USESO 2024

Training Camp Exam

Free-Response

Instructions:

- Section II consists of 5 multipart problems that further assess geoscience knowledge predominantely in the form of free-response questions.
- You have 2 hours and 15 minutes to complete this section.
- Any type of calculator is allowed.
- Participating in this exam is agreement to our Academic Integrity Policy.

Problem 1

Question	1	2	3	4	Total
Points	4	3	6	7	(20%)

This problem explores several aspects of clay minerals and their effect on climate and the environment.

1. Two of the most common types of clays are illite and smectite. These two minerals have similar structures, an example of which is shown below.

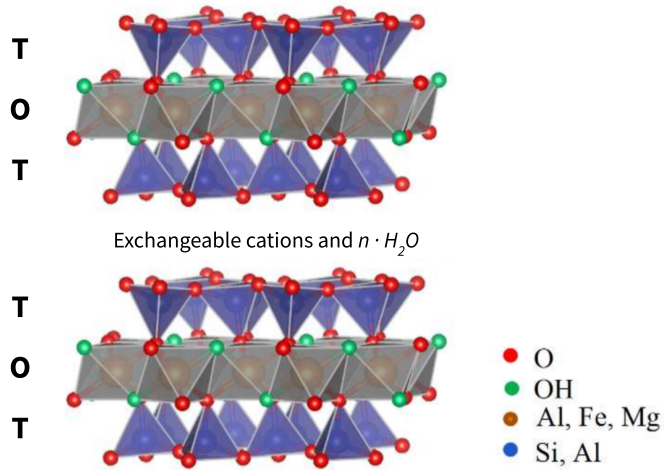

Figure 1: The tetrahedral-octahedral-tetrahedral structure common to illites and smectites.

The primary difference between these minerals is the presence of substitutions within the mineral. The sheets in illites generally have strong negative charges because cations with smaller charges substitute into the structure, most commonly Al^{3+} for Si^{4+} and Mg^{2+} for Al^{3+}. This substitution occurs to a lesser extent overall in smectites.

(a) (2 points) Cation exchange capacity (CEC) refers to the ability of cations to enter and leave a mineral. In clays, this exchange primarily occurs in the region between mineral layers. A high CEC allows clays to supply important nutrients to plants. Would illites or smectites be better for growing plants in soil? **Explain.**

(b) (2 points) A geologist isolates two samples of clays and identifies the relative presence of various elements in its structure. Their results are represented below.

Element	**Sample A**	**Sample B**
Si	7.82	6.40
Al (substituted)	0.18	1.60
Al (base)	2.92	3.25
Fe	0.60	0.40
Mg	0.48	0.35
Ca	0.10	0.05
Na	0.16	0.10
K	0.35	1.45

Which sample is composed of illite and which is composed of smectite? **Explain.**

2. (3 points) These minerals can be compared to talc, another sheet-based silicate with a similar T-O-T structure.

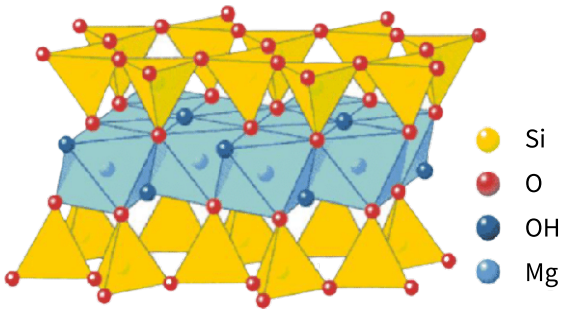

Figure 2: The structure of a single layer of talc, $Mg_3Si_4O_{10}(OH)_2$.

Pure talc is uniquely soft because it has weak intermolecular forces between layers. **Explain** how substitutions within the mineral's layers, such as Na^+ replacing Mg^{2+} in the middle layer, would affect talc's hardness **and** one other property.

3. Clays are secondary minerals formed from the weathering of primary minerals, one of the major drivers of changes in climate on Earth. Researchers recently simulated a small change in Earth's surface composition and found that it increased carbon burial by nearly 50%. Their results are shown below.

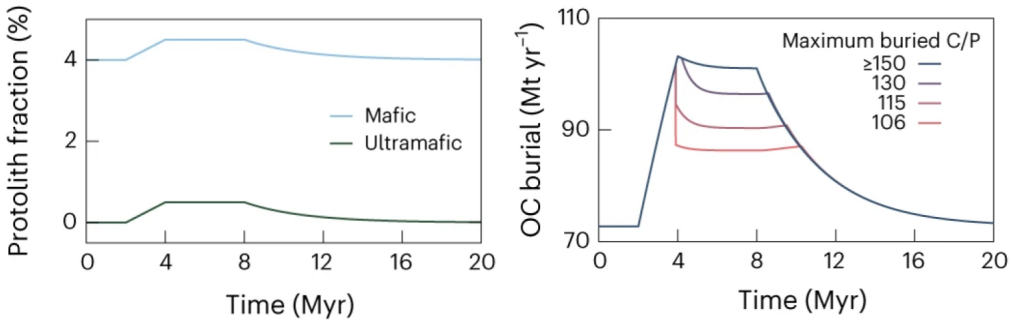

Figure 3: Simulation of surface composition change and the resulting effect on organic carbon (OC) burial. Adapted from Murray & Jagoutz 2024.

