Week 8: Chapter 12 notes

Describe the main characteristics of Earth’s ocean ridges.

The volcanism of the ocean ridges drives a global circulation system connecting solid Earth, ocean and atmosphere. Below is a cartoon of the solid Earth plate tectonic cycle. I would like you to make note specifically of the following: where partial melting occurs, where dewatering and melting occur, where you’d find intrusive magma, the location of earthquakes in the subducting slab, the main volcanic differences between the subduction volcanism and volcanism at mid-ocean ridges, and the flow direction of mantle convection.

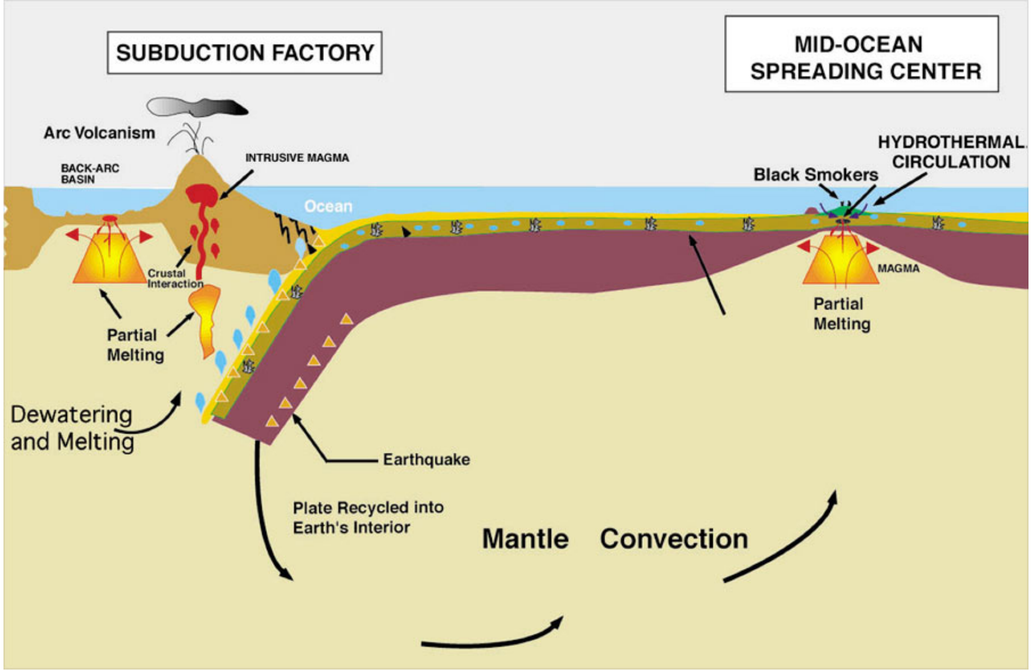


Figure 2.9.1. A diagram outlining plate tectonics and its associated volcanic processes. Localized upwelling of mantle material at mid-ocean ridges leads to the creation of new oceanic crust. At oceanic trenches cold, dense oceanic crust is then subducted beneath the continental crust and recycled in the mantle. As the slab is subducted, dewatering and partial melting provides a source of magma for arc volcanism and spreading in the back-arc basin. As the melt rises from the subducting slab through the continental crust it is enriched in silica which decreases its density and increases its viscosity.

One of the main characteristics of Earth’s ocean ridges is *ridge architecture*. Ridges consist of segment defined by offsets—not volcano names. The origin of ridge segments is poorly understood. Are they simply surface features unrelated to the mantle below? Are there variations in the extent of melting on the segment scale?

