USESO 2022

Astronomy KEY

Instructions:

- Section I consists of 10 multiple choice questions, with each question worth 2 points. There is only one correct option on multiple choice questions
- Section II consists of 2 multipart free response questions
- A calculator is allowed; show all work for calculations unless otherwise stated
- Recommended time management: 30 minutes on each section

Section I

1. The Moon is not a sphere. Identify all of the following which are true of its sphericity. (*Note: oblateness is how 'squished' a spheroid is.*)

   I) The Moon is thicker on its near side due to the Earth's gravity.

   II) Due to its slower rate of rotation, the Moon is less oblate than the Earth.

   III) The Moon is oblate primarily due to tidal forces from the Earth.

   A. II only

   B. III only

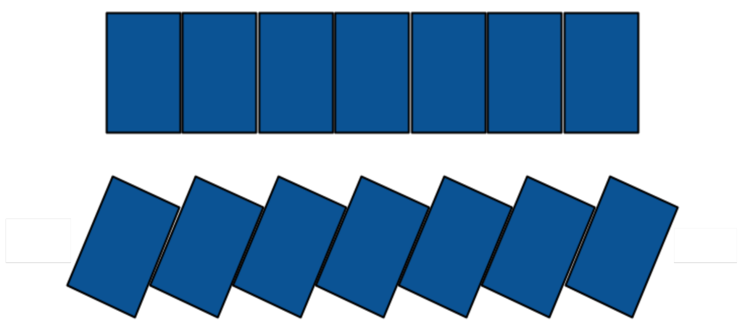
   C. I and III

   D. II and III

   E. None

   Solution: I and III are both false because oblateness is caused by rotation (generally and in the case of the Moon) rather than gravity or a gradient in the gravitational field over different parts of the Moon. The degree of oblateness can be determined in part by rotation rate, and since the Moon completes one rotation about every 27 days, the Moon is indeed much less oblate - II is true.

Refer to the following figure for questions 2–3: Ganymede is well-known for its grooved terrain with alternating high and dark regions 5-10 km apart. The diagram above shows a proposed explanation for these grooves called *tilted block faulting*.



2. Which of the following best describes the faults of this kind of topography?

   A. All normal faults dipping in the same direction

   B. All normal faults dipping in alternating directions

   C. All reverse faults dipping in the same direction

   D. All reverse faults dipping in alternating directions

   E. Alternating normal and reverse faults

   Solution: The tilting of the blocks indicates an extensional environment in which normal faults would form. The hanging wall slips downward relative to foot walls at each fault, confirming that these are normal faults. Each block tilts in the same direction in the image and moves identically.

3. A hypothetical mining company on Ganymede drills down through the faulted region to the rock below. Which of the following would it most likely encounter below this?

   A. Fault breccias and mylonites

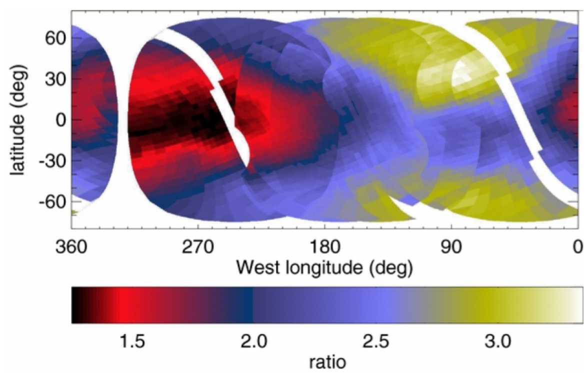
   B. Plastic extension and boudinage

   C. A high-grade metamorphic complex

   D. A rising diapir

Solution: As the brittle upper crust extends and becomes thinner, rock from below is exhumed to the surface. This would likely include high-grade metamorphic core complexes from deeper inside the moon, including facies equivalent to eclogite and granulite.

