USESO 2025

Training Camp Exam

Free-Response

Instructions:

- Section II consists of 5 multipart problems that further assess geoscience knowledge predominantly 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	7	2	5	6	(20%)

This problem explores several features in the Himalayan region.

1. A geologist comes across an outcrop of schist in the Himalayas surrounded by phyllite, as shown in Figure 1 below. They determine that the outcrop has been deformed due to the presence of a fold.

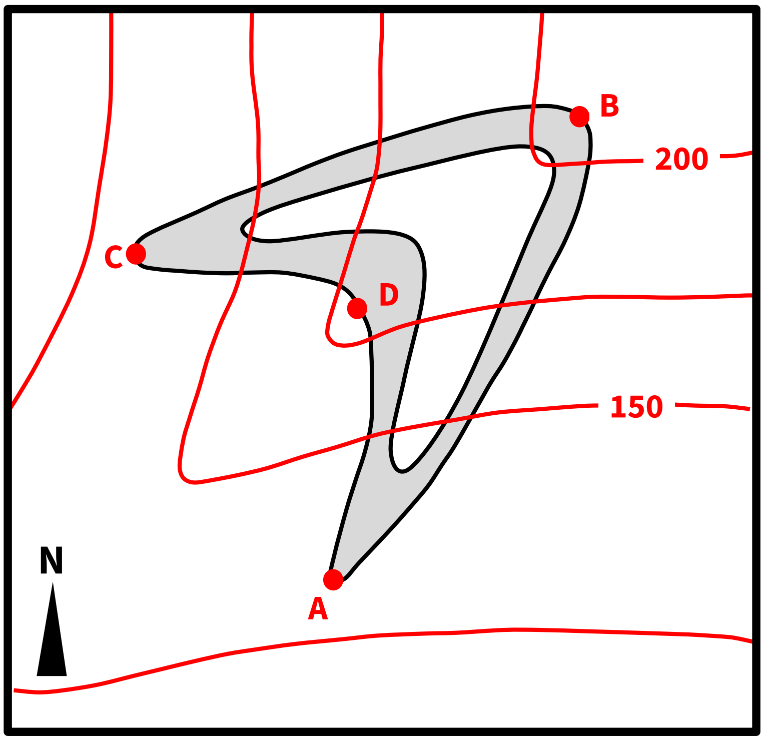

Figure 1: Map view of schist outcrop (gray) contacting with surrounding phyllite (white). Red contours denote the elevation of the local terrain.

(a) (2 points) Notice that the perimeter of the outcrop is curved near each point A-D. At which point(s) on the outcrop is this curving likely due to regional folding rather than effects of the local terrain? **Explain.**

(b) (2 points) What is the strike of the fold's hinge line as viewed from above? Express your answer in azimuthal notation to the nearest 45° and **explain** your reasoning.

(c) (1 point) Is the fold a synform or antiform? **Briefly explain** your reasoning.

(d) (1 point) Given that the outcrop in Figure 1 is located in the Himalayas, **propose a mechanism** that could have created the local surface topography.

(e) (1 point) Does an observer walking from B to D observe a shallower dip angle than an observer walking from B to A? **Briefly explain** your reasoning.

2. (2 points) Rocks in the Himalayas undergo metamorphism due to processes such as folding. One notable region in which metamorphism has occurred is known as the Yardoi gneiss dome, shown below in Figure 2.

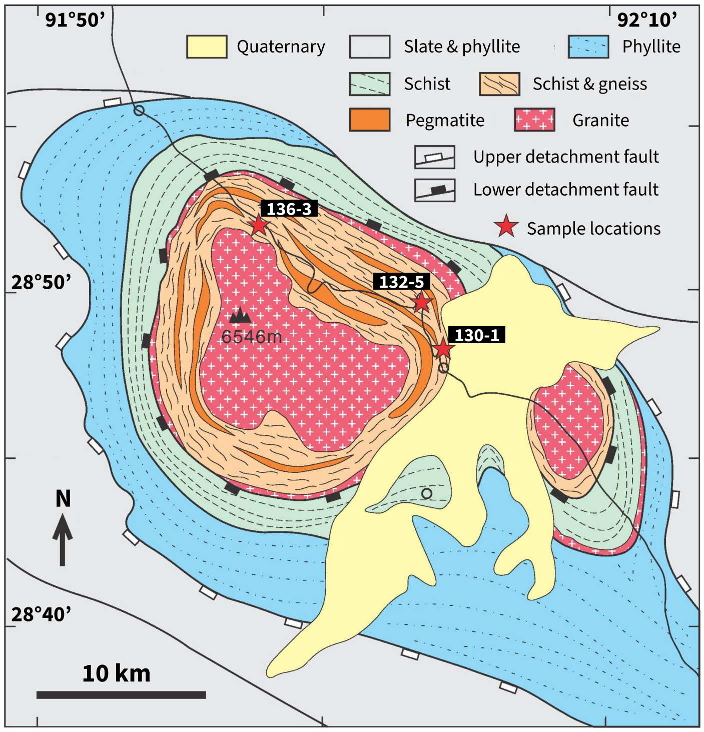

Figure 2: Map view of the Yardoi gneiss dome. Adapted from Ding et al. (2016).

Metamorphic core complexes (MCCs) form in areas where crustal upwelling has occurred, resulting in high-grade metamorphic facies rising beneath a faulted surface layer. If a geologist hypothesizes that the Yardoi dome is an instance of a MCC, what should they propose as the dominant stress (extensional, compressional, or shear) responsible for its occurrence? **Explain.**

3. Geologists collect schist samples at three locations in the Yardoi dome. Photomicrographs of samples 132-5 and 130-1 are shown in Figure 3 below.