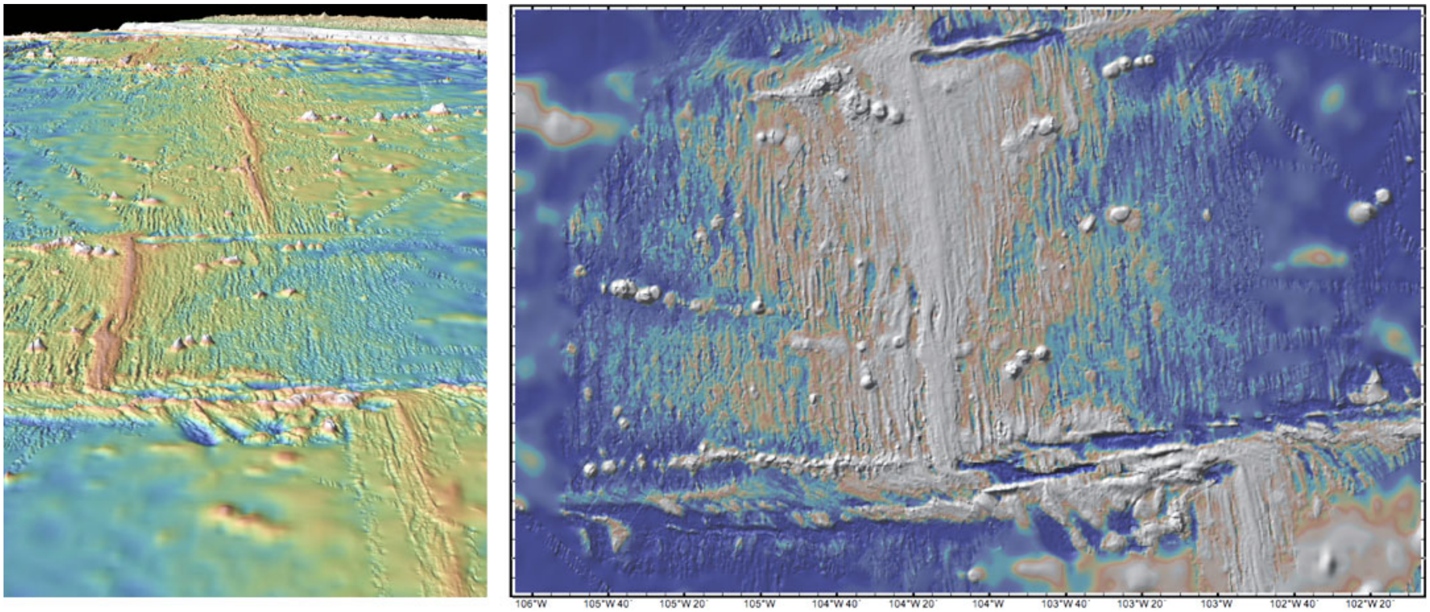


Figure 2.9.2. Two rendered images of seafloor bathymetric data over sections of a mid-ocean ridge. The red and white colors show the regions with the highest potions of the ridges which marks their spreading axis while the blue regions show regions with older and denser oceanic crust. From their spreading axis the ridges step done in a roughly symmetric matter. Note how sections of the ridge are offset laterally by transform fault zones.

In the figures above you'll notice the blue areas are farthest from the ridge. In both images, you can clearly see the architecture of the ridge and several offsets where the ridge line suddenly jumps left or right.