4. A proxy for water ice purity uses the ratio of albedos at different wavelengths of light. The diagram below shows this ratio for the surface of Jupiter's icy moon Europa. Higher values indicate purer water ice.



(Brown et al., 2013)

One hypothesis for the uneven distribution of ice purity is the introduction of salt particles from Europa's briny subsurface ocean as heat partially melts the ice shell from below.

Applying this knowledge to the diagram above, which of the following best describes Europa's meridional (i.e., north-south) a) heat distribution and b) ice shell movement?

   A. a) More heat near the equator; b) Towards the equator

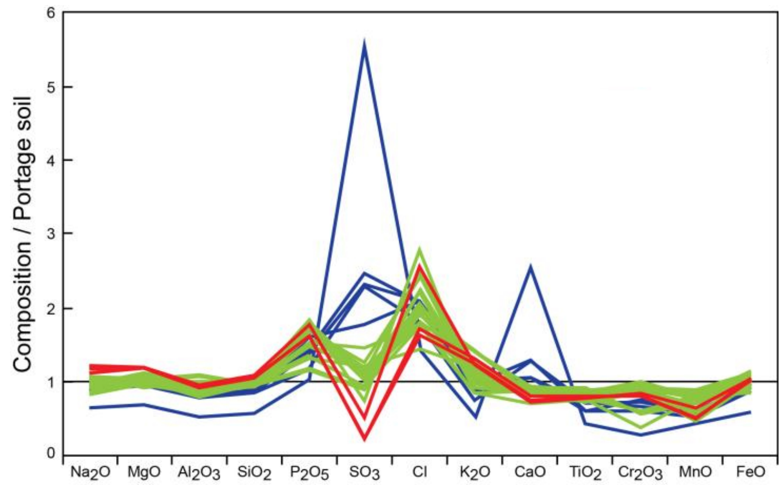
   B. a) More heat near the equator; b) Towards the poles

   C. a) More heat near the poles; b) Towards the equator

   D. a) More heat near the poles; b) Towards the poles

Solution: a) Ice is less pure near the equator, suggesting that the ice shell is thinner in the equatorial region from more heat melting the ice below. b) Because heat generally indicates rising water in the subsurface ocean, water would rise at the equator and spread out as it reaches the shell. Ice would then follow this poleward movement.

5. Consider the graph below. This shows the composition of various compounds in three types of Martian rocks compared to a local soil sample. Red and green lines are normal rock samples, while the blue lines are an unusual group of samples.



Which of the following hypotheses most likely explains the unique trend seen in the blue group of samples?

A. They formed from heavily weathered sediment.

B. They formed from heavily leached soils.

C. They formed from soils where leached minerals accumulated.

D. They have been altered by regional metamorphism.

E. They have been altered by hydrothermal processes.

Solution: Notice that the blue group of samples are enriched in sulfur and calcium compared to the green group. These elements are often found after hydrothermal alteration, as they are present in the minerals that commonly make up hydrothermal veins.

6. The geochemical differentiation of the Moon provides evidence for the hypothesis that the Moon's crust and mantle solidified from a primordial magma ocean. Which of the options correctly orders the sequence of crystallization from first to last?

I) Fe-rich olivine

II) Ca-rich plagioclase

III) Plagioclase rich in rare earth elements (REEs)

A. I, II, III

B. I, III, II

C. II, I, III

D. III, II, I

E. III, I, II

Solution: Since the Moon's bulk composition is similar to the Earth's mantle and crust, we can use Bowen's reaction series to infer the order of crystallization. Fe-rich olivine, with the highest melting point, crystallizes first, followed by Ca-rich plagioclase. REEs tend to stay in the melt due to their low compatibility. Phases containing REEs crystallized last and are contained in a layer called KREEP (rocks rich in Potassium, REE, Phosphorus).

7. During a lunar eclipse, the Moon is known to appear a red or blood orange color. This phenomenon is commonly known as a "Blood Moon." Identify all of the following which is/are true during a total lunar eclipse.