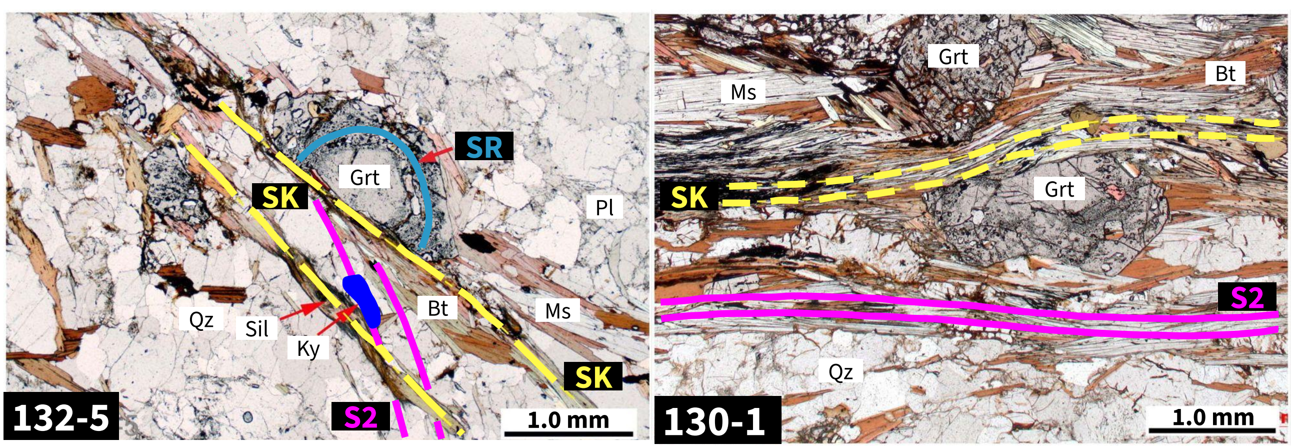

Figure 3: Photomicrographs of sample 132-5 and sample 130-1. Foliation (SR, SK, S2) is marked by lines. The dark blue feature in sample 132-5 denotes a kyanite grain; the elongated dark grain is sillimanite. Mineral abbreviations are as follows: Qz (Quartz), Sil (Sillimanite), Ky (Kyanite), Grt (Garnet), Ms (Muscovite), Bt (Biotite), Pl (Plagioclase). Adapted from Ding et al. (2016).

(a) (2 points) The geologists determine that three stages of deformation occurred in the Yardoi schists associated with a prograde, peak, and retrograde mineral assemblage. They have identified that deformation resulting in the S2 foliation comprised the middle stage. Does the deformation that produced the SR foliation occur before or after the deformation that produced the SK foliation? **Explain.**

(b) (1 point) The geologists plot potential P-T-t paths of the Yardoi schists on Figure 4 below.

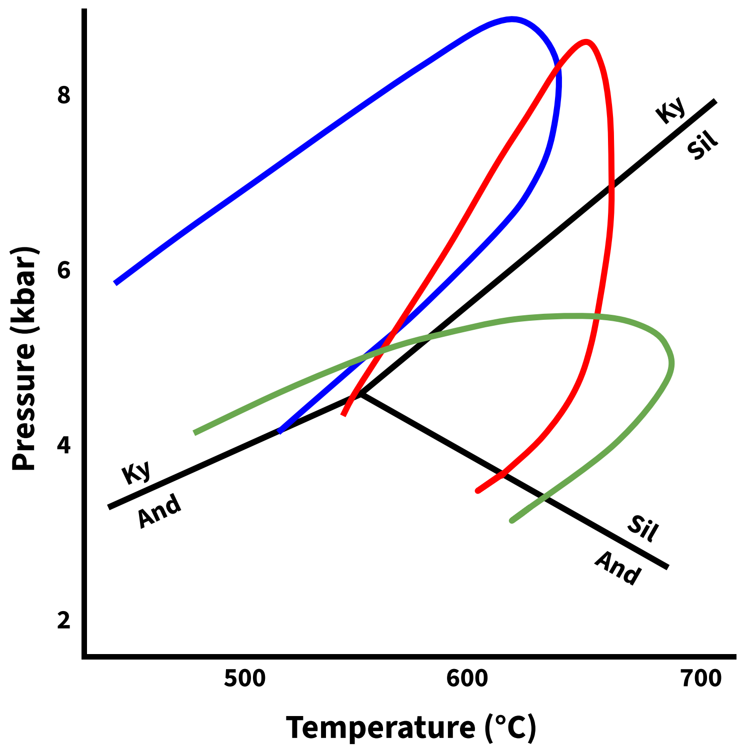

Figure 4: Potential P-T-t paths for schists in the Yardoi dome. Mineral abbreviations are as follows: Kyanite (Ky), Sillimanite (Sil), Andalusite (And).

Which of the following is most likely the correct path and path direction?

A. Blue path, clockwise

B. Blue path, anti-clockwise

C. Red path, clockwise

D. Red path, anti-clockwise

E. Green path, clockwise

F. Green path, anti-clockwise

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

4. The Yardoi dome contains zircons that can be used for radiometric dating. A common technique for dating zircons is to compare both the $^{238}U/^{206}Pb$ and $^{235}U/^{207}Pb$ ratios, which over time evolve along the black curve shown in Figure 5. ^{238}U decays into ^{206}Pb with a half-life of 4.47 billion years; ^{235}U decays into ^{207}Pb with a half-life of 710 million years.

   A group of researchers use Pb/U isotope ratios to determine the age of the Yardoi schists. They plot them against the expected curve and notice some anomalous samples to the right of the curve. After taking more samples from these locations, they identify an anomalous trend, shown in purple in Figure 5.

