USESO 2025

National Open Exam

Section II

KEY

Instructions:

- Section II consists of 4 multipart problems that further assess geoscience knowledge in the form of free-response and multiple choice questions.
- A calculator is allowed. Show all work for calculations.
- Any space on the page may be used for scratch paper, but only work on your Answer Sheet will be graded.
- Print your **USESO Student ID** on every page of the Answer Sheet.

Problem 1

Question	1	2	3	4	Total
Points	2	7	4	2	15 (25%)

The Sierra Nevada mountain range was primarily formed by the subduction of the Farallon Plate beneath the North American Plate during the Mesozoic Era. This problem will explore several aspects of this region's geology and Earth's interior.

1. (2 points) The Farallon Plate exhibited a shallower subduction angle compared to typical subduction zones. Which of the following sets of conditions would be most likely to create a shallow-angle subduction zone?

   A. High convergence rate, old oceanic crust

   B. High convergence rate, young oceanic crust

   C. Low convergence rate, old oceanic crust

   D. Low convergence rate, young oceanic crust

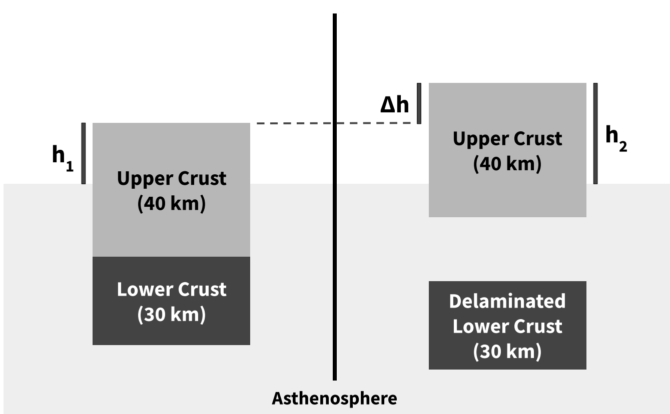
   Solution: When tectonic plates converge at a high rate, the subducting plate has less time to sink into the mantle and a shallower angle is created. Younger oceanic crust is generally more buoyant than an older crust due to its lower density, creating a shallower subduction angle. The correct answer is thus B.

2. Crustal delamination is the process by which lower layers of the crust and asthenosphere separate from the upper continental crust. Delamination is common along convergent margins.

   (a) (2 points) Although the crust is less dense than the asthenosphere upon formation, the section of the lower crust that delaminates from the upper crust becomes denser than the asthenosphere that replaces it. Briefly explain why this occurs.

   Solution: Regions of the lower crust are subjected to increased pressure and temperature. These conditions can result in metamorphism, which often increases the density of the daughter rock relative to the protolith.

   Consider a simple model of an isolated crustal block "floating" in the asthenosphere. The block consists of an upper and lower section with different densities and only experiences the forces of gravity and buoyancy. At some point in time, the lower crust separates from the upper crust, as shown in Figure 1 below.



Upper block thickness	40 km
Lower block thickness	30 km
Upper block density	2700 kg/m^3
Lower block density	4500 kg/m^3
Asthenosphere density	4000 kg/m^3

Figure 1: A diagram depicting the initial state of the crustal block (left) and the state of the crustal block after delamination (right). A table of relevant quantities is provided.

(b) (2 points) Given the information in the table, calculate the initial height of the crustal block, h_1, above the asthenosphere. **Show your work.**

> **Solution:** By Archimedes' principle, the upward buoyant force on the crustal block is equal to the weight of the fluid that the block displaces. This upward buoyant force is balanced by the downward gravitational force.
>
> The upward buoyant force is proportional to $4000 \times (70 - h_1)$. This is because the density of the displaced asthenosphere is 4000 kg/m^3 and the volume of the displaced fluid is proportional to $70 - h_1$; the weight of the displaced fluid is proportional to the product of density and volume. By similar reasoning, the downward gravitational force is proportional to $40 \times 2700 + 30 \times 4500$. Setting the two forces equal and solving for h_1, we obtain $h_1 = \boxed{9.25 \text{ km}}$.

