
Water	1.0	Carbon	2.3
Aluminum	2.7	Silicon	2.3
Iron	7.9	Lead	11.3
Gold	19.3	Uranium	19.1

common materials, we see that the mean densities of the terrestrial planets are about halfway between those of silicon and iron. Both of these elements are highly abundant throughout the Earth, and thus we can postulate that the terrestrial planets are mostly composed of iron, silicon, with additional elements like carbon, oxygen, aluminum and magnesium. The Jovian planets, however, must be mostly composed of lighter elements, such as hydrogen and helium. In fact, the Jovian planets have similar densities to that of the Sun: 1.4 gm/cm<sup>3</sup>. The Sun is 70% hydrogen, and 28% helium. Except for small, rocky cores, the Jovian planets are almost nothing but hydrogen and helium.

The terrestrial planets share other properties, for example they all rotate much more slowly than the Jovian planets. They also have much thinner atmospheres than the Jovian planets (which are almost *all* atmosphere!). Today we want to investigate the geologies of the terrestrial planets to see if we can find other similarities, or identify interesting differences.

## 12.2 Topographic Map Projections

In the first part of this lab we will take a look at images and maps of the surfaces of the terrestrial planets for comparison. But before we do so, we must talk about what you will be viewing, and how these maps/images were produced. As you probably know, 75% of the Earth's surface is covered by oceans, thus a picture of the Earth from space does not show very much of the actual rocky surface (the "crust" of the Earth). With modern techniques (sonar, radar, etc.) it is possible to reconstruct the true shape and structure of a planet's rocky surface, whether it is covered in water, or by very thick clouds (as is the case for Venus). Such maps of the "relief" of the surface of a planet are called *topographic* maps. These maps usually color code, or have contours, showing the highs and lows of the surface elevations. Regions of constant elevation above (or below) sea level all will have the same color. This way, large structures such as mountain ranges, or ocean basins, stand out very clearly.

There are several ways to present topographic maps, and you will see two versions today. One type of map is an attempt at a 3D *visualization* that keeps the relative sizes of the continents in correct proportion (see Figure 12.1, below). But such maps only allow you to see a small part of a spherical planet in any one plot. More commonly, the entire surface of the planet is presented as a rectangular map as shown in Figure 12.2. Because the surface of a sphere cannot be properly represented as a rectangle, the regions near the north and south poles of a planet end up being highly distorted in this kind of map. So keep this in

mind as you work through the exercises in this lab.

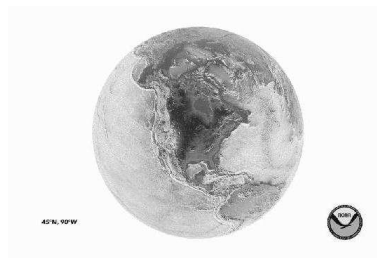


Figure 12.1: A topographic map showing one hemisphere of Earth centered on North America. In this 3D representation the continents are correctly rendered.

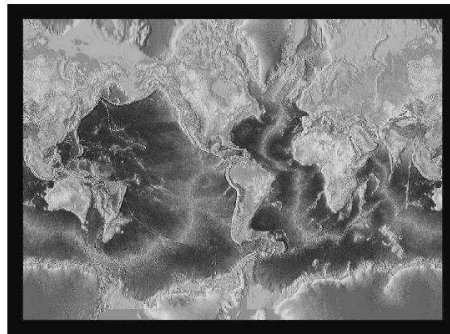


Figure 12.2: A topographic map showing the entire surface of the Earth. In this 2D representation, the continents are incorrectly rendered. Note that Antarctica (the land mass that spans the bottom border of this map) is 50% smaller than North America, but here appears massive. You might also be able to compare the size of Greenland on this map, to that of the previous map.

### 12.3 Global Comparisons

In the first part of this lab exercise, you will look at the planets in a *global* sense, by comparing the largest structures on the terrestrial planets. Note that Mercury has only been visited by a single space craft (Mariner 10) way back in 1974. So, we do not have the same quality of data for that planet—but new data will soon be coming from the Messenger spacecraft!

