USESO 2022

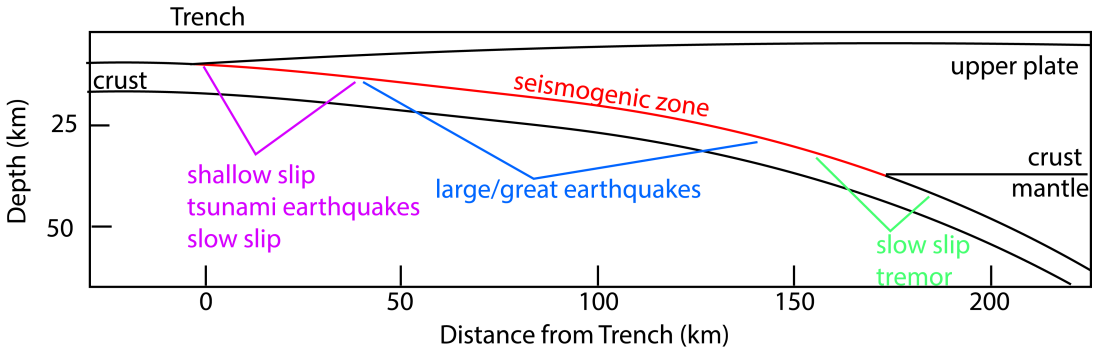
Geosphere KEY

Instructions:

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

Section I

1. Almost all high-magnitude earthquakes occur at megathrust faults, and their significant displacement means they have a high likelihood of generating tsunamis. The strongest earthquakes occur with greater seismic coupling (i.e. high friction); faults slip slowly and aseismically where seismic coupling is weaker.



(Bilek et al., 2018)

Increasing which of the following would make strong megathrust earthquakes more likely?

I) Increasing the age of the subducting slab

II) Increasing the convergence rate of the subduction zone

III) Increasing fluid pressure at the subduction zone

A. II only

B. III only

C. I and II

D. II and III

E. None

Solution: Older crust is generally cooler and denser. It sinks more rapidly and has a higher dip angle, reducing contact area between the plates - I is false. Increasing the convergence rate increases both the friction between the plates and the amount of stored energy at the fault - II is true. Increasing fluid pressure lubricates the fault, decreasing friction and allowing more aseismic slip - III is false.

2. Below are three sedimentary structures. Which of the following corresponds to the likely directions of the currents that produced each?

A. Right, right, left

B. Right, left, right

C. Left, left, right

D. Left, right, left

E. Left, right, right

Solution: The first image displays cross-bedded dunes. The top surface of each slip face is angled towards the current direction (to the left). The rocks in the second image possess imbrication, the tilting by rushing water such that the top points in the direction of current (to the right). The third image shows ripple marks, where the steepest side is downstream (to the left).

3. Most modern coal formed in wetlands after a global glaciation. Which of the following are effects of glaciation that lead to coal-forming conditions?

I) Newly exposed continental shelf led to the formation of more wetlands.

II) Lower water availability prevented plant matter from decomposing.

III) Lower temperatures led to slower biodegradation.

