USESO 2025

Training Camp Exam

Free-Response

KEY

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.

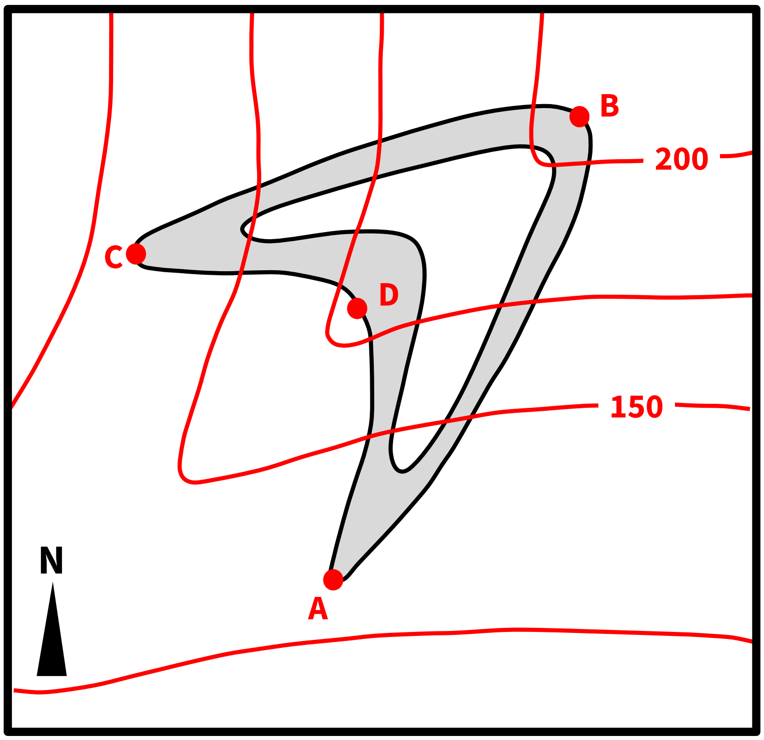

Figure 1: Map view of schist outcrop (gray) contacting with surrounding phyllite (white). Red contours denote the elevation of the local terrain.

(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.**

> **Solution:** The bends at B and D occur on a ridge defined by a V-shaped arrangement of topographic contours. These curves are likely due to the effect of the local terrain and are not an expression of folding. Meanwhile, the bends at A and C are not related to a particular topographic feature and occur on uniformly sloping valley sides. A and C thus likely represent folds.

(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.

> **Solution:** 315°. The hinge line, by definition, passes through all points of the fold with maximum curvature. In this scenario, those points are A and C.

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

Solution: Looking at the outcrop from the side by facing toward the topographic ridge axis, both point A and point C would appear as tilted troughs indicative of synforms.

(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.

Solution: The sharp V-shaped ridge could have been created by a glacial arête flanked by cirques. Other feasible mechanisms acceptable.

(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.

Solution: Yes. The most direct dip angle is directly south, which is closest to the direction from B to A.

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.

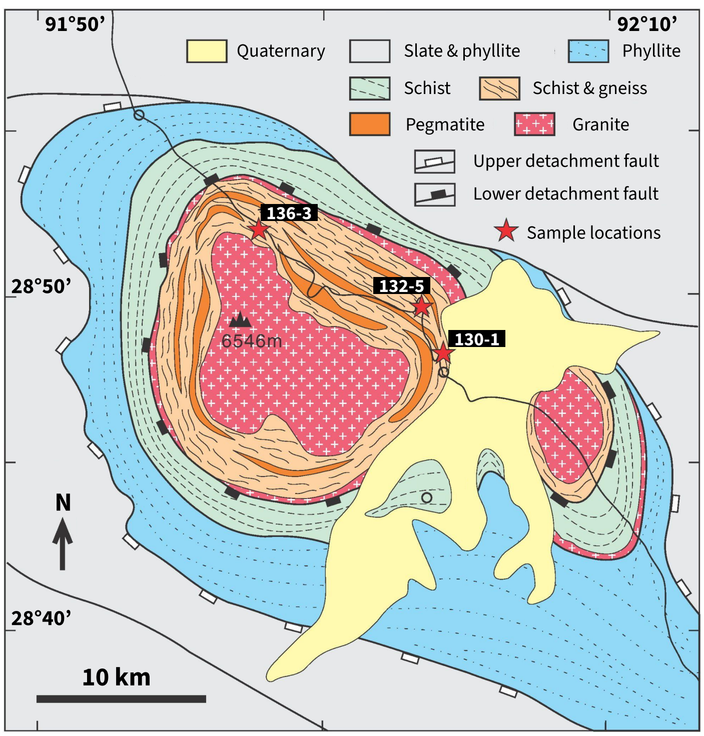

Figure 2: Map view of the Yardoi gneiss dome. Adapted from Ding et al. (2016).

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.**

Solution: Extensional. We expect crustal upwelling to occur when the overburden of the overlying rock significantly reduces in conjunction with extensional stresses in the region, resulting in a force that pulls up surrounding deeper material.

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.