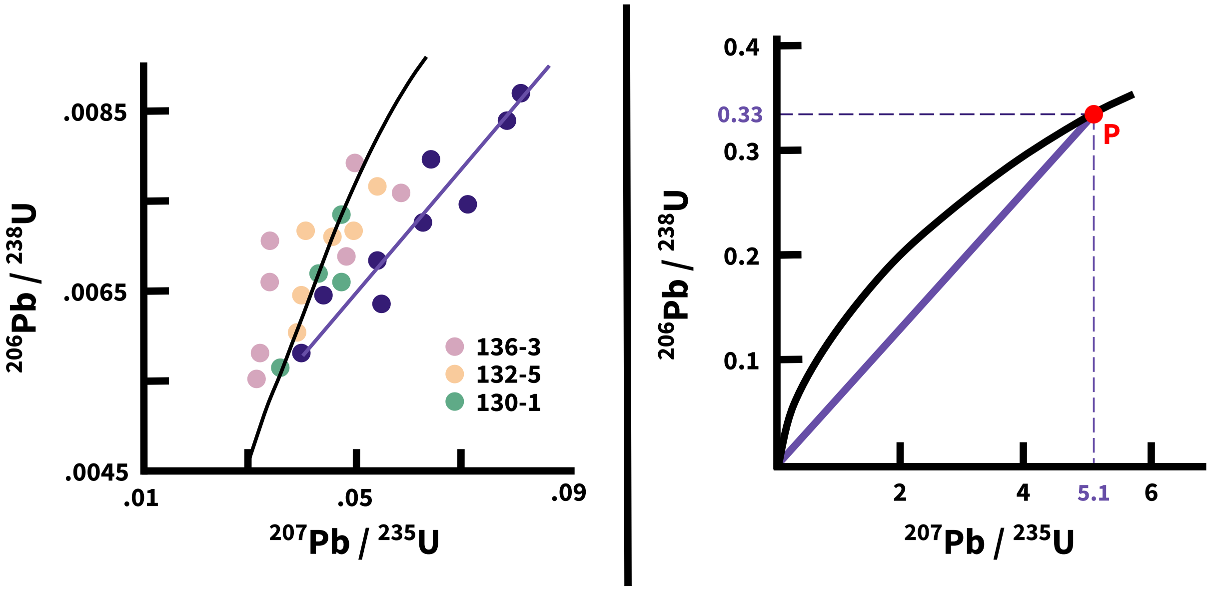

Figure 5: (a) A diagram of Pb/U isotope ratios for the samples collected from the Yardoi gneiss dome. Anomalous samples are shown in purple. Adapted from Ding et al. (2016). **(b)** An extended version of Figure 5(a). The black curve follows the expected evolution of a normal sample; the purple line extends the trend of the anomalous samples.

(a) (2 points) **Explain** why the expected evolution of these two isotope ratios curves to the right.

(b) (2 points) **Describe** a process that could have created the anomalous trend. **What information** can we get from the location of point P in Figure 5(b)?

(c) (2 points) Geologists use multiple isotope ratios in order to confirm their calculated dates. **Estimate** the age of the conditions at Point P and **verify** that both isotope ratios give you a similar answer.

Problem 2

Question	1	2	3	Total
Points	7	8	5	20 (20%)

This problem explores various aspects of weather and climate over land.

1. Conditions favoring wildfire growth can be predicted and projected, and wildfires can have significant impacts on the climate system.

   (a) (2 points) Vapor pressure deficit (VPD), a proxy for fire activity, is defined as the difference between saturation vapor pressure (e_s) and actual vapor pressure (e_a), i.e., VPD $= e_s - e_a$. Under a warming climate and assuming constant relative humidity, the trend in VPD is generally:

      A. Increasing

      B. Decreasing

      C. Unchanging

   (b) (2 points) Based on Figure 1 below, **infer** whether climate models have underestimated or overestimated near-surface VPD. Assume model projections of temperature are accurate. **Justify** your answer.

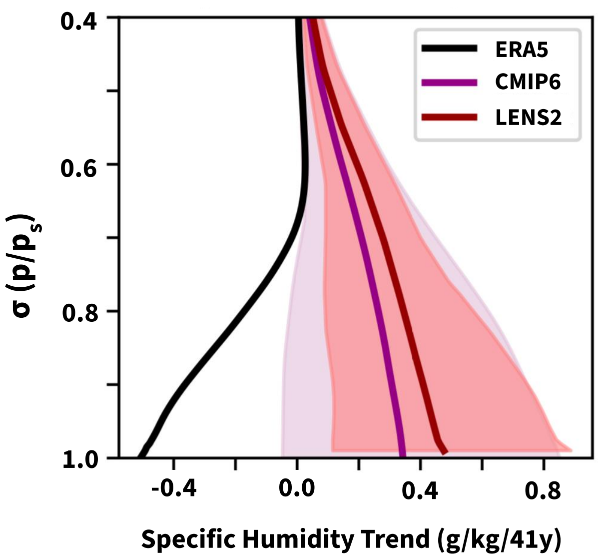

Figure 1: 1980-2020 trend in the specific humidity (grams of water vapor per kilograms of dry air) profile in the southwestern US. The y-axis is the ratio of pressure to surface pressure and the black line (ERA5) shows assimilated observational trends. The purple and red (CMIP6/LENS2) lines show climate model simulated trends; shading indicates model spread. Adapted from Simpson et al. (2024).

(c) (1 point) Seasons of enhanced wildfire activity can be anticipated in advance, as soil moisture anomalies can persist for months, affecting vegetative cover. For the southwestern US, which combination of ENSO states in the preceding winters maximizes wildfire activity in Summer 2?

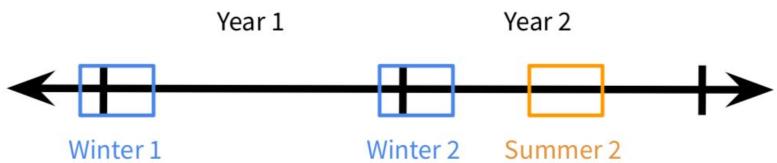

Figure 2: Timeline of Year 1 winter, Year 2 winter, and Year 2 summer.

A. Winter 1: El Niño, Winter 2: La Niña

B. Winter 1: La Niña, Winter 2: El Niño

C. La Niña in both winters

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

2. While uncommon, droughts can and have affected the eastern US.

(a) (2 points) Which of the upper-level maps in Figure 2 favors drought over the eastern US if the pattern persists? What is the sign of the ω anomaly over point B? (Note that $\omega \approx \Delta p/\Delta t$, the rate of change of pressure of an air parcel.)

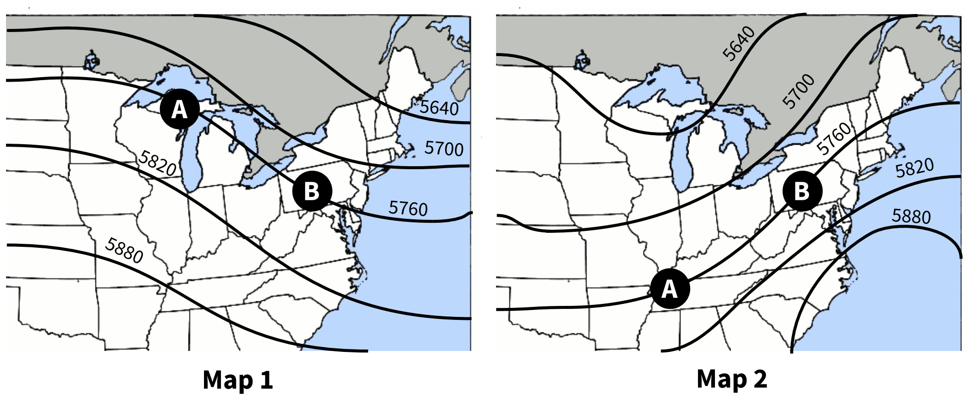

Figure 3: Two upper-level isobaric maps.