(c) (3 points) Calculate the change in height of the crustal block, Δh, that results from delamination. **Show your work.**

> **Solution:** We repeat the calculation in (b) to find the new height of the crustal block above the asthenosphere, this time ignoring the effects of the lower portion. Thus $4000 \times (40 - h_2) = 40 \times 2700$ and $h_2 = 13$ km. The change in height of the crustal block is given by $h_2 - h_1 = 13 - 9.25 = \boxed{3.75 \text{ km}}$.

3. The mantle's 660-km discontinuity is characterized by a mineral phase transition, represented by Figure 2 below. A geologist synthesizes a mineral sample at conditions within the gray region of the figure.

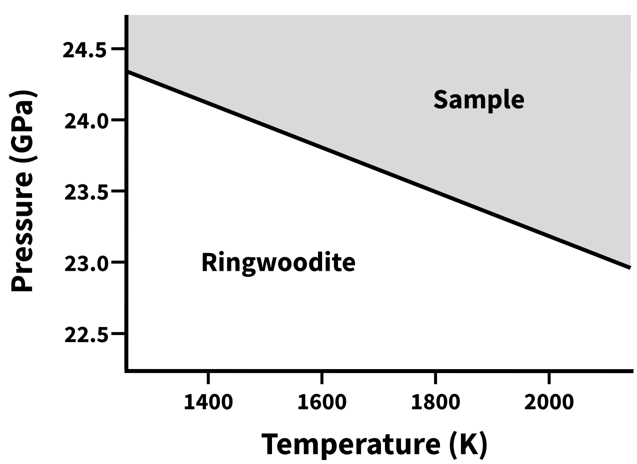


Figure 2: A diagram of the transition between ringwoodite and an unknown mineral phase. The solid line denotes the conditions at which this transition occurs.

(a) (1 point) The 660-km discontinuity is associated with a transition from ringwoodite to what **two** minerals?

> **Solution:** Ringwoodite transitions to bridgmanite and ferropericlase (also known as magnesiowüstite) at the 660-km discontinuity.

(b) (3 points) Based on the diagram, would you expect the actual depth of the discontinuity to be greater than, equal to, or less than 660 km beneath a delaminating slab? Explain.

Solution: The delaminating slab is cooler than the rest of the mantle. Based on the phase diagram depicted in Figure 2, lower temperatures correspond to higher pressures for the bridgmanite phase transition to occur. The 660-km discontinuity would therefore be at a greater depth than the typical value of 660 kilometers.

4. (2 points) Extremely dense subducted plates can sink to the bottom of the mantle and accumulate in what is known as the D" region. Was this phenomenon more or less likely to occur early in Earth's history during the Archean Eon? Explain.

Solution: More likely. Earth's mantle was significantly hotter during the Archean, resulting in it being less dense and more similar to the density of the subducting plate. This makes the plate less buoyant and more likely to sink to the core-mantle boundary. (The crust during the Archean was also enriched in heavier elements such as iron and magnesium, further minimizing the density contrast.)

Problem 2

Question	1	2	3	4	5	Total
Points	1	3	6	2	3	15 (25%)

In June 1991, Mount Pinatubo in the Philippines erupted and released enormous amounts of aerosols that rose into the stratosphere and spread around the world. This problem will explore the impact of these aerosols on Earth's atmosphere.

