USESO 2024

National Open Exam

Section II

KEY

Instructions:

- Section II consists of 4 multipart questions 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.

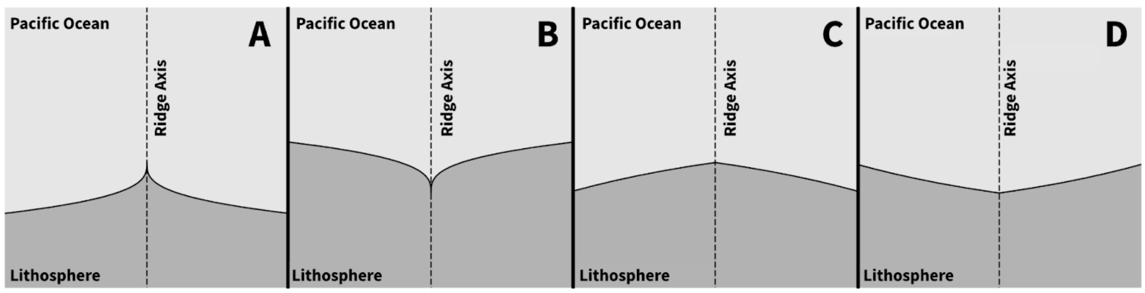
Problem 1

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

This problem will explore several aspects of the ocean floor.

1. The production of new crust occurs at mid-ocean ridges.

   (a) (1 point) Which of the following diagrams best models the topography of a mid-ocean ridge?



Solution: A. Ridge topography reaches maximum elevation and is concave up near the ridge axis.

Referencing the diagram you selected, answer the following questions.

   (b) (1 point) Why does ocean depth increase or decrease farther from the ridge axis?

Solution: Increase. As newly-formed rock moves away from the ridge, it cools and becomes denser. This means older crust sits lower in the mantle and crustal height decreases, increasing ocean depth.

   (c) (2 points) Does the topography near the ridge axis enhance or inhibit plate motion? **Explain.**

Solution: Divergent motion is enhanced. Gravity pulls elevated crust downwards and pushes it to the side via ridge push. The higher slope near the ridge axis results in greater push, enhancing plate motion.

   (d) (2 points) The presence of certain compounds or organisms within a sediment layer can provide information about where that layer was formed. Would a sediment layer containing significant amounts of calcareous ooze be more likely to form close to or away from the ridge axis? **Explain.**

Solution: Close to the ridge axis. Calcareous ooze is more likely to form near mid-ocean ridges because greater elevation near the ridge allows ooze to stay above the carbonate compensation depth, meaning carbonate debris accumulates faster than it dissolves.

2. Mid-ocean ridges are commonly surrounded on either side by belts of faulting known as fracture zones. The figure below displays a segment of the Mid-Atlantic ridge and its associated fracture zones.

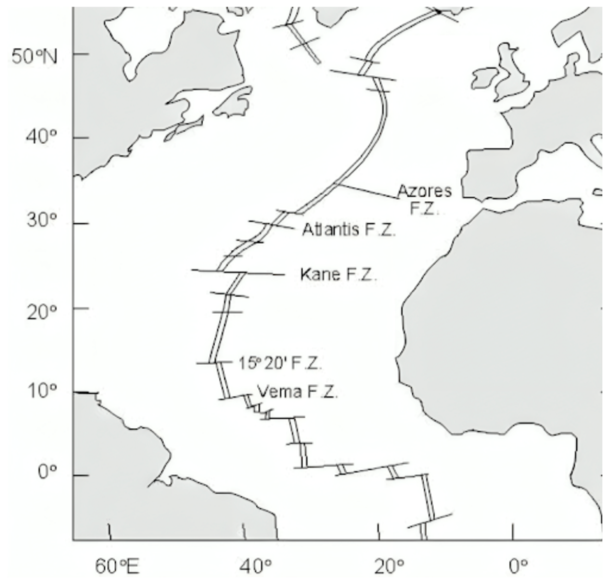


Figure 1: Map of fracture zones (abbreviated F. Z.) in the Atlantic Ocean.