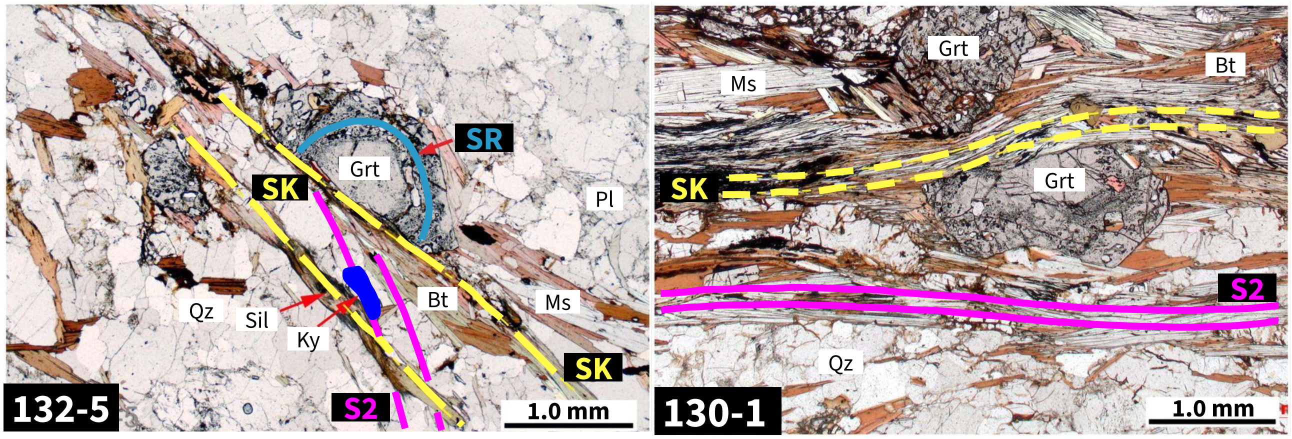

Figure 3: Photomicrographs of sample 132-5 and sample 130-1. Foliation (SR, SK, S2) is marked by lines. The dark blue feature in sample 132-5 denotes a kyanite grain; the elongated dark grain is sillimanite. Mineral abbreviations are as follows: Qz (Quartz), Sil (Sillimanite), Ky (Kyanite), Grt (Garnet), 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.**

Solution: Before. The SK foliation produced shear bands that wrap around the garnet porphyroblasts, while the SR foliation consists of mineral trails within the garnets. This suggests that the SR deformation occurred during garnet growth, which occurred before SK deformation.

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

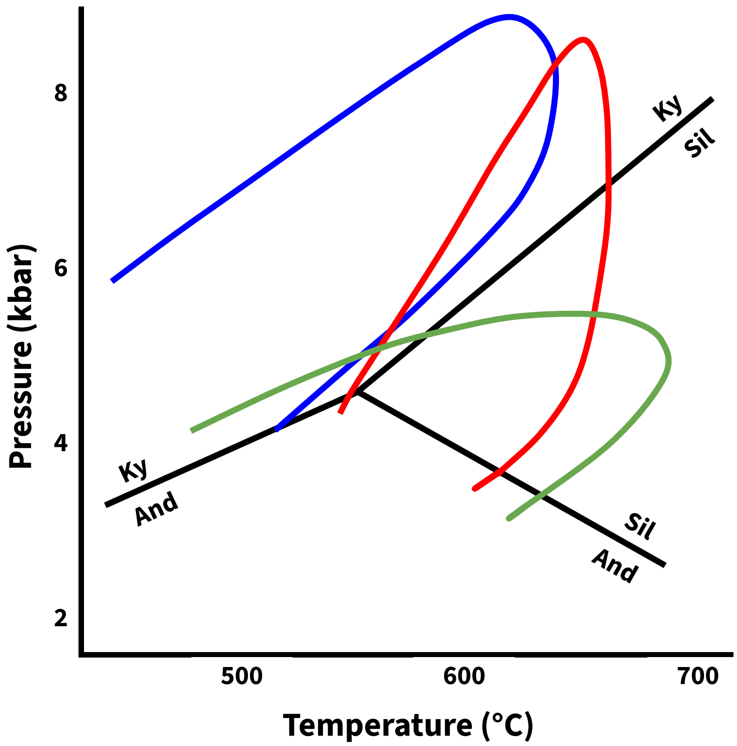

Figure 4: Potential P-T-t paths for schists in the Yardoi dome. Mineral abbreviations are as follows: Kyanite (Ky), Sillimanite (Sil), Andalusite (And).

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.

Solution: Given that the retrograde mineral assemblage contains sillimanite, we can remove the blue path from consideration because it does not pass through the sillimanite range. We can also determine that the path direction must be clockwise such that the metamorphism is retrograde when it passes through the sillimanite range. Given that the peak mineral assemblage contains kyanite, we can remove the green path from consideration because its peak lies in the sillimanite range.

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.

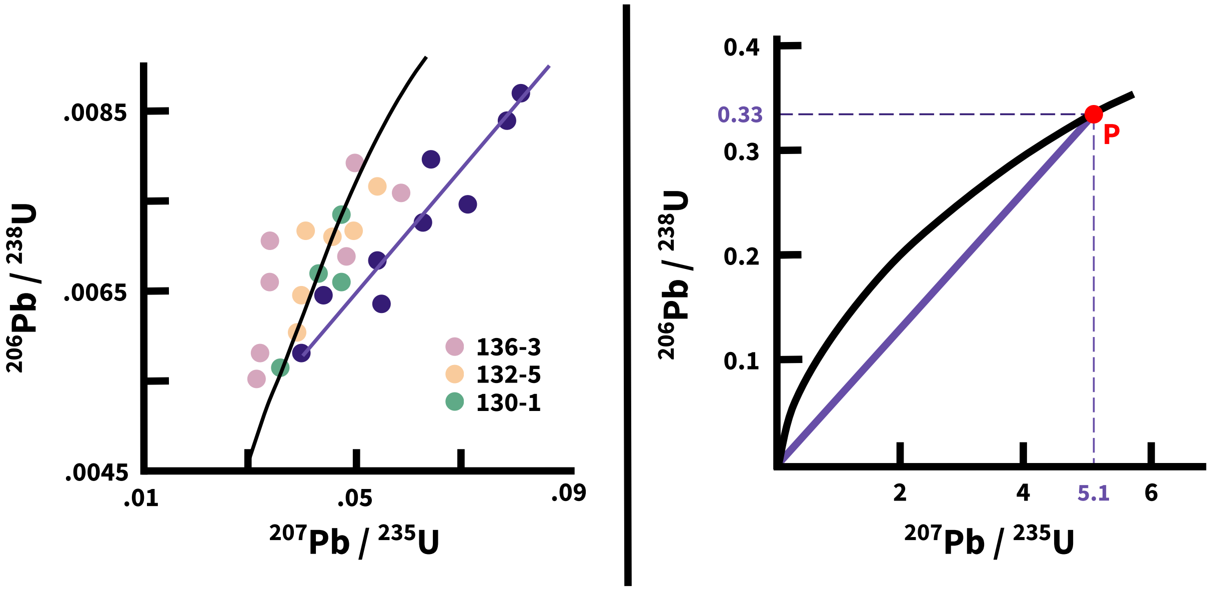

Figure 5: (a) A diagram of Pb/U isotope ratios for the samples collected from the Yardoi gneiss dome. Anomalous samples are shown in purple. Adapted from Ding et al. (2016). **(b)** An extended version of Figure 5(a). The black curve follows the expected evolution of a normal sample; the purple line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