A. Map 1, positive

B. Map 1, negative

C. Map 2, positive

D. Map 2, negative

(b) (2 points) Recall that the absolute vorticity ν (derived from column rotation), planetary vorticity f (derived from Earth's rotation), and relative vorticity ζ are related by $\nu = f + \zeta$. For the map you selected in (a), winds from A are *advecting* ______ values of f and ______ values of ζ towards B, assuming constant ν.

A. Higher, higher

B. Higher, lower

C. Lower, higher

D. Lower, lower

(c) (2 points) During periods of drought, would you expect diurnal (daily) temperature ranges to be greater, less than, or near normal? **Justify** your answer in terms of atmospheric processes (i.e., neglect interactions with land).

(d) For each of the following two cases, **classify** each as part of a positive feedback loop, negative feedback loop, or no feedback loop in response to a drier atmosphere. **Briefly justify** your answer to each.

i. (1 point) Plant stomata close in response to water stress, reducing transpiration.

ii. (1 point) A landfalling tropical cyclone replenishes soil moisture.

3. One proposal to mitigate extreme heat is to paint the surfaces of buildings and roofs white, known as land radiative management (LRM). In their simulations, Cheng and McColl (2024) use the following domain, where the high-albedo region is known as the LRM region. Neglect effects of cloud cover throughout this question.

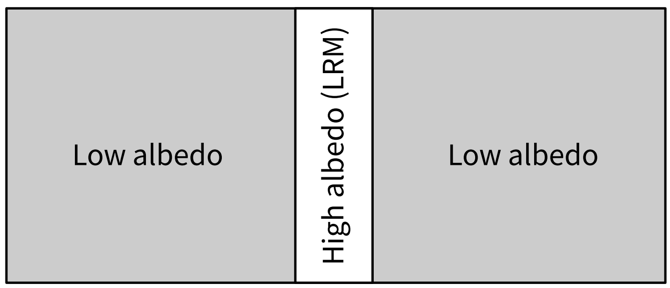

Figure 4: Map view of low and high albedo regions in the study.

(a) (2 points) It was found that less precipitation fell in the LRM region than outside the region. **Describe two** mechanisms behind this result. *(Hint: the albedo difference induces a circulation pattern across the regions, yet the reduced precipitation can be explained even without this circulation.)*

(b) (1 point) In the LRM region, the soil moisture is lower than surrounding regions. What is the effect of reduced soil moisture on the temperature of the LRM region? (Note that LHF stands for latent heat flux.)

A. LHF is increased, amplifying the cooling

B. LHF is increased, partially counteracting the cooling

C. LHF is decreased, amplifying the cooling

D. LHF is decreased, partially counteracting the cooling

(c) (2 points) When taking into account atmospheric mixing, the precipitation near the LRM region has a smooth gradient instead of a sharp drop. The resulting temperature response also displays a gradient, as shown in the topmost plot below.

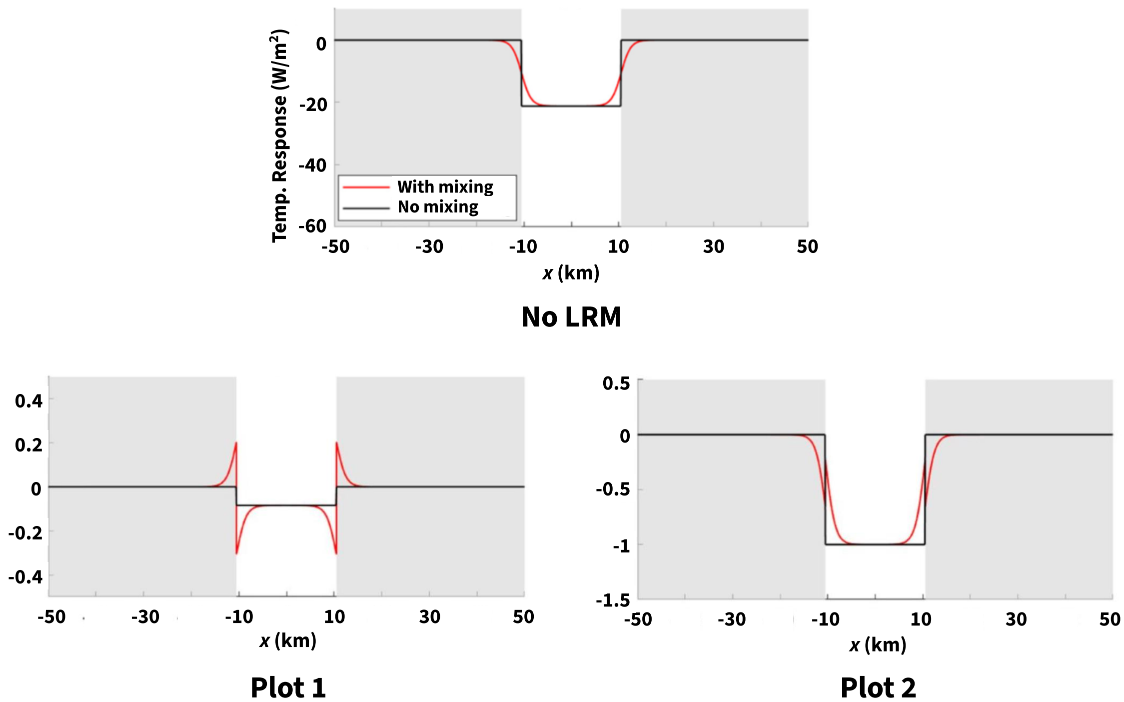

Figure 5: Radiative response due to precipitation anomalies when mixing is applied (red) or not applied (black).

