Homework 3:

Ocean Basin Physiography & Plate Tectonics

3-1. THE OCEAN BASIN

The world ocean basin is an extensive suite of connected depressions (or basins) that are filled with salty water; covering 72% of the Earth’s surface. The ocean basin bathymetric profile in Figure 3-1 highlights features of a typical ocean basin, which is bordered by continental margins at the ocean’s edge. Starting at the coast, the sea floor the slopes slightly across the continental shelf to the shelf break where it plunges down the steeper continental slope to continental rise and the abyssal plain, which is flat because accumulated sediments.

![Figure 3-1. Cross section showing bathymetric features of the sea floor. Gray areas are sediments.](image1)

The continental shelf is the flooded edge of the continent -extending from the beach to the shelf break, with typical depths ranging from 130 m to 200 m. The sea floor slopes over wide shelves are 1° to 2° - virtually flat- and somewhat steeper over narrower shelves. Continental shelves are generally gently undulating surfaces, sometimes interrupted by hills and valleys (see Figure 3-2).

![Figure 3-2. Submarine canyon and fan.](image2)
The **continental slope** connects the **continental shelf** to the **deep ocean**, with typical depths of 2 to 3 km. While appearing steep in these vertically exaggerated pictures, the bottom slopes of a typical continental slope region are modest angles of $4^\circ$ to $6^\circ$. Continental slope regions adjacent to deep ocean trenches tend to descend somewhat more steeply than normal. Sediments derived from the weathering of the continental material are delivered by rivers and continental shelf flow to the upper continental slope region just beyond the continental shelf break. These sediment accumulations eventually become unstable creating under water landslides called **turbidity currents**. The sediment-laden turbidity currents are density currents that flow rapidly down-slope under the force of gravity and scouring the bottom to form **submarine canyons** (see Figure 3-2).

Upon reaching the bottom, the turbidity currents spread laterally, slow, and deposit their sediments in enormous fan-shaped accumulations called **submarine fans**. Eventually their sediment load is delivered to the **continental rise** region in the form of a **submarine fan** (Figure 3-2). The continental rise regions, which are composed of land-derived sediment accumulations that may be up to several kilometers thick and tens of kilometers wide, have slopes between $1^\circ$ and $5^\circ$ (Figure 3-2). Overlapping submarine fans are believed to form the continental rise, which transitions to the **abyssal plain** (Figure 3-1).

The abyssal plain is remarkably flat and featureless due to the long-term rain particles that have formed sediments that have buried most sea floor irregularities. The abyssal plain region transitions to the **abyssal hill region**, where isolated **knolls** and **seamounts** protrude through the sedimentary cover. The sea floor exhibits increasing numbers of knolls and seamounts as we move seaward toward the **mid-ocean ridge** (Figure 3-1) because the sedimentary cover is increasing thinner.

Oceanic ridges (Figure 3-1) - volcanic in origin - form mountain chains that extend throughout of the world ocean basins. The **oceanic ridge crest** is formed by a pair of the highest peaks that bracket the narrow **rift valley** that marks the axis of the ocean ridge (Figure 3-1). The mid-ocean ridge is composed of offset segments, which are defined by a pairs of **transform faults** (Figure
The rock in the region of a transform fault is under extreme stress and thus periodically fractures. The rocks on either side of the fault slide past each other in opposite directions creating a fracture zone or band of distorted and broken rocks. The transform faults together with their associated fracture zones appear as gashes or scars that run perpendicular to the oceanic ridge rift valleys (see Figures 3-3 and 3-4). These fracture zone scars become gradually more obscured by sediments the further one moves away from the ocean ridge.

Oceanic trenches are another of the prominent feature of the ocean sea floor not shown in these particular pictures. These very deep, long, narrow, relatively steep-sided depressions in the ocean basin usually occur around the rims of ocean basins. Volcanism is not unusual in the region of deep ocean trenches.

3-2. PHYSIOGRAPHIC MAPS

Physiographic maps provide a three-dimensional perspective view of a region. An example in Figure 3-4 is of the sea floor bathymetry of the western Pacific Ocean basin. Note that the variation in the vertically-exaggerated elevation of the sea floor features is indicated by differences in shading.