One carbon sequestration feedback involves ions like Ca^{2+} and Mg^{2+} entering the ocean after being released by weathering. One equation for the release of these ions, involving the weathering of Mg-rich olivine to form a clay mineral, is as follows:

$$8\,Mg_2SiO_4 + 2\,(Al^{3+}, Fe^{3+}) + 26\,H^+ \longrightarrow Mg_2 \cdot 7\,(Al, Fe)_2Si_8O_{20}(OH)_4 + 13.3\,Mg^{2+} + 8\,H_2O + 6\,H^+$$

(a) (2 points) **Briefly explain** how ions like Ca^{2+} and Mg^{2+} result in carbon sequestration when they enter the ocean.

(b) (2 points) **Briefly explain** why the weathering of felsic minerals would be unlikely to result in the process described in part (a).

(c) (2 points) Despite the small change in composition, the study predicted a 40% increase in average clay mineral surface area, allowing them to absorb more carbon and increase direct carbon burial. **Explain** why mafic and ultramafic minerals account for an unusually large proportion of clay mineral formation.

4. The Middle Eocene Climatic Optimum (MECO) was an extended warming period about 40 million years ago. Recent research suggests that this warming caused a transition from *congruent* weathering, involving the complete dissolution of primary minerals into ions, to *incongruent* weathering, leaving some remnants of secondary clay minerals.

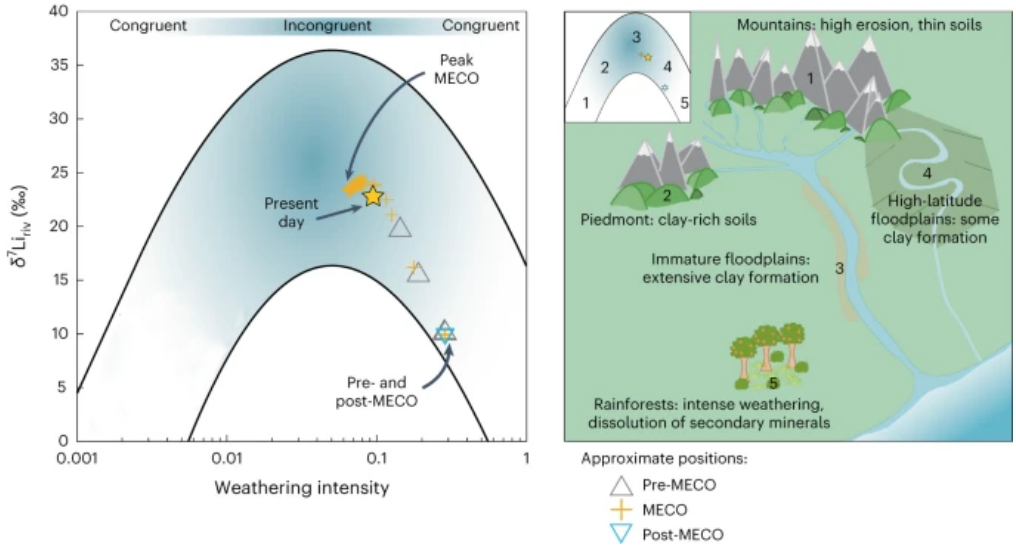

Figure 4: A shift in weathering intensity caused a transition to incongruent weathering, associated with high riverine ^{7}Li concentrations, during the MECO. "Weathering intensity" equals $\frac{W}{W+E}$, where W is the rate of weathering and E is the rate of erosion. Adapted from Krause et al. 2023.

Based on Figure 4, the chemical equation given in question 3, and your answers to parts 3(a) through (c), answer the following three questions:

(a) (1 point) Which of the following most likely describes typical conditions on Earth both before and after the MECO?

A. High sea levels and dry climates

B. High sea levels and wet climates

C. Low sea levels and dry climates

D. Low sea levels and wet climates

(b) (4 points) Does the shift in weathering conditions during the MECO constitute a positive or negative feedback loop? **Explain.**

(c) (2 points) Based on the present-day conditions labeled in Figure 4, if a shift in the same direction occurred today, would it constitute a positive or negative feedback loop? **Explain.**

Problem 2

Question	1	2	3	4	Total
Points	7	5	5	3	20 (20%)

This problem explores the structures, compositions, and effects of two Paleogene intrusions in North America.

The first intrusion is the Bungalow pluton, a **felsic** intrusion near the Idaho-Montana border. The intrusion formed throughout the Paleocene and Eocene and contains biotite-rich granite and granodiorite.

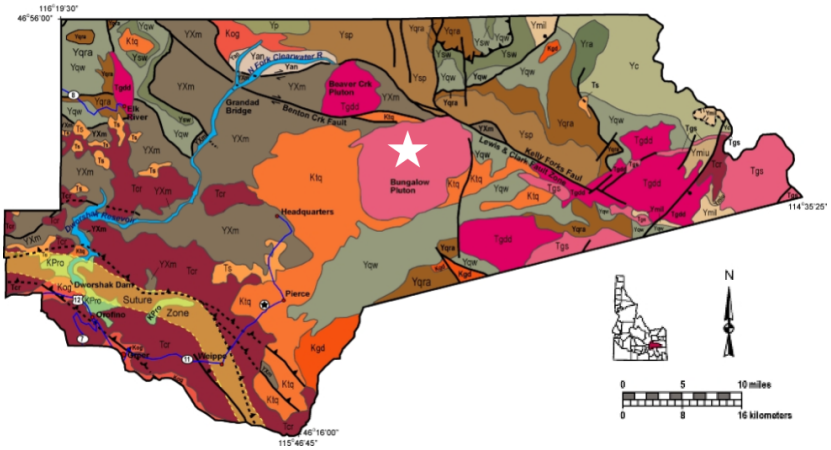

Figure 1: Map of the Bungalow pluton (marked by a white star) and the surrounding area. Adapted from the Digital Atlas of Idaho.