**Exercise #1:** At station #1 you will find images of Mercury, Venus, the Earth, the Moon, and Mars. The images for Venus and the Earth are in a false color to help emphasize different features, while the image of Mars is in “true color”.

Impact craters can come in a variety of sizes, from tiny little holes, all the way up to the large “maria” seen on the Moon. Impact craters are usually round.

1. On which of the planets are large meteorite impact craters obvious? (**1 point**)
2. Does Venus or the Earth show any signs of large, round maria (like those seen on the Moon)? (**1 point**)
3. Which planet seems to have the most impact craters? (**1 point**)
4. Compare the surface of Mercury to the Moon. Are they similar? (**3 points**)

Mercury is the planet closest to the Sun, so it is the terrestrial planet that gets hit by comets, asteroids and meteoroids more often than the other planets because the Sun's gravity tends to collect small bodies like comets and asteroids. The closer you are to the Sun, the more of these objects there are in the neighborhood. Over time, most of the largest asteroids on orbits that intersect those of the other planets have either collided with a planet, or have been broken into smaller pieces by the gravity of a close approach to a large planet. Thus, only smaller debris is left over to cause impact craters.

5. Using the above information, make an educated guess on why Mercury does not have as many large maria as the Moon, even though both objects have been around for the same amount of time. [Hint: Maria are caused by the impacts of *large* bodies.] (**3 points**)

Mercury and the Moon do not have atmospheres, while Mars has a thin atmosphere. Venus has the densest atmosphere of the terrestrial planets.

6. Does the presence of an atmosphere appear to reduce the number of impact craters? Justify your answer. **(3 points)**

**Exercise #2:** Global topography of Venus, Earth, and Mars. At station #2 you will find topographic maps of Venus, the Earth, and Mars. These maps are color-coded to help you determine the highest and lowest parts of each planet. You can determine the elevation of a color-coded feature on these maps by using the scale found on each map. [Note that for the Earth and Mars, the scales of these maps are in meters, while for Venus it is in planetary radius! But the scale for Venus is the same as for Mars, so you can use the scale on the Mars map to examine Venus.]

7. Which planet seems to have the least amount of relief? **(2 points)**

8. Which planet seems to have the deepest/lowest regions? **(2 points)**

9. Which planet seems to have the highest mountains? **(2 points)**

On both the Venus and Mars topographic maps, the polar regions are plotted as separate circular maps so as to reduce distortion.

10. Looking at these polar plots, Mars appears to be a very strange planet. Compare the elevations of the northern and southern hemispheres of Mars. If Mars had an abundance of surface water (oceans), what would the planet look like? (**3 points**)

## 12.4 Detailed Comparison of the Surfaces of the Terrestrial Planets

In this section we will compare some of the smaller surface features of the terrestrial planets using a variety of close-up images. In the following, the images of features on Venus have been made using radar (because the atmosphere of Venus is so cloudy, we cannot see its surface). While these images look similar to the pictures for the other planets, they differ in one major way: in radar, smooth objects reflect the radio waves differently than rough objects. In the radar images of Venus, the rough areas are “brighter” (whiter) than smooth areas.

In the Moon lab, there is a discussion on how impact craters form (in case you have not done that lab, read that discussion). For large impacts, the center of the crater may “rebound” and produce a central mountain (or several small peaks). Sometimes an impact is large enough to crack the surface of the planet, and lava flows into the crater filling it up, and making the floor of the crater smooth. On the Earth, water can also collect in a crater, while on Mars it might collect large quantities of dust.

**Exercise #3:** Impact craters on the terrestrial planets. At station #3 you will find close-up pictures of the surfaces of the terrestrial planets showing impact craters.