I) Nearly all of the light illuminating the Moon passes first through the Earth's atmosphere.

II) Optical dispersion through Earth's atmosphere causes blue light to be refracted at a smaller angle than red light, leading it to miss the Moon.

III) Rayleigh scattering in Earth's atmosphere prevents blue light from reaching the viewer in significant quantities.

IV) The majority of blue light is converted into lower energy red light upon absorbance and subsequent emission from molecules in the Earth's atmosphere.

A. I only

B. I and II

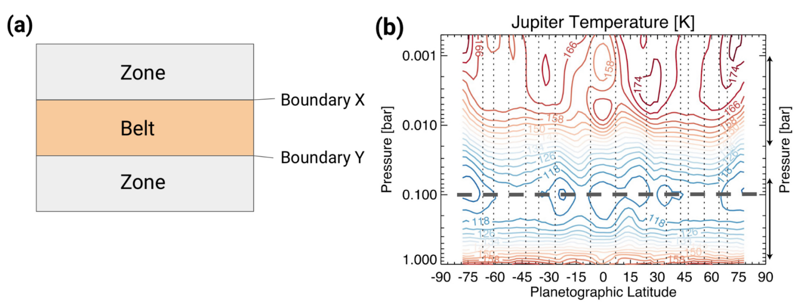
C. I and III

D. III and IV

E. IV only

Solution: I is correct. While the Moon is fully within the shadow of Earth, Earth's atmosphere refracts some sunlight such that it reaches the Moon. II is false. This is a common misconception (blue light also refracts at a larger angle than red light); regardless of the difference in angle of refraction of different wavelengths, light is refracted in a way that can illuminate the Moon at any point of its orbit. III is correct. The light from the Sun has to pass through significantly more atmosphere to reach the viewer, and much of the blue light is scattered along the way. This is the primary cause for the color of the Blood Moon. IV is false. Although some molecules that emit red light, they do not make up a significant part of our atmosphere.

8. Jupiter's atmosphere exhibits a circulation pattern consisting of horizontal bands called *belts* and *zones*. Belts represent regions of sinking air whereas zones represent regions of rising air.



(a) Simplified map view of a section of Jupiter's belt-zone circulation in its Northern Hemisphere. (b) Temperature contours on a pressure vs. latitude chart (modified from Fletcher et al., 2020). A dashed line indicates the 0.1 bar pressure level.

Which of the following statements is/are true about Jupiter's belt-zone circulation?

I) At the top of circulation cells, geostrophic winds blow to the west at Boundary X and to the east at Boundary Y.

II) The belt-zone circulation exists mainly above the dashed line.

III) The belt-zone circulation exists mainly below the dashed line.

A. II only

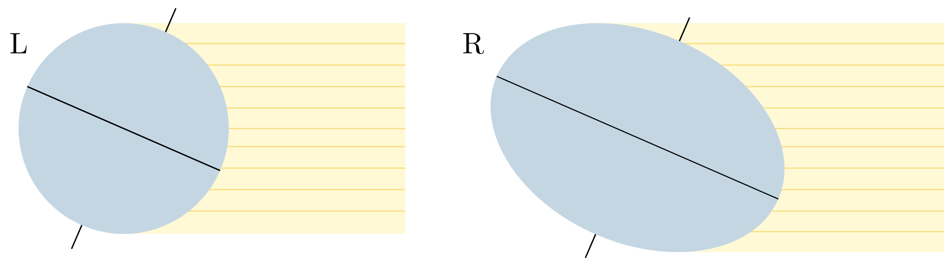
B. III only

C. I and II

D. I and III

Solution: Belts represent regions of upper-level low pressure (sinking air) and zones represent regions of upper-level high pressure (rising air). The pressure-gradient force therefore points inwards towards the belts, and the Coriolis force points outwards towards the zones. Geostrophic winds then point west at X and east at Y. Convection driving belt-zone circulation occurs with warmer air rising from beneath cooler air, which is found below the dashed line.