The second intrusion is the Skaergaard intrusion, a **mafic** intrusion on the eastern coast of Greenland that formed during the late Paleocene. The intrusion formed within a plateau of basalt and gabbro and is one of the largest mafic intrusions in the world.

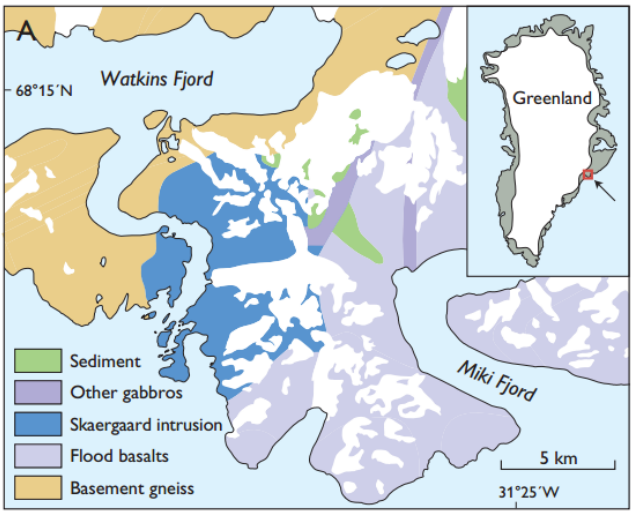

Figure 2: Map of the Skaergaard intrusion (dark blue) and surrounding area. Adapted from Nielsen 2016.

1. The image below shows two thin sections, one found in each intrusion. Sample A, seen in plane-polarized light below, contains augite (Aug), magnetite (Mag), and plagioclase (Pl). Sample B, seen in cross-polarized light below, contains quartz (Qz) and plagioclase.

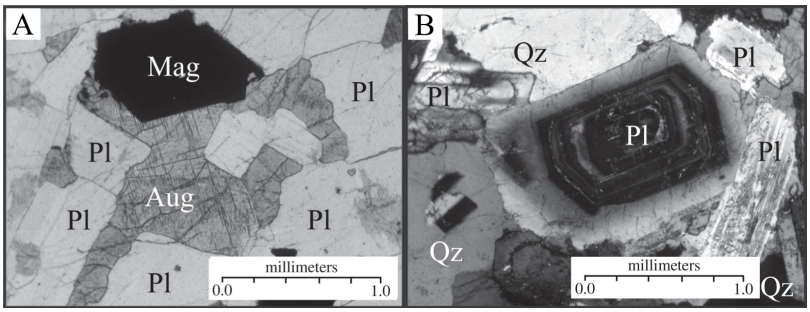

Figure 3: Thin sections from the Bungalow pluton and Skaergaard intrusion. Adapted from *Essentials of Igneous and Metamorphic Petrology* by Robert and Carol Frost.

(a) (1 point) **Identify** which thin section came from the Bungalow pluton and the Skaergaard intrusion, respectively.

(b) **Identify** whether each of the following statements are true or false. **Explain** your reasoning.

i. (2 points) Magnetite is generally more euhedral than plagioclase.

ii. (2 points) Sample B formed in a magma chamber with weak convection.

iii. (2 points) The plagioclase in Sample B is isotropic.

2. Since the Bungalow pluton and Skaergaard intrusion are approximately the same size, their differences in formation and composition can be directly compared.

(a) (3 points) **Briefly describe** one reason why intrusions near the surface often have a felsic or intermediate composition. Why would the presence of large flood basalts surrounding the Skaergard intrusion make it more likely to be mafic?

(b) (2 points) When they reached the upper crust, would the Bungalow pluton or Skaergaard intrusion likely have resulted in greater planetary warming? **Explain.**

3. The Skaergaard intrusion is separated into several distinct layers as shown below.

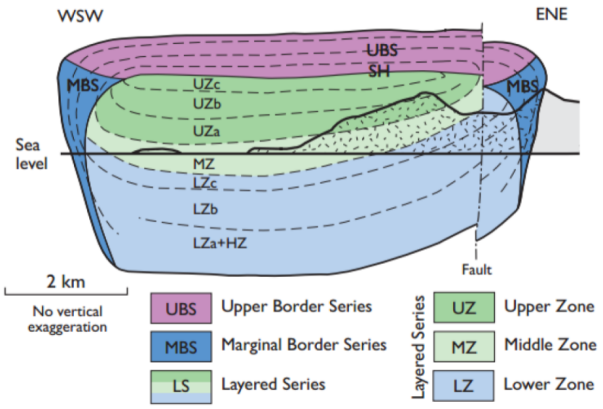

Figure 4: Cross-section of distinct layers within the Skaergaard intrusion. Adapted from Nielsen 2016.

(a) (1 point) A core is drilled in the center of the intrusion to collect samples from the entire Upper Border Series and Layered Series. Which of the following best describes how the silica content of the intrusion changes as the depth of the core increases?

A. Uniformly increases

B. Uniformly decreases

C. Increases, then decreases

D. Decreases, then increases

(b) (2 points) **Justify** your answer to the previous question.

(c) (2 points) Notice that much of the Skaergaard intrusion is currently above sea level and exposed to the surface. **Propose a mechanism** by which the intrusion may have been uplifted from its original position.

4. (3 points) To study the effects of each intrusion on the surrounding rock, researchers collect hornfel samples at the same distance away from each intrusion. Sample C, seen in plane-polarized light below, contains epidote and chlorite crystals in a groundmass composed mostly of muscovite and quartz. Sample D, seen in cross-polarized light below, contains andalusite and cordierite crystals in a groundmass composed mostly of biotite.