11. Compare the impact craters seen on Mercury, Venus, Earth, and Mars. How are they alike, how are they different? Are central mountain peaks common to craters on all planets? Of the sets of craters shown, does one planet seem to have more lava-filled craters than the others? (**4 points**)

12. Which planet has the sharpest, roughest, most detailed and complex craters? [Hint: details include ripples in the nearby surface caused by the crater formation, as well as numerous small craters caused by large boulders thrown out of the bigger crater. Also commonly seen are “ejecta blankets” caused by material thrown out of the crater that settles near its outer edges.] **(2 points)**

13. Which planet has the smoothest, and least detailed craters? **(2 points)**

14. What is the main difference between the planet you identified in question #12 and that in question #13? [Hint: what processes help erode craters?] **(2 points)**

You have just examined four different craters found on the Earth: Berringer, Wolfe Creek, Mistastin Lake, and Manicouagan. Because we can visit these craters we can accurately determine when they were formed. Berringer is the youngest crater with an age of 49,000 years. Wolf Creek is the second youngest at 300,000 years. Mistastin Lake formed 38 million years ago, while Manicouagan is the oldest, easily identified crater on the surface of the Earth at 200 million years old.

15. Describe the differences between young and old craters on the Earth. What happens to these craters over time? (4 points)

## 12.5 Erosion Processes and Evidence for Water

Geological erosion is the process of the breaking down, or the wearing-away of surface features due to a variety of processes. Here we will be concerned with the two main erosion processes due to the presence of an atmosphere: wind erosion, and water erosion. With daytime temperatures above 700°F, both Mercury and Venus are too hot to have liquid water on their surfaces. In addition, Mercury has no atmosphere to sustain *water or a wind*. Interestingly, Venus has a very dense atmosphere, but as far as we can tell, very little wind erosion occurs at the surface. This is probably due to the incredible pressure at the surface of Venus due to its dense atmosphere: the atmospheric pressure at the surface of Venus is 90 times that at the surface of the Earth—it is like being 1 km below the surface of an Earth ocean! Thus, it is probably hard for strong winds to blow near the surface, and there are probably only gentle winds found there, and these do not seriously erode surface features. This is not true for the Earth or Mars.

On the surface of the Earth it is easy to see the effects of erosion by wind. For residents of New Mexico, we often have dust storms in the spring. During these events, dust is carried by the wind, and it can erode (“sandblast”) any surface it encounters, including rocks, boulders and mountains. Dust can also collect in cracks, arroyos, valleys, craters, or other low, protected regions. In some places, such as at the White Sands National Monument, large fields of sand dunes are created by wind-blown dust and sand. On the Earth, most large dune fields are located in arid regions.

**Exercise #4:** Evidence for wind blown sand and dust on Earth and Mars. At station #4 you will find some pictures of the Earth and Mars highlighting dune fields.

16. Do the sand dunes of Earth and Mars appear to be very different? Do you think you could tell them apart in black and white photos? Given that the atmosphere of Mars is only 1% of the Earth's, what does the presence of sand dunes tell you about the winds on Mars? (**3 points**)

**Exercise #5:** Looking for evidence of water on Mars. In this exercise, we will closely examine geological features on Earth caused by the erosion action of water. We will then compare these to similar features found on Mars. The photos are found at Station #5.

As you know, water tries to flow “down hill”, constantly seeking the lowest elevation. On Earth most rivers eventually flow into one of the oceans. In arid regions, however, sometimes the river dries up before reaching the ocean, or it ends in a shallow lake that has no outlet to the sea. In the process of flowing down hill, water carves channels that have fairly unique shapes. A large river usually has an extensive, and complex drainage pattern.

