USESO 2023

Open Exam

Section II - **KEY**

Instructions:

- Section II consists of 4 multipart questions that further assess geoscience knowledge in the form of free-response and multiple choice questions.
- A non-graphing, non-programmable calculator is allowed. Show all work for calculations.
- Any space on the page may be used for scratch paper, but only work on your answer sheet will be graded.
- Write your full name on every page of the answer sheet.

Problem 1

Question	1	2	3	4	5	6	Total
Points	4	2	2	2	2	3	15 (25%)

On February 6, 2023, two major earthquakes shook eastern Turkey and Syria, killing tens of thousands and causing massive structural damage. These earthquakes took place at two different sites surrounding the city of Kahramanmaraş. Below is a diagram displaying the direction and magnitude of movement at each section of the fault during the main earthquake.

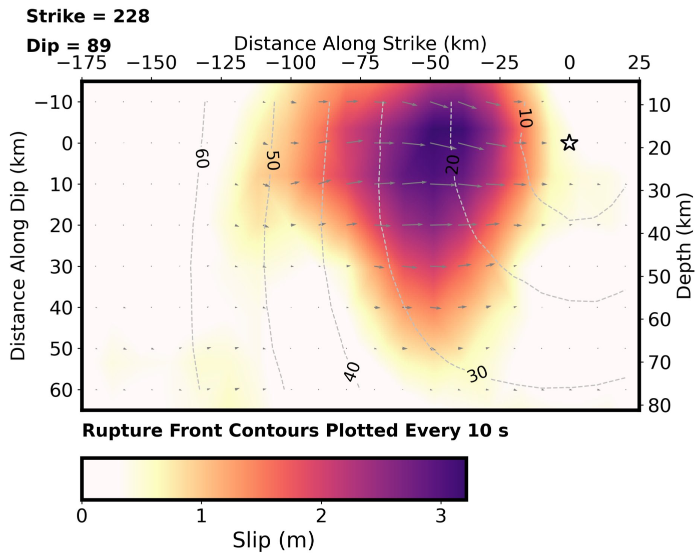

Figure 1: values for strike and dip of the fault are in the top left corner.

1. (a) (2 points) What does a dip of 89 indicate about the fault?

   A. The fault runs almost perfectly north-south

   B. The fault runs almost perfectly west-east

   C. The fault plane is nearly horizontal

   D. The fault plane is nearly vertical

   Solution: The dip measures the angle the fault plane makes with the horizontal. A dip of 89 indicates that the fault plane is almost perfectly perpendicular to the horizontal and must be vertical, a common feature of strike-slip faults.

   (b) (2 points) The fault strike is 228 as measured clockwise from north. If the fault is left-lateral, in what cardinal (e.g. north, west) or ordinal (e.g. northwest, southeast) direction is the region *north* of the fault moving? Briefly justify your answer.

   Solution: Southwest. The strike indicates that the fault runs approximately NE-SW. Because the fault is left-lateral, each side will move to the left compared to the other side, so the northern side will move southwest and the southern side will move northeast. The lack of vertical movement in the image indicates that each side is moving along the strike line rather than towards or away from it.