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

> **Solution:** As time goes on, ^{235}U concentration goes to zero much more quickly than ^{238}U concentration. As such, the $^{207}Pb/^{235}U$ ratio skyrockets relatively quickly, while the $^{206}Pb/^{238}U$ ratio increases at a relatively constant rate.

(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)?

> **Solution:** Anomalies like this typically arise when a zircon crystal forms after recrystallization and contains lead and uranium from its original formation. These samples must have lost nearly all of their lead and uranium, but a small amount remains with the isotope ratios from the original sample. The extension of the purple line represents varying degrees of lead and uranium loss from the original sample. Point P represents the isotope ratios of the lead and uranium from the original zircon crystal; this can be used to determine its age.

(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.

Solution: We determine the age of the sample here using the $^{238}\text{U} \rightarrow {}^{206}\text{Pb}$ decay system. The standard radioactive decay formula gives the proportion of ^{238}U remaining after time t (in billions of years) as $0.5^{t/4.47}$. The proportion of ^{206}Pb is given by 1 minus this value.

$$\begin{aligned} \frac{^{206}\text{Pb}}{^{238}\text{U}} &= \frac{1 - 0.5^{\,t/4.47}}{0.5^{\,t/4.47}} \\ 5.1 &= \frac{1 - 0.5^{\,t/4.47}}{0.5^{\,t/4.47}} = -1 + \frac{1}{0.5^{\,t/4.47}} \\ \frac{1}{6.1} &= 0.5^{\,t/4.47} \\ t &= 4.47 \cdot \log_{0.5}\left(\tfrac{1}{6.1}\right) \\ &\approx 1.839 \text{ billion years.} \end{aligned}$$

The same calculations apply for ^{235}U, which gives an age of 1.852 billion years.

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

   Solution: Relative humidity (RH) is the ratio between the actual vapor pressure and saturation vapor pressure. The saturation vapor pressure e_s increases exponentially with temperature (at approximately 7% per °C warming). Even when RH is fixed, the exponential increase in numerator and denominator means that the gap between e_s and e_a is increasing.

   (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.

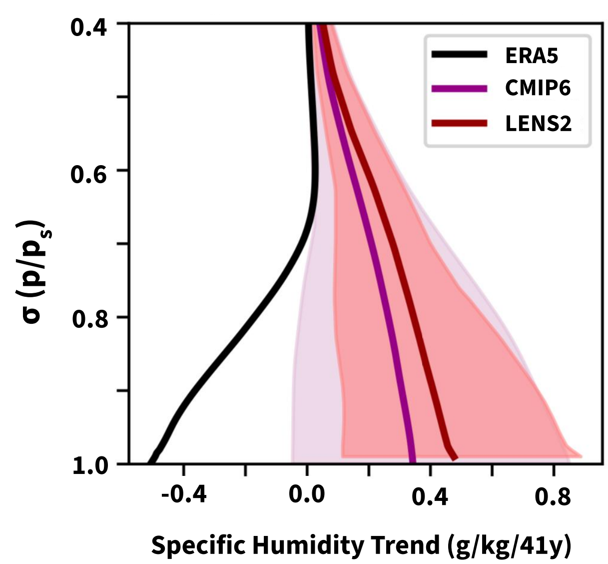

Figure 1: 1980-2020 trend in the specific humidity (grams of water vapor per kilograms of dry air) profile in the southwestern US. The y-axis is the ratio of pressure to surface pressure and the black line (ERA5) shows assimilated observational trends. The purple and red (CMIP6/LENS2) lines show climate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

Solution: Climate models have overestimated near-surface specific humidity (models show an increase, where observed trends show a decrease). As specific humidity (related to the amount of water vapor) is roughly proportional / closely related to e_a, climate models have a positive bias for e_a, suggesting a smaller gap between it and e_s. Thus, climate models have underestimated VPD.

(Note: since e_s is related to temperature, the assumption that temperature projections are accurate also assumes no model bias in e_s. So the VPD bias (in this question) hinges only on the bias in e_a. Students need not include this in their explanations.)

(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?

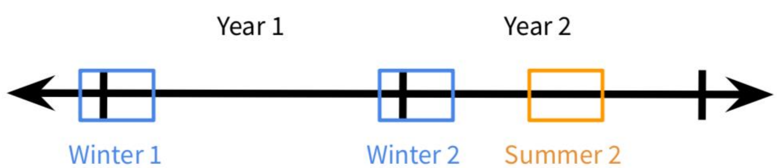

Figure 2: Timeline of Year 1 winter, Year 2 winter, and Year 2 summer.

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.

Solution: In the Southwestern US, El Niño tends to bring above normal precipitation and La Niña tends to bring below normal precipitation. Buildup of vegetation/biomass from Year 1 becomes dried up by Summer 2, maximizing potential fuel for wildfires. (La Niñas in both winters favor a dry Summer 2, but with less biomass that can be burnt. An El Niño in Winter 2 would disfavor dry soils in Summer 2.)

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.)