Which plot shows the temperature response to LRM? **Justify** your answer by explaining how the variation in the temperature response occurs as a result of mixing in either the non-LRM or LRM region.

Problem 3

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

This problem explores several aspects of water masses.

1. One way that different water masses can be distinguished is by analyzing the concentration of isotopes in each water mass. This is because certain isotopes, such as Thorium-230 and Protactinium-231, can act like tracers that maintain their concentrations as they move with water.

   An oceanographer creates a model of ^{230}Th and ^{231}Pa concentrations based on an ocean circulation model, as shown in Figure 1 below. They then compare the model results to sample data.

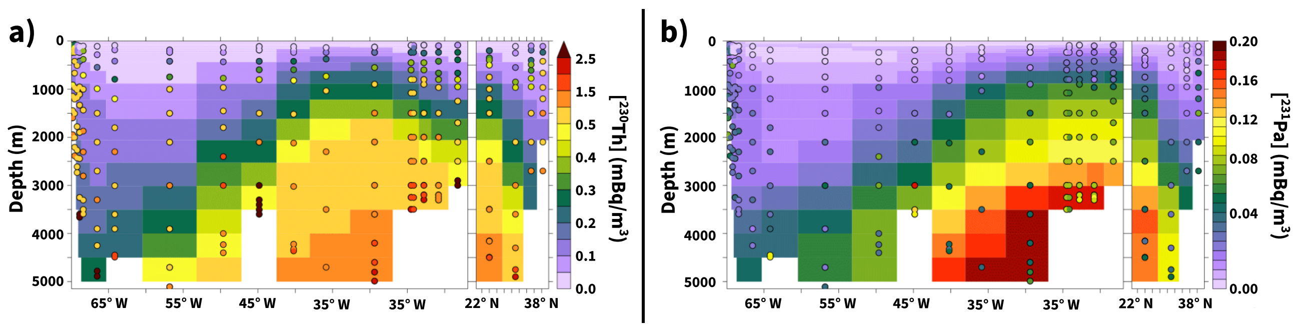

Figure 1: Radioactivity (concentration proxy) of isotopes ^{230}Th and ^{231}Pa on small particles in a cross section of the Atlantic Ocean. Colored boxes represent model predictions while colored circles represent sample data. Note the different color scaling between (a) and (b). Adapted from Hulten et al. (2018).

   (a) (2 points) The oceanographer determines that ^{230}Th and ^{231}Pa have approximately equal dissolved concentrations in seawater and that ^{230}Th has around double the half-life of ^{231}Pa. Based on Figure 1, which isotope likely has the shorter residence time in the Atlantic Ocean? **Briefly explain** your answer.

   (b) (2 points) Notice that the model underestimates the settled concentration of both isotopes around 45° W. **Briefly explain** why this discrepancy likely occurs.

Figure 2: Map of the Atlantic Ocean with 45° W marked in red. The dashed blue line indicates the transect along which the sample data was collected.

   (c) (3 points) The ^{231}Pa/^{230}Th ratio in oceanic sediments is commonly used to reconstruct the characteristics of past ocean currents. Given your answer to part (a), would you expect a relatively high ^{231}Pa/^{230}Th ratio to correspond to a relatively low or high deep water current velocity? **Explain.**

2. (1 point) The Antarctic Intermediate Water (AAIW) is a water mass that forms around 50-60° S. Its occurrence is commonly linked with changing temperature and salinity conditions as cold surface water from further south propagates northward, as shown in the sketch below.

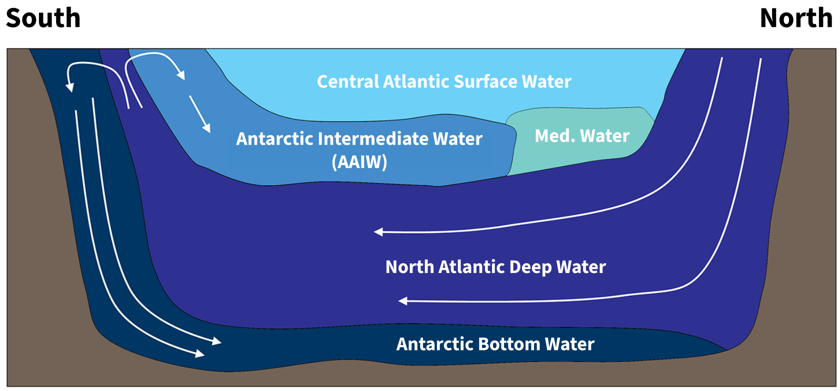

Figure 3: Rough sketch of water masses in the Atlantic Ocean.

Give one reason why the AAIW remains just below the Central Atlantic Surface Water and does not sink deeper despite originating from extremely cold water in the Southern Ocean.

3. The AAIW extends northward through the Atlantic and into the Caribbean Sea, located above South America at around 15° N. As it moves north into the Caribbean, it is overlain by a relatively warm and saline water mass known as the Subtropical Underwater (STUW). A scientist samples the AAIW at eight points (1-4, A-D) as shown in Figure 4(a) below.

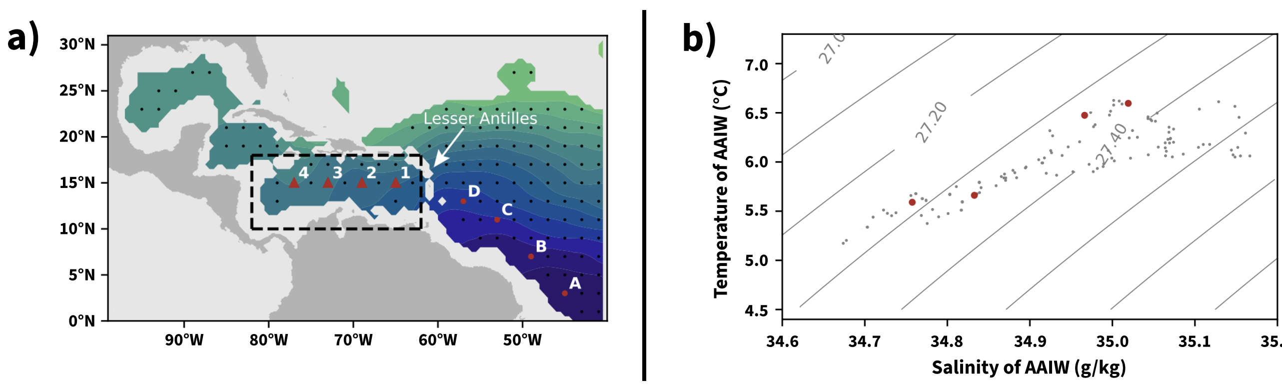

Figure 4: (a) Map depicting the locations of the eight samples. Ignore the color gradient and the dashed box. **(b)** Temperature-salinity diagram with four red dots corresponding to four of the eight samples. Gray contours represent density. Adapted from van der Boog et al. (2022).