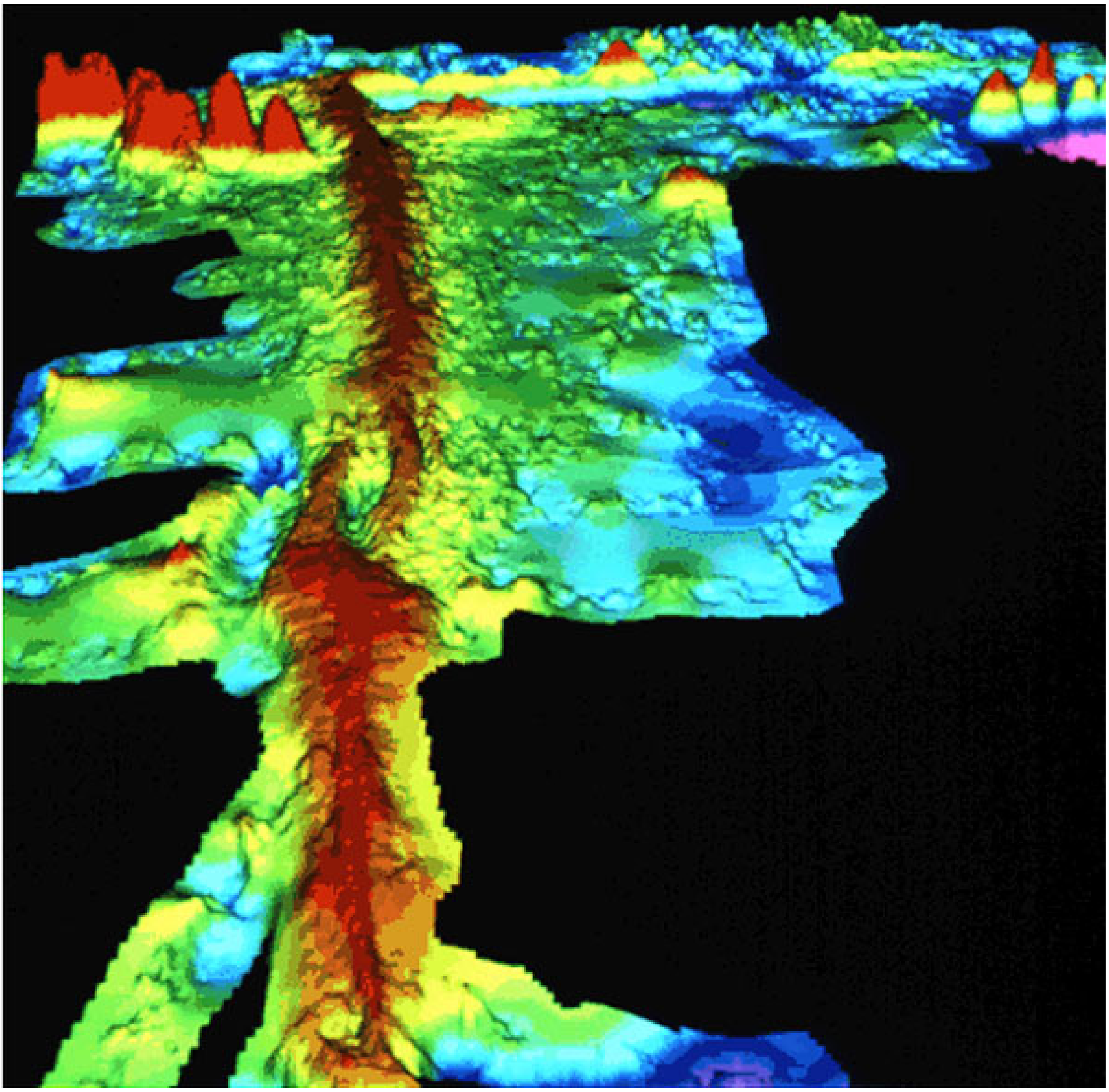


Figure 2.9.3. A bathymetric model of a section of the East Pacific Rise. In the center of this region there is a small section in which the ends of 2 ocean ridge segments appear to overlap.

Above is a bathymetric map of the East Pacific Rise, off the coast of South America. In the center of the map, you'll notice a slight overlap of the ridges—how did that happen? I also want to point out the scale of this map. The length of the entire ridge (including the overlap section) is 200 km and the total depth is a few hundred meters. This is characteristic of ridge volcano architecture—long and shallow volcanos.

How does ridge spreading speed affect ridge architecture? Below is a fast-spreading ridge map with a bathymetric profile across the ridge in the graph below.