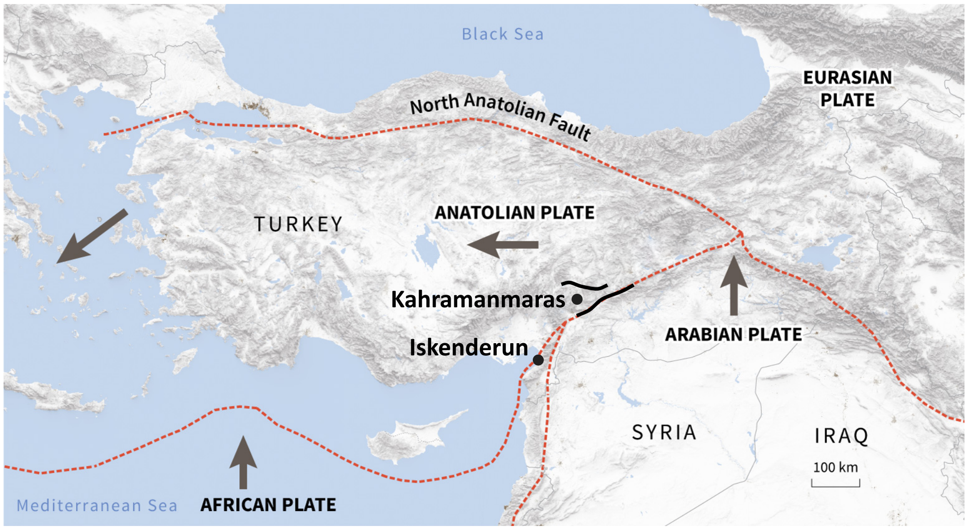

Figure 2: A map displaying the tectonic plates surrounding Turkey. The faults where the two earthquakes occurred are shown near Kahramanmaraş.

2. (2 points) Suppose a fault just south of Kahramanmaraş is oriented north-south. If plate movement caused this fault to rupture with the same magnitude of displacement as the faults in the image, would it likely have more or less vertical movement? Explain.

Solution: More. Strike-slip faults typically have little to no vertical movement because the two plates slide past each other without any uplift. When faults are oriented perpendicular to the direction of movement, they become dip-slip faults with significant vertical movement. In this case, the fault would be a normal fault, with one block of crust subsiding as it extends along the fault plane.

3. (2 points) After the earthquake, subsidence in İskenderun caused significant flooding. Which of the following can be inferred about the region as a result of this subsidence?

   A. Saltwater intruded into previously fresh groundwater

   B. The bedrock is loose and unconsolidated

   C. The bedrock is primarily composed of carbonates

   D. The water table is relatively low

Solution: Subsidence after an earthquake is typically caused by the liquefaction and destabilization of the ground. This occurs when the ground is loose and water can infiltrate between particles, making it less stable and easily compressible.

Turkey's geologic setting is strongly influenced by the subduction of the African Plate beneath the Anatolian Plate.

4. (2 points) Much of Turkey's bedrock is mélange—mixed material scraped off of the subducting African Plate. Part of this material is derived from oceanic igneous activity. Does this material likely have a higher or lower silica content than surface volcanoes in Turkey? Briefly explain.

Solution: Lower. Oceanic crust is thinner and closer to the mantle, so igneous material formed there will be less differentiated and more mafic, leaving it with a lower silica content. In fact, much of this material comes from ophiolites, which include mafic and ultramafic rocks like basalt and peridotite.

5. (3 points) Seismic tomography data is collected in the region underneath the Anatolian Plate. In this data, would the subducted slab from the African Plate have a higher or lower seismic wave velocity than the surrounding mantle? Explain.

   Solution: Higher. Seismic waves move faster in the subducted plate because it is more rigid, transferring energy faster than in the surrounding weaker mantle. The surrounding mantle, especially the mantle above the slab, is part of the weaker asthenosphere and will likely be less rigid or partially molten.

6. (2 points) The Taurus Mountains in southern Turkey are dominated by karst topography and have bedrock primarily composed of limestone. **Briefly** propose a method by which this limestone could have been deposited.

   Solution: Multiple answers accepted. Limestone is typically formed in marine environments, so it could not have formed on the surface in the mountains. This limestone was deposited when the Taurus Mountains were submerged during the early Cenozoic, then was exposed when a period of uplift brought them to their current height.

Problem 2

Question	1	2	3	Total
Points	4	3	8	15 (25%)

The Pliocene epoch, particularly the mid-Piacenzian warm period (3.0–3.3 Ma), was the most recent period of elevated global temperatures with near-present atmospheric CO_2 concentrations. The Pliocene is thus used as an analogue for the climate in the near future.

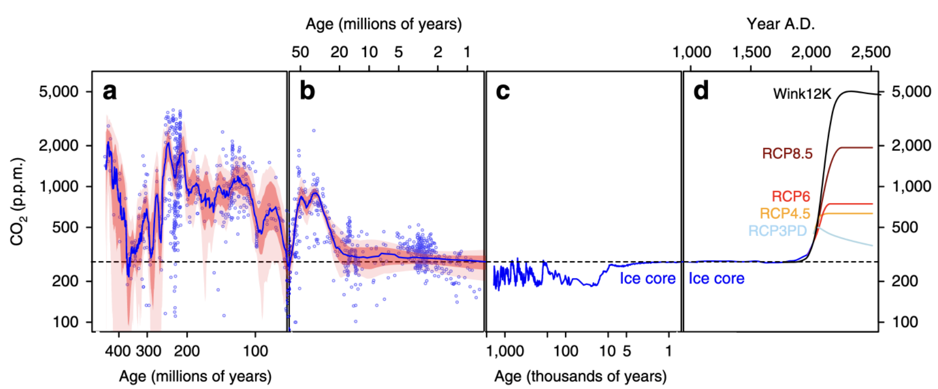

Figure 1: inferred CO_2 concentrations in the past half billion years, with the current level dashed.