(a) (1 point) The scientist knows that the red dots in Figure 4(b) correspond to samples 1, 4, D, and B (not necessarily in that order). From left to right, **give the ordering** of samples that each red dot corresponds to. (For instance, if the ordering was 1, 4, D, B from left to right, you should write "14DB".)

(b) (3 points) The boundary between the AAIW and STUW is not stable. Based on your answer to the previous part, **explain** why the boundary would change over time after the two water masses come into contact. Be sure to include a discussion of temperature and salinity in your response.

4. The scientist now takes a profile of the temperature and salinity at some location in the Caribbean and produces Figure 5 using the data they collect.

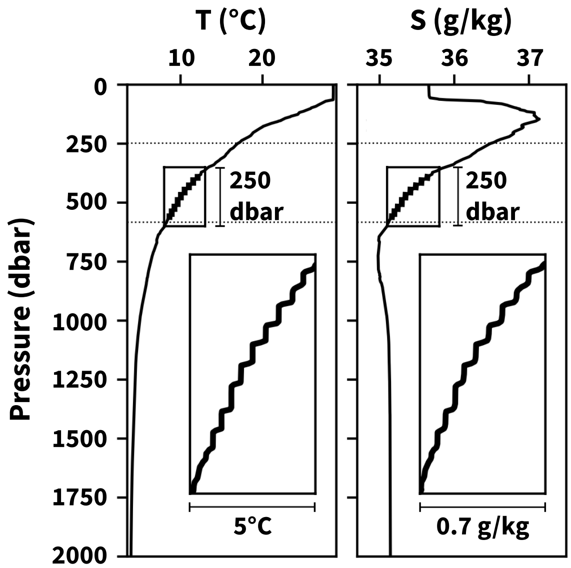

Figure 5: Profile of temperature and salinity at a location in the Caribbean. Adapted from van der Boog et al. (2022).

(a) (1 point) **At what pressures** are the STUW and AAIW water masses approximately located, respectively? Your answer should be two numbers with units of dbar.

(b) Notice that a staircase structure forms in the thermocline and halocline of the temperature and salinity profiles. One potential mechanism for the formation of this structure is known as negative density diffusion, which we will now explore.

i. (2 points) What is the direction of net mass flux at the boundary of the AAIW and STUW? **Explain.**

ii. (2 points) **Explain** why negative density diffusion is not conducive to the formation of a smooth gradient in temperature and salinity. Be sure to define the term and explain how it relates to the STUW and AAIW in your response.

5. The Brunt–Väisälä frequency (N) is a measure of the stability of a fluid to vertical perturbations. It is given by the equation

$$N^2 = -\frac{g}{\rho_0}\frac{\Delta\rho_\theta}{\Delta z}$$

where ρ_0 is some reference density, ρ_θ is the fluid density, and z is *negative* depth (e.g. $z = -10$ at a point 10 meters below sea level).

(a) (2 points) What values does N take on for fluids that are unstable to begin with? **Explain.**

(b) (1 point) Does a smaller or larger value of N correspond to a more stable fluid? **Briefly explain.**

Problem 4

Question	1	2	3	4	5	Total
Points	6	4	5	4	1	20 (20 %)

Europa is thought to have a thick layer of ice at its surface atop a subsurface ocean. Much of this ocean is nutrient-rich and at a habitable temperature, making it one of the primary candidates for extraterrestrial life in the Solar System. This problem explores several aspects of Europa's icy surface and proposed oceanic interior.

1. Europa's ice-ocean system is considered similar to Earth's tectonic system: both have a rigid crust overlying a convecting mantle. As such, many of Europa's surface features can be interpreted using methods originally applied to Earth's features.

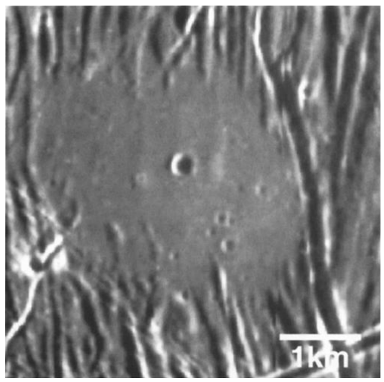

Figure 1: A circular plain seen on the surface of Europa. From Greeley et al. (2000).

(a) (2 points) **Propose** a mechanism of formation for the circular plain seen in Figure 1.

(b) (1 point) Astronomers use data from the James Webb Space Telescope to identify tracers on Europa that indicate recent crystallization of ice (within the last ∼15 days). Would the plain in Figure 1 likely have these tracers? **Explain** how you know.

(c) (3 points) Europa has many ridges on its surface. Many of these ridges, as shown in Figure 1 below, are "doublet ridges" with a central depression separating each side of the ridge. A recent study found that tidal forces may be responsible for the formation of doublet ridges. The authors suggest that these ridges form due to the presence of a subsurface reservoir of water fed by a fissure that connects to the subsurface ocean.

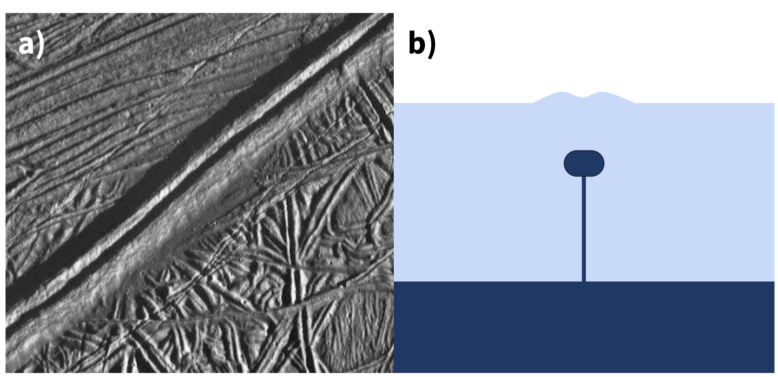

Figure 2: **(a)** A doublet ridge seen on the surface of Europa. From Greeley et al. (2000). **(b)** A diagram of the proposed reservoir underlying doublet ridges. Adapted from Cashion et al. (2024).