(a) (2 points) **Briefly explain** why fracture zones often form along mid-ocean ridges. As part of your response, identify the dominant type of faulting at these zones.

> **Solution:** Different seafloor spreading rates at different locations generate shear stresses on the ocean floor. This stress produces networks of transform faults known as fracture zones.

(b) (2 points) The presence of fracture zones allows seawater to seep into oceanic crust. **Explain** how this introduction of fluids affects the rate of metamorphism at mid-ocean ridges.

> **Solution:** Hydrothermal fluids, formed as seawater interacts with hot oceanic crust, can dissolve ions in heated rock and transport them across long distances relatively quickly in a process called metasomatism. This speeds up the recrystallization of metamorphic minerals, leading to metamorphism on shorter timescales.

A typical example of the metamorphism described in part (b) is the alteration of anorthite ($CaAlSi_2O_8$). The chemical equation for this alteration is as follows:

$$Mg^{2+} + CaAlSi_2O_8 + \frac{12}{5} H_2O + \frac{1}{5} SiO_2 \longrightarrow Ca^{2+} + \frac{1}{5} Mg_5Al_2SiO_3O_{10}(OH)_8 + \frac{4}{5} Al_2Si_2O_5(OH)_4$$

(c) (2 points) If the rate of seafloor spreading increased, would magnesium concentration in the ocean be expected to increase or decrease? **Explain.**

> **Solution:** Decrease. Greater seafloor spreading rates lead to more fracturing around the ridge axis, resulting in more seawater infiltrating oceanic crust. Increased spreading also creates more crust for this infiltration to occur. The rate of hydrothermal alteration would therefore increase, leading to a decrease of ocean magnesium content over geologic timescales.

3. (3 points) During the Late Miocene Cooling (LMC) lasting from 7.0 to 5.3 million years ago, global ocean surface temperatures decreased by about 6°C. What change most likely occurred to the rate of crustal production at mid-ocean ridges during this period? **Explain.**

Solution: The rate of crustal production likely decreased. A decrease in crustal production corresponds to less tectonic activity. Greenhouse gas emissions from volcanic activity would therefore be reduced, allowing more of Earth's thermal energy to escape and lowering global surface temperatures.

Problem 2

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

This problem will explore several implications of rising air.

1. Uneven heating of Earth's surface generates a pressure system at the surface in the state of Oklahoma as shown in Figure 1.

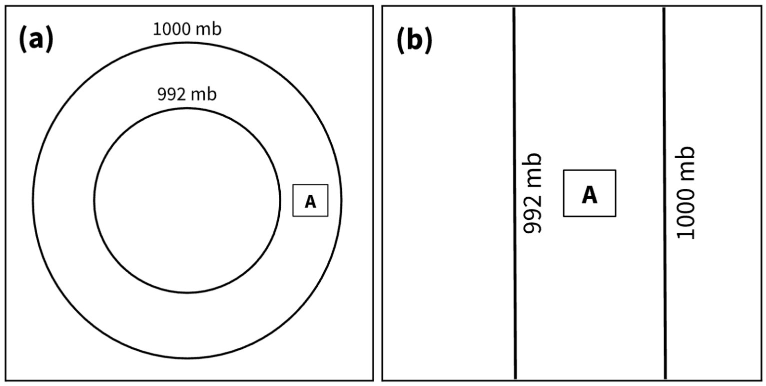


Figure 1a: Simplified surface weather map with curved isobars and Region A within the system; **Figure 1b**: Enlarged view of Region A with isobars **approximated** as straight.

Assume for this question that **friction is negligible** and wind is in **geostrophic balance**. Isobars are approximated as straight under these conditions (see Figure 1b).

(a) (1 point) Does the system shown in Figure 1 represent a low or high pressure center?

Solution: Low pressure center. Air pressure is lower closer to the center of the system.

