Homework #3
Ocean Basin Bathymetry & Plate Tectonics

3-1. THE OCEAN BASIN

The **world's oceans** cover 72% of the Earth's surface. The bathymetry (depth distribution) of the interconnected **ocean basins** has been sculpted by the process known as **plate tectonics**. For example, the bathymetric profile (or cross-section) of the North Atlantic Ocean basin in Figure 3-1 has many features of a typical ocean basins which is bordered by a **continental margin** at the ocean's edge. Starting at the **coast**, there is a slight deepening of the sea floor as we cross the **continental shelf**. At the **shelf break**, the sea floor plunges more steeply down the **continental slope**; which transitions into the less steep **continental rise**; which itself transitions into the relatively flat **abyssal plain**.

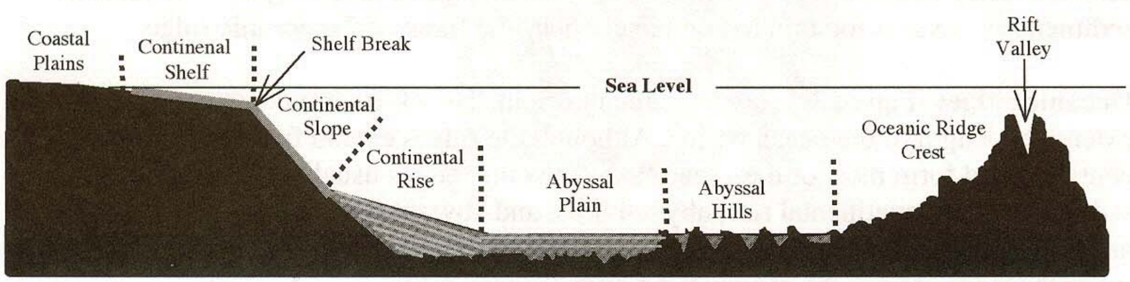

Figure 3-1. Cross section showing bathymetric features of the sea floor. Gray areas are sediments.

The *continental shelf* is the seaward edge of the continent - extending from the **beach** to the **shelf break,** with typical depths ranging from 130 m to 200 m. The seafloor of the continental shelf is gently sloping with undulating surfaces - sometimes interrupted by hills and valleys (see Figure 3-2). Sediments - derived from the weathering of the continental mountain rocks - are delivered by rivers to the continental shelf and beyond. Over *wide* continental shelves, the sea floor *slopes* are 1° to 2°, which is virtually flat. Over *narrower* continental shelves, the sea floor slopes are somewhat steeper.

The **continental slope** connects the **continental shelf** to the **deep ocean** with typical depths of 2 to 3 km. While the bottom slope of a typical continental slope region appears steep in the vertically-exaggerated valleys pictured (see Figure 3-2), they are typically quite gentle with modest angles of only 4° to 6°. Finer grain riverine sediments are delivered by ocean currents to the *upper continental slope region* - just beyond the continental shelf break. These sediment accumulations eventually become unstable and break free to become underwater landslides called **turbidity currents**. The sediment-laden turbidity currents are density currents that flow rapidly down-slope under the force of gravity. Repeated turbidity currents over the years scour the sea floor to form **submarine canyons** (see Figure 3-2).

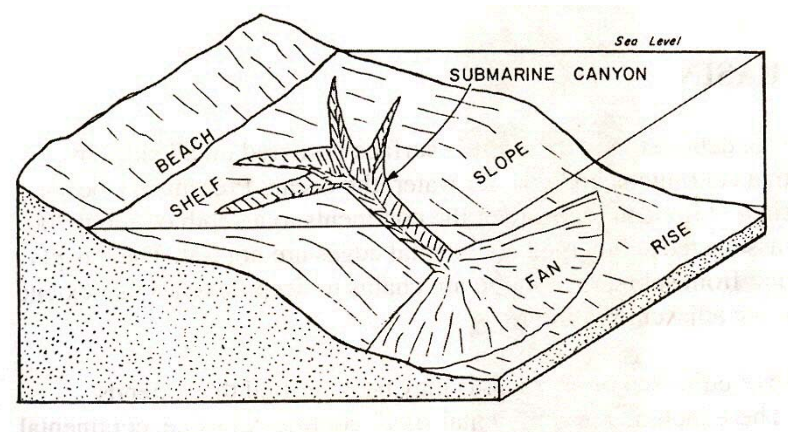

Figure 3-2. Submarine canyon and fan.