1. (4 points) There are many periods in Earth's past that resemble possible near-future climate conditions (see Figure 1). **Give two reasons** for why the Pliocene serves as a more useful analogue for studying near-future climate change than periods further in the past.

   Solution: Since the Pliocene is relatively recent, more paleoclimate proxies (ice cores, sediment cores, etc.) are available for study. This means that Pliocene conditions are better constrained than periods farther back in Earth's history. Tectonic configurations, which affect ocean circulation and ice cap formation, were also similar to present during the Pliocene. This means that the geologic conditions that affect climate during the Pliocene are similar to present day.

2. (3 points) During the Pliocene, ice sheet melt caused global mean sea level rise dramatically. Give **one** reason why local sediment deposits in Greenland would seem to indicate much less sea level rise. In your answer, be sure to explain the physical processes in your reason.

   Solution: Local sea level change in Greenland differed from global mean sea level change. With the loss of ice mass over Greenland, isostatic adjustment upwards opposes sea level rise. Ice loss also decreases gravitational attraction of water to Greenland, which has a significant effect on the scale of the Greenland ice sheet.

3. A geochemical method useful for studies of glacier retreat involves the production and radioactive decay of ^{10}Be (beryllium-10) within quartz crystals.

   (a) (1 point) There is essentially no ^{10}Be within quartz when it crystallizes from melt. Instead, ^{10}Be forms in quartz *when it is exposed to the surface* via the following reaction:

$$^{16}O + p^+ \rightarrow {}^{10}Be + {}^{4}He^{2+} + 3\,p^+ + 4\,e^-.$$

   Above, p^+ and e^- refer to a proton and an electron, respectively. Surface materials also collect some ^{10}Be from similar reactions occuring with atmospheric O_2 and N_2. **Name** or **describe** the physical phenomenon responsible for the production of ^{10}Be in both of these cases.

Solution: Cosmic rays.

(b) (5 points) ^{10}Be is a radioactive isotope and decays to ^{10}B (boron-10) with a half-life of 1.4 million years. The amount of ^{10}Be in a quartz crystal is thus dependent on both the production process and the decay process.

Suppose we wish to infer the rate of retreat for an alpine glacier following the Last Glacial Maximum. If we know the constant rate of ^{10}Be production for its location, then **qualitatively describe** how the rate of glacial retreat can be inferred by measuring ^{10}Be concentrations in quartz samples. In your answer, be sure to comment on where/what your measurements are sampled from. (*Hint: the sample should be taken something that has not shifted or been overturned, since the rate of* ^{10}Be *formation is dependent on the orientation of the sample*)

Solution: The amount of ^{10}Be in a quartz sample is a proxy for how much time it has been exposed to the surface, since cosmic rays can only penetrate into quartz crystals on the surface. Since glaciers carry sediment at their base, the location of the past glacial terminus can be inferred by measuring ^{10}Be concentrations in quartz-containing sediment deposited at the glacial terminus. It is also necessary to be sure that the sediment has not been overturned, as the rate of ^{10}Be formation depends on the cosmic ray flux, which varies with insolation angle. Thus, large boulders situated in stable positions are preferable and are least likely to generate systematic error.

(c) (2 points) Is the method described above suitable for measurement of mid-Pliocene (3.0 Ma) episodes of glacial retreat? **Give one** reason why or why not.

Solution: There are many reasons why this method would not be suitable for studies of mid-Pliocene episodes of glaciation. The method of cosmogenic nuclide dating for exposure ages is very sensitive to disturbances (e.g., flipping, movement) in the sample rock, so it is very difficult to be sure that a boulder has not been disturbed since the mid-Pliocene.

Problem 3

Question	1	2	3	Total
Points	4	3	8	15 (25%)

This question will explore several aspects of the El Niño Southern Oscillation (ENSO), which is the most prominent mode of climate variability.