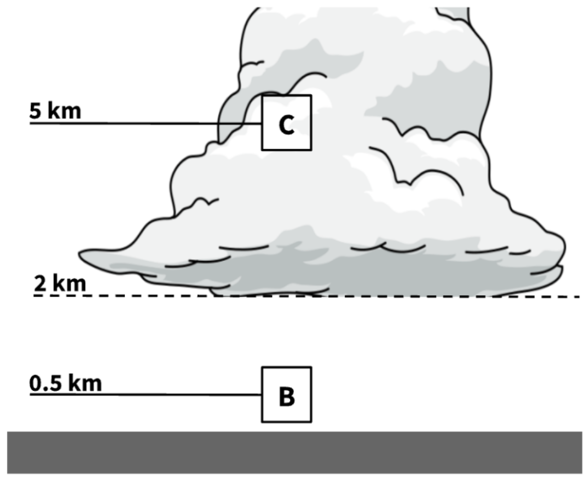
(b) (2 points) **Draw and label** two vectors (each represented by an arrow) originating from Region A representing the Coriolis force (CF) and pressure gradient force (PGF) exerted on air at Region A. Indicate direction and relative magnitude for each vector.

Solution: CF points towards the outside of the circle perpendicular to isobars while PGF points towards the center of the circle perpendicular to isobars. The two vectors are equal in magnitude.

(c) (2 points) Still assuming geostrophic conditions, **draw and label** an arrow originating from Region A approximating the wind direction at Region A. **Briefly explain** your reasoning.

Solution: Wind moves toward the top of the page. Air initially flows perpendicular to isobars and moves toward the left; the Coriolis force causes air to be deflected right until the net air flow is toward the top of the page. Geostrophic winds always flow parallel to isobars, although in reality the wind direction would be directed more towards the center of the system due to the presence of friction.

2. In reality, the lower part of the troposphere is affected by friction and thus air spirals inward before rising. At a certain point on its journey upward, air cools below dew point and condensation occurs as shown in Figure 2.



Environmental lapse rate (ELR)	13°C/km
Dry adiabatic lapse rate (DALR)	11°C/km
Moist adiabatic lapse rate (MALR)	6°C/km
Dew point lapse rate	1.5°C/km

Figure 2: Diagram of cloud formed from rising air with table of associated lapse rates.

(a) (3 points) **Explain** why the MALR is less than the DALR. As part of your response, indicate at what elevation the DALR shifts to the MALR as air rises.

Solution: The DALR shifts to the MALR when air becomes saturated and condensation occurs. Release of latent heat upon condensation reduces the rate at which temperature decreases with height, making the MALR less than the DALR. The shift from the DALR to the MALR occurs at 2 km in this question (the level of initial cloud formation).

(b) (2 points) Suppose that a parcel of air rises from Elevation B to Elevation C. **Calculate** the temperature of air at Elevation C given that the temperature of air at Elevation B is 17°C. **Show your work.**

Solution: From Elevation B to the lifting condensation level (LCL) at 2 km, the air parcel would decrease in temperature by 11°C/km × 1.5 km; from the LCL to Elevation C, the parcel would decrease in temperature by 6°C/km × 3 km. Thus, the temperature at Elevation C would be 17°C – 16.5°C – 18°C = $\boxed{-17.5°C.}$

3. Heating of Earth's surface can lead to the development of thunderstorms by influencing stability and cloud formation.

(a) (2 points) Reference the diagram below.

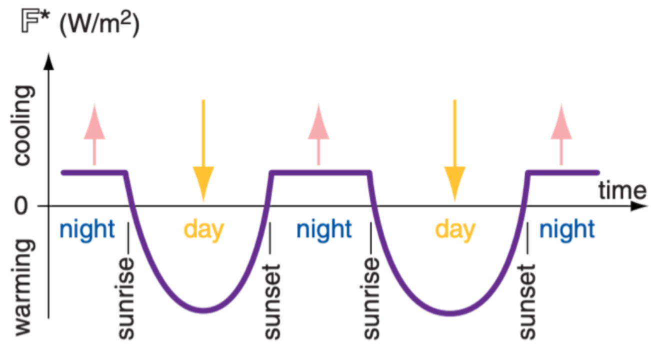


Figure 3: Diagram of daily warming and cooling cycles over the land surface during summer; arrows represent direction of net energy flux at the surface (adapted from Stull 2017).