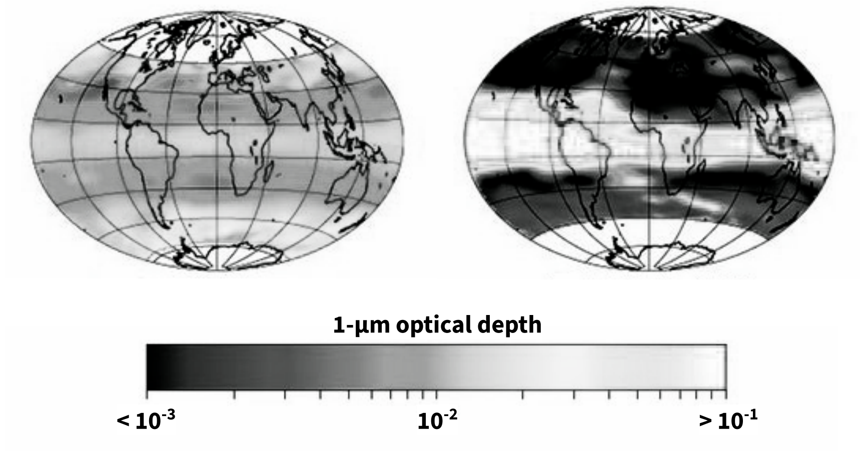


Figure 1: Depiction of stratospheric optical depth, a proxy for aerosol concentration, after the eruption of Mount Pinatubo. White represents high optical depth (i.e. high aerosol concentration).

1. (1 point) The two images in Figure 1 correspond to stratospheric conditions in different years. Data from which time period is represented in each image?

   A. Left: June-July 1991; Right: August 1993

   B. Left: August 1993; Right: June-July 1991

   Solution: We expect aerosol concentration to be highest around the time that Mount Pinatubo erupted. Thus, the high aerosol concentrations depicted in the right image correspond with the June-July 1991 period.

2. Answer the following questions regarding prevailing winds in the Northern Hemisphere.

   (a) (2 points) In the Northern Hemisphere Hadley cell, ______ air **aloft** near the equator and ______ air **aloft** near the Tropic of Cancer create a net movement of air towards the ______.

   A. Converging; diverging; north

   B. Converging; diverging; south

   C. Diverging; converging; north

   D. Diverging; converging; south

   Solution: Along Earth's equator, air converges at the surface and rises before **diverging** aloft and spreading toward the poles. In the Northern Hemisphere, this air **converges** around the subtropics with air traveling toward the equator from farther north. The resulting net movement of air between the equator and the subtropics is **northward**.

(b) (1 point) The Coriolis force deflects the winds described in the previous part to the ______, creating net movement of air to the ______ in the upper troposphere.

A. West; southwest

B. West; northeast

C. East; southwest

D. East; northeast

Solution: The Coriolis force deflects wind to the right of the direction of travel in the Northern Hemisphere. Because winds are moving north, this means that an **eastward** deflection occurs and air is observed to move toward the **northeast**.

3. The quasi-biennial oscillation (QBO) refers to a cycle of wind patterns in the stratosphere near the tropics in which the dominant wind direction reverses with a period of approximately two years. Figure 2 graphs the dominant wind direction at different altitudes over time.

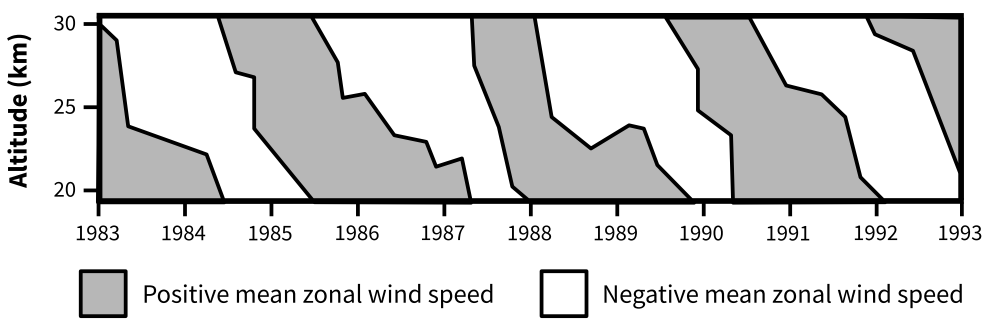


Figure 2: A graph of QBO flow measurements as a function of altitude and time. Positive zonal flow indicates westerly winds; negative zonal flow indicates easterly winds.