9. Below is a schematic comparing insolation (depicted as yellow rays) on two planets, L and R.



Assuming all else the same (including axial tilt and distance from pole to pole), which of the following accurately compares insolation on the two planets?

A. The poles of R experience greater variation in insolation than L.

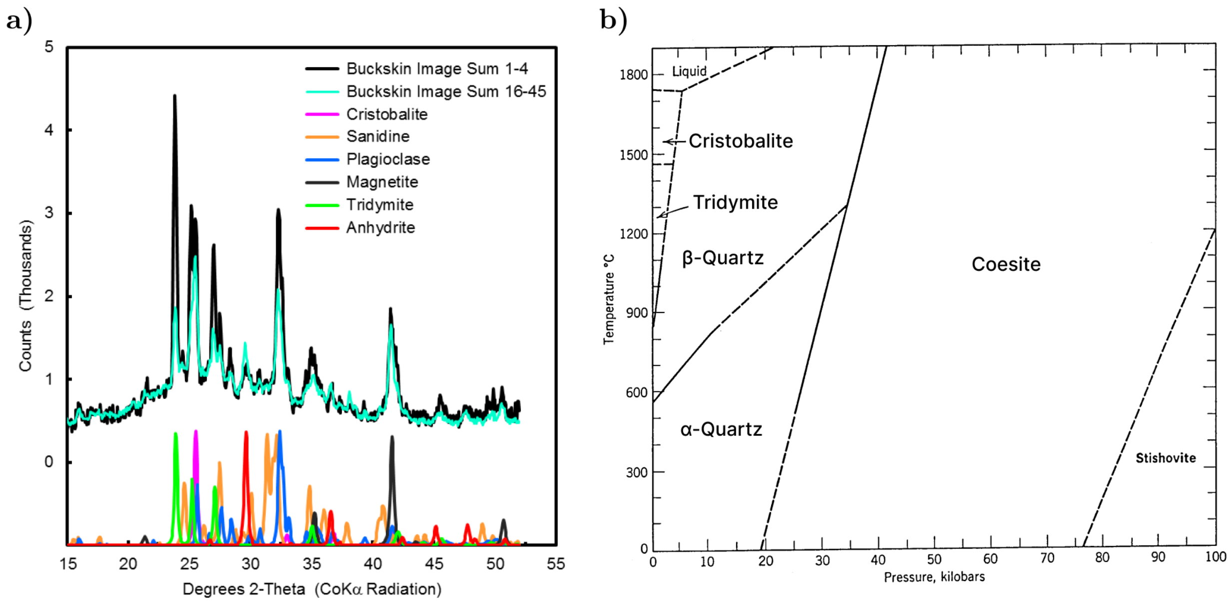
B. Any given mid-latitude location on R experiences greater variation in insolation than L.

C. The maximum latitude that can receive direct sun (rays at right angle) is higher in L than R.

D. Over one year, L receives a higher cumulative insolation than R.

Solution: At the poles, the maximum angle of the Sun over the horizon is the same for L and R because their axial tilt is equal, so the range of insolation is the same. Throughout the mid-latitudes, the max Sun angle is lower for R, so R experiences less variation in insolation than L. Direct sunlight reaches a maximum latitude equal to the axial tilt for a spherical planet such as L. Because R is a spheroid, the latitude at which direct sunlight can reach is lower. Lastly, L has a smaller area that receives insolation, so R receives more total insolation.

10. The X-ray diffraction (XRD) instrument onboard the Mars rover *Curiosity* can be used to study the composition of drill samples *in-situ*. Shown below is XRD data collected in 2016 from a drill core at the Buckskin outcrop.



(Morris et al., 2016)

Which of the following describes a petrogenic (rock-forming) environment that best explains the observations shown above?