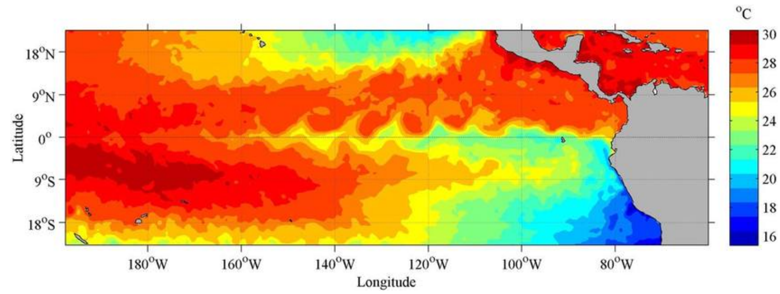

Figure 1: a snapshot of sea surface temperature in the tropical Pacific in June 2010.

1. Explain how general atmospheric and oceanic circulation maintain the following aspects of the tropical Pacific's mean state (a few sentences are sufficient).

   (a) (2 points) There is a band of relatively lower sea surface temperatures centered about the eastern equatorial Pacific.

   Solution: Easterly trade winds cause upwelling of cooler subsurface water along the equator. This is because the Ekman transport is northward north of the equator and southward south of the equator, so the net surface divergence must be compensated by upwards vertical flow.

   (b) (2 points) The thermocline of the equatorial Pacific is deeper in the west than the east.

   Solution: The topographic barrier at the western edge of the Pacific basin means that the easterly trade winds cause warm equatorial water to "pile up" in the western Pacific.

2. (3 points) ENSO is driven by the close coupling between the ocean and atmosphere. **Explain** how a positive sea surface temperature anomaly in the eastern Pacific generates an anomaly in the zonal (east-west) winds. Then, **explain** how that atmospheric response reinforces the sea surface temperature anomaly.

   Solution: A positive sea surface temperature (SST) anomaly in the eastern Pacific causes anomalous low pressure in the eastern Pacific, which weakens the Walker circulation (east-to-west surface winds and west-to-east winds aloft). A weakened Walker circulation lessens equatorial upwelling and causes the warm pool to extend eastward, since the surface easterly winds become weakened.

3. While the growth-decay cycle of ENSO is well-understood, predicting the beginning of an El Niño event remains difficult. An existing theory for El Niño initiation is that short-lasting anomalies in the trade winds called *westerly wind bursts* cause warming in the eastern Pacific.

   (a) (4 points) Since westerly wind bursts occur on much shorter timescales (weeks) than the ENSO cycle (years), they might be considered to be forcing that is external to ENSO variability. Shown below is a composite of westerly wind burst events (measured by the westerly wind anomaly over the equatorial Pacific) and the western extent of the 29°C sea surface temperature isotherm (a proxy for the Pacific warm pool).

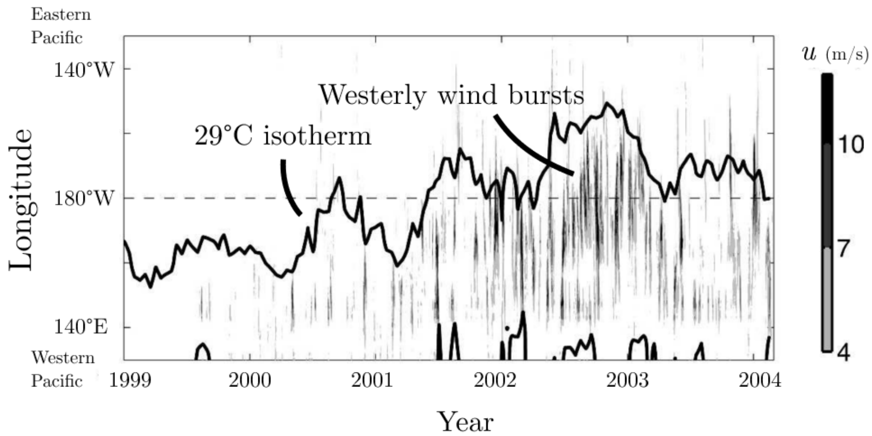

Figure 2: composite of westerly wind burst events and the extent of the 29°C SST isotherm. Note that 140°W corresponds to the **eastern** Pacific and 140°E corresponds to the **western** Pacific.