A. I only

B. II only

C. III only

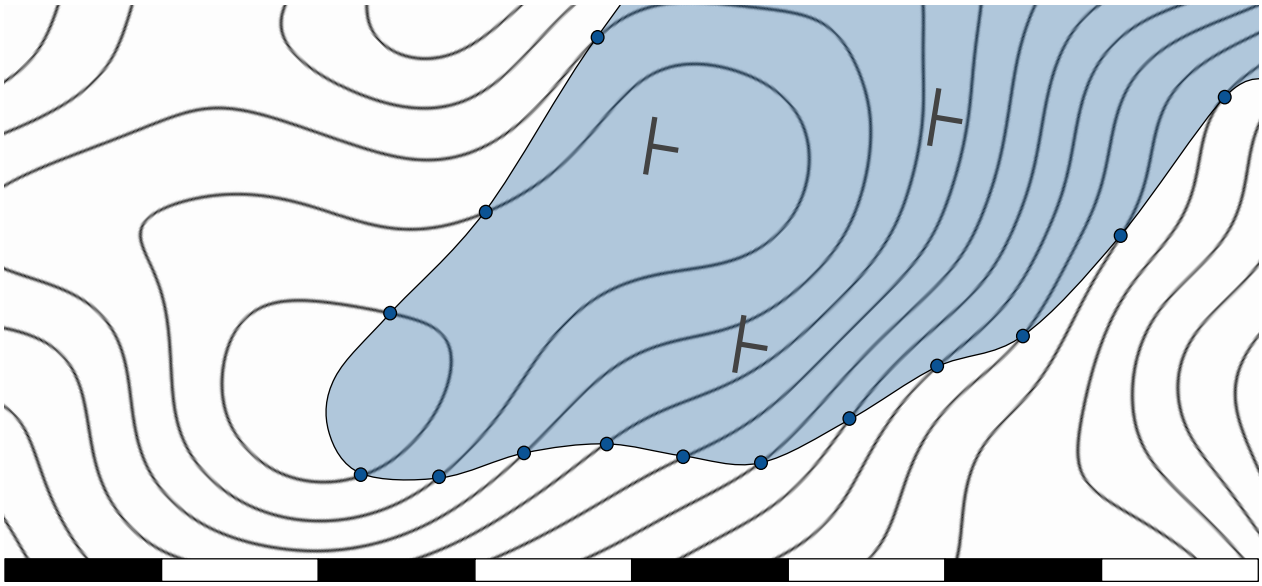
D. II and III

E. I, II, and III

F. None

Solution: By storing water as ice over land, global glaciation lowers sea level and exposes a greater area of land. More wetlands could form, where coal forms - I is true. The water in wetlands is essential to preventing plant matter from decomposing rather than enabling decomposition, so II is false. Lastly, while lower temperatures is associated with slower biodegredation, colder periods restrict the production of plant matter - III is also false.

4. Consider the contour map below. The contour interval of the map is 10 m, and each rectangular bar on the bottom the image is 100 m. The border of the shaded region shows the area where a uniform planar bed has been exposed by weathering. The strike at any point on the bed is N10E.



Which of the following is closest to the dip angle of this bed?

A. 2°

B. 6°

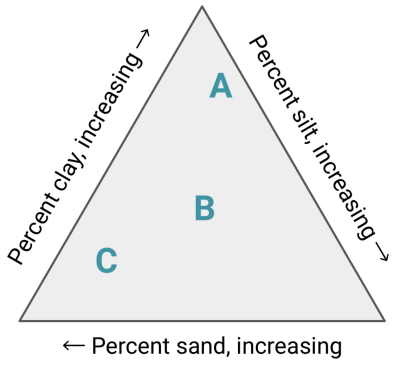
C. 11°

D. 22°

E. 32°

Solution: One method for estimating dip uses two points that lie along the dip direction. Points used may vary, but suppose we use the most northern points on the west and east sides of the bed. The dip angle will be $\tan^{-1}\frac{d_v}{d_h}$, where d_v and d_h are the vertical and horizontal distance between the points, respectively. On the map, the two points are separated by almost exactly four bars, so d_h is 400 m. The two are also separated by eight contour lines, so d_v is 80 m. The dip angle is approximately $\tan^{-1}\frac{80}{400} =$ C) 11°.

5. Consider the simplified soil texture triangle shown below. The letters A, B, and C represent the compositions of three different soil samples.



Which of the following is/are true of these samples?

I) Of the three soil samples, soil A is best suited for plants requiring high soil moisture.

II) Of the three soil samples, soil B is most likely to be found in a low-energy depositional environment .

III) If soil B is subjected to wind erosion, the resulting soil composition would be closer to soil C.

A. I only

B. II only

C. III only

D. I and II

E. I and III

F. II and III

Solution: Soil A is mostly clay with low silt and sand percentages, giving it the lowest permeability. Water will not drain as easily through soil A, which helps to retain soil moisture - I is true. Soil B has less clay than soil A as well as more silt and sand. With the higher proportion of larger sediment particles, soil B is associated with a higher energy depositional environment than Soil A - II is false. Finer particles such as clay and silt erode more readily than coarser particles like sand. Weathered soil will have a larger percentage of sand and a smaller percentage of clay, which is true of soil C relative to soil B - III is true.

6. Even though metamorphic reactions are reversible in theory, retrograde metamorphism is rarely observed. Which of the following may explain this?

I) Reactions between solid phases are typically slow and require a catalytic fluid to proceed.

II) Slow uplift to the surface allows the rock to equilibrate to surface conditions.