In the next section, the geologic processes responsible for these features are discussed.
Figure 3-4. Physiographic Map of the Pacific Ocean basin.
3-3. PLATE TECTONICS

Plate tectonics is the dynamic response of the Earth’s surface crust to the processes deep within the Earth that facilitate the upward escape of heat generated within. The ocean basin bathymetric features that we actually observe are the result of the competition between plate tectonics and sedimentation. Plate tectonic processes involve the creation, movement and destruction of the Earth’s crust – all of which tend to produce sharp, jagged crustal features. But these features are partially or fully buried by a rain of small sediment particles – a mixture of inorganic particles produced by weathering of terrestrial rocks and organic particles produced by oceanic biology. Because the sea floor is 10s to 100s of millions of years old, the sedimentary processes have the time to build-up sediment layers that smooth and even bury the jagged features. Next we explore the plate tectonic processes that produce the jagged features of the ocean sea floor.

The heat escapes from the Earth’s interior through a set of highly-organized convection cell flows of the semi-solid (i.e. plastic) rock material of the asthenosphere (Figure 3-5). This upwelling molten rock called magma divides under the mid-ocean ridge, each branch going in opposite directions under the mid ocean ridge. The oceanic ridge crest system is a bathymetric high because the whole system is hotter and thus less dense than the rest of the ocean sea floor.

Figure 3-5 Cross-section of a hypothetical section of the outer portion of the Earth. Convection in the asthenosphere drags the ocean and continental crust along with it toward the left. A neighboring convection cell drags the ocean crustal plate to the left. When the leading edge of the continental crustal plate collides with the less dense thinner ocean crustal plate, the latter subducts to form a deep ocean trench

Plate Creation: The mid-ocean ridge upwelling of molten rock called magma creates a tension that produces a gap or central rift valley between an adjacent pair of solid, but brittle
**lithospheric plates.** Magma upwells into the rift valley (Figure 3-5), solidifies rapidly as it hits the cold water, adding this new rock called **basalt** to the edges of both lithospheric plates. Thus this pair of lithospheric plates diverge as they move away in opposite directions from the rift valley and mid-ocean ridge zone of **plate divergence**.

**Plate Movement and Evolution:** On both sides of the mid-ocean ridge, the deeper asthenospheric rock, which is moving horizontally as part of the convection cell, drags the lithospheric plates above it along (see Figure 3-5). The geometry of plates moving away (or diverging) from a mid-ocean ridge over the spherical Earth’s surface, causes the mid-ocean ridge to be segmented by pairs of transform faults (see Figure 3-3). Earthquakes are formed when the plates on either side of the transform fault move relative to each other.

With time the asthenospheric and lithospheric rock above it move horizontally, they cool and become denser, and thus sink deeper into the Earth’s interior (Figure 3-5). With time the moving ocean crust gradually accumulates a thick sediment layer that may obscure the mountainous features of its youth. This process explains the gradual change from rugged oceanic ridge crest to abyssal hills to the abyssal plains; only interrupted by isolated islands, island chains, undersea seamounts, and seamount chains.

What is the origin of the island and seamount chains? The answer is that, in addition to the major convection cells associated with the oceanic ridge systems, there are also stationary and isolated “**hot spots**” within the asthenosphere. These super-heated fountains of mantle rock, called **mantle plumes** (Figure 3-6, top), typically generate large volcanic islands. As the oceanic plate gradually moves across the plume, the volcanic island loses its lava source and becomes extinct, being replaced by a young volcanic island at its former location. Thus a linear series of volcanic islands and undersea seamounts are generated; revealing the direction of plate movement. The pattern of the island chains in Figure 3-7/middle indicates a distinct change in ocean plate movement many millions of years ago.

When moderately long-lived mantle plume is located near a ridge crest, a chain of larger than normal volcanoes called an aseismic ridge can be created (Figure 3-6, bottom). Aseismic ridges
tend to be aligned perpendicularly to the ridge crest and parallel to transform faults and fracture zones. Aseismic ridges can also indicate if there has been a change in direction of plate motion. Occasionally short-lived or weak mantle plumes is located near a ridge crest generate undersea volcano (or seamount) which then will ride on the moving oceanic crustal plate away form the oceanic ridge.