17. The drainage pattern for streams and rivers on Earth has been termed “dendritic”, which means “tree-like”. In the first photo at this station (#23) is a dendritic drainage pattern for a region in Yemen. Why was the term dendritic used to describe such drainage patterns? Describe how this pattern is formed. (**3 points**)

18. The next photo (#24) is a picture of a sediment-rich river (note the brown water) entering a rather broad and flat region where it becomes shallow and spreads out. Describe the shapes of the “islands” formed by this river. (**3 points**)

In the next photo (#25) is a picture of the northern part of the Nile river as it passes through Egypt. The Nile is 4,184 miles from its source to its mouth on the Mediterranean sea. It is formed in the highlands of Uganda and flows North, down hill to the Mediterranean. Most of Egypt is a very dry country, and there are no major rivers that flow into the Nile, thus there is no dendritic-like pattern to the Nile in Egypt. [Note that in this image of the Nile, there are several obvious dams that have created lakes and reservoirs.]

19. Describe what you see in this image from Mars (Photo #26). (**2 points**)

20. What is going on in this photo (#27)? How were these features formed? Why do the small craters not show the same sort of “teardrop” shapes? (**2 points**)

21. Here are some additional images of features on Mars. The second one (Photo #29) is a close-up of the region delineated by the white box seen in Photo #28. Compare these to the Nile. (**2 points**)

22. While Mars is dry now, what do you conclude about its past? Justify your answer. What technique can we use to determine when water might have flowed in Mars’ past? [Hint: see your answer for #20.] (**4 points**)

## 12.6 Volcanoes and Tectonic Activity

While water and wind-driven erosion is important in shaping the surface of a planet, there are other important events that can act to change the appearance of a planet's surface: volcanoes, earthquakes, and plate tectonics. The majority of the volcanic and earthquake activity on Earth occurs near the boundaries of large slabs of rock called "plates". As shown in Figure 12.3, the center of the Earth is very hot, and this heat flows from hot to cold, or from the center of the Earth to its surface (and into space). This heat transfer sets up a boiling motion in the semi-molten mantle of the Earth.

As shown in the next figure (Fig. 12.4), in places where the heat rises, we get an upwelling of material that creates a ridge that forces the plates apart. We also get volcanoes at these boundaries. In other places, the crust of the Earth is pulled down into the mantle in what is called a subduction zone. Volcanoes and earthquakes are also common along subduction zone boundaries. There are other sources of earthquakes and volcanoes which are not directly associated with plate tectonic activity. For example, the Hawaiian islands are all volcanoes that have erupted in the middle of the Pacific plate. The crust of the Pacific plate is thin enough, and there is sufficiently hot material below, to have caused the volcanic activity which created the chain of islands called Hawaii. In the next exercise we will examine the other terrestrial planets for evidence of volcanic and plate tectonic activity.

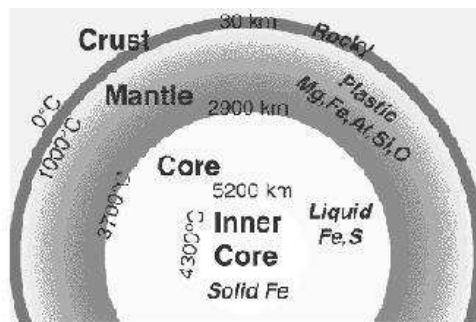


Figure 12.3: A cut away diagram of the structure of the Earth showing the hot core, the mantle, and the crust. The core of the Earth is very hot, and is composed of both liquid and solid iron. The mantle is a zone where the rocks are partially melted ("plastic-like"). The crust is the cold, outer skin of the Earth, and is very thin.

**Exercise #6:** Using the topographical maps from station #2, we will see if you can identify evidence for plate tectonics on the Earth. Note that plates have fairly distinct boundaries, usually long chains of mountains are present where two plates either are separating (forming long chains of volcanoes), or where two plates run into each other creating mountain ranges. Sometimes plates fracture, creating fairly straight lines (sometimes several parallel features are created). The remaining photos can be found at Station #6.