A. I only

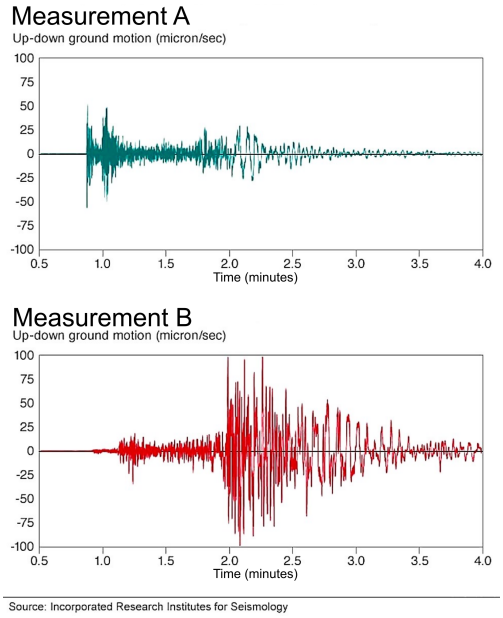
B. II only

C. I and II

D. None

Solution: During prograde reactions, water is typically lost as it escapes through rock pores. Since reactions between solid phases are inefficient, they can proceed only through the catalytic activity of water - I is true. Slow uplift is conducive to retrograde metamorphism because there is more time for retrograde reactions to proceed, so II is false.

7. The following image shows two seismograms, one of a nuclear test and one of an earthquake. Which of the following correctly identifies the earthquake and gives the best evidence to support the claim?



A. Measurement A is the earthquake, as evidenced by the clear gap between the arrival times of P and S waves at 0.8 and 1 minute respectively.

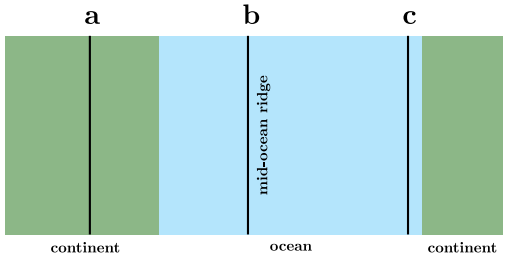
B. Measurement A is the earthquake, as evidenced by the much greater magnitude of P and S waves as compared to the surface waves.

C. Measurement B is the earthquake, as evidenced by the clear gap between the arrival times of P and S waves at approximately 1.1 and 1.9 minutes respectively.

D. Measurement B is the earthquake, as evidenced by the sudden increase in magnitude at the arrival of the surface waves after the arrival of P and S waves.

Solution: Surface waves generally arrive at seismometers with a much higher amplitude than P and S waves. The highest amplitude signals in Measurement A occur at the beginning of the event, indicating that the disturbance was at the surface. Meanwhile, in Measurement B surface waves arrive after the body waves as typical of earthquakes.

8. Terranes are crustal fragments that are transported across ocean basins and accrete onto the margins of continents. The figure below shows continental crust (green), oceanic crust (blue), and three tectonic boundaries labeled A, B, and C. Boundary B is a mid-ocean ridge. Boundaries A and C are either rifting or subduction zones. For continental crust fragment on the left to eventually accrete onto the continent on the right, which of the following conditions must be true?



I) Boundary A is an extensional environment.

II) The rate of rifting/subduction of Boundary A exceeds that of Boundary B.

III) The rate of rifting/subduction of Boundary C exceeds that of Boundary B.

A. II only

B. III only

C. I and II

D. I and III

Solution: First, Boundary A must be an extensional environment for a fragment of continental crust to form; a rift would generate oceanic lithosphere that eventually separates the continent to the left of Boundary A from the land to other side of Boundary A - I is true. Then for this new terrane to reach the continent on the right, the oceanic lithosphere must be consumed by subduction, which it must at Boundary C (since Boundary B is an mid-ocean ridge, it by definition a rift zone). Subduction must outpace rifting such that the ocean basin shortens - II is false and III is true.

9. Which of the following sets of features is associated with continental margins that contain accreted terranes?

A. Uplift and earthquakes

B. Uplift and coastal aquifers

C. Subsidence and flooded valleys

D. Subsidence and marine terraces

Solution: Terranes are accreted onto continents at active margins, where there would be a convergent boundary at least at the time of accretion. The only answer choice that contains two other features of active margins is A) Uplift and earthquakes.

10. The marine organisms are better recorded in the fossil record than terrestrial organisms. Which of the following about marine environments provides the best explanation?

A. Oceanic lithosphere is younger on average compared to continental lithosphere.

B. Deep sea sediments accumulate more slowly than alluvial sediments.

C. Marine environments more readily form calcareous deposits.

D. Marine deposits are exposed to less wind and running water.

Solution: Remaining undisturbed is a critical requirement for fossilization. On land, remains are almost always destroyed by erosive agents such as wind and water if they have not already decayed. In addition to inhibiting decomposition, the ocean bottom provides an environment that is still enough to preserve the organism. B) is related to this idea, but the slow accumulation of sediments is only another effect of the deep ocean environment.