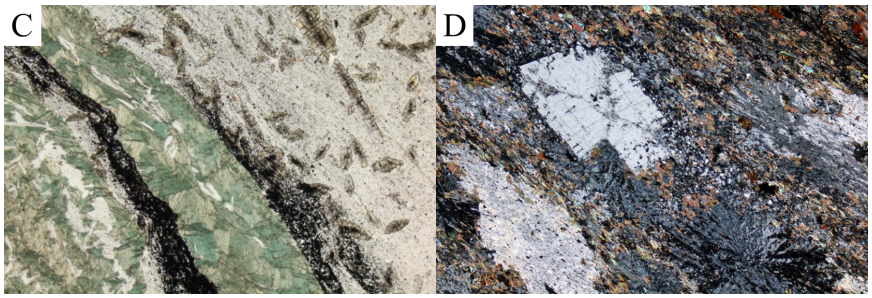

Figure 5: Samples from aureoles surrounding the Bungalow and Skaergaard intrusions. Adapted from Alessandro Da Mommio.

Based on the conditions necessary for these samples to form, which sample likely comes from the Bungalow pluton and Skaergaard intrusion, respectively? **Explain.**

Problem 3

Question	1	2	3	4	Total
Points	3	5	4	8	20 (20%)

This problem explores various aspects of tropical weather and climate.

1. The El Niño-Southern Oscillation (ENSO) has wide-ranging impacts on the tropical atmosphere.

   (a) (1 point) **Identify** the effects of El Niño conditions on vertical wind shear **and** hurricane activity over the Atlantic Ocean.

   (b) (2 points) The effect of El Niño on Hadley cell strength has been found to be zonally asymmetric (i.e. varying across longitudes). Abbreviate the central/eastern Pacific Hadley cell as CEHC and the western Pacific Hadley cell as WPHC. **Describe** the effect of El Niño conditions on the CEHC **and** WPHC. **Justify** your answer.

2. Some coupled climate models tend to exhibit biases in sea-surface temperature (SST).

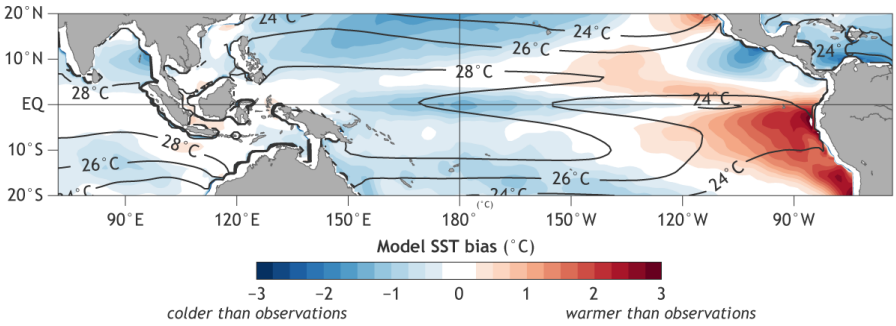

Figure 1: Diagram of model sea surface temperature and bias. Adapted from NOAA.

(a) (2 points) Compared to observations, models likely show greater _____ of eastern Pacific surface winds and a(n) _____ anomaly in central Pacific 200 hPa winds.

A. convergence; easterly

B. convergence; westerly

C. divergence; easterly

D. divergence; westerly

(b) (3 points) Marine stratocumulus (Scu) clouds are flat, low-level clouds that typically require an inversion to form, as shown in the sketch below.

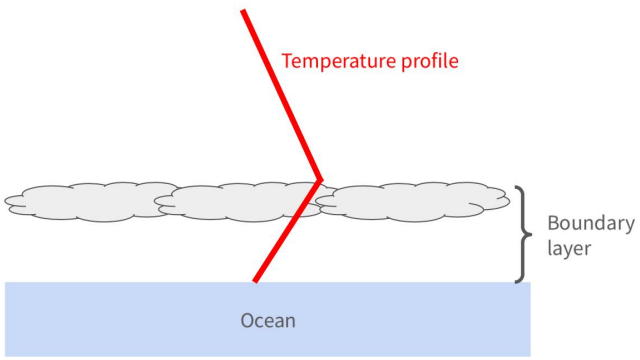

Figure 2: Sketch of Scu clouds and a temperature inversion above the ocean.

A lack of Scu clouds is projected in some coupled models with a warm SST bias. Consider the effect of removing some Scu clouds from the sketch above, which would result in a feedback loop. **Describe** the steps of this loop and **classify** the loop as either positive or negative. *(Hint: how would boundary layer mixing change?)*

3. The Madden-Julian Oscillation (MJO) is an intraseasonal oscillation in the tropics that consists of a propagating disturbance with a dipole structure. The following time versus longitude plot shows anomalies (shaded) in outgoing longwave radiation (OLR) associated with the MJO, averaged from 15°S to 15°N. The green and purple contours may be ignored.

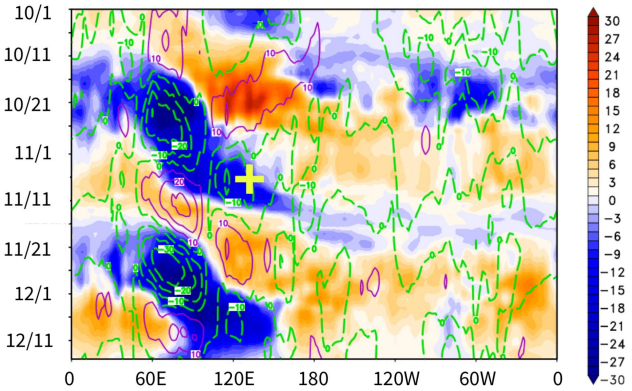

Figure 3: Plot of OLR anomalies from early October to mid-December. Adapted from Sahai et al. 2016.