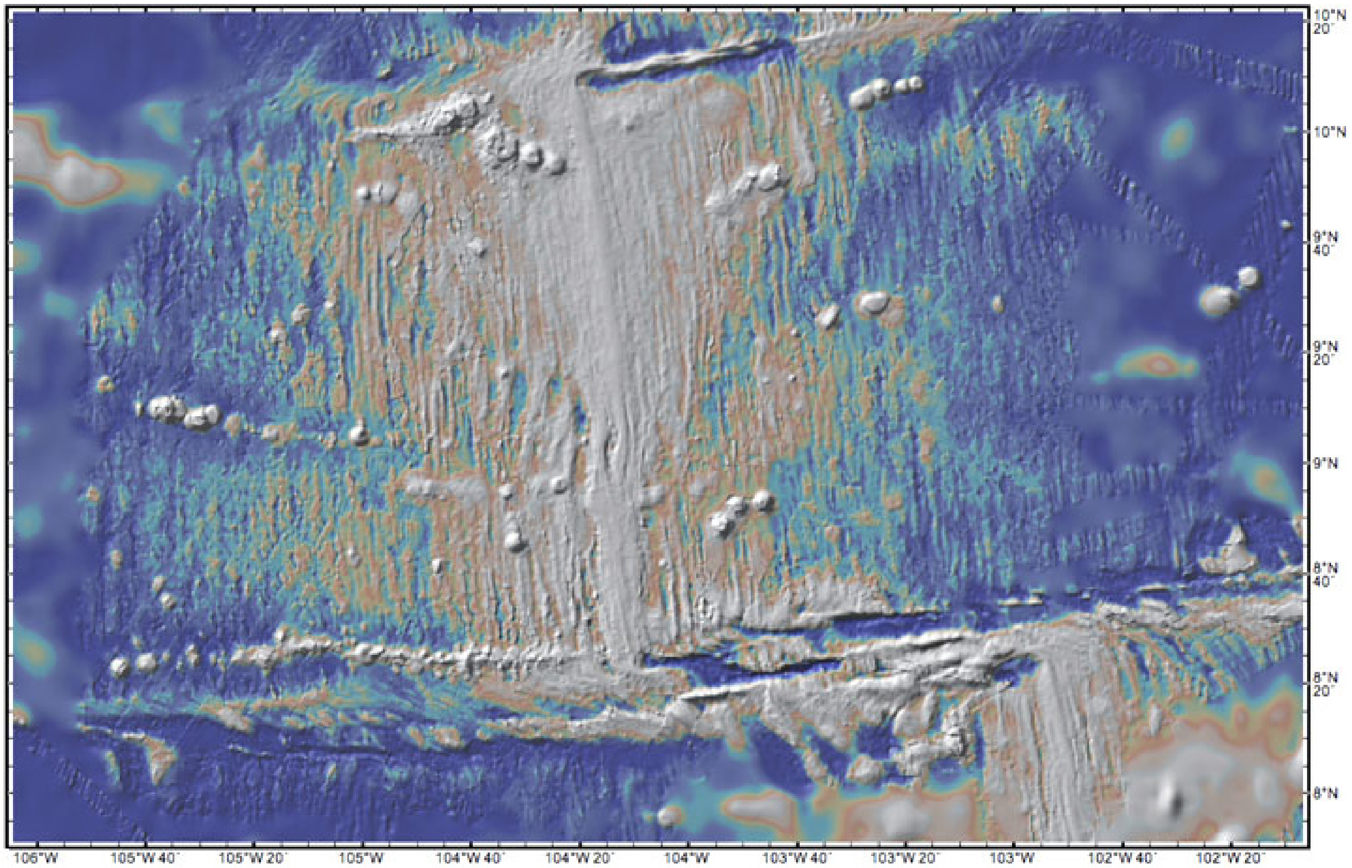


Figure 2.9.4. A bathymetric map across a section of mid-ocean ridge which has a fast spreading rate (> 10 cm/year). Note that the spreading axis is marked by a bathymetric high since there is plenty of upwelling magma to fill the forming rift with warm and therefore more buoyant oceanic crust.