Would thunderstorms be most likely to develop around midnight, midday, sunset, or sunrise? **Explain.**

Solution: Thunderstorms are most likely to develop around sunset. Warm air over the land surface is associated with instability in the atmosphere and storm formation. As the diagram depicts warming between sunrise and sunset but cooling at all other times, air would warm throughout the entire day and therefore be warmest and most unstable at sunset. Further, since this diagram represents the change in thermal energy, maximum thermal energy must be reached where this function shifts from warming to cooling.

(b) (2 points) **Explain** whether divergence of air aloft promotes or inhibits the formation of thunderstorms. As part of your response, indicate the effect of this divergence on pressure at the surface.

Solution: Divergence of air aloft promotes thunderstorm formation. Divergence aloft reduces the weight of the local air column and thus reduces pressure at the surface. To compensate, air at the surface would spiral inward and rise, strengthening the updrafts that drive thunderstorms.

(c) (1 point) Thunderstorms that develop due to updrafts initiated by rising air also exhibit downdrafts during their mature phase. What effect do these downdrafts have on the subsequent evolution of the storm? **Briefly explain** your reasoning.

Solution: Thunderstorms are primarily driven by warm updrafts originating from the surface. Downdrafts lead to the weakening of thunderstorms as they effectively block the rising air that sustains them.

Problem 3

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

Thwaites Glacier, located on the edge of Antarctica, has been extensively studied due to its large size and potential for causing significant sea level rise. This problem will explore several aspects related to Antarctic circulation and Thwaites' melting.

1. (2 points) Thwaites Glacier's melting is primarily driven by changes in Antarctic ocean currents, which are created by two different sets of winds. To the north of the Southern Ocean are the mid-latitude westerlies, which blow water eastward to create the strong Antarctic Circumpolar Current (ACC). To the south, the polar easterlies blow in the opposite direction to create the weaker Antarctic Subpolar Current (ASC) on the edge of the continent.

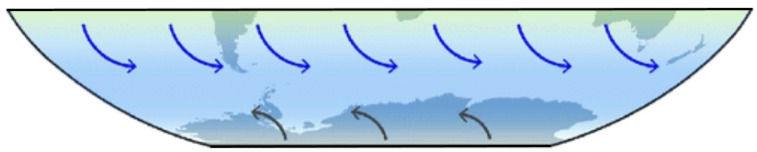


Figure 1: Map of large-scale wind patterns in the Southern Ocean.

Briefly describe how these winds cause upwelling of deep water surrounding Antarctica.

> **Solution:** Subsurface water moves leftward of wind direction in the Southern Hemisphere due to Ekman transport. Underneath the ACC, the net water movement is northward, while underneath the ASC, the net water movement is southward. This motion forces deep water to rise and replace the diverging surface water.

2. The Southern Annular Mode (SAM) is an oscillation of wind patterns in the Southern Ocean that affects the ACC.

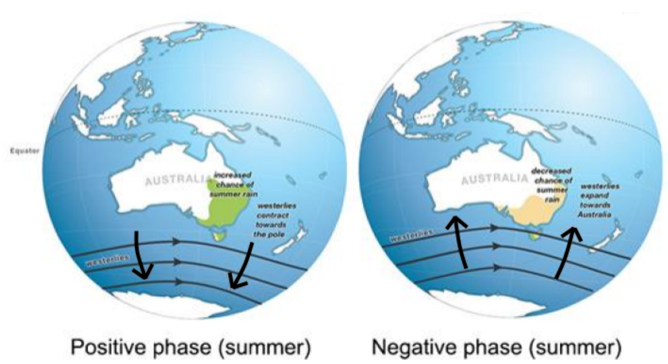


Figure 2: Diagram showing the two phases of the SAM.