Section II: Problem 1

Question	1	2	3	4	Total
Points	3	7	2	3	15 (30%)

The chemical weathering of silicate minerals plays an important role in regulating the carbon cycle, thereby affecting other Earth systems. In this problem we will consider the impacts of silicate weathering on oceans, and on geologic timescales, the climate.

While uncommon, wollastonite ($CaSiO_3$) is a simple mineral that exemplifies a pattern of silicate weathering. The chemical equation for this weathering is as follows:

$$2\,H_2O + CO_2 + CaSiO_3 \longrightarrow 2\,HCO_3^- + Ca^{2+} + SiO_2$$

1. (a) (1 point) The carbon produced from silicate weathering is transported into the ocean. Marine organisms cannot use the bicarbonate produced directly from weathering, yet are able to incorporate the carbon into calcium carbonate. What chemical change must bicarbonate undergo?

   Solution: To produce calcium carbonate ($CaCO_3$), marine organisms can only use carbonate (CO_3^{2-}), not bicarbonate (HCO_3^-). For bicarbonate to form carbonate, a H^+ ion must be released into the ocean.

   (b) (2 points) A signficant amount carbon dioxide produced by human activity enters the ocean, where it reacts with water to form carbonic acid (H_2CO_3). How might an increase in carbonic acid inhibit the reaction that forms calcium carbonate as described in part (a)?

   Solution: By definition, an acid adds H^+ ions to the ocean and decreases pH, which shifts the chemical equilibrium of the reaction converting between bicarbonate and calcium carbonate. Because of carbonic acid increases the concentration of H^+ ions, it becomes less favorable for bicarbonate to lose an H^+ ion, and therefor less favorable for the formation of calcium carbonate.

2. (a) (2 points) Consider a hypothetical scenario in which strengthened mantle convection increases the spreading rate at a mid-ocean ridge. Briefly explain how faster seafloor spreading would likely affect the average global temperature.

   Solution: Like other instances of mantle material surfacing, seafloor spreading releases volatiles that include greenhouse gases like carbon dioxide. More active spreading increases the release of greenhouse gases, resulting in net warming.

   (b) (3 points) Explain how the effect of seafloor spreading on climate in part (a) is connected to the carbonate-silicate cycle.

   Solution: Volatiles like carbon dioxide are introduced to the mantle from the subduction of crustal sediments. These sediments are deposited on longer timescales via the carbonate-silicate cycle as marine organisms sequester carbon in the form of calcium carbonate.

(c) (2 points) The strengthening of mantle convection also increases the rate of subduction, resulting in larger mountain ranges and island arcs. What effect does this have on climate? Briefly explain.

Solution: An increase in the formation rate of mountain ranges results in an increase in weathering of those same ranges. Weathering in the carbonate-silicate cycle sequesters carbon dioxide, reducing its concentration in the atmosphere and resulting in a net cooling effect.

3. (a) (1 point) The most important aspect of the carbonate-silicate cycle is its dependence on global temperature. Suppose that human CO_2 emissions increase Earth's temperature significantly and last long enough to affect geologic processes. Describe how the weathering of silicates would change in rate in response to anthropogenic warming.

Solution: Weathering is more active at high temperatures, so it would increase as a result of climate change.

(b) (1 point) On long timescales, what kind of feedback is exhibited by the temperature dependence of silicate weathering?

A. Positive

B. Negative

C. Both positive and negative

Solution: While silicate weathering increases with higher temperatures, an increase in weathering consumes carbon dioxide. With enough time, lower levels of atmospheric carbon dioxide also lowers global temperatures. In this way, silicate weathering acts as a temperature regulator as part of a negative feedback loop.