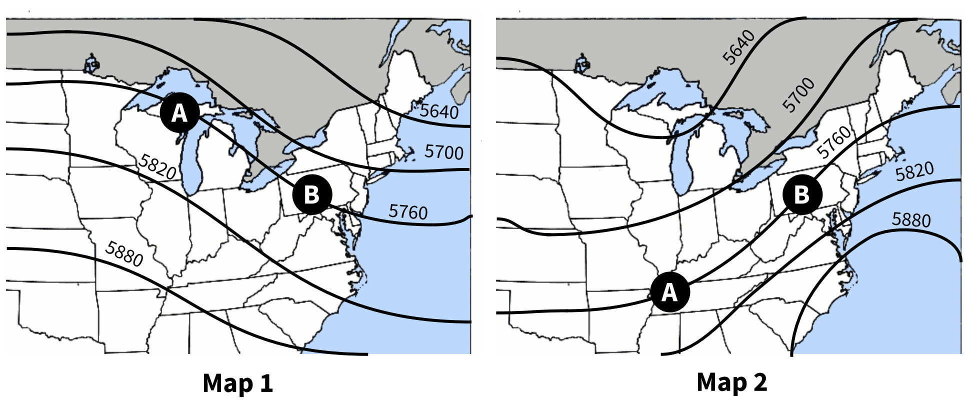

Figure 3: Two upper-level isobaric maps.

A. Map 1, positive

B. Map 1, negative

C. Map 2, positive

D. Map 2, negative

> **Solution:** Map 1 shows an upper-level ridge to the west of B and an upper-level trough to the east of B. This pattern favors convergence aloft and divergence at the surface, promoting high pressure and sinking air. More sinking air than normal translates to a greater downward velocity (higher rate of pressure increase) since pressure increases as altitude is lowered, so ω should have a positive anomaly.

(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

> **Solution:** Planetary vorticity increases with latitude due to a stronger Coriolis effect at higher latitudes. In Map 1, air at A is at a higher latitude than B, so higher f at A is being advected (transported) towards B. Since ν is constant, the sign of ζ advection is the opposite: lower values of ζ are being advected towards B. Also, negative (relative) vorticity advection typically occurs to the downstream of ridges.
>
> (Choice C is correct if the student selected Map 2, with the reverse chain of reasoning.)

(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).

> **Solution:** Diurnal temperature ranges would be greater than normal, with warmer or similarly warm days and cooler nights. The reduced water vapor / humidity in the atmosphere would reduce daytime cloud cover and allow more outgoing longwave radiation to escape at night without being backscattered. (Or, drought conditions are usually associated with high pressure and calm winds, so less mixing allows for the development of a radiation inversion and greater cooling.)
>
> Note that "higher specific heat of water vapor" is not an acceptable answer. The variations in atmospheric moisture don't contribute significantly to changes in atmospheric heat capacity. Greater partitioning of energy gains/losses into sensible heat flux relative to latent heat flux also plays a role, but this relates to land/soil moisture, so is not an accepted response here.

(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.

Solution: Positive feedback loop, since a dry atmosphere results in less transpiration, reinforcing dryness.

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

Solution: No feedback loop. The landfalling tropical cyclone is not a response or result of drought and can be regarded as independent/external of the drought.

(Note: If drought causes X, and X causes increased soil or atmospheric moisture, then X is part of a negative feedback loop. But there is no physical link between drought and tropical cyclone impacts, nor does drought make it more likely for a tropical cyclone to bring rainfall.)

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.

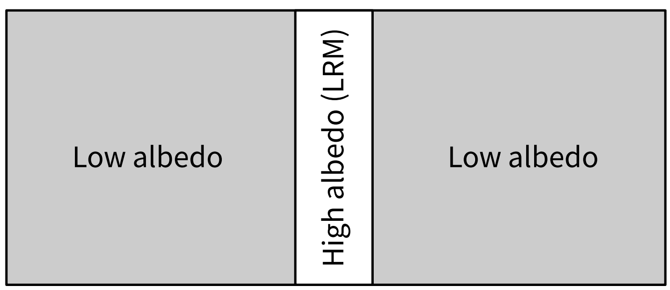

Figure 4: Map view of low and high albedo regions in the study.

(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.)*

Solution: Cooler conditions in the LRM region and warmer conditions outside create a (thermally direct) circulation where air sinks above the LRM region and diverges at the LRM surface — similar to the development of a daytime lake breeze (in which the LRM is analogous to the "lake"). Less net radiation in the LRM region leads to less evaporation and less moisture recycling, resulting in locally reduced precipitation.

(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

Solution: Less soil moisture can be evaporated, so the evaporative cooling effect is reduced. Thus, less radiative energy is partitioned into evaporation/latent heat flux.

(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.