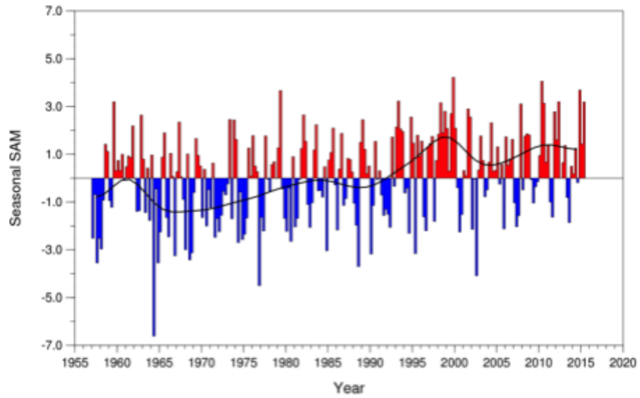


Figure 3: Graph of SAM phases since 1956. Notice the overall positive trend.

(a) (1 point) When the SAM is in its positive phase, it extends the range of the mid-latitude westerlies, causing the ACC to contract inward towards Antarctica. **Explain** how this change contributes to upwelling of deep water surrounding Antarctica.

Solution: This extension both increases the area of the northward movement caused by the ACC and the southward movement caused by the ASC. Northward water movement causes upwelling by pulling water away from the coast, forcing deep water to be brought up. An increase in this northward water movement would therefore promote upwelling.

(b) (1 point) When the SAM is in its positive phase, it causes the mid-latitude westerlies and the ACC to strengthen. **Explain** how this change contributes to upwelling of deep water surrounding Antarctica.

Solution: The Coriolis effect and Ekman transport would strengthen as ocean currents travel faster. This increased Ekman transport would move more water northward, promoting upwelling.

(c) (3 points) A researcher tries to construct a timeline of SAM changes before active records were kept. They intend to do this using the oxygen content of oceanic sediment deposited by Antarctic deep water as a proxy. Would a positive SAM phase correspond to high or low sediment oxygen content? **Explain.**

Solution: Low sediment oxygen content. Most oxygen in deep water originates from surface water that has absorbed oxygen from the atmosphere. To reach deep water, this surface water must undergo downwelling, a process common around Antarctica due to the formation of the Antarctic Bottom Water. A positive SAM phase results in upwelling, which would disrupt the natural cycle of overturning and bottom water formation that brings oxygen downward.

3. The main deep water mass surrounding Antarctica is the warm Circumpolar Deep Water (CDW) as shown in the image below.

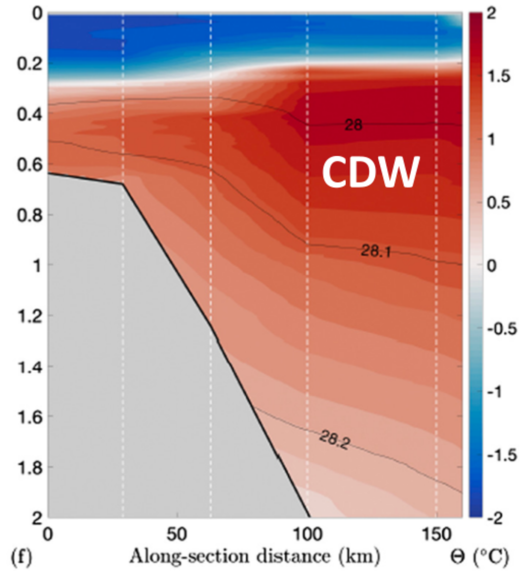


Figure 4: Figure displaying water temperature (shading) and salinity (numbered lines) near Thwaites Glacier, with a continental shelf present on the left (adapted from Thompson et al. 2018).

(a) (3 points) Notice the downward slope of the salinity gradient as the distance from the coast increases. How could coastal water movement create this trend? Does this correspond to a positive or negative-phase SAM? **Explain.**

> **Solution:** Elevated isohalines along the coast suggest that the warm, salty deep water from the CDW is pulled up near the coast. This indicates the occurrence of upwelling near the coast, which is associated with a positive-phase SAM and the strengthening of the ACC.