(a) (1 point) From the figure, identify the direction of propagation and estimate the period of the MJO.

A. Westward, 30-40 days

B. Westward, 50-60 days

C. Eastward, 30-40 days

D. Eastward, 50-60 days

(b) (3 points) Consider the yellow cross labeled above at 135°E (around the western Pacific) on November 6, 2011. Based on the plot, **explain** whether there would likely be a risk of drought or flooding at this location and time. Would an ongoing La Niña at this time enhance or reduce this risk?

4. Tropical cyclones are key features of the tropical atmosphere and climate system.

(a) (2 points) Consider the following satellite image of Hurricane Frances approaching the east coast of Florida. The direction of the storm is shown and several locations are labeled.

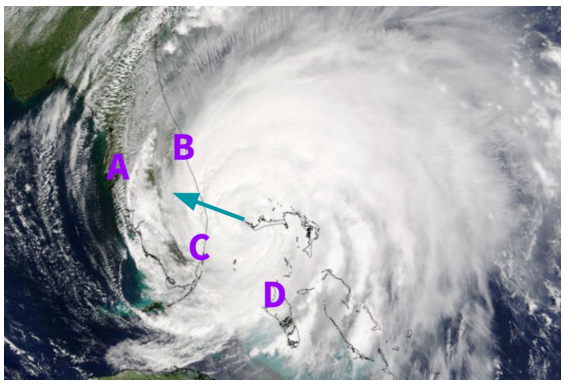

Figure 4: Satellite image of Hurricane Frances. Adapted from NASA Earth Observatory.

Which of the following statements is/are true?

I) Southwest winds are blowing at A

II) Over the next several hours, the greatest increase in storm surge risk occurs at C

III) The pressure tendency (rate of pressure change) is positive at D

A. I only

B. II only

C. III only

D. I and II

E. II and III

(b) (1 point) Which of these, if any, is/are true about lapse rates in tropical cyclones?

I) The environmental lapse rate is typically less than the moist adiabatic lapse rate

II) Above the lifting condensation level (LCL), the lapse rate of an air parcel increases with height

A. I only

B. II only

C. I and II

D. None

(c) (2 points) High concentrations of dust aerosols can inhibit tropical cyclone formation. For a given amount of moisture present, **explain** how increasing dust concentration prevents the formation of raindrops. As part of your response, **indicate** how the equilibrium vapor pressure of droplets would be affected.

(d) (2 points) **Explain** how reducing the translation speed (forward motion) of a tropical cyclone over the ocean may change its intensity by affecting the flow of underlying ocean currents.

(e) (1 point) A recent study found a relationship between tropical cyclone rain rate and translation speed.

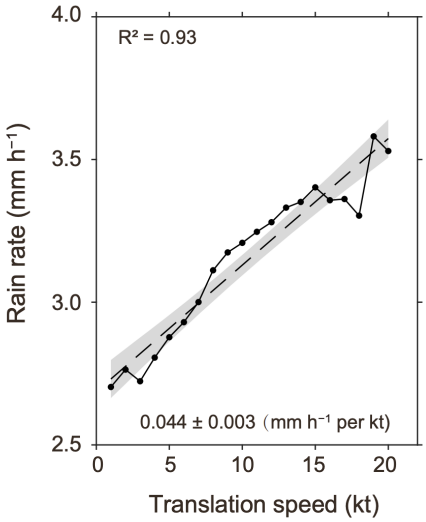

Figure 5: Graph of tropical cyclone rain rate versus translation speed. Adapted from Tu et al. 2022.

Based on the figure, **describe** the implications this relationship has on the total precipitation that a location would experience as translation speed varies. Disregard the effect of other factors such as storm size.

Problem 4

Question	1	2	3	4	5	Total
Points	5	2	5	4	4	20 (20 %)

This problem explores several aspects of lakes.

1. A lake in the shape of a trapezoidal prism with volume 3.1×10^9 m^3 is shown below. Assume that the dominant source of water inflow and outflow is through two circular openings with radius $r = 2.6$ m and $v_{\text{in}} = v_{\text{out}} = 0.08$ m/s.

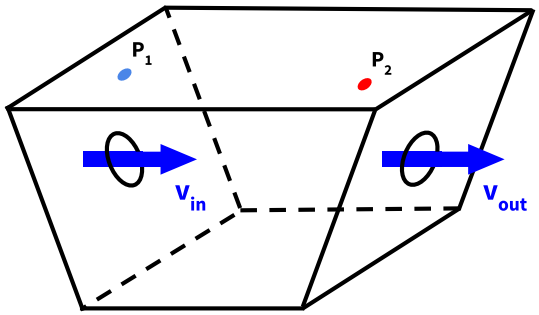

Figure 1: Diagram of a lake in the shape of a trapezoidal prism.

   (a) (2 points) A pollutant is added to the lake at a rate of 220 kg/day. Given that the pollutant is soluble in water and mixes uniformly throughout the lake, **calculate** the steady-state concentration in ppm that the pollutant would reach. **Show your work.** (Note: 1 kg/m^3 = 1000 ppm.)

   (b) (1 point) Now assume that the lake loses water through evaporation. If v_{in} stays the same while v_{out} decreases to 0.06 m/s and the lake remains in equilibrium, **calculate** the new steady-state concentration in ppm that the pollutant would reach. **Show your work.**

   (c) (2 points) If the surrounding water table slopes toward the lake, **explain** how an increase in hydraulic conductivity would likely affect the pollutant concentration.