Plate Destruction: At some point the laterally moving asthenospheric material converges with that of a neighboring convection cell (left in Figure 3-5). The associated lithospheric plates collide in what is called a plate convergence zone and generally one of the plates slides below the other. However, there are there are distinctly different examples of how the different plates that make up the Earth’s crust are destroyed.

Figure 3-6. (top) Cross section showing how a mantle plume can produce a sequence of volcanic islands and undersea seamounts. (middle) Map view of the volcanic island chain and the indicated change of plate movement direction. (bottom) Map view of aseismic ridge of volcanic islands and seamounts produced by a mantle plume near a mid-ocean ridge.
Plate Configuration: The Earth’s crustal lithospheric layer is composed of **12 major plates** as illustrated in the Figure 3-7. These evolving oceanic plates collide in a variety of ways. Where plates converge, the sea floor is greatly depressed and forms a trench (Figure 3-5), where one plate descends below or subducts beneath the other (e.g., Pacific and North American plate boundary along the Aleutian Trench). Such areas are called subduction zones. When the collisions occur between relatively thin and denser oceanic plate and the thicker less dense continental crust the oceanic plate subducts (e.g., Nazca and South American plate boundary along the Peru-Chile Trench).

![Figure 3-7 Lithospheric plates of the Earth.](image)

If the overriding plate in the area of subduction zone is oceanic crust (e.g., Eurasian and Australian plate boundary along the Java Trench), then a chain of islands, called an **island arc**, is formed parallel the trench. This happens because as the subducting plate plunges deeper into the asthenosphere, it melts to become magma. Because hot magma is less dense than surrounding rocks, it migrates upward, melting its way through the overlying lithosphere to form volcanoes of the island arc chain.
If the overriding plate in the area of subduction is a continent, a volcanic mountain chain paralleling the trench (e.g., Peru-Chile Trench) forms on the continent. Subduction can eventually eliminate an entire ocean basin causing continents to collide, forming large, structural, non-volcanic mountain chains. The collision of India and Asia formed the Himalayas and eliminated the ocean basin between them.

**Summary**

*Oceanic lithospheric plates are:*

1. Created at ocean ridges, which consist of a central rift valley that is paralleled by a pair of ridge crest mountain ranges;

2. Dragged away from oceanic ridges (parallel to the transform faults in the ridge) by underlying convection-driven flow of a semi-molten asthenosphere;

3. Are youngest at the oceanic ridge and progressively older away from the ridge.

4. Covered by thicker layers of sediment near the continents

5. Penetrated by mantle hot spot plumes that create chains of volcanic islands/seamounts that can indicate the directions of past and present plate movement;

6. Moving toward deep ocean trenches;

7. Are destroyed in ocean trenches, with either an island arc or volcanic mountain chain forming in the overriding plate.
3-4. ESTIMATING RATES OF OCEAN BASIN EXPANSION

It is possible to determine the average rate at which the sea floor is spreading outward from the rift valley, if the age of sea floor volcanic rocks at different distances from the spreading center is known. Average rate of sea floor spreading (ASFSR) is equal to the distance the rocks have traveled (one way or the other) from the rift valley (Distance) divided by the time (Time) according to the relation:

$$\text{Average Sea Floor Spreading Rate} = \text{ASFSR} = \frac{\text{Distance}}{\text{Time}}$$

The ASFSR that we are computing here applies to one side of the oceanic ridge. If the ocean basin is symmetrical about the mid-ocean ridge, like the Atlantic Ocean, then the ASFSR will be the same on either side of the ridge. Thus Average Ocean Basin rate of Expansion Rate (AOBSR) will be equal to twice the ASFSR according to:

$$\text{Average Ocean Basin Expansion Rate} = \text{AOBSR} = 2 \times \left( \frac{\text{Distance}}{\text{Time}} \right)$$

Example 1:
Volcanic sea floor rocks, which are located 400 km west of the mid-ocean ridge rift valley are determined (by magnetic anomalies) to be 20 million years old.