Using the observational evidence shown in Figure 2, **argue** why westerly wind bursts should **not** be considered to be external forcing that is decoupled (separate) from ENSO variability.

Solution: We see from Figure 2 that there is interannual variability in the strength (darkness of the lines in the figure), frequency, and eastward extent of westerly wind bursts that is correlated with the eastward extent of the 29°C isotherm. Specifically, during El Niño conditions (warm pool extends into the eastern Pacific; see years 2002–2003 in figure), westerly wind burst events are stronger and more frequent. So even though individual westerly wind bursts are short-timescale events, they display interannual variability that coincides with the ENSO cycle and thus cannot be considered external forcing that is decoupled from ENSO variability. In other words, we cannot be sure that the only causal relationship is "wind burst causes ENSO".

(b) (4 points) To test the possible two-way coupling between ENSO and westerly wind bursts, the following simulations were run using a climate model:

- **Experiment 1**: westerly wind bursts are artificially added to the simulated wind field when the Pacific warm pool extends past some threshold longitude.
- **Experiment 2**: westerly wind bursts are added randomly, while the amplitude and frequency of bursts are kept the same as experiment 1.

It was found that the simulated ENSO cycle in experiment 1 had twice the amplitude than that of experiment 2, shown below.

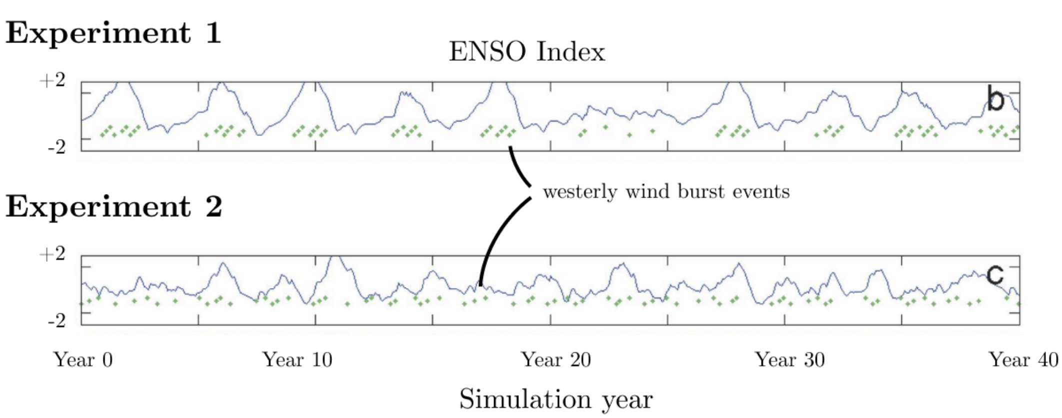

Figure 3: for both experiments, the ENSO index is shown by the line and westerly wind bursts are denoted by dots.

Justify why these results imply that westerly wind bursts are coupled with the ENSO cycle. In your answer, briefly explain how the experimental setup itself is important for making this conclusion. Here, coupling refers to a two-way causal relationship. (*Hint: how might the ENSO cycle and westerly wind bursts feed back on each other?*)

Solution: Experiment 1 is designed to represent perfect coupling between ENSO and westerly wind bursts, since wind bursts are set to occur only during El Niño years. Experiment 2, on the other hand, represents weak coupling since wind bursts occur randomly. The ENSO cycle is found to have greater amplitude and display more coherent interannual variability in Experiment 1 compared to Experiment 2, suggesting that the interannual ENSO cycle and interannual wind burst cycle feed back on each other. Also note that in Experiment 1, westerly wind burst events are clustered during El Niño years, which is consistent with what is seen in observations (see Figure 2).

For further reading, the figures and results from this question were sourced from Eisenman et al., 2005.

Problem 4

Question	1	2	3	Total
Points	2	4	9	15 (25%)

This question will explore several aspects of Saturn's rings.

1. (2 points) A recent theory suggests that Saturn's rings were created early in its lifetime from the stripped outer layers of a large, differentiated moon that fell inwards towards the planet. Using this information, explain why Saturn's rings are mostly composed of water ice.