Upon reaching the bottom of the continental slope, the turbidity currents spread slowly and laterally, depositing their sediments in enormous fan-shaped accumulations called **submarine fans**. Overlapping submarine fan-formation events form the **continental rise** region at the base of the continental slope (Figure 3-2). Continental rise regions, which may be up to several kilometers thick and tens of kilometers wide (Figure 3-2), have slopes ranging between 1° and 5° that gradually transition to the **abyssal plain** (Figure 3-1).

The abyssal plain - a remarkably flat and featureless section of the sea floor - is formed by **sedimentation –** the long-term rain of fine oceanic sediment particles. This sediment particle rain has buried most of the underlying rocky irregularities. The abyssal plain transitions to the **abyssal hill region,** where isolated **knolls** and **seamounts** protrude through a thinning sediment cover. As we move through the abyssal hill region, the sedimentary layer continues to thin; until the sediment layer virtually disappears in the region of the **mid-ocean ridge** (Figure 3-1). The ridge area has a rugged terrain leading into the spreading **rift valley** (Figure 3-1).

Physiographic maps provide a three-dimensional perspective view of a real ocean seafloor region.

The example in Figure 3.3 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.

Figure 3-3. Physiographic Map of the Pacific Ocean basin.

Now we explore how modern understanding of **plate tectonics** explains the relationships among these many different kinds of ocean basin bathymetric features.

3-2. PLATE TECTONICS

Plate tectonics is the dynamic response of the Earth’s surface crust to the convective processes deep within the Earth’s interior continuously moving heat upward. The variety of bathymetric features in a typical ocean basin are the result of the competition between *plate tectonics* and *sedimentation* over 10s to 100s of millions of years. Plate tectonic processes involve the creation of the Earth’s crust at mid-ocean ridges, lateral 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 the long-term rain of small sediment particles – a mixture of inorganic particles produced by weathering of terrestrial rocks and organic particles produced by oceanic biology. Thus, even the most jagged features of the original crustal rocks can be buried by the 10s to 100s of millions of years of sediment rain. How do the plate tectonic processes produce the jagged features of the ocean sea floor?

Radioactive decay deep within the Earth creates heat. 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 in the **asthenosphere** (see Figure 3-4). (These flows are exceedingly slow! – sometimes taking 100 million years to cross an ocean basin). A stream of molten rock called **magma** rises under the mid-ocean ridge, splits into two flows near the surface; each moving in opposite directions. The sea floor in the region of the mid-ocean ridge (MOR) stands higher than the nearby seafloor because the underlying rocks are hotter and thus less dense than the more distant rocks on the flanks. In the colder part of the convection cell, the asthenosphere rocks sink to 100s of kilometers and slowly flow back toward the mid-ocean ridge; completing a circuit that can take 10s to 100s of millions of years.