This ridge has a spreading rate of more than 10 cm per year. In the bathymetric profile below, you'll notice the shape of this ridge is quite distinct. With fast spreading rates, hot mantle reaches the surface and magma oozes along the entire length of the crack—it's like "a wound that never heals" according to Jeff Fox.

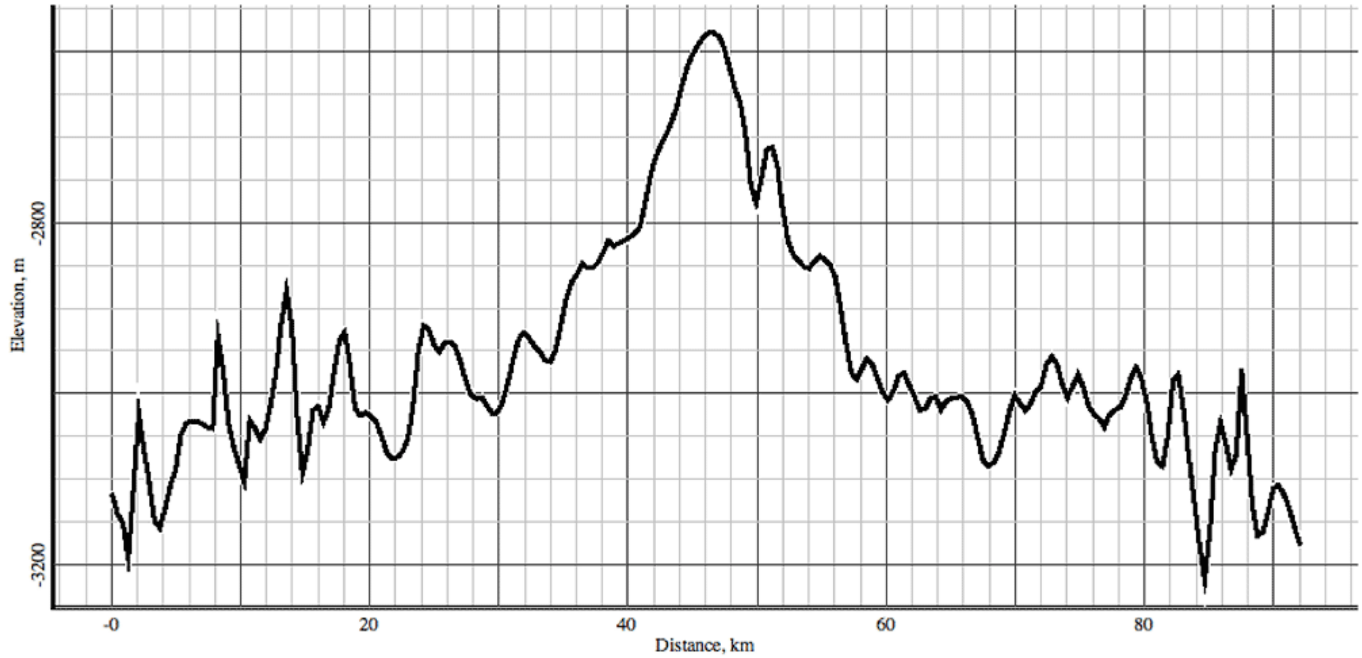


Figure 2.9.5. A bathymetric profile showing the characteristic central peak with symmetrically tapering flanks of a mid-ocean ridge with a fast spreading rate.

Below is a slow-spreading ridge map with a bathymetric profile across the ridge in the graph below.