(a) (2 points) Given that aerosols from the Pinatubo eruption were primarily injected at altitudes of 20-25 kilometers, in which direction did they generally move?

A. North

B. South

C. East

D. West

Solution: The diagram in Figure 2 indicates that between 20-25 kilometers, there was positive mean zonal wind speed in 1991. This observation corresponds with westerly winds, which means that winds blew from the west and moved air toward the east.

When comparing the aerosol distribution of this volcanic eruption to similar low-latitude volcanic eruptions, researchers noticed that aerosols exited the lower stratosphere at a rate higher than expected, while they exited the upper stratosphere at a lower rate than expected.

(b) (2 points) Would you expect aerosol-carrying air parcels to have an easier time mixing across an area with high rates of change in wind velocity (i.e. high **horizontal** wind shear) or areas with low rates of change in wind velocity (i.e. low **horizontal** wind shear)? Explain.

Solution: Low horizontal wind shear. It would be harder for air parcels, which carry the aerosols, to mix across boundaries with significantly different velocities (i.e. high wind shear) as parcel velocity would have to change more compared to a region with low wind shear.

(c) (2 points) Given that stratospheric winds **outside** the tropics are primarily westerly, would you expect poleward aerosol transport to be faster in the lower or upper stratosphere in 1991? Explain.

Solution: Lower stratosphere. Because lower stratospheric winds were westerly in 1991 (from part (a)) and the stratospheric winds just outside the tropics were also westerly, there was less wind horizontal shear in the lower stratosphere and aerosols were able to spread more rapidly in the poleward direction.

4. (2 points) Stratospheric aerosol injection (SAI) is a proposed strategy to mitigate climate change that would increase the albedo of aerosols in the stratosphere. However, SAI would also increase the absorbance of the stratospheric aerosol layer. How would you expect the temperatures of the troposphere and stratosphere to change due to SAI? Explain.

Solution: Tropospheric temperatures would decrease because there would be less incident light due to increased reflection and absorption in the stratosphere. Stratospheric temperatures would increase because more energy would be absorbed by the stratosphere.

5. Recall that the optical depth τ of a cloud is a proxy for aerosol concentration. It can be calculated using the expressions:

$$\tau = LWC \times \frac{3h}{2\rho_w r} \qquad \textit{or} \qquad \tau = \ln\left(\frac{\phi_i}{\phi_t}\right)$$

where LWC is the liquid water content of the cloud, h is the thickness of the cloud, ρ_w is the density of water, r is the average radius of aerosols, ϕ_i is the incident radiation flux, and ϕ_t is the transmitted radiation flux.

(a) (1 point) Assuming similar values for aerosol radii, cloud thicknesses, and incident radiation, which of the following cloud types would you expect to reflect the least amount of radiation?

A. Stratus B. Cumulus C. Cumulonimbus **D. Cirrus**

(b) (2 points) Explain your answer to the previous part.

Solution: Less reflection given an equal amount of incident radiation implies a greater amount of transmitted light and thus a smaller optical depth. Given similar values for r, h, and ρ_w, optical depth depends only on LWC. Cirrus clouds have the lowest liquid water content as they are located high in the atmosphere and are composed almost entirely of ice, so they will reflect the least amount of radiation.

Problem 3

Question	1	2	3	4	Total
Points	4	3	3	5	15 (25%)

This problem focuses on several aspects of the Ganges Delta on the Indian subcontinent.

1. The Ganges Delta is fed by a network of rivers that carry sediment suspended in their waters. Figure 1 depicts idealized profiles for two properties relevant to this sediment.