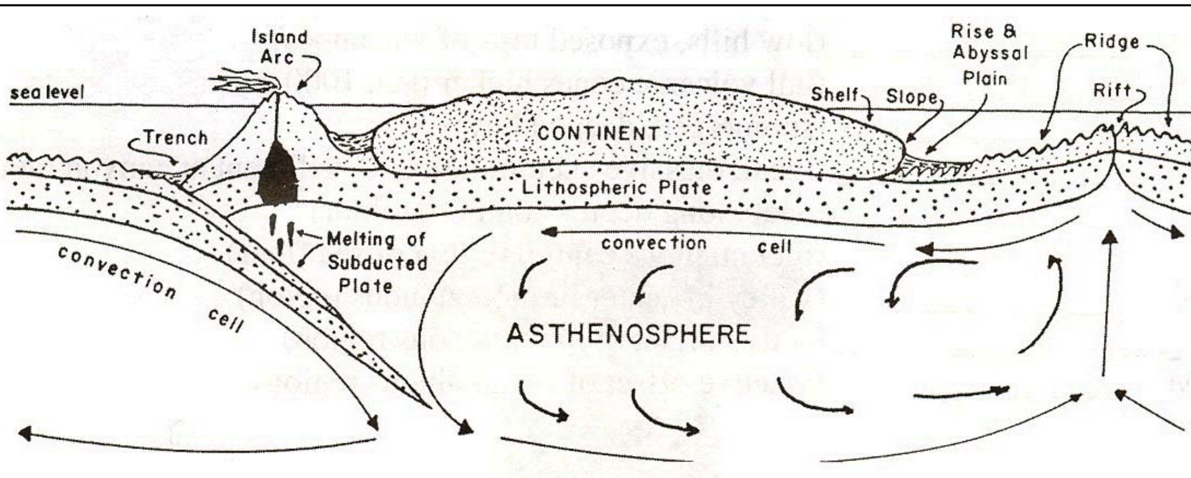

Figure 3-4 A schematic of the role of a convection cell in the uppermost layers of the Earth. Ocean crust is formed when rising magma hits the cold water in the rift valley part of the mid-ocean ridge. The convection motion of semi-molten rocks in the asthenosphere carries the ocean and continental crust along with it toward the left. In the left part of the picture, a neighboring convection cell drags the ocean crustal plate downward. When the leading edge of the continental crustal plate in the center collides with a less dense, thinner ocean crustal plate, the latter subducts below that plate to form a deep ocean trench.

Plate Formation: Mid-oceanic ridges - volcanic in origin – make up mountain chains which extend throughout of the world ocean basins. The mid-ocean **ridge crest** - defined by a pair of the highest peaks - bracket the narrow **rift valley** which marks the axis of the ocean ridge (Figure 3-1). Upwelling magma creates a tension that produces the central **rift valley** between an adjacent pair of solid, but brittle **lithospheric plates** (see Figure 3-4)**.** As magma hits the cold water, it solidifies rapidly into new rock called **basalt;** adding to the edges of both lithospheric plates. Because this pair of lithospheric plates move away in opposite directions – that is *diverge* - the rift valley and mid-ocean ridge is a zone of **plate divergence**.

Plate Movement and Evolution: On both sides of the mid-ocean ridge, the deeper, horizontally-moving asthenospheric rocks drag the overlying lithospheric plates along with them (see Figure 3-4). Geometrical constraints on divergent plate movement on a *spherical Earth surface* require that the mid-ocean ridge to be composed of offset segments as shown in Figure 3-5. Each segment is defined by a pair of **transform faults** that mark the relative movement of sea floor rock on either side of the of a transform fault. The transform faults appear as gashes or scars that run perpendicular to the oceanic ridge rift valleys (see Figure 3-5). As these sections of sea floor slide in opposite directions by each other, periodically the sea floor rocks break - creating a **fracture zone** or band of distorted and broken rocks.

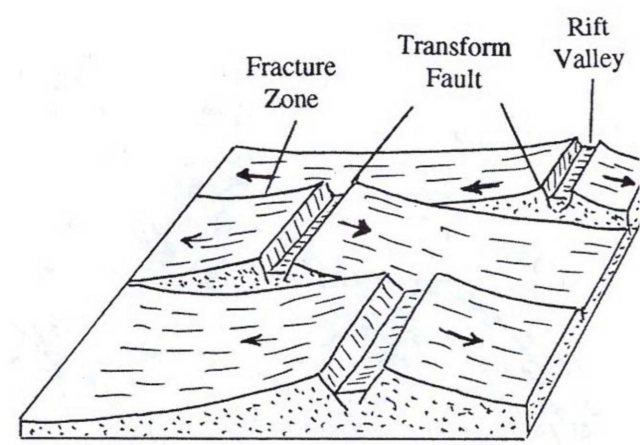

Figure 3-5 Transform faults exist between ridge segments where plates are moving in opposite directions. The fracture zones extend further.

With time (10s or 100s of million years), the horizontally-moving asthenospheric and overlying lithospheric rock cool, become denser and sink deeper into the Earth's interior (Figure 3-4). During this time, the very slowly-moving ocean crust gradually accumulates a thick sediment layer that tends to obscure the jagged mountainous features of its youth. For example, the fracture zone scars (see Figure 3-5) become gradually more obscured by sediments the further one moves away from the ocean ridge. This plate tectonic process explains the gradual change from rugged oceanic ridge crest to abyssal hills to the abyssal plains.

But what are the origins of the isolated islands, island chains, undersea seamounts, and seamount chains that are seen in the middle of large expanses of abyssal plains? 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 3-6/middle indicates a distinct change in ocean plate movement many millions of years ago.