Solution: In gas giant moons, rocky material typically falls to the center of the moon to form a solid rocky core surrounded by an icy mantle and crust. When this moon entered Saturn's Roche limit, the only material removed from the moon would have been the icy outer layers, while the rocky core would have fallen deeper into Saturn and joined the planet's own core material.

There are gaps within Saturn's rings that are caused by orbital resonances with its many moons. The largest gap is called the Cassini Division. Its inner edge includes the Huygens Gap, which is in a 2:1 resonance with Mimas (for every two orbits of an object within the gap, Mimas orbits once).

Mass of Saturn	5.68×10^{26} kg
Semi-major axis of Huygens Gap	1.18×10^{8} m
Gravitational constant (G)	6.67×10^{-11} N m^2 kg^{-2}

2. (4 points) Using the parameters above, **calculate** the period of Mimas's orbit, in hours. **Show your work!**

Solution: The period of an object within the Huygens Gap can be found using Kepler's Third Law:

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

Using the parameters listed in the table, we find that $T = 41378$ seconds $= 11.49$ hours. Since Mimas has twice the period of an object in the Huygens Gap, the period of Mimas's orbit is approximately $\boxed{\text{22.99 hours.}}$

The main rings are within Saturn's *Roche limit*, defined as the distance from the center of a celestial body at which an orbiting satellite will disintegrate due to tidal forces. You will derive a simplified equation for the Roche limit d by considering a spherical, rigid moon orbiting at exactly the Roche limit. For this question, let the mass of Saturn be M, the orbital radius of the moon be d, and the radius of the moon be r.

3. (a) (2 points) The derivation of the formula involves the tidal force. In this case, we define the tidal force on a mass m as the positive difference between the gravitational force exerted by Saturn on a mass at the center of the moon and the same mass at a point on the moon's surface closest to Saturn. (It may help to draw a picture.)

Give an algebraic expression of the tidal force F_T in terms of M, m, d, r, and the gravitational constant G. Since the tidal force is a positive difference of gravitational forces, give your answer in the form of $F_T = F_2 - F_1$ where $F_2 > F_1$.

Solution: The gravitational force exerted by Saturn on a mass at the center of the moon is

$$F_1 = \frac{GMm}{d^2}.$$

The gravitational force exerted by Saturn on a mass at the surface of the moon is

$$F_2 = \frac{GMm}{(d-r)^2}.$$

The tidal force is then

$$F_T = F_2 - F_1 = \boxed{\frac{GMm}{(d-r)^2} - \frac{GMm}{d^2}}$$

(b) (3 points) The expression above can be simplified by assuming that $r \ll d$. Using the fact that for small x, $(1+x)^n \approx 1 + nx$, **derive a simplified expression** for tidal force in terms of the same variables as above. (*Hint: rewrite one of the terms involving* r *and* d *in the form* $(1-x)^n$.)

Solution:

$$F = GMm\left(\frac{1}{(d-r)^2} - \frac{1}{d^2}\right)$$

$$F = GMm\left(\frac{1}{d^2}\left(\frac{1}{(1-\frac{r}{d})^2} - 1\right)\right) \quad \text{use series expansion since } r/d \text{ is small}$$

$$= GMm\left(\frac{1}{d^2}\left(1 + 2\frac{r}{d} - 1\right)\right)$$

$$= \boxed{\frac{2GMmr}{d^3}}$$

If you cannot obtain an answer for (b), use $F_T = \frac{GMmr}{d^3}$ for (c).

(c) (4 points) **Derive an algebraic expression** for the Roche limit d in terms of Saturn's mass M and the density of the moon ρ. (*Hint: recall that the moon disintegrates within the Roche limit because the tidal force exceeds its own self-gravitation.*)

Solution: At the Roche limit, the tidal force on a mass m at the moon's surface will exactly equal the gravitational force exerted on m by the moon. So setting $F_T = F_G$ and solving for d, we get

$$\frac{2GMmr}{d^3} = \frac{GM_{\text{moon}}m}{r^2}$$

$$d = r\sqrt[3]{\frac{2M}{M_{\text{moon}}}}$$

$$= r\sqrt[3]{\frac{2M}{\frac{4}{3}\pi r^3 \rho}}$$

$$= \boxed{\sqrt[3]{\frac{3M}{2\pi\rho}}}$$

END OF SECTION II