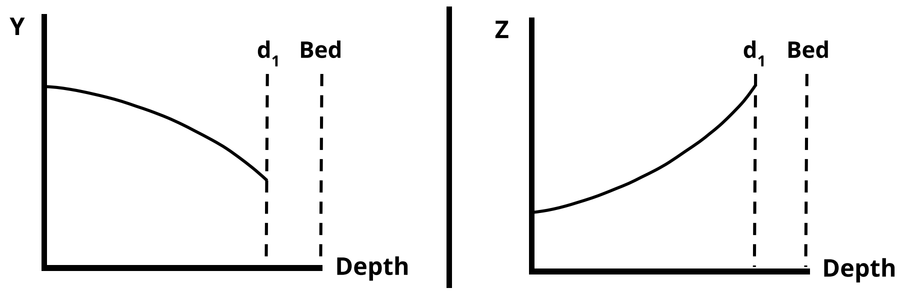


Figure 1: Graphs of two functions Y and Z related to properties of sediment suspended in a river. No sediment is suspended in the river below depth d_1.

(a) (1 point) A hydrologist determines that one property corresponds to wave-averaged sediment concentration and the other corresponds to current velocity. What do properties Y and Z correspond to, respectively?

Solution: Y corresponds to current velocity and Z corresponds to sediment concentration.

(b) (1 point) Briefly explain why you assigned Y to sediment concentration or current velocity.

Solution: Current velocity is expected to be lowest near the river bed due to friction from the bed.

(c) (1 point) Briefly explain why you assigned Z to sediment concentration or current velocity.

Solution: Sediment concentration is expected to be highest near the river bed due to the influence of gravity and increased proximity to a source of sediment.

(d) (1 point) Notice that no sediment is suspended in the river below depth d_1. Does sediment transport occur below d_1? If so, briefly describe one method of transport in this region. If not, briefly explain why not.

Solution: Yes. Sediment below d_1 constitutes the bed load of the river channel and moves by rolling, sliding, and saltating.

The sediment transported by the rivers is eventually deposited into the Ganges Delta and the regions around it.

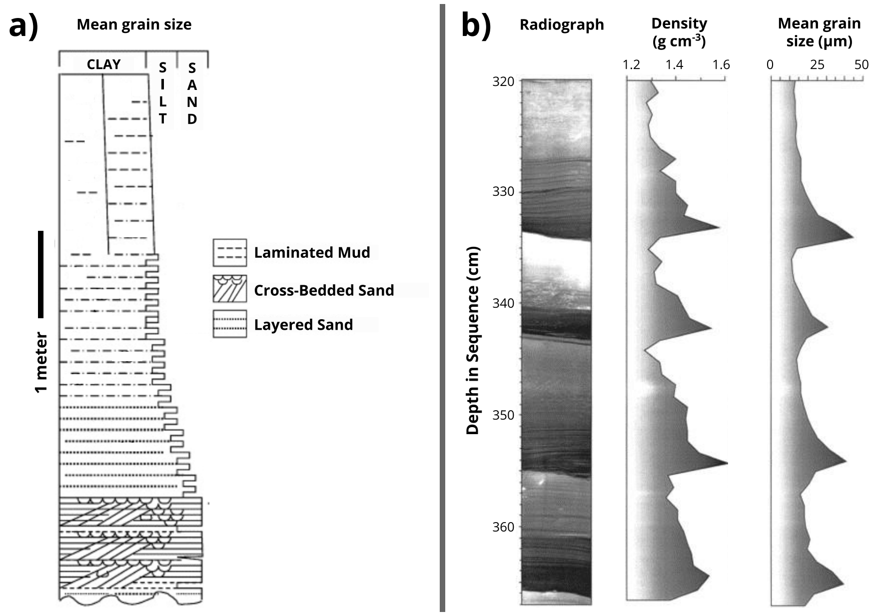


Figure 2a: Depiction of a depositional sequence taken from the Ganges Delta.
Figure 2b: Depiction of a depositional sequence imaged from a submarine canyon south of the Ganges Delta.