What is the Average Sea Floor Spreading Rate (ASFSR) over the last 20 million years?

$$\text{ASFSR} = \frac{\text{Distance}}{\text{Time}} = \frac{400 \text{ km}}{20,000,000 \text{ yr}} = 2 \text{ cm/yr}$$

Using what you learned in the Lab1 homework exercise, can you show that this calculation is correct? Probably, but it is easier if you convert the very large numbers into ones using “scientific notation” as described in the following digression.

************************************************************************
DIGRESSION
************************************************************************
The numbers associated with sea floor spreading are very large; such as spreading distances of 400 km (= 400,000 m) over time spans of 20,000,000 yr. Thus it is convenient to use scientific notation when writing the numbers. Scientific notation employs the means to depict different powers of 10 easily. A modified Table 1 (from Lab1) below shows how to specify very large and very small numbers as powers of 10, which are written as 10 with a numerical exponent.
Table 1 Metric Prefixes, their Numerical Meanings, and Scientific Notation (Powers of 10)

Note that number less than 1 are fractions.

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Size</th>
<th>Scientific Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>giga</td>
<td>1,000,000,000.0</td>
<td>1 billion</td>
</tr>
<tr>
<td>mega</td>
<td>1,000,000.0</td>
<td>1 million</td>
</tr>
<tr>
<td>kilo</td>
<td>1,000.0</td>
<td>1 thousand</td>
</tr>
<tr>
<td>hecto</td>
<td>100.0</td>
<td>1 hundred</td>
</tr>
<tr>
<td>deka</td>
<td>10.0</td>
<td>ten</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>one</td>
</tr>
<tr>
<td>deci</td>
<td>0.1</td>
<td>1 tenth</td>
</tr>
<tr>
<td>centi</td>
<td>0.01</td>
<td>1 hundredth</td>
</tr>
<tr>
<td>milli</td>
<td>0.001</td>
<td>1 thousandth</td>
</tr>
<tr>
<td>micro</td>
<td>0.000001</td>
<td>1 millionth</td>
</tr>
<tr>
<td>nano</td>
<td>0.00000001</td>
<td>1 billionth</td>
</tr>
</tbody>
</table>

**RULES for CONVERTING NUMBERS to SCIENTIFIC NOTATION**

**EXAMPLE**

For numbers that are **1.0 or GREATER**

1,000,000.0

1. Move the decimal point to the left (counting “the number of places”; e.g. 6).

2. Write the new number multiplied by 10 raised to the “number of places”.

1.0 x 10^6

For numbers that are **LESS than 1.0**

0.0000010

1. Move the decimal point to the right (counting “the number of places”; e.g. 6).

2. Write the new number multiplied by 10 raised to the “- number of places”

1.0 x 10^-6

**RULES for MULTIPLYING and DIVIDING NUMBERS in SCIENTIFIC NOTATION**

When **Multiplying** numbers expressed in Scientific Notation

1,000,000 x 200

1.0 x 10^6 x 2.0 x 10^2

1. Algebraically add the powers of 10 to get a “sum”;

6 + 2 = 8

2. Multiply the numbers; and

1.0 x 2.0 = 2.0

3. Multiply by a 10 with the exponent = the “sum”

2.0 x 10^8

OR

200,000,000
When **Dividing** numbers expressed in Scientific Notation

\[
\frac{200}{1,000,000} \quad \text{OR} \quad \frac{(2.0 \times 10^2)}{(1.0 \times 10^6)}
\]

1. Compute the fraction

\[
(2.0 \times 10^2) \times (1.0 \times 10^{-6})
\]

2. Algebraically add the powers of 10 to get a “sum”;

\[
2 + (-6) = -4
\]

3. Multiply the leading numbers to get their “product”; and

\[
1.0 \times 2.0 = 2.0
\]

4. Multiply their “product” by a 10 with the exponent = the “sum”

\[
2.0 \times 10^{-4}
\]