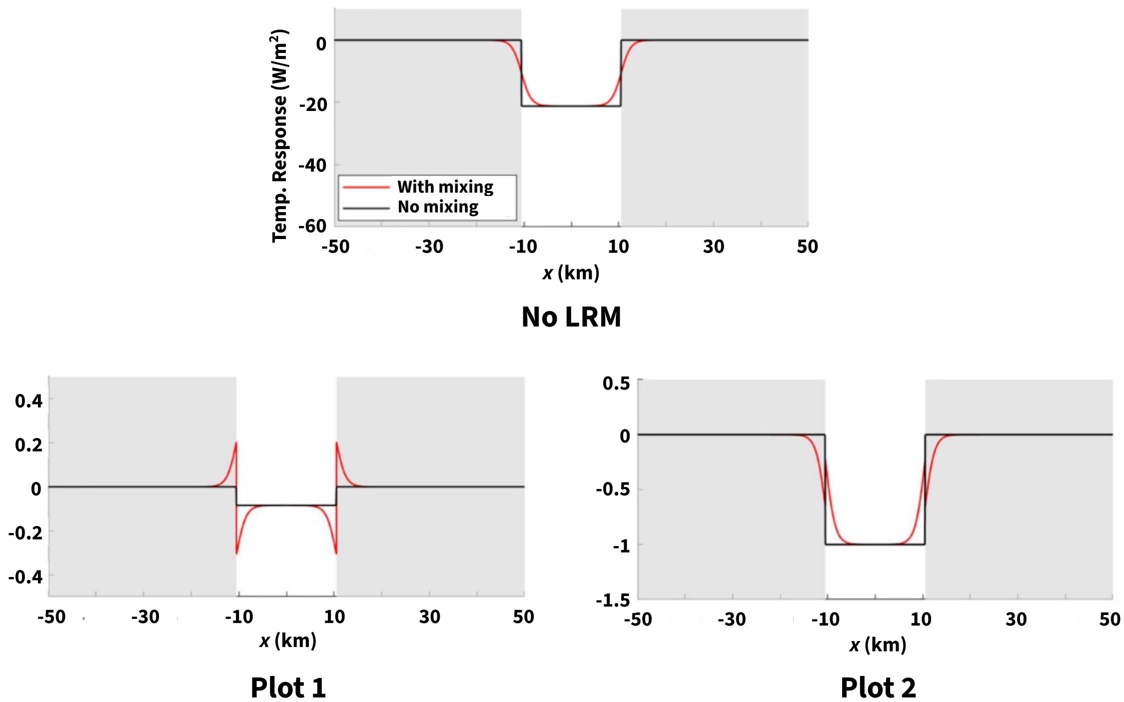

Figure 5: Radiative response due to precipitation anomalies when mixing is applied (red) or not applied (black).

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.

Solution: Plot 1. Just outside of the LRM region, precipitation is reduced relative to locations further from the LRM. This reduces soil moisture, but with the same albedo, less evaporative cooling occurs, leading to warmer conditions. (Likewise, just inside the LRM region, precipitation is higher than in the center of the LRM region. More evaporative cooling leads to lower temperatures at the LRM edge than in the center of the 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.

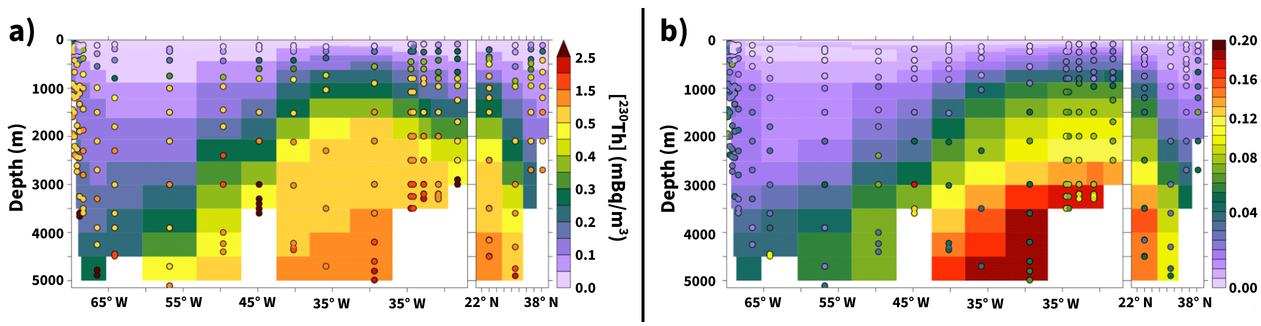

Figure 1: Radioactivity (concentration proxy) of isotopes ^{230}Th and ^{231}Pa on small particles in a cross section of the Atlantic Ocean. Colored boxes represent model predictions while colored circles represent sample data. Note the different color scaling between (a) and (b). Adapted from Hulten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

   Solution: While both are found in approximately equal dissolved concentrations in seawater, the proportion of ^{230}Th settling on particles at depth is around a magnitude larger, suggesting it is deposited onto sediments at a much higher rate and thus exhibits a shorter residence time. The fact that ^{230}Th has a longer half-life supports this conclusion. Because ^{230}Th decays more slowly, it must be removed more quickly to compensate and produce the elevated radioactivity levels observed at depth.

   (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.

Solution: The Mid-Atlantic Ridge contains hydrothermal vents that emit a large number of particles. These particles accumulate ^{230}Th and ^{231}Pa isotopes, increasing the sampled concentration of both.

(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.**

Solution: A higher ^{231}Pa/^{230}Th ratio indicates that particles with ^{231}Pa had more time to settle onto the ocean floor before being redistributed by deep water currents. From part (a), ^{231}Pa settles much more slowly than ^{230}Th and is therefore depleted in regions with fast deep water currents but abundant in regions with slow deep water currents. Thus, a higher ^{231}Pa/^{230}Th ratio implies a relatively low deep water current velocity.

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.

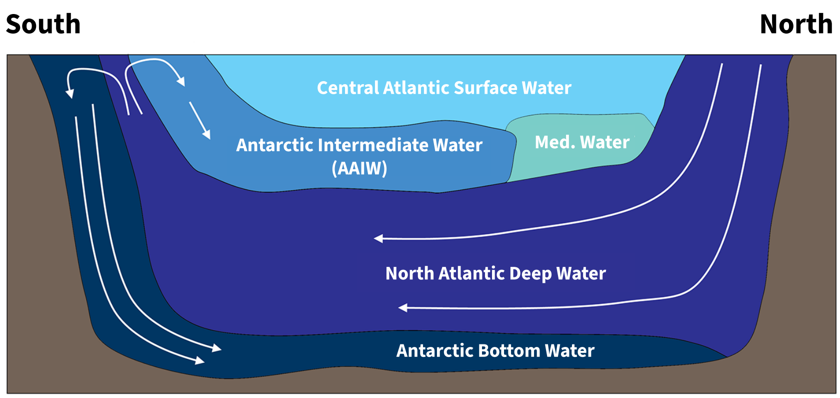

Figure 3: Rough sketch of water masses in the Atlantic Ocean.

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.

Solution: The AAIW is relatively cold but also relatively fresh (i.e. low salinity) due to (1) precipitation at the polar lows around 60° S and (2) melting of sea ice due to contact with warmer water to the north. Thus, it cannot sink further and lies above the cold and salty North Atlantic Deep Water.

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.