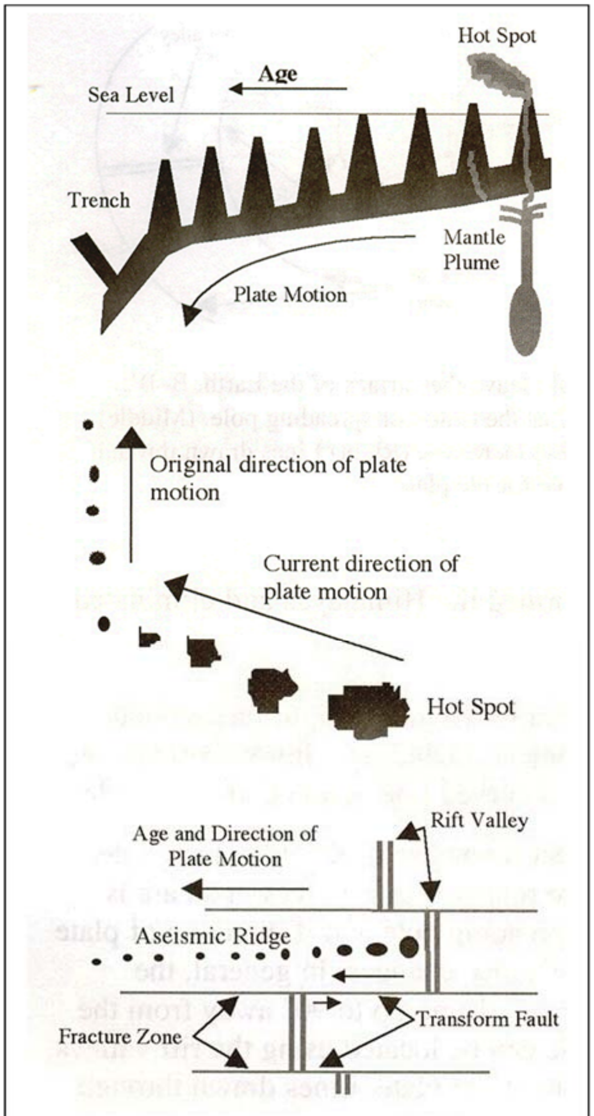

Figure 3-5. (**top**) Cross section showing how a mantle plume can produce a sequence of volcanic islands and undersea seamounts. (**middle**) Map view of the volcanic island chain and the indicated change of plate movement direction. (**bottom**) Map view of aseismic ridge of volcanic islands and seamounts produced by a mantle plume near a mid-ocean ridge.

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 a short-lived or weak mantle plume located near a ridge crest generates an undersea volcano (or **seamount**) which then will ride on the moving oceanic crustal plate away from the oceanic ridge.

Plate Destruction: At some point the laterally moving asthenospheric material converges with that of a neighboring convection cell (left in Figure 3-4). 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 distinctly different examples of how the different plates that make up the Earth's crust are destroyed in the **oceanic trench** regions of the world's oceans. Oceanic trenches are prominent features of the ocean sea floor, particularly in the Pacific Ocean basin (see Figure 3-3)**.** They are very deep, long, narrow, relatively steep-sided depressions in the ocean basin usually occurring around the rims of ocean basins. Volcanism is usual in the region of deep ocean trenches.

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. In many cases where plates converge, one plate descends below or subducts beneath the other plate – thus forming a deep ocean trench in what is called a **subduction zones**. When the collisions occur between relatively thin and denser oceanic plate and the thicker less dense continental crust the oceanic plate subducts. For example, the Nazca plate subducts under the South American plate along the Peru-Chile Trench (see Figure 3-7) – an original collision that formed the Andes.

If the overriding plate in a subduction zone is oceanic crust (e.g., Eurasian and Australian plate boundary along the Java Trench in Figure 3-7), then a chain of islands, called an **island arc,** is formed parallel the trench. This happens because the subducting plate plunges unusually deep into the asthenosphere and 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.

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 plates formed the Himalayas after eliminating the ocean basin between them.