2. (2 points) A hydrologist records a periodic oscillation in water level at two points on the surface of the lake (labeled P_1 and P_2 in Figure 1). Their data is displayed below.

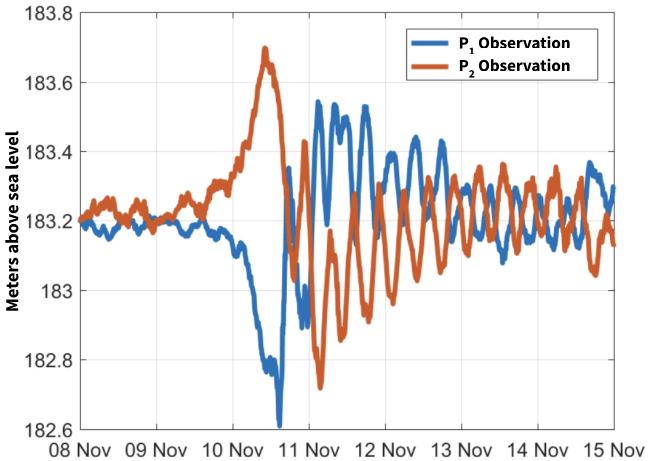

Figure 2: Graph of water level versus time. Adapted from Jay Austin, UMN Duluth.

Explain why the water why the oscillations maintain a constant period despite gradually decreasing in amplitude.

3. Lake Furnas is a warm monomictic lake (mixing once annually in winter) located on an island in the North Atlantic. A chemical tomography of Lake Furnas and a map of the surrounding region are provided below. The bright yellow asterisks on the lake's surface in Figure 3a represent flares of highly concentrated CO_2.

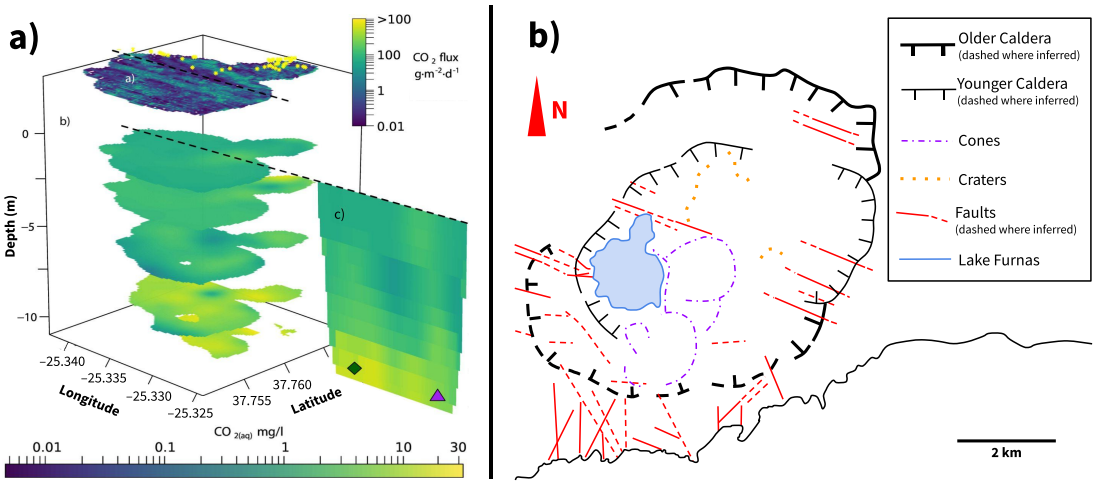

Figure 3a: Chemical tomography of Lake Furnas revealing the spatial distribution of CO_2. Adapted from Tamburello et al. 2024. **Figure 3b**: Map of the region surrounding Lake Furnas. Adapted from Guest et al. 1999.

(a) (2 points) **Describe** the likely mechanism responsible for producing these flares.

(b) (1 point) Are the subsurface structures of these flares better represented by the region above the green diamond or purple triangle in Figure 3a?

A. Green diamond, because the concentration of CO_2 is greater at depth

B. Purple triangle, because the concentration of CO_2 is lower at depth

C. Green diamond, because the concentration of CO_2 near the surface and at depth are relatively different

D. Purple triangle, because the concentration of CO_2 near the surface and at depth are relatively similar

(c) (2 points) **Explain** what general direction you would expect the flares to align. Give your answer in degrees clockwise from north (e.g. an east-west alignment could be indicated as either 90°or 270°).

4. To better understand the structure of Lake Furnas, a scientist creates several profiles of its waters as shown below.

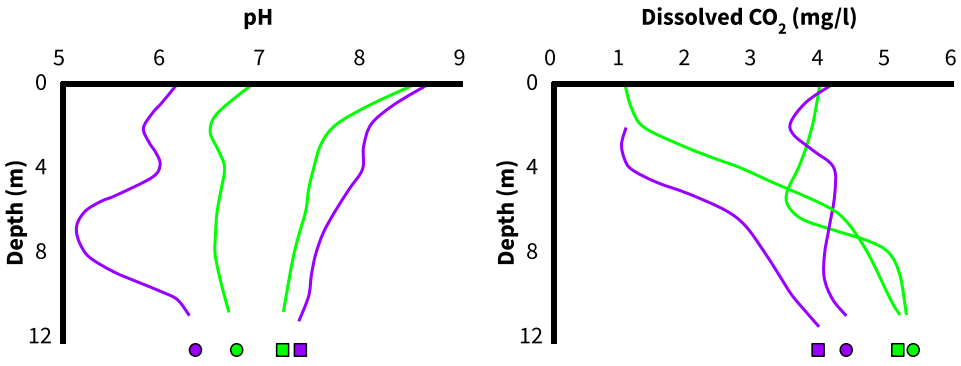

Figure 4: Profiles of pH and dissolved CO_2 for Lake Furnas. Lines marked with the same shape correspond to the same month of sampling; lines of the same color correspond to the same sampling location. Adapted from Andrade et al. 2016.