2. The following parts refer to the sequence in Figure 2a taken from the lower plain of the Ganges Delta.

(a) (2 points) The regions above and below the intertidal zone are referred to as the supratidal and subtidal zones, respectively. Assuming no overturning occurred, does the sequence represent a transition from a supratidal to a subtidal environment or from a subtidal to a supratidal environment? Explain your reasoning using **two** distinct pieces of evidence from the figure.

Solution: Subtidal to supratidal. The presence of cross-beds in the lower layers indicates that they were deposited in a subtidal environment where the flow of water created angled layers. Additionally, the fining upward trend indicates that the top layers were deposited in a lower energy, supratidal environment. Since the top layers were deposited more recently by the law of superposition, the environment has shifted from subtidal to supratidal over time.

(b) (1 point) Which of the following best characterizes the processes responsible for forming the sequence?

A. Delta retrogradation associated with marine transgression

B. Delta retrogradation associated with marine regression

C. Delta progradation associated with marine transgression

D. Delta progradation associated with marine regression

Solution: A subtidal to supratidal transition implies a marine regression as more land was exposed to the atmosphere. The transition also suggests that the delta prograded over time, or extended further, as sediments built up and the relative sea level decreased.

3. The following parts refer to the sequence in Figure 2b taken from the Swatch of No Ground, a submarine canyon in the Indian Ocean to the south of the Ganges Delta.

    (a) (1 point) Identify the process responsible for the cyclic pattern seen in the sequence.

    Solution: Successive turbidity currents were responsible for the cyclic pattern of deposition.

    (b) (2 points) As the Ganges Delta has migrated east in the last several thousand years, portions of the southwest region of the delta face increased threats of coastal erosion. Considering your answer to part (a), briefly explain whether the presence of the Swatch of No Ground region contributes to or prevents this erosion.

    Solution: Sediment is funneled through the Swatch of No Ground, a submarine canyon, due to processes such as the turbidity currents identified in (a). This leaves less sediment along the coast and contributes to erosion.

4. The Ganges Delta discharges into the Bay of Bengal located in the northeastern part of the Indian Ocean.

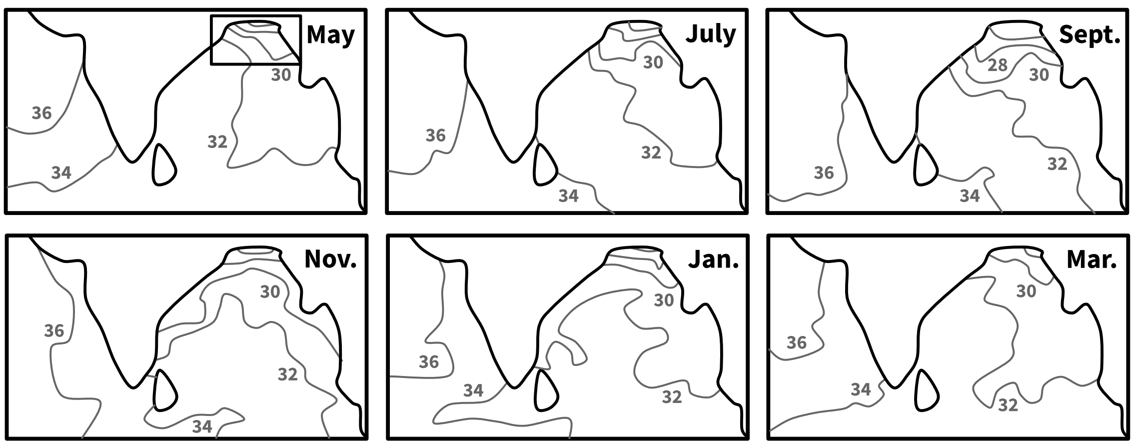


Figure 3: A map of sea surface salinity throughout the year in the Bay of Bengal. The boxed region in the first panel denotes approximately where the Ganges Delta discharges into the bay.

    (a) (2 points) Notice that low-salinity water accumulates where the delta discharges into the bay between May and September. Given that this phenomenon repeats annually, briefly explain why it occurs.