**END OF DIGRESSION**

Now applying these principles to the present sea floor spreading example, we have

\[
\text{ASFSR} \quad = \quad \frac{\text{Distance}}{\text{Time}} \quad = \quad \frac{400 \text{ km}}{20,000,000 \text{ yr}}
\]

But we can convert \(20,000,000\) yr into \(20.0 \times 10^6\) yr by moving the decimal 6 places to the left. Thus the above can be written

\[
\text{ASFSR} \quad = \quad \frac{400 \text{ km}}{20 \times 10^6 \text{ yr}}
\]

Likewise, we can convert \(400\) km into \(4.0 \times 10^2\) yr by moving the decimal 2 places to the left. Thus the above can be written

\[
\text{ASFSR} \quad = \quad 40 \times 10^1 \text{ km}/20 \times 10^6 \text{ yr}
\]

\[
\text{OR} \quad \text{ASFSR} \quad = \quad (40/40) \times 10^1/10^6 \text{ km/yr}
\]

Since \(1/10^6 = 10^{-6}\) and \(40/20 = 2\), the above becomes

\[
\text{ASFSR} \quad = \quad 2 \times (10^1 \times 10^{-6}) \text{ km/yr}
\]

\[
\text{OR} \quad \text{ASFSR} \quad = \quad 2 \times 10^{-5} \text{ km/yr}
\]

To produce a more understandable results convert units from km/yr to cm/yr by using the correct conversion factors as follows

\[
\text{ASFSR} \quad = \quad 2 \times 10^{-5} \text{ km/yr} \times 10^3 \text{ m/km} \times 10^2 \text{ cm/m}
\]

So that

\[
\text{ASFSR} \quad = \quad 2 \text{ cm/yr}
\]
This means that the Average Ocean Basin Expansion Rate (AOBSR) average yearly ocean basin expansion rate over the last 20 million years for this ocean basin is

$$\text{AOBSR} = 2 \times \frac{\text{Distance}}{\text{Time}}$$

$$= 2 \times 2 \text{ cm/yr}$$

$$= 4 \text{ cm/yr}$$

These spreading rates estimated above may be deceptive however, because spreading rates can change with time. For example, the sea floor may have spread rapidly to a distance of 400km during the first 10 million years and then ceased to spread at all for the next 10 million years. Our 20 million year average rate obscure such shorter-term variations in the spreading rates. The way to determine the more detailed history of ocean basin spreading rates, it is necessary to work with shorter segments of the sea floor (with age ranges less than 20 million years) ..as we will do next.
Example 2:

Volcanic sea floor rocks at three locations at different measured distances from the crest of the mid-ocean ridge have been dated as indicated below.

<table>
<thead>
<tr>
<th>Location</th>
<th>Age (million years)</th>
<th>Distance to Crest (kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15</td>
<td>525</td>
</tr>
<tr>
<td>B</td>
<td>32</td>
<td>1392</td>
</tr>
<tr>
<td>C</td>
<td>40</td>
<td>1488</td>
</tr>
</tbody>
</table>

Determine the average sea floor spreading rate (ASFSR) between each pair of locations.

(1) The spreading rate between location A and the crest is determined just as in Example 1.

Crest to location A ASFSR = Distance / Time = 525 km / 15,000,000 yr
= 525 km / 15 x 10^6 yr
= 35 x 10^{-6} km/yr
= 35 x 10^{-6} km/yr x 10^3 m/km x 10^2 cm/m
= **3.5 cm/yr**

(2) The spreading rate between locations A and B, is determined by (a) computing the distance between A and B and (b) dividing it by the time interval over which that spreading occurred. This is done as follows.

A to B Spreading Distance = distance of B from rift - distance of A from rift
A to B Spreading Distance = 1392 km - 525 km
A to B Spreading Distance = 867 km

A to B Spreading Time = Age of B - Age of A
A to B Spreading Time = 32 x 10^6 yr - 15 x 10^6 yr
A to B Spreading Time = 17 x 10^6 yr
Crest to location A ASFSR \[= 867 \text{ km} / 17 \times 10^6 \text{ yr} \]
\[= 51 \times 10^{-6} \text{ km/yr} \]
\[= 51 \times 10^{-6} \text{ km/yr} \times 10^3 \text{ m/yr} \times 10^2 \text{ m/km} \]
\[= 5.1 \text{ cm/yr} \]

(3) Similarly, the spreading rate between locations B and C is found to be \textbf{1.2 cm/yr}. (Convince yourself of this results by doing the calculation.)