A. A slowly-cooled felsic intrusion akin to granitic batholiths on Earth

B. A volcano erupting lava with (Martian) mantle-like composition

C. A basin that accumulated eroded felsic volcanic rocks

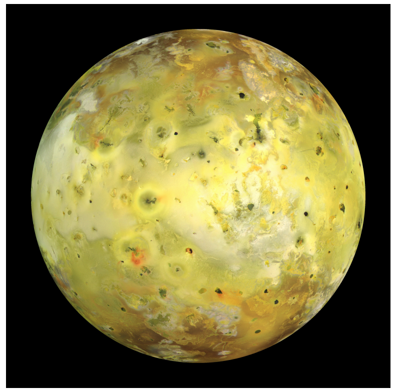
D. An impact crater with shock metamorphism

E. A hydrothermal vein system that was eventually oxidized

Solution: First, the quartz polymorphs cristobalite and tridymite indicate high temperature, low pressure environments (as well as sanidine, a potassium feldspar) that rules out A) and D). The abundance of silica rules out B). An oxidizing environment would likely contain more hematite than magnetite, ruling out E). Confirming that C) is the best answer, the presence of the evaporite anhydrite is consistent with a sedimentary basin.

Section II: Problem 1

Question	1	2	3	4	5	Total
Points	2	3	3	3	4	15 (30%)



Io, pictured above, is the first Galilean moon and the most volcanically active body in the solar system. (*Note: For the following questions, you may assume all orbits are circular.*)

1. (2 points) Given the following table of values, calculate the orbital period of Io, in seconds. You **do not** need to show your work.

Orbital radius of Io (a_i)	4.217×10^5 km
Mass of Jupiter (m_J)	1.898×10^{27} kg
Mass of Io (m_I)	8.932×10^{22} kg
Gravitational constant (G)	6.674×10^{-11} N m^2 kg^{-2}

Solution: By Kepler's Third Law,

$$T^2 = (\frac{4\pi^2}{G(m_J+m_I)})a_i^3$$

Note that the radius needs to be converted to meters. Solve for orbital period T.

$$T = \sqrt{\frac{4\pi^2(4.217\times10^8)^3}{6.674\times10^{11}(1.898\times10^{27}+8.932\times10^{22})}} = \boxed{1.529\ \times 10^5 s}$$

2. (3 points) Ganymede is in a 4:1 orbital resonance with Io and Europa is in a 2:1 orbital resonance with Io. Would the inclusion of Ganymede and Europa in the calculations for orbital period increase, decrease or have no effect on the calculated orbital period? Explain.

Solution: Increase. Both Ganymede and Europa have orbits farther from from Jupiter compared to Io, in effect reducing the denominator (which accounts for gravitational force) of our calculation by a small amount. Moons in general have this kind of effect regardless of resonance.

3. (3 points) There is one Newtonian effect of Ganymede on Io's orbital period that is already accounted for in the first calculation. Identify this effect and explain its impact on Io's orbital period.

Solution: The effect is an increased orbital radius of Io, which is already reflected in the measured value. This would serve to increase its orbital period, as is expected by a further distance which would give a lower gravitational pull by Jupiter.

4. (3 points) Ganymede also affects the tidal forces on Io. Tidal acceleration is defined as the difference in gravitational accelerations of the near and far sides of a body. Given the following table of values, to the nearest order of magnitude, calculate the ratio of the strength of the tidal acceleration from Jupiter and the tidal force from Ganymede at its closest to Io. **Show your work** and box your final answer.

Orbital radius of Ganymede (a_G)	1.070×10^6 km
Mass of Ganymede (m_G)	1.482×10^{23} kg
Radius of Io (r_I)	1.822×10^3 km

Solution: Gravitational acceleration $= \frac{GM}{r^2}$ To get an order of magnitude estimate of the ratio of these forces we can take the ratio of the masses and multiply by the ratio of the squares of the distances (two significant figures is sufficient): $\frac{1.9\times10^{27}}{1.5\times10^{23}}\frac{10.7-4.2}{4.2}^2$ 10^4

The exact calculations are below.