Using this model, **explain** how tidal forces would result in the formation of a doublet ridge. (*Hint: How would tidal forces allow water to enter the reservoir, and what stresses are present in the ice surrounding the reservoir?*)

2. Europa's magnetic field, as with most planetary magnetic fields, is thought to be created by the dynamo effect. One way to understand this effect is by considering moving electrical charges as loops of current, which create a magnetic field B at their center according to the equation

$$|\vec{B}| = \frac{\mu_0 I}{2\pi r}$$

where μ_0 is the magnetic permeability constant of the material, I is the current in the loop, and r is the radius of the loop.

(a) (1 point) Models of Earth's dynamo effect predict that Earth must have some superrotation, a phenomenon in which the inner core rotates faster than the rest of the planet. Does the presence of superrotation create a stronger or weaker dynamo effect? **Explain.**

(b) (1 point) **Briefly explain** what properties of a subsurface ocean on Europa could allow it to create a magnetic field.

(c) (2 points) Given the following table of magnetic permeabilities, explain how the difference in composition between Earth and Europa affects the relative strength of their magnetic fields.

Saltwater	1.26×10^{-6}
Granite	1.32×10^{-6}
Peridotite	1.51×10^{-6}
Nickel	7.56×10^{-4}
Iron	6.3×10^{-3}

3. Europa is thought to have potential for life near hydrothermal vents on the floor of its subsurface ocean. In part, this is because vents provide a flux of H_2 and other nutrients for microbes to use.

(a) (2 points) A 2016 paper by Vance et al. suggests that Europan hydrothermal vents primarily form via thermal cracking, creating fissures in the surface that allow water movement through the subsurface. **Explain** how variations in rock temperature result in thermal cracking.

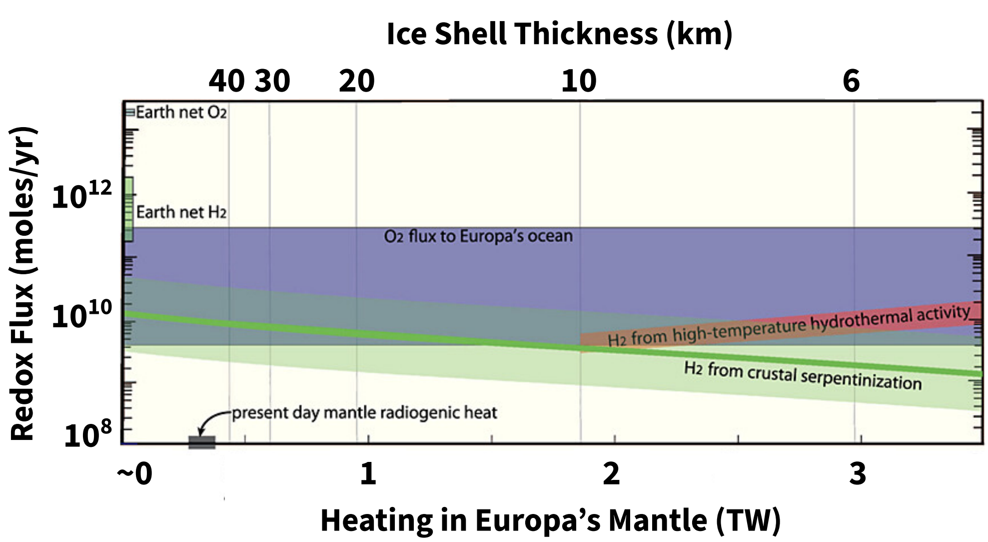

Figure 3: A graph of fluxes of H_2 (red and green) and O_2 (purple) in Europa's ocean. The x-axis includes two corresponding measurements; note that increased heating corresponds to a thinner ice shell. Adapted from Vance et al. (2016).

(b) (2 points) Europa's H_2 is mainly produced by serpentinization reactions on the ocean floor. Using the thermal cracking model, **explain** why these reactions are less likely to occur at higher temperatures.

(c) (1 point) Europa's O_2 is thought to be produced on the outer surface of Europa's icy crust. **Propose a mechanism** by which O_2 could be formed on Europa's surface.

4. The rate of tidal heating for a tidally locked satellite like Europa is given by

$$E_{\text{tidal}} \propto \frac{M^2 R^5 e^2}{a^6}$$

where M is the mass of the central body, R is the radius of the satellite, e is the eccentricity of the satellite's orbit, and a is the semimajor axis of the satellite's orbit.

(a) (1 point) **Describe** the mechanism by which a higher orbital eccentricity results in increased tidal heating on Europa.

(b) (3 points) Europa's icy crust may be able to undergo subduction, which would allow nutrients to reach the ocean below. Subduction is unlikely today but may have occurred during past periods of resonance with other moons that significantly increased its eccentricity. A recent study found that subduction on Europa can only occur with a crustal thickness of less than 10 kilometers. Given this requirement, the information in Figure 3, and the values in the table below, **calculate** the minimum orbital eccentricity necessary for subduction on Europa to become viable.

Present radiogenic heat flux	0.35 TW
Present tidal heat flux	0.018 TW
Present orbital eccentricity	0.0094

5. (1 point) Because Europa's magnetic field is generated by its subsurface ocean, changes in ocean activity affect its magnetic field strength. Would an increase in hydrothermal vent activity strengthen or weaken Europa's magnetic field? **Briefly explain.**

Problem 5

Question	1	2	3	4	Total
Points	6	3	3	8	20 (20 %)

Researchers have been closely studying the West Antarctic Ice Sheet due to its vulnerability to collapse in a few years. In their studies of the bed topography, they found a number of ridges and cones indicating some type of past or present volcanic activity. This problem will explore the effects of this volcanic activity on Antarctica's cryosphere and atmosphere.