(b) (2 points) The influx of the CDW onto the continental shelf is the primary mechanism of Thwaites Glacier's subsurface melting. Considering how the recent trend towards positive SAM affects this influx, does this constitute a positive or negative climate feedback loop? **Explain.**

> **Solution:** Positive. Global warming causes a shift towards positive SAM, which increases upwelling along the Antarctic coast. This increased upwelling would bring more warm water from the CDW onto the continental shelf, which would cause further glacial melting. Glacial melting typically results in warming, since it often releases greenhouse gases and increases energy absorption by decreasing albedo. Overall, climate change would lead to more climate change, resulting in a positive feedback loop.

4. (3 points) Thwaites Glacier contains about 258,000 km^3 of ice above sea level. Given that Earth has a radius of 6378 km and 71% of Earth's surface is covered by water, **estimate** the sea level change, in meters, that would be caused by the complete melting of Thwaites Glacier. Assume that the proportion of land covered by water stays constant and thermal expansion does not occur. **Show your work.**

> **Solution:** Let A, V, and h represent surface area covered by water, volume of water released by melting, and sea level change, respectively. A equals the surface area of Earth, $4\pi r^2$, multiplied by the proportion of that area covered by water, 0.71. Thus, $A = (0.71)(4\pi)(6.378 \times 10^6)^2 = 3.63 \times 10^{14}\ \text{m}^2$. $V = 2.58 \times 10^{14}\ \text{m}^3$ using the value given in the problem. h equals the volume of water added to the ocean divided by the area it is distributed over: $h = V/A \approx \boxed{0.71\ \text{m.}}$

Problem 4

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

This problem will explore several aspects of Mars' surface, atmosphere, and orbit around the Sun.

1. The image below depicts a network of erosional features found in Warrego Valles, a region located along the southern edge of a Martian plateau.

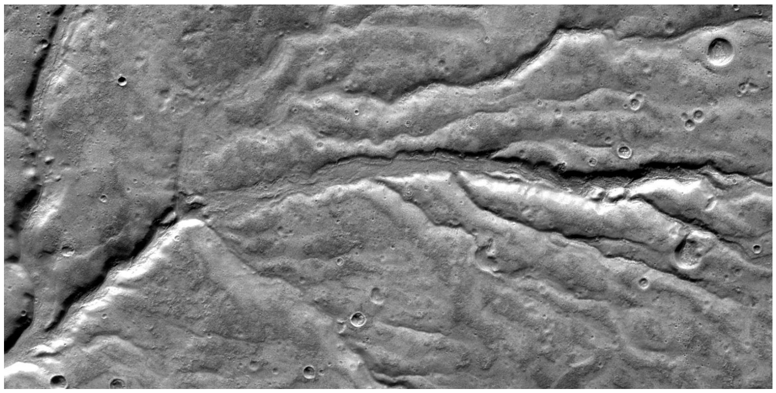


Figure 1: Erosional features found in Warrego Valles on Mars.

(a) (1 point) What do these erosional features indicate about Mars' past climate?

Solution: The erosional features found in Warrego Valles are thought to have been carved by water, indicating that Mars' climate was once wetter than it is today.

(b) Features similar to those found in Warrego Valles are no longer being produced on Mars' surface.

i. (2 points) **Give one reason** why the thinning of the Martian atmosphere may have contributed to this change.

Solution: Decreased atmospheric pressure reduced the stability of liquid water on Mars' surface. Thus, water could not remain as a liquid, forming surface ice or escaping from the atmosphere.

ii. (2 points) A major contributor to atmospheric escape is the relatively low gravity of Mars. **Describe** how Mars' rate of heat loss relative to Earth may have also contributed to the loss of its atmosphere.

Solution: Mars' lower mass led to more rapid heat escape, weakening convection in the outer core and reducing the strength of the planet's magnetic field. This resulted in greater stripping of the atmosphere by solar wind as no magnetic field was present to deflect charged particles.