(a) (2 points) Were samples for the lines marked with squares most likely taken closer to May or November? **Justify** your answer using the mixing regime of the lake.

(b) (2 points) Were samples for the lines colored green most likely taken from a location in the northern, southwestern, or southeastern region of the lake? **Justify** your answer.

5. High-activity, hyperacidic volcanic lakes are conventionally considered to be perfectly mixed reservoirs due to consistent heating provided by the volcanic source. However, a separate model explores the possibility of these lakes being stratified as shown in Layer A in the diagram below.

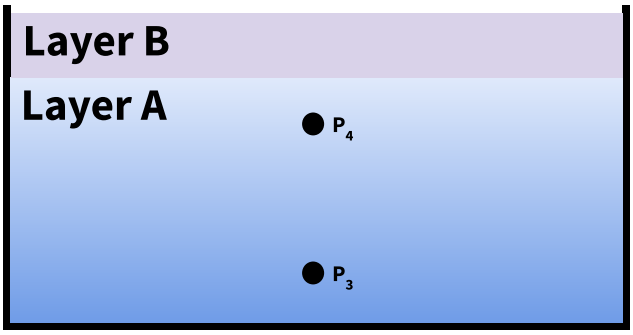

Figure 5: A simplified cross-section of a high-activity volcanic lake.

(a) (1 point) Assume that Layer A is in equilibrium. Compared to water at P_3, water at P_4 has a _____ temperature and _____ salinity.

A. higher; higher

B. higher; lower

C. lower; higher

D. lower; lower

(b) (2 points) A burst of heavy rain falls upon the lake and forms Layer B as depicted in Figure 5. Given that chemical diffusion within the lake occurs at a significantly faster rate than thermal conduction, **explain** how the stability of the lake's stratification would likely change shortly afterward. *(Hint: Consider how the formation of rainwater in the atmosphere influences its properties.)*

(c) (1 point) If this model is correct, **identify** a new hazard people living near high-activity volcanic lakes might face.

Problem 5

Question	1	2	3	4	5	Total
Points	4	2	7	3	4	20 (20 %)

This problem explores various aspects of planet formation.

1. (4 points) Asteroids can provide clues about the nature of primitive solar system material. Consider an asteroid on an elliptical orbit observed at a distance of 1.92 AU from the Sun. Using the table below, **calculate** the velocity of the asteroid in m/s given that the total energy of its orbit may be expressed as $\frac{-GMm}{2a}$, where a is the semi-major axis of the orbit. **Show your work.**

Gravitational constant (G)	6.67×10^{-11} N $\cdot$ m^2/kg^2
1 AU	1.50×10^{11} m
Mass of Sun (M)	1.99×10^{30} kg
Mass of asteroid (m)	4.80×10^{16} kg
Semi-major axis (a)	2.51 AU

2. (2 points) Consider the model of planet formation displayed below.

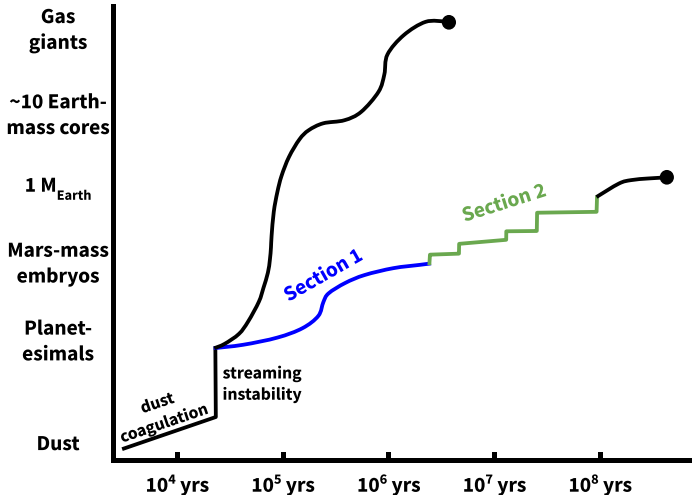

Figure 1: A model of planet formation. Adapted from Raymond & Morbidelli 2022.

Briefly describe the difference between the mechanisms responsible for the increases in mass along Section 1 versus Section 2.

3. As seen in Figure 1, the coagulation of dust plays a critical role in early planetary development. However, the surrounding gas exerts a drag force on the dust that causes it to drift inward within the protoplanetary disk, disrupting planet formation by accreting dust to the central star instead of growing planet embryos.

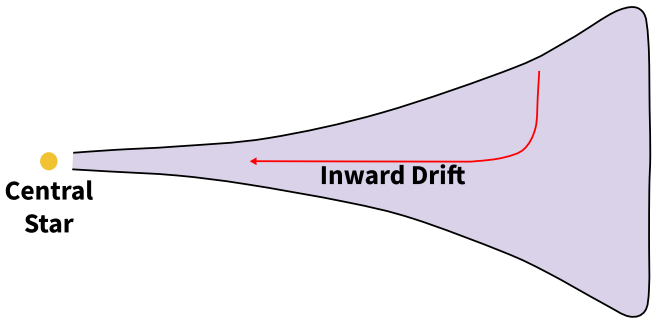

Figure 2: Simplified schematic showing the motion of a small dust particle experiencing inward drift toward the central star. Adapted from C.P. Dullemond, Universität Heidelberg.