(4) Thus, the average sea floor spreading rate (ASFSR) in this hypothetical ocean basin is found to have \textbf{varied} between \textbf{1.2 cm/yr} and \textbf{5.1 cm/yr}.

Now put your new found skills to work by doing the following exercises.
Exercise 1 - Physiographic Map

Write in the general name of each of the lettered ocean sea floor features in the illustration of the western North Atlantic Ocean in Figure 3-8. The phrases (in the parentheses) provide hints.

A. ____________________
   (flooded edge of the continent)

B. ____________________
   (inclination toward the sea floor)

C. ____________________
   (thick sedimentary accumulation at the continent's base)

D. ____________________
   (featureless part of the sea floor)

E. ____________________
   (low hills, exposed tops of volcanoes)

F. ____________________
   (tall volcanic cones)

G. ____________________
   (submerged, deep valley)

H. ____________________
   (local, massive accumulation of sediment at canyon mouth)

I. ____________________
   (deep, long depression in sea floor)

J. ____________________
   (mountainous central region of sea floor)

K. ____________________
   (valley in center of mountainous region)

L. ____________________
   (active offset of mountainous region)

M. ____________________
   (inactive offset of mountainous region)
Figure 3-8. Physiographic map of the sea floor features of the western North Atlantic Ocean basin.
Exercise 2 - Plate Tectonics

1. Physiographic Map of the Western North Atlantic Ocean Basin

   a. On the Figure 3-8 map, draw lines that indicate the edges of the plates that are relevant to this part of the ocean. (Reference to Figure 3-7 may be helpful).

   b. Place arrows on the map indicating the direction in which these plates are moving.

   c. For the Figure 3-8 portion of the North Atlantic, where would the oldest part of the sea floor be located?

   d. Why is the ridge in the middle of the ocean in the North Atlantic (see Figure 3-7)?

   e. Where would the following be expected to occur in this ocean basin?
      - Oldest sediment
      - Thickest sediment
      - Volcanic activity

   f. The linear series of seamounts at location N in Figure 3-8 was produced as the plate moved slowly across a mantle “hot spot” plume. Knowing what you know about the western Atlantic Ocean oceanic plate movement direction:

      Where would the oldest volcano in the series be located?

      Why?

   g. Note the deep ocean trench just to the west of the Antilles and east of Puerto Rico. Describe the plate motion in this area, including which plate is being subducted and evidence supporting your answer.
Laboratory 3: Exercise 3
–Computing The Rate of Sea Floor Expansion–
Volcanic sea floor rocks at six different measured distances from the mid-ocean ridge crest have been dated as indicated below. In answering the following questions, show your work.

<table>
<thead>
<tr>
<th>Location</th>
<th>Age (million years)</th>
<th>Distance to Rift (kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>375</td>
</tr>
<tr>
<td>C</td>
<td>33</td>
<td>807</td>
</tr>
<tr>
<td>D</td>
<td>39</td>
<td>1233</td>
</tr>
<tr>
<td>E</td>
<td>43</td>
<td>1353</td>
</tr>
<tr>
<td>F</td>
<td>70</td>
<td>1674</td>
</tr>
</tbody>
</table>

1. What is the average rate of sea floor spreading for this entire section of ocean basin?

2. What is the average rate of ocean basin expansion for the entire basin?
3. Determine the average rate of sea floor spreading and the average rate of ocean basin expansion for each segment of the ocean basin.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Average Sea Floor Spreading Rate (cm/yr)</th>
<th>Average Basin Expansion Rate (cm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-crest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B -C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C -D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D-E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E -F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. How representative is the average rate of sea floor spreading compared to the true history of basin expansion?