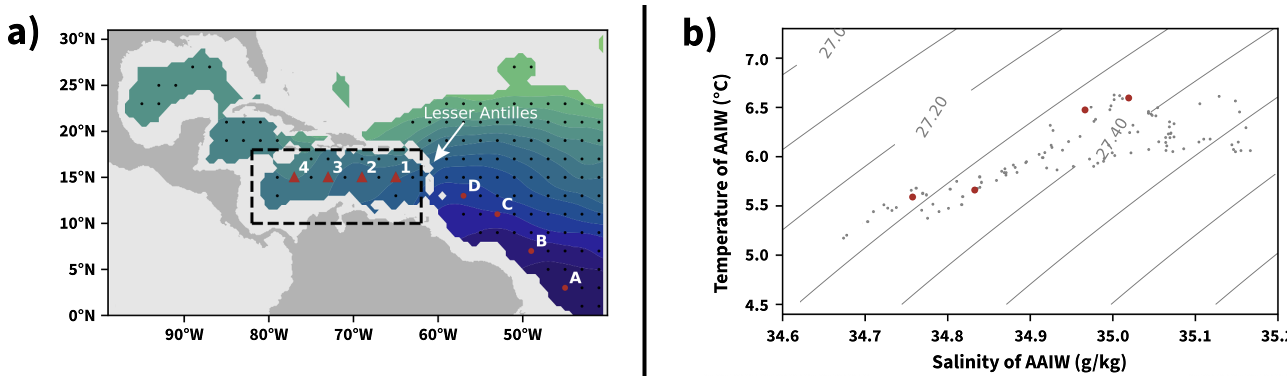

Figure 4: **(a)** Map depicting the locations of the eight samples. Ignore the color gradient and the dashed box. **(b)** Temperature-salinity diagram with four red dots corresponding to four of the eight samples. Gray contours represent density. Adapted from van der Boog et al. (2022).

(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".)

> **Solution:** It is given that the AAIW is colder and fresher than the overlying STUW. As the AAIW moves northward (from A to D to 1 to 4), we expect it to warm because heat diffuses from regions of higher temperature to lower temperature. We also expect the AAIW to become more salty because salt diffuses from regions of higher salinity to lower salinity. Thus, correct ordering is BD14.

(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.

> **Solution:** Heat diffuses significantly faster than salt, so we would expect the AAIW to warm much faster than it becomes more saline, thus becoming more buoyant and extending upward. Meanwhile, we would expect the STUW to cool much faster than it becomes less saline, thus becoming less buoyant and extending downward (via salt fingering).

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.

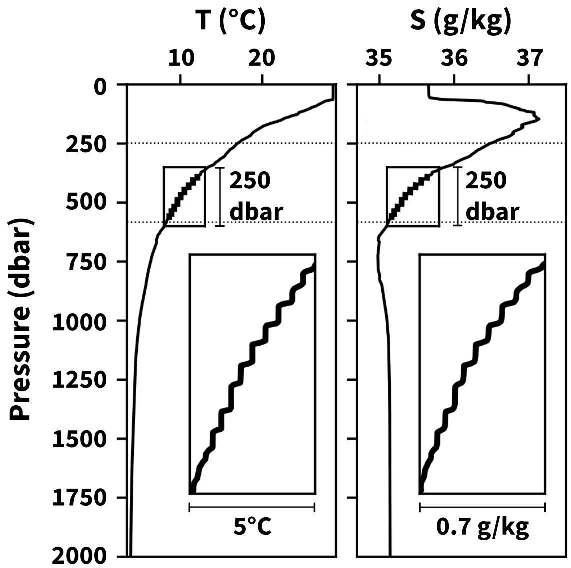

Figure 5: Profile of temperature and salinity at a location in the Caribbean. Adapted from van der Boog et al. (2022).

(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.

Solution: The STUW is located around 125 dbar and the AAIW is located around 750 dbar. These pressure values correspond to the salinity maximum and minimum as observed in Figure 4, respectively.

(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.**

Solution: Parts of the STUW become denser and sink while parts of the AAIW become less dense and rise. If a volume of water with greater density sinks a distance h while an equivalent volume of water with less density rises the same distance h, there is a net loss in gravitational potential energy. This implies that net mass flux is downward.

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.

Solution: While normal density diffusion involves a flux in the same direction as the gradient (which is from high density regions to low density regions), negative density diffusion involves a flux from regions of low to high density. Indeed, mass flux at the boundary is directed downward from the less dense STUW toward the more dense AAIW. This sharpens rather than smooths existing fluctuations in temperature and salinity, which is conducive to staircase formation. See Merryfield (2000) for more information and additional hypotheses regarding staircase formation.

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.**

Solution: A fluid that is unstable to begin with is characterized by decreasing density with depth. Thus, ρ_θ decreases as z gets more negative (decreases); $\frac{\Delta\rho_\theta}{\Delta z}$ is positive. A positive value for $\frac{\Delta\rho_\theta}{\Delta z}$ results in an imaginary value for N.

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

Solution: A stable fluid is characterized by increasing density with depth. The absolute value of $\frac{\Delta\rho_\theta}{\Delta z}$ increases as the fluid becomes more stable, resulting in larger values of N.

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.

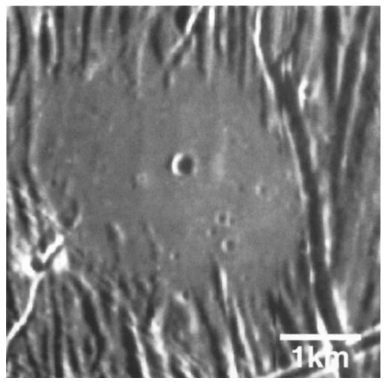

Figure 1: A circular plain seen on the surface of Europa. From Greeley et al. (2000).

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

Solution: Since the circular plain overlies the ridges and valleys on Europa's surface, it must have formed new ice relatively recently. The most likely mechanism of formation is that cryovolcanism deposited a fresh, smooth layer of ice. This could also form if a heat source caused localized recrystallization of ice, possibly a mantle plume-like structure from the bottom of Europa's subsurface ocean.