For Ganymede: $6.674 \times 10^{11} * 1.4819 \times 10^{23}(\frac{1}{1.070\times10^9-4.217\times10^8-1.822\times10^6} - \frac{1}{1.070\times10^9-4.217\times10^8+1.822\times10^6}) =$ 85.75 m/s

For Jupiter: $6.674 \times 10^{11} * 1.898 \times 10^{27}(\frac{1}{4.217\times10^8-1.822\times10^6} - \frac{1}{4.217\times10^8+1.822\times10^6}) = 2.595 * 10^6$ m/s

Dividing these we get 10^4

5. (4 points) The Moon and Io are both tidally locked with their parent body, yet the Moon shows little recent volcanic activity and Io is the most volcanically active body in the solar system. Account for this discrepancy, and give a brief justification for your claim.

Solution: Tidal volcanism is not driven by tidal forces but changes in tidal forces that drive deformation in the body. The Moon observes a nearly constant magnitude and direction of tidal force from the Earth. Io is similarly affected Jupiter but is subjected to tidal forces from two other moons in orbital resonance with it.

Section II: Problem 2

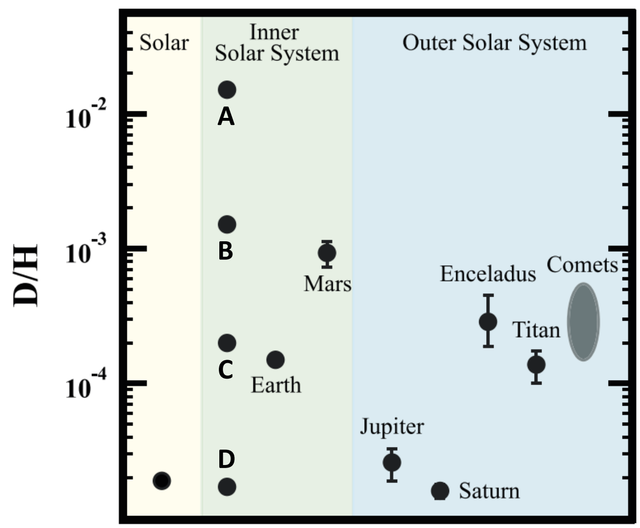
Question	1	2	3	4	5	Total
Points	1	4	4	3	3	15 (30%)

Recent research has suggested that Venus was formerly a habitable, temperate planet like Earth. The shift to its current state is thought to have occurred during a global resurfacing event, where immense volcanic activity covered most of the surface in lava and caused a runaway greenhouse effect.

1. (1 point) Identify a change in the composition of Venus's atmosphere that would result from a resurfacing event.

Solution: Volcanic activity typically releases gases such as carbon dioxide and sulfur dioxide.

Consider the chart below. The y-axis measures the ratio of deuterium (an isotope of hydrogen with one extra neutron) compared to normal hydrogen.



2. (a) (2 points) Which of the following most likely represents the evolution of Venus's D/H ratio from before its resurfacing event to now? (*Hint: consider how atmospheric gases might be lost to space.*)
   - A. A to C
   - **B. C to A**
   - C. B to D
   - D. D to B