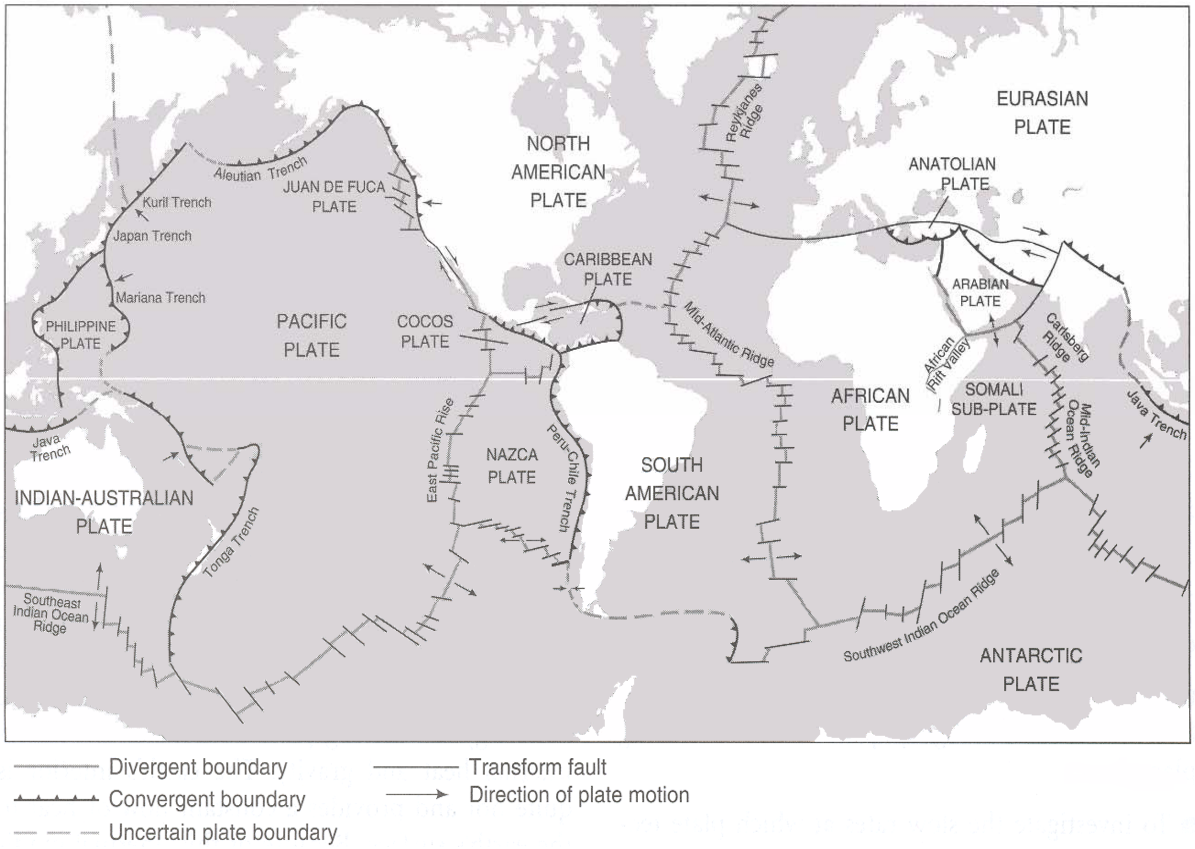

Figure 3-7 Lithospheric plates of the Earth.

Summary

<u>Oceanic lithospheric plates are:</u>

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.

3-3. 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. The Average Sea Floor Spreading Rate (**ASFSR**) is equal to the distance the original crustal rocks have traveled from the rift valley (**Distance**) divided by the time (**Time**), according to the following relation

ASFSR = **Distance** / **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, the Average Ocean Basin Expansion Rate (**AOBSR)** will be **equal to twice the ASFSR** according to:

AOBSR = 2 x (**Distance/Time**)

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?

ASFSR = Distance / Time = 400 km / 20,000,000 yr
= **2 cm/yr**

Using what you learned in the Homework-1, 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.

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DIGRESSION

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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**.**

Prefix		**Size**			**Scientific Notation**
giga	(G)	1,000,000,000.0	1 billion		= 1.0×10^{9}
mega	(M)	1,000,000.0	1 million		= 1.0×10^{6}
kilo	(k)	1,000.0	1 thousand		= 1.0×10^{3}
hecto	(h)	100.0	1 hundred		= 1.0×10^{2}
deka	(da)	10.0	ten		= 1.0×10^{1}
		1.0	one		= 1.0×10^{0}
deci	(d)	0.1	1 tenth	=1/10	= 1.0×10^{-1}
centi	(c)	0.01	1 hundredth	=1/100	= 1.0×10^{-2}
milli	(m)	0.001	1 thousandth	=1/1,000	= 1.0×10^{-3}
micro	*(μ)*	0.000001	1 millionth	=1/1,000,000	= 1.0×10^{-6}
nano	(n)	0.000000001	1 billionth	=1/1,000,000,000	= 1.0×10^{-9}

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". — **1.0×10^{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" — **1.0×10^{-6}**