1. The melting of glaciers can significantly affect subglacial volcanoes primarily by decreasing overburden pressure.

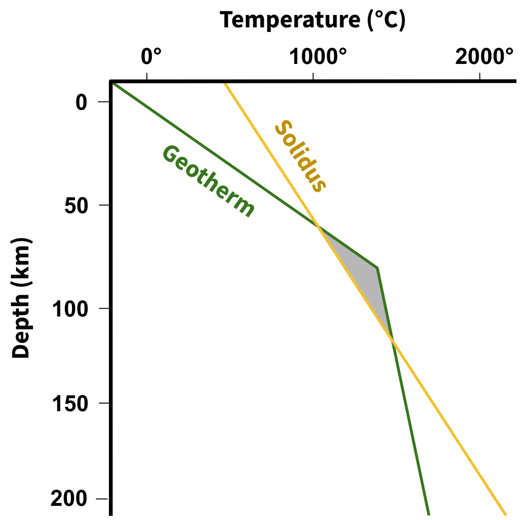

Figure 1: A diagram showing the geotherm and solidus in the crust and upper mantle.

   (a) (2 points) **Briefly explain** why the shaded region in Figure 1 is important in the mantle. What feature in Earth's mantle is located at this depth?

   (b) (2 points) **Explain** how a decrease in overburden pressure will affect the rates of magma formation. In your response, be sure to include how the components depicted in Figure 1 change.

   (c) (2 points) Suppose an area of magma is located in the lower crust. Glacial melting at the surface causes isostatic rebound, causing the crust to flex upward. **Explain** how physical changes in the crust as a result of this flexure could affect volcanic activity.

2. Antarctic volcanism can also significantly affect glacial activity.

   (a) (1 point) How would you expect rates of glacial flow and ablation, respectively, to change due to the presence of subglacial or surface volcanism?

      A. Increase, increase

      B. Increase, decrease

      C. Decrease, increase

      D. Decrease, decrease

   (b) (2 points) One of the major effects of volcanic eruptions on glacial activity is the deposition of soot on the surface of glaciers. **Briefly describe** the effect this has on the extent of glaciers. Given your answer to part (b) of the previous question, is this a positive or negative feedback loop?

3. (3 points) Various lakes and ponds exist in the few regions of Antarctica not covered by ice. One of these is Don Juan Pond, a shallow, hypersaline lake near the coast of Antarctica. To determine the origin of the lake and its salt content, researchers have extensively analyzed the concentrations of different isotopes within its water.

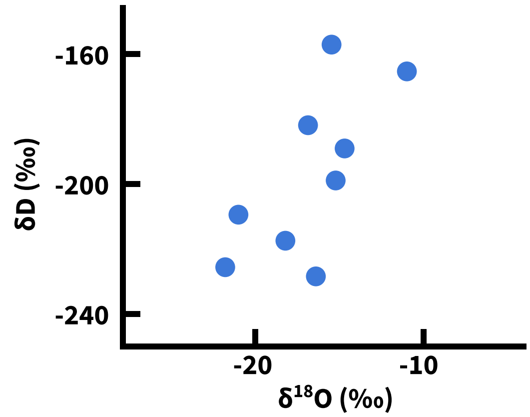

Figure 2: A plot of ^{2}H (deuterium) and ^{18}O concentrations in various samples collected from Don Juan Pond.

Explain why ^{2}H and ^{18}O concentrations are correlated in Don Juan Pond **and** why the lake has negative anomalies of both isotopes.

4. The stratospheric Southern Polar Vortex (SPV) is a consistent system of cold, rotating air above Antarctica. This vortex has a significant impact on tropospheric weather dynamics, making it important for scientists to understand.

   (a) (3 points) Using basic atmospheric principles, **explain** why the stratospheric SPV forms and predict its direction of rotation. (*Hint: What factors are responsible for wind formation in the upper atmosphere?*)

   (b) (2 points) The largest eruption of the 21st century was the 2022 Hunga Tonga-Hunga Ha'apai eruption. The volcano, located at 20°S latitude, produced an enormous cloud of debris and aerosols that reached well into the lower stratosphere.

   The impact of volcanic aerosols on climate is difficult to understand fully. Recent research suggests that their impact may depend on aerosol size, as smaller aerosols are more likely to reflect light and larger aerosols are more likely to absorb light. **Describe** how aerosol residence times depend on particle size, and **explain** how the effect of aerosols on climate evolve over time as a result.

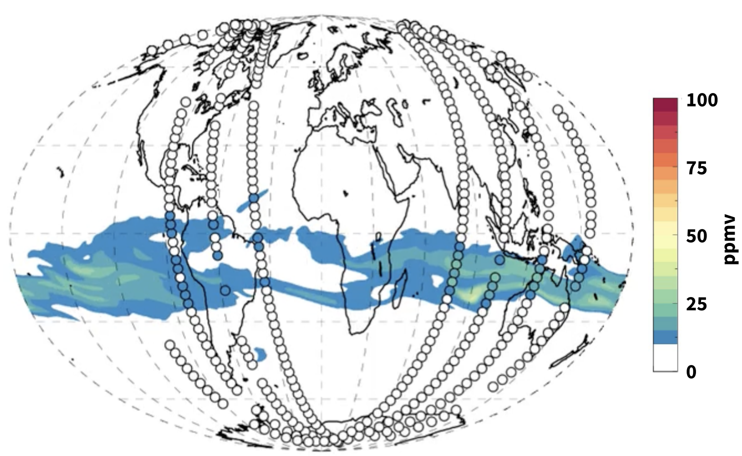

Figure 3: A map of stratospheric water vapor concentrations one month after the Hunga Tonga-Hunga Ha'apai eruption. Typical stratospheric water vapor concentrations are less than 10 ppmv, a range not shown in this map. Adapted from Wargan et al. (2022).

(c) (2 points) Based on the information presented in Figure 3, **predict** how the Hunga Tonga-Hunga Ha'apai eruption likely affected the strength of the SPV. **Explain** your reasoning.

(d) (1 point) Would a similar eruption from an Antarctic volcano have a different effect? **Briefly explain** why or why not.

END OF FREE-RESPONSE