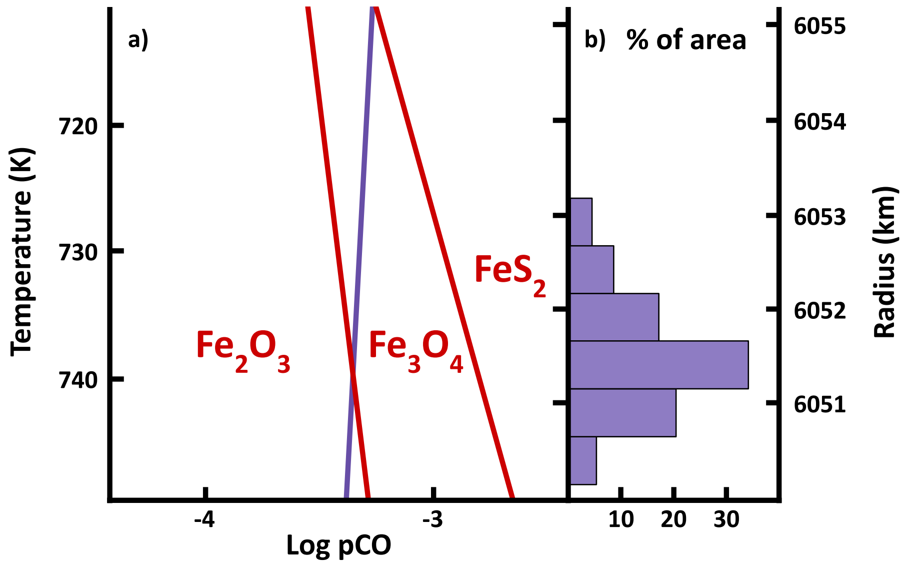
   (b) (2 points) Briefly explain your answer above.

Solution: A high D/H ratio typically indicates more H has been lost to space, as light hydrogen is preferentially lost compared to deuterium. Venus's initial state likely would have been comparable to Earth. After resurfacing, Venus is thought to have increased rapidly in temperature, vaporizing any water and allowing it to escape easily, resulting in an increase in the D/H ratio.

The evolution of Venus's atmosphere is thought to be controlled by a geochemical buffer on the surface. A possible chemical equation for this system is as follows:

$$2\,Fe_3O_4 + CO_2 \rightleftharpoons 3\,Fe_2O_3 + CO$$

Consider the figure below. Chart (a) shows the stability ranges of various minerals (red) defined by the partial pressure of carbon monoxide (pCO) and altitude (represented by corresponding temperatures K), with the approximate atmospheric conditions shown in purple. Chart (b) shows the relative distribution of land area on Venus by altitude. Both charts have the same y-axis scale.



3. (4 points) Using the figure, describe how the composition of the iron oxides on Venus's surface may have changed due to resurfacing. In your answer, consider the pre-resurfacing composition, post-resurfacing composition, and the variation with altitude.

> **Solution:** It is expected that Venus's state prior to resurfacing was dominated by magnetite with some pyrite in highlands. A vast amount of CO_2 was released during resurfacing, shifting equilibrium to the right and changing magnetite into hematite. However, this change primarily took place in the lowlands, as this was the only region with a high enough temperature for hematite to be stable. Resurfacing also significantly increased surface temperature, promoting hematite stability.

4. (3 points) Notice that pCO in Venus's atmosphere increases slightly with altitude. Given this, predict the effect of latitude on surface pCO as a result of planetary atmospheric circulation.

> **Solution:** CO concentrations increase with latitude. On Venus, two Hadley cells move air upwards at the equator and downwards at the poles. Downward movement would bring air to the surface from higher altitudes, which would contain more CO. In contrast, upward movement at the equator would prevent CO-rich air from reaching the surface.

5. Venera 14 visited Venus and recorded some data about the surface lithology. The probe discovered very fine layering in the rock thin enough to approach the maximum image resolution of its cameras. The probe also found that the rock was unusually weak.

   (a) (2 points) Propose a method of formation for this rock that explains Venera 14's observations.

Solution: This rock likely formed from weak compaction of aeolian sediments on the Venusian surface. This may be typical sediments (e.g. from weathering of basalts), similar to loess deposits, or volcanic ash and debris, similar to tuff.

(b) (1 point) Which of the following minerals would likely be most prominent in this rock?

A. Pyrite

B. Magnetite

C. Hematite

Solution: Sediment deposition would most likely occur in lowlands, where hematite is more stable than magnetite or pyrite.