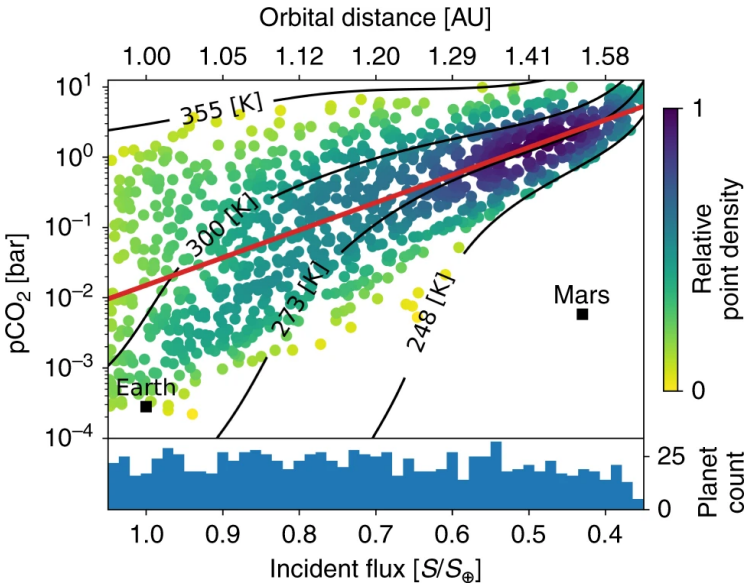


Figure 1: Expected distribution of Earth-like exoplanets in pCO_2 and orbital distance. (Lehmer et al., 2020)

4. (3 points) In Earth's infancy, the Sun was likely only about 70% as bright as it is now. All else the same, Earth would have been too cold to sustain a liquid ocean at a temperature of about 248 K. However, there is strong evidence for the presence of oceans during this time, indicating that Earth had a much stronger greenhouse effect than today. Explain how the carbonate-silicate cycle could have played a role in keeping Earth's temperature more consistent throughout its evolution.

Solution: The negative feedback of the carbonate-silicate cycle allows regulation of planetary temperature. Earth's early atmosphere had high concentrations of carbon dioxide, warming the planet via the greenhouse effect. As the Sun grew brighter, Earth's temperature initially increased, resulting in more active surface weathering. Because this weathering sequesters carbon, it would have lowered atmospheric pCO_2, decreasing the greenhouse effect and returning Earth to a habitable temperature.

Section II: Problem 2

Question	1	2	3	4	5	6	7	Total
Points	4	2	1	2	2	1	3	15 (30%)

The Himalayas form the longest mountain range in Asia. This problem explores its crustal deformation in a cross section and the Main Himalayan Thrust.

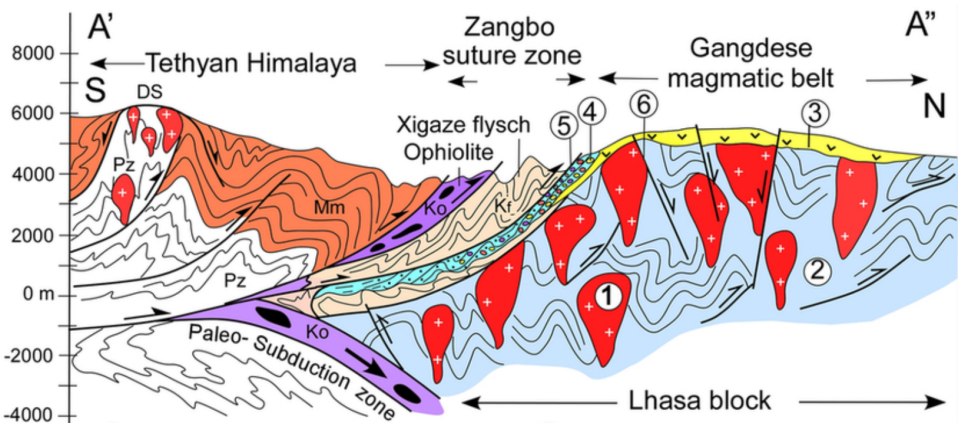


Figure 1: Cross section of Himalayas. (Wang et al., 2015)

1. (a) (2 points) Contemporary sinking near the Zangbo suture zone is causing the Gangdese magmatic belt to rise. Explain how this motion is an example of isostatic adjustment.

   Solution: The Tethyan Himalaya places a large vertical load on underlying lithosphere. Because the asthenosphere behaves as a liquid beneath the lithosphere, the downward bending from the weight of the mountain is accommodated by a nearby upward bend to approach isostatic equilibrium. This is sometimes known as lithospheric flexure.

   (b) (2 points) Within the Zangbo suture zone is flysch composed of folded units that transition from turbidites to dark shales to coarse fluvial deposits. Describe the changes in depositional environment reflected in this flysch in relation to the collision of the Indian subcontinent with Asia.

   Solution: The flysh records the depositional environment changing from deep marine to fluvial, consistent with uplift from mountain building. The water-filled region that became the suture zone between the Indian subcontinent and Asia was once deep, as indicated by turbidites and shales, but then became shallow enough for river deposits as the collision progressed.