    Solution: The Indian Summer Monsoon (ISM) increases rainfall over the Indian subcontinent during the summer months, thus increasing freshwater discharge into the Bay of Bengal from the Ganges Delta.

    (b) (3 points) Consider a map of surface chlorophyll-a concentration for the Bay of Bengal in July. In what region(s) would you expect the map to indicate elevated chlorophyll-a levels? Explain your reasoning. *Hint: Consider factors other than sea surface salinity.*

    Solution: We would expect elevated levels of chlorophyll in parts of the bay near the Ganges Delta and the coast of India. Riverine water from the Ganges Delta provides a consistent source of nutrient-laden water during the summer. Southwesterly winds due to the ISM result in Ekman transport away from the coast of India, resulting in upwelling of nutrient-rich water in those regions. However, additional factors complicate the situation; for further reading see Chowdhury et al. 2021.

Problem 4

Question	1	2	3	Total
Points	4	4	7	15 (25%)

This problem analyzes and draws comparisons between several aspects of Mercury and the Moon.

1. Figure 1 depicts the orbits of Earth and Mercury around the Sun and the orbit of the Moon around Earth. Locations A, B, and C represent potential orientations of Mercury relative to Earth. Assume that the orbits of each body are counterclockwise and perfectly circular in the plane of the ecliptic and that each body is small enough such that it does not block light from reaching other bodies.

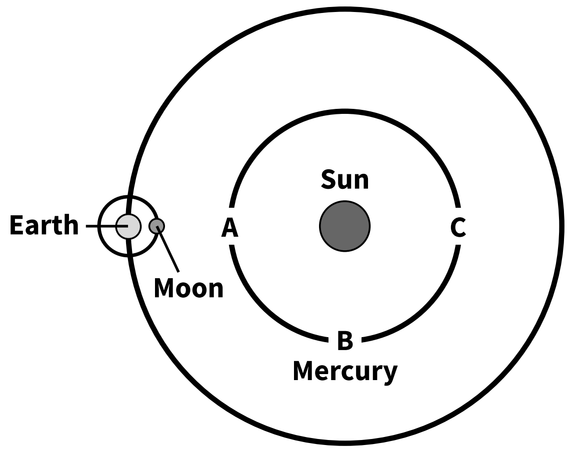


Figure 1: An idealized model of the orbits of Earth, Mercury, and the Moon. Not to scale.

(a) (2 points) At which location in Mercury's orbit will the planet appear to be exactly half illuminated as seen from Earth?

A. At location A

B. Between locations A and B

C. At location B

D. Between locations B and C

E. At location C

Solution: Mercury appears half illuminated when it is at a point of greatest elongation relative to Earth. This is because at greatest elongation, the line of sight between Earth and Mercury is perpendicular to the line between Mercury and the Sun and exactly half of Mercury is lit up from Earth's perspective. The point of greatest elongation occurs between A and B.

(b) (1 point) If Mercury is at location B, an observer on Mercury would see that Earth is in what phase?

A. New B. Crescent C. Half **D. Gibbous** E. Full

Solution: Earth would appear to be in the gibbous phase because the line between Earth and the Sun forms an acute angle with the line between Earth and Mercury, meaning more than half of Earth appears illuminated from Mercury's perspective.

(c) (1 point) If Mercury is at location B, an observer on Mercury would see that the Moon is in what phase?

A. New B. Crescent C. Half **D. Gibbous** E. Full

Solution: By similar reasoning in (b), the Moon would appear to be in the gibbous phase as the line between the Moon and the Sun forms an acute angle with the line between the Moon and Mercury.

2. Since the 1980s, scientists have generally accepted the giant-impact hypothesis, which states that the Moon formed after a large planetary body called Theia collided with Earth. Briefly explain whether the following two observations support or oppose the giant-impact hypothesis.

(a) (2 points) The Moon has a much smaller core relative to Earth.