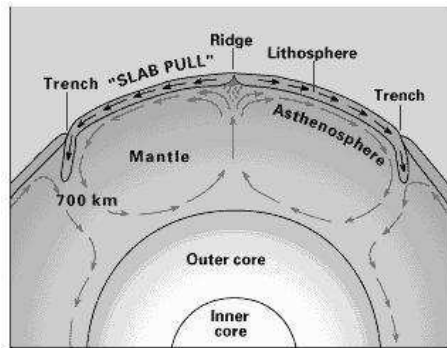


Figure 12.4: The escape of the heat from the Earth's core sets-up a boiling motion in the mantle. Where material rises to the surface it pushes apart the plates and volcanoes, and mountain chains are common. Where the material is cooling, it flows downwards (subsides) back into the mantle pulling down on the plates ("slab-pull"). This is how the large crustal plates move around on the Earth's surface.

23. Identify and describe several apparent tectonic features on the topographic map of the Earth. [Hint: North and South America are moving away from Europe and Africa]. (2 points)

24. Now, examine the topographic maps for Mars and Venus (ignoring the grey areas that are due to a lack of spacecraft data). Do you see any evidence for large scale tectonic activity on either Mars or Venus? (3 points)

The fact that there is little large-scale tectonic activity present on the surfaces of either Mars or Venus today does not mean that they never had any geological activity. Let us examine the volcanoes found on Venus, Earth and Mars. The first set of images contain views of a number of volcanoes on Earth. Several of these were produced using space-based radar systems carried aboard the Space Shuttle. In this way, they better match the data for Venus. There are a variety of types of volcanoes on Earth, but there are two main classes of large volcanoes: "shield" and "composite". Shield volcanoes are large, and have very gentle slopes. They are caused by low-viscosity lava that flows easily. They usually are rather flat

on top, and often have a large “caldera” (summit crater). Composite volcanoes are more explosive, smaller, and have steeper sides (and “pointier” tops). Mount St. Helens is one example of a composite volcano, and is the first picture (Photo #31) at this station (note that the apparent crater at the top of St. Helens is due to the 1980 eruption that caused the North side of the volcano to collapse, and the field of devastation that emanates from there). The next two pictures are also of composite volcanoes while the last three are of the shield volcanoes Hawaii, Isabela and Miakijima (the last two in 3D).

25. Here are some images of Martian volcanoes (Photos #37 to #41). What one type of volcano does Mars have? How did you arrive at this answer? **(2 points)**

26. In the next set (Photos #42 to #44) are some false-color images of Venusian volcanoes. Among these are both overhead shots, and 3D images. Because Venus was mapped using radar, we can reconstruct the data to create images as if we were located on, or near, the surface of Venus. *Note, however, that the vertical elevation detail has been exaggerated by a factor of ten!* It might be hard to tell, but Venus is also dominated by one main type of Volcano, what is it? **(2 points)**



## 12.7 Take Home Exercise (35 points total)

As we have seen, many of the geological features common to the Earth can be found on the other terrestrial planets. Each planet, however, has its own peculiar geology. For example, Venus has the greatest number of volcanoes of any of the terrestrial planets, while Mars has the biggest volcanoes. Only the Earth seems to have active plate tectonics. Mercury appears to have had the least amount of geological activity in the solar system and, in this way, is quite similar to the Moon. Mars and the Earth share something that none of the other planets in our solar system do: erosion features due to liquid water. This, of course, is why there continues to be interest in searching for life (either alive or extinct) on Mars. On a separate sheet of paper, write a report answering the following questions:

- Describe the surfaces of each of the terrestrial planets, and the most important geological forces that have shaped their surfaces.
- Of the four terrestrial planets, which one seems to be the least interesting? Can you think of one or more reasons why this planet is so inactive?
- If you were in charge of searching for life on Mars, where would you want to begin your search?

## 12.8 Possible Quiz Questions

1. What are the main differences between Terrestrial and Jovian planets?
2. What is density?
3. How are impact craters formed?
4. What is a topographic map?

## 12.9 Extra Credit (ask your TA for permission before attempting, 5 points)

Since Mars currently has no large bodies of water, what is probably the most important erosion process there? How can we tell? What is the best way to observe or monitor this type of erosion? Researching the images from the several small landers and some of the orbiting missions, is there strong evidence for this type of erosion? What is that evidence?