2. (2 points) The surface of Mars appears red due to the presence of iron oxides. **Explain** how Mars' lower mass contributed to the significantly higher concentration of iron oxides at its surface compared to Earth despite both planets forming from roughly the same material.

Solution: Mars' smaller size results in the planet being less differentiated than Earth. Differentiation typically brings heavy elements like iron towards the center of the planet, so reduced differentiation would allow these elements to remain at the surface in greater concentrations.

3. Assume for this question that Mars and Earth have circular, coplanar orbits.

Orbital radius of Mars	2.28×10^{11} m
Orbital radius of Earth	1.50×10^{11} m
Mass of Mars	6.39×10^{23} kg
Mass of Earth	5.97×10^{24} kg
Mass of the Sun	1.99×10^{30} kg
Gravitational constant (G)	6.67×10^{-11} N m^2 kg^{-2}

(a) (2 points) **Calculate** Mars' sidereal orbital period in days given the parameters in the table above. **Show your work.**

Solution: Mars' sidereal orbital period T can be calculated by applying Kepler's third law:

$$T^2 = \frac{4\pi^2}{GM}r^3$$

Using r as 2.28×10^{11} m and M as 1.99×10^{30} kg, Mars' sidereal orbital period is approximately 5.94×10^7 s, which is equal to $\boxed{\text{687 days.}}$

If you cannot obtain an answer for part (a), take Mars' sidereal orbital period to be 840 days.

(b) (3 points) Mars reaches opposition when it moves into a straight-line configuration with Earth and the Sun, where Earth is located between Mars and the Sun. **Calculate** the number of days it would take Mars to next reach opposition. **Show your work.**

Solution: The time between consecutive oppositions is equal to the synodic orbital period of Mars. This period can be calculated using the following equation:

$$T_{\text{synodic}} = \frac{1}{f_{\text{Earth}} - f_{\text{Mars}}} = \frac{1}{\frac{1}{365\text{ days}} - \frac{1}{687\text{ days}}} \approx \boxed{\text{779 days.}}$$

Intuitively, Mars must gain a full revolution (equal to 2π radians) between consecutive oppositions. Thus, dividing 2π by the difference in angular velocities of Earth and Mars ($\frac{2\pi}{365}$ and $\frac{2\pi}{687}$, respectively) results in the same answer.

4. The figure below compares the surface topography of Earth to that of Mars.

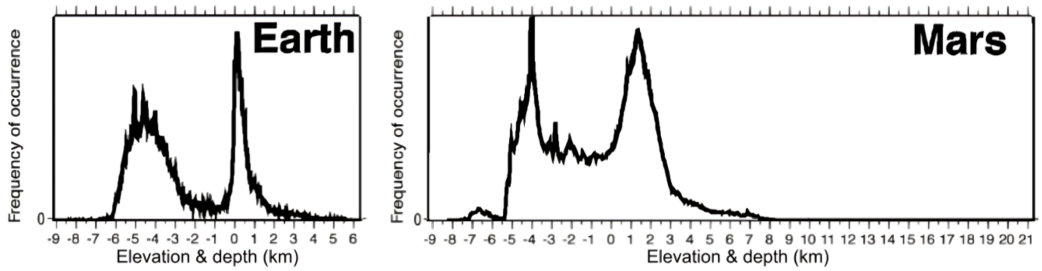


Figure 2: Distribution of surface elevation and depth on Earth and Mars (adapted from Dohm et al. 2016).

(a) (2 points) Given your understanding of Earth's surface, **explain** how one might use these diagrams to justify the existence of plate tectonics on Mars.

Solution: Earth's curve displays two peaks corresponding to the differing elevations of continental crust versus oceanic crust. The two peaks present on Mars could indicate the same features, suggesting that Mars may have had tectonic activity that created two distinct types of crust.

(b) (1 point) In reality, Mars does not exhibit plate tectonics. **Name or describe** the feature of Mars' surface that accounts for the shape of the curve in the right diagram.

Solution: Hemispheric dichotomy. Mars' northern hemisphere is at a lower elevation than its southern hemisphere.

END OF SECTION II