2. (2 points) Around 20 million years ago, monsoons around the Himalayas intensified. How might this have affected the vertical movement of the Himalayas?

   Solution: Intensification of monsoons increases erosion, which is especially true of high-relief topography such as the Himalayas. A decrease in mass causes the lithosphere to isostatically rebound.

3. (1 point) A geologist finds pillow basalt in the Himalayas. In which region(s) of this cross-section could the geologist potentially be in?

I) Tethyan Himalayas

II) Zangbo Suture Zone

III) Gangdese Magmatic Belt

A. I only

B. II only

C. III only

D. I and III

E. None

Solution: Pillow basalts are indicative of basalt erupting underwater. They are often found in ophiolites, in which fragments of the oceanic crust are sutured onto continental crust instead of being subducted.

4. (2 points) Some of the Tethyan Himalaya is strongly folded but is only weakly metamorphosed. How can igneous intrusions create these conditions?

Solution: Intrusions can cause rock to deform and fold around them. The host rock surrounding intrusions undergo contact metamorphism, which is not considered a high metamorphic grade.

5. (2 points) Some of the igneous rocks in the Gangdese magmatic belt are derived from basaltic melts. Meanwhile, the yellow unit on surface has a different composition from the rest of the belt. Briefly explain the process that created the yellow unit.

Solution: The basaltic melt is from partial melting of the mantle due to water from subduction. Through fractional crystallization as this melt ascended, the basaltic magma evolved to become more felsic, making the yellow unit andesitic.

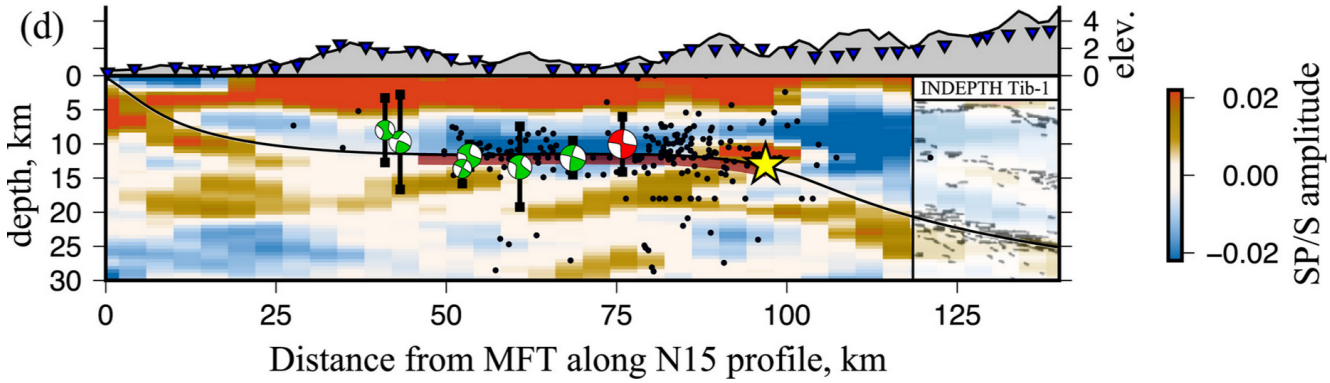


Figure 2: The Main Himalayan Thrust, a basal detachment fault, (Duputel et al., 2016)

6. (1 point) Relative to the bottom half of the image, towards what direction is the top half of the image moving?

   A. Right

   B. Left

   C. Neither

Solution: The black line represents the detachment fault between two crustal blocks. The fault is a thrust fault, a low-angle reverse fault. Under compressive stresses in the Himalayas, the top block moves left relative to the bottom block.

7. (a) (2 points) At depths between 10-15 km is a low-velocity zone, an area of anomalously slow seismic wave velocity that may be caused by the introduction of water. Describe two mechanisms that explain how subducted material acts as a source of water to the mantle.

Solution: Water is derived from subducted plate material, and can come two sources. An increase in pressure drives water from the pore spaces of rock and sediment. As rocks metamorphose with further subduction, chemically-bound water is released from hydrated minerals.

(b) (1 point) Another low-velocity zone is present deeper in the mantle. This structure is thought to be a result of which of the following phenomena?

   A. Volatiles at depth

   B. Partial melting

   C. Metamorphism

   D. Faulting

Solution: Partial melting is also the origin of the more shallow low-velocity zone described in part (a). The origin of its deeper instance is still contested, but volatiles, metamorphism, and faulting are not among those considerations.