(a) (3 points) Using only gas density (ρ), change in pressure (ΔP), and change in radial distance (Δr), **write an expression** for the force exerted on gas particles per unit mass (f_{gas}) by the radial pressure gradient within the protoplanetary disk.

(b) (2 points) Small dust particles are not significantly influenced by f_{gas}. Considering how this affects their relative motion within the protoplanetary disk, **explain** whether small dust particles accumulate at local minimums or maximums in pressure.

(c) (2 points) The efficiency of the dust's motion with respect to gas is controlled by the Stokes number (St), which is calculated by dividing a dust particle's stopping time (the time taken for the particle's velocity to adjust to that of the surrounding gas) by orbital period. **Explain** why dust particle size can be used as a proxy for St and **indicate** whether a low St corresponds to smaller or larger particles.

4. The streaming instability is a mechanism for seeding planetesimal formation that occurs after dust coagulation. Four panels depicting the evolution of this instability through time are displayed below.

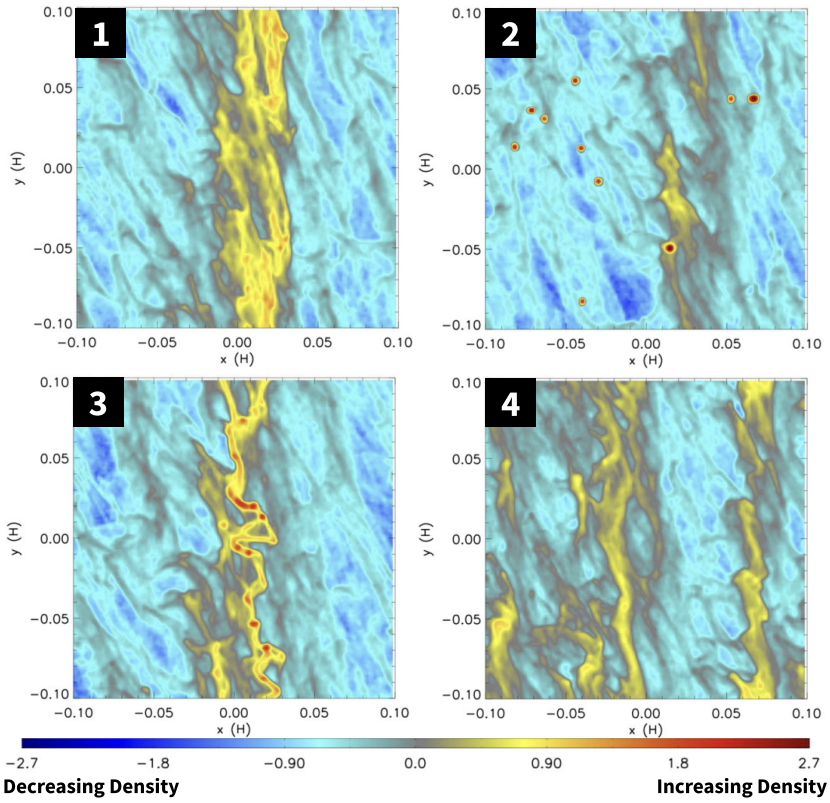

Figure 3: Panels depicting evolution of the streaming instability with color gradient correlating to vertically integrated surface density. Adapted from Simon et al. 2016.

(a) (2 points) **Order** the panels chronologically from the first to last to form and **briefly explain** your answer. Format your ordering as a string of numbers (e.g. "1234").

(b) (1 point) **Identify** the first panel in which the developing planetesimals exhibit self-gravitation. Format your answer as a single number.

5. There are multiple hypotheses that explain how Earth may have acquired water during its formation. One such hypothesis involves a mechanism termed "pebble snow" and is depicted below.

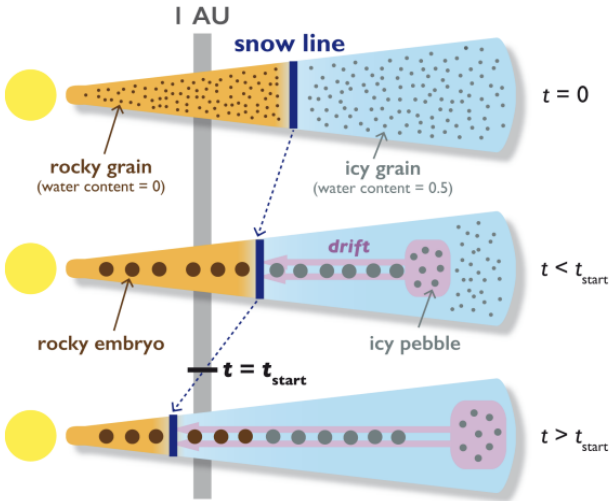

Figure 4: Snapshots of the evolution of a protoplanetary disk in which water may have been delivered to rocky planets by icy pebbles that drifted inward as the snow line moved closer to the Sun. The pink region represents the location in the disk where icy pebbles grow from dust. Adapted from Meech & Raymond 2019.

Non-carbonaceous and carbonaceous chondrites are two classes of meteorites that are believed to have been formed in the inner and outer solar system, respectively. Earth's water has a deuterium/hydrogen ratio close to that of carbonaceous chondrites, suggesting that they could have delivered water to Earth via pebble snow.

Explain whether each of the following statements support or refute the validity of pebble snow as the dominant source of Earth's water.

(a) (2 points) There are no known classes of chondritic meteorites with compositions that lie between carbonaceous and non-carbonaceous chondrites.

(b) (2 points) As the protoplanetary disk contracted, the radial velocity of retreating gases was greater than the speed at which the snow line moved inward.

END OF FREE-RESPONSE