(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 $\sim$15 days). Would the plain in Figure 1 likely have these tracers? **Explain** how you know.

Solution: No. Although the plain represents relatively fresh ice, the craters on its surface suggest that it must have existed for much longer than 15 days.

(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.

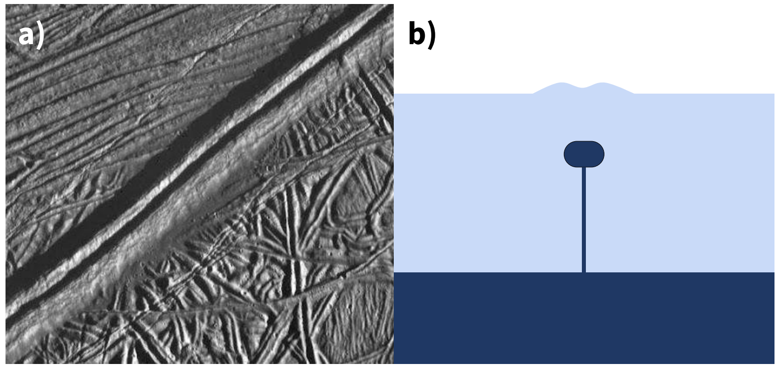

Figure 2: **(a)** A doublet ridge seen on the surface of Europa. From Greeley et al. (2000). **(b)** A diagram of the proposed reservoir underlying doublet ridges. Adapted from Cashion et al. (2024).

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?*)

Solution: Tidal forces cause repeated extension and compression of the surface of the ice; a "high tide" corresponds to compression and a "low tide" corresponds to extension. During a period of extension, this fissure widens, and water is pushed into the fissure by the pressure of the surrounding ice. During a period of compression, this fissure is closed, pushing some water back down and some water up into the reservoir. The reservoir simultaneously grows vertically, which pushes the overlying ice upwards, and horizontally, which pushes the overlying ice outwards and creates the separation within the ridge.

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.**

Solution: Superrotation causes convection to be faster and creates more individual convection loops as interactions at the outer core's boundaries create turbulence and new convection. Increasing the number of loops and the current through those loops both increase the magnetic field strength, creating a stronger dynamo effect.

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

Solution: Saltwater is conductive and has dissolved ions, so convection in the ocean produces loops of moving charges that 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}

Solution: A higher magnetic permeability makes the magnetic field stronger in a material, meaning the same moving charges/currents will create a stronger field. Since Earth's field is generated by iron and nickel while Europa's is generated by saltwater, Europa will have a weaker field than Earth.

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.

Solution: Rocks expand proportionally to increases in temperature. A changing temperature causes repeated expansions and contractions, which create stresses that break rocks apart. This is the same as the mechanism associated with freeze-thaw cycles that cause jointing in rocks on Earth.

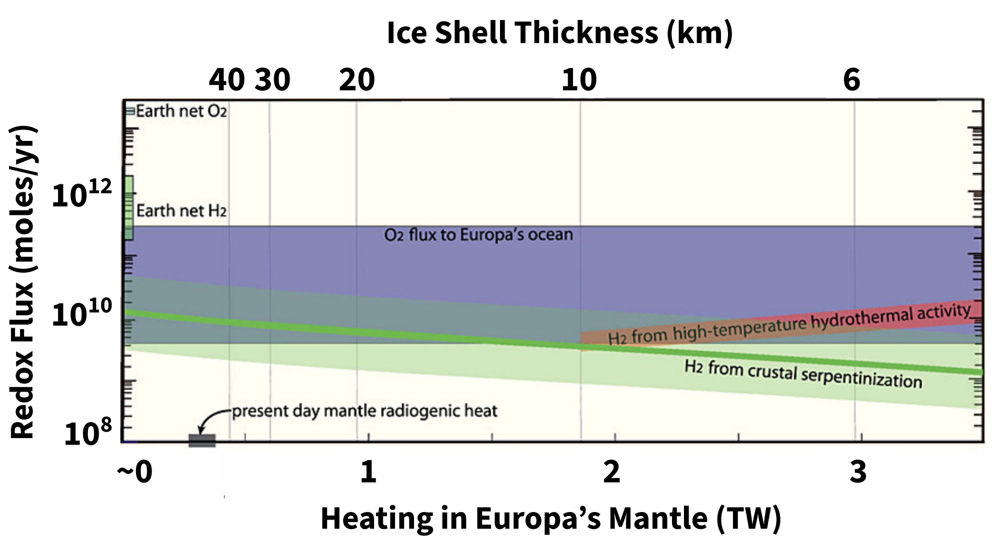

Figure 3: A graph of fluxes of H_2 (red and green) and O_2 (purple) in Europa's ocean. The x-axis includes two corresponding measurements; note that increased heating corresponds to a thinner ice shell. Adapted from Vance et al. (2016).

(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.

> **Solution:** Like all chemical reactions, serpentinization reactions occur faster when there is more exposed surface area for them to act. This extra surface area is created by fracturing related to thermal cracking, which requires rock to be brittle rather than ductile. At higher temperatures, rock is more likely to deform rather than crack, reducing the surface area for serpentinization to occur.

(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.

> **Solution:** O_2 can be created by the splitting of water into oxygen and hydrogen. This is done through a process called radiolysis, where incoming high-energy radiation provides the energy necessary to split the molecule.

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.

> **Solution:** Tidal cycles cause repeated extension and contraction of different parts of the moon. This differential movement creates friction that then heats up the interior of the planet.

(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

> **Solution:** Figure 3 indicates that a crustal thickness of less than 10 kilometers corresponds to at least 1.85 TW of heat flux, which would require at least 1.5 TW of tidal heat flux to achieve. Since the tidal heat flux is proportional to eccentricity squared, we know that the ratio between the two heat fluxes is proportional to the ratio between the two eccentricities squared: $\frac{1.5}{0.018} = (\frac{e}{0.094})^2$. Rearranging and solving for e gives $e = 0.086$ as a rough minimum eccentricity.