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

Example

When **Multiplying** numbers expressed in Scientific Notation

1,000,000 x 200
OR
$(1.0 \times 10^6) \times (2.0 \times 10^2)$

(1) Algebraically add the powers of 10 to get a "sum"; **$6 + 2 = 8$**

(2) Multiply the leading numbers; and **$1.0 \times 2.0 = 2.0$**

(3) Multiply by a 10 with the exponent = the "sum" **$\underline{2.0 \times 10^8}$**

OR

200,000,000

When **Dividing** numbers expressed in Scientific Notation

200 / 1,000,000
OR
$(2.0 \times 10^2)/$ **(1.0×10^6)**

(1) Compute the fraction $(2.0 \times 10^2) \times$ **(1.0×10^{-6})**

(2) Algebraically add the powers of 10 to get a "sum"; **$2 + (-6) = -4$**

(2) Multiply the leading numbers to get their "product"; and **$1.0 \times 2.0 = 2.0$**

(3) Multiply their "product" by a 10 with the exponent = the "sum" **$\underline{2.0 \times 10^{-4}}$**

OR

0.0002

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END OF DIGRESSION

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

ASFSR = Distance / Time = 400 km / 20,000,000 yr

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

ASFSR = 400 km/20 x **10^6** yr

Likewise, we can convert **400** km into **4.0×10^2** yr by moving the decimal 2 places to the left.

Thus the above can be written

ASFSR $= 40 \times \mathbf{10^1}$ km/20 x $\mathbf{10^6}$ yr

OR

ASFSR $= (40/40) \times \mathbf{10^1/10^6}$ km/yr

Since **$1/10^6 = 10^{-6}$** and 40/20 =2, the above becomes

ASFSR $= 2 \times (\mathbf{10^1 \times 10^{-6}})$ km/yr

OR

ASFSR $= 2 \times \mathbf{10^{-5}}$ km/yr

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

ASFSR $= 2 \times 10^{-5}$ km/yr x $\underline{10^3 \text{ m/km}}$ x $\underline{10^2 \text{ cm/m}}$

So that

ASFSR = **2 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

AOBSR = 2 x (Distance / Time)
= 2 x **2 cm/yr**
= **4 cm/yr**

However, these ocean basin spreading rates estimated above may be deceptive, 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:

Vo1canic sea floor rocks at three locations at different measured distances from the crest of the mid-ocean ridge have been dated as indicated below.

Location	*Age (million years)*	*Distance to Crest (kilometers)*
A	15	525
B	32	1392
C	40	1488

How to interpret this diagram:

Location A traveled 525 km away from the crest over 15,000,000 years.

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 10^6yr

= 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 10^6yr - 15 x 10^6yr

A to **B** Spreading Time = 17 x 10^6yr

Crest to location **A ASFSR** $= 867\ \text{km}/17 \times 10^6\text{yr}$

$= 51 \times 10^{-6}\ \text{km/yr}$

$= 51 \times 10^{-6}\ \text{km/yr} \times 10^3\ \text{m/yr} \times 10^2\ \text{m/km}$

= **<u>5.1 cm/yr</u>**

(3) Similarly, the spreading rate between locations **B** and **C** is found to be **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 **varied** between **1.2 cm/yr** and **5.1 cm/yr.**

<u>Now put your new found skills to work by doing the following exercises.</u>

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. ___________________
(1ocal, 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 beings subducted and evidence supporting your answer.

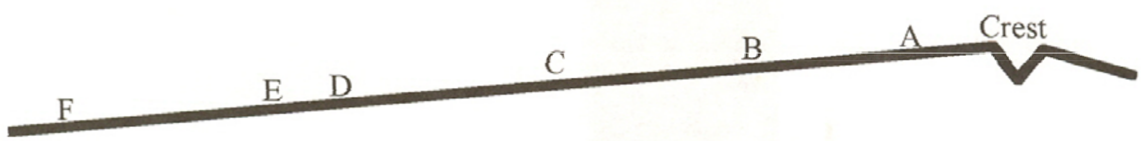
Exercise 3 – Computing Sea Floor Expansion Rates

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.

Location	*Age (million years)*	*Distance to Rift (kilometers)*
A	10	100
B	15	375
C	33	807
D	39	1233
E	43	1353
F	70	1674

How to interpret this diagram:

Location A traveled 100 km away from the crest over 10,000,000 years.



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.

Segment	Average Sea Floor Spreading Rate (cm/ yr)	Average Basin Expansion Rate (cm/yr)
A-crest		
A-B		
B -C		
C -D		
D-E		
E -F		

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