Solution: A collision with Theia would mostly eject Earth's outer layers and less of its metal-rich core. There would therefore be less dense material sinking to form the Moon's core during differentiation, resulting in a smaller core size and supporting the giant impact hypothesis.

(b) (2 points) The Moon has a much lower volatile content relative to Earth.

Solution: A collision with Theia would generate intense temperatures that would vaporize a large fraction of the volatiles ejected, resulting in fewer volatiles being included in the lunar composition and supporting the giant impact hypothesis.

3. You will now estimate the ratio between the maximum height of mountains on the Moon and Mercury assuming similar crustal compositions.

(a) (2 points) Let g_{Moon} and g_{Mercury} equal the gravitational accelerations at the surfaces of the Moon and Mercury, respectively. Given the following table of information, calculate the ratio $\frac{g_{\text{Moon}}}{g_{\text{Mercury}}}$. **Show your work.**

Radius of the Moon	1738 km
Radius of Mercury	2440 km
Average density of the Moon	3344 kg/m^3
Average density of Mercury	5429 kg/m^3

Solution: We begin by noting that $g = \frac{GM}{r^2}$, where G is the gravitational constant, M is the mass of the body, and r is the radius of the body. Substituting $M = \frac{4\pi r^3}{3}\rho$, where ρ is the average density of the body, we get $g = \frac{4G\pi\rho r}{3}$. Thus, the ratio $\frac{g_{\text{Moon}}}{g_{\text{Mercury}}}$ simplifies to

$$\frac{\rho_{\text{Moon}} r_{\text{Moon}}}{\rho_{\text{Mercury}} r_{\text{Mercury}}} = \frac{3344 \times 1738}{5429 \times 2440} \approx \boxed{0.44}.$$

Mountains on Mercury and the Moon cannot be arbitrarily tall because after a certain point, the pressure exerted by the mountain on the underlying material becomes so great that material begins to "flow" from beneath the mountain. The maximum pressure that can be sustained by the material is given by Young's modulus Y, typically given in units of newtons per square meter.

(b) (3 points) The formula for the maximum height a mountain can reach is given by $h_{\max} = kY^a\rho^b g^c$, where k is a dimensionless constant, Y is Young's modulus, ρ is the density of the material, and g is the gravitational acceleration at the surface of the body. Find the values of a, b, and c. **Show your work.**

Solution: First, determine the units of each of the variables in the equation. Let M, L, and T represent units of mass, length, and time respectively. $h_{\max}$ has units of length (L), Y has units of force over area ($ML^{-1}T^{-2}$), ρ has units of density (ML^{-3}), and g has units of acceleration (LT^{-2}).

The units on either side of the equation $h_{\max} = kY^a\rho^b g^c$ must be consistent. Thus, $L = M^aL^{-a}T^{-2a}$ $M^bL^{-3b}L^cT^{-2c}$. Equating the exponents for each of M, L, and T, we get the system of equations $a + b = 0$, $-a - 3b + c = 1$, and $-2a - 2c = 0$. Solving, $\boxed{a = 1,\ b = -1, \text{ and } c = -1}$.

If you cannot obtain an answer for (a), use $\frac{g_{\text{Moon}}}{g_{\text{Mercury}}} = 0.5$ for (c).

(c) (2 points) Synthesizing your answers from (a) and (b), estimate the value of $\frac{h_{\text{max, Moon}}}{h_{\text{max, Mercury}}}$. Assume that mountains on the Moon and Mercury are made of similar material. **Show your work.**

Solution: From (b), h_{max} is inversely proportional to gravitational acceleration. Because we are told that the material composing the mountains on both bodies are similar, ρ and Y will cancel once the respective values of h_{max} are divided. Thus,

$$\frac{h_{\text{max, Moon}}}{h_{\text{max, Mercury}}} = \frac{g_{\text{Mercury}}}{g_{\text{Moon}}} \approx \frac{1}{.44} \approx \boxed{2.28}.$$

END OF SECTION II