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.**

Solution: An increase in hydrothermal vent activity would result in more heat being transferred to the ocean, which would produce more circulation and instability. Since this circulation is responsible for Europa's magnetic field, this change would strengthen the magnetic field.

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.

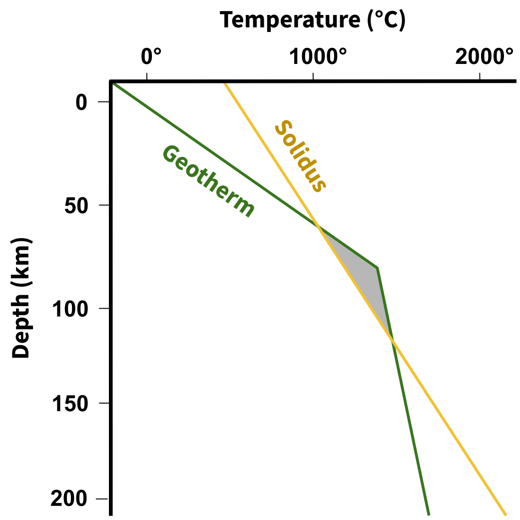

Figure 1: A diagram showing the geotherm and solidus in the crust and upper mantle.

(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?

> **Solution:** The geotherm is higher than the rock's melting point, causing melting. This is where the asthenosphere and/or low-velocity zone (LVZ) is located.

(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.

> **Solution:** The reduction in overburden pressure will move the solidus left because melting is more favorable at lower pressures. This is because higher pressure favors the formation of lower volume phases which the solid phase would be. This will increase the range of the zone of depths at which melting can occur, increasing the rate of magma formation.

(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.

> **Solution:** This creates tension in the upper crust, which allows for the intrusion and rising of magma within the crust, often leading to dike complexes and 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

Solution: Increased heat flux due to volcanism results in increased melting and mass loss. This allows the glacier to flow more easily because it is more plastic and its movement is lubricated by meltwater.

(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?

Solution: The deposition of soot decreases glacial albedo, which causes increased energy absorption and warming. This then melts glaciers and reduces their extent. Since a reduction in overburden pressure promotes magma formation, this melting will cause an increase in volcanic activity, which produces more soot and more melting in a positive 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.

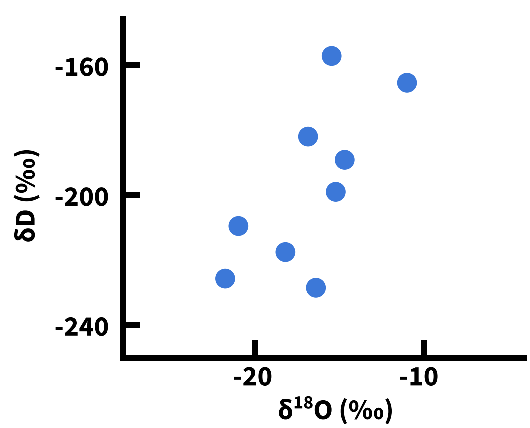

Figure 2: A plot of ^{2}H (deuterium) and ^{18}O concentrations in various samples collected from Don Juan Pond.

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

Solution: ^{2}H and ^{18}O are both heavier isotopes of the elements found in seawater. Their concentrations are correlated because their variation is driven by the same mechanism. Because they are heavier, water molecules with these isotopes require more energy to evaporate and are thus rarely found in the atmosphere. They have unusually low concentrations in glacier-fed lakes because glaciers themselves are fed by rainwater from the atmosphere.

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?*)

   Solution: In the upper atmosphere, there is generally a pressure gradient directed from the equator to the poles. This is because warm air near the equator is less dense and more of it lies above any given altitude, creating a relatively high pressure that pushes air towards the poles. In the Southern Hemisphere, the Coriolis effect deflects winds to the left. The southward winds will thus deflect to the east and produce a clockwise rotation.

   (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.

   Solution: Larger aerosols have shorter residence times because they are quicker to fall to the ground. Larger aerosols will be more common initially and cause more warming. Later, only small aerosols will be left, producing a prolonged cooling effect.

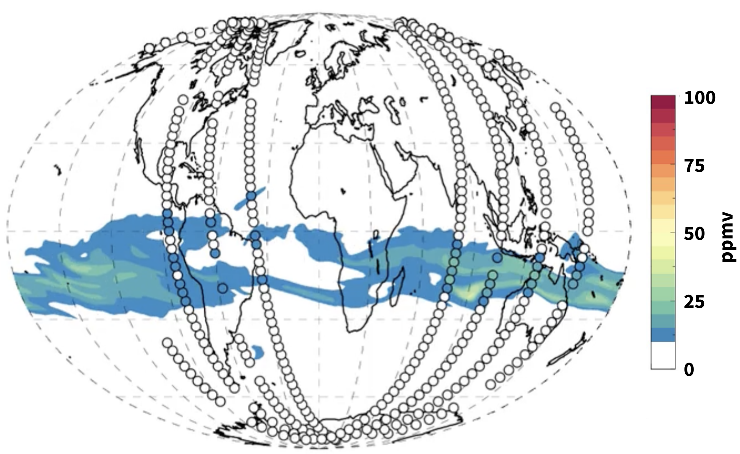

Figure 3: A map of stratospheric water vapor concentrations one month after the Hunga Tonga-Hunga Ha'apai eruption. Typical stratospheric water vapor concentrations are less than 10 ppmv, a range not shown in this map. Adapted from Wargan et al. (2022).

   (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.

   Solution: Water vapor is a greenhouse gas and causes warming. Because most water vapor produced by the eruption is located near the equator, warming will primarily occur near the equator, which strengthens the upper-level pressure gradient and thus strengthens the SPV.

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

> **Solution:** Yes. An eruption near Antarctica would produce warming near the poles, which would decrease the strength of the upper-level pressure gradient and thus weaken the vortex.

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