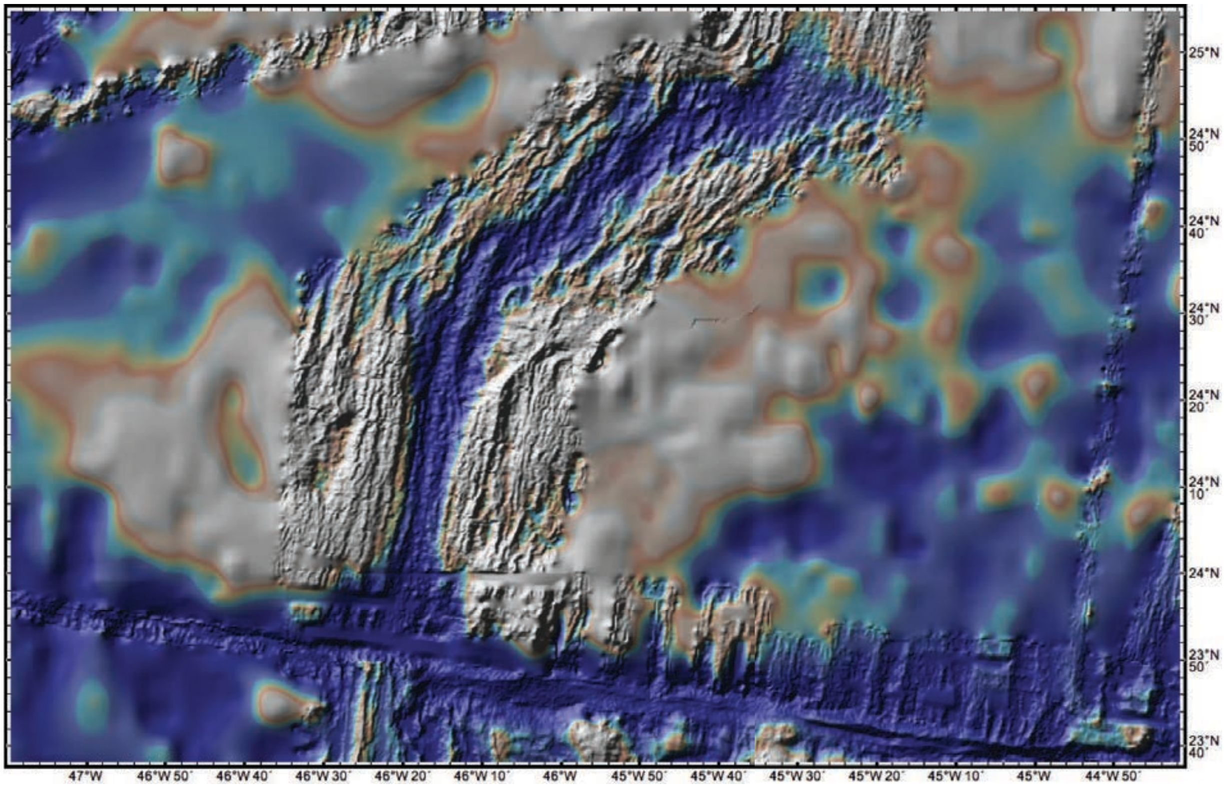


Figure 2.9.6. A bathymetric map across a section of mid-ocean ridge which has a slow spreading rate (~ 4 cm/year). Unlike the fast spreading ridge, this spreading axis is marked by a faulted trench or basin with tapering ridges on either side. This extensional

faulting is a result of slow rates of mantle upwelling and lower crustal temperatures at the slowly spreading ridges.

This ridge has a spreading rate of about 4 cm per year. The spreading center along this ridge is still a elongated crack, but because the mantle upwelling is relatively slow, such that temperatures are not as hot as they are at the fast-spreading ridges. This allows parts of the lithosphere to thicken closest to the spreading center. This thickening created a "lid", which leads to faulting deep within the ridge and for magma-focusing along the axis of the ridge. These features, in turn, lead to large changes in depth across the ridge axis—that grow deeper toward the location of transform faults along the ridge. You'll notice this characteristic ridge architecture of slow-spreading ridges in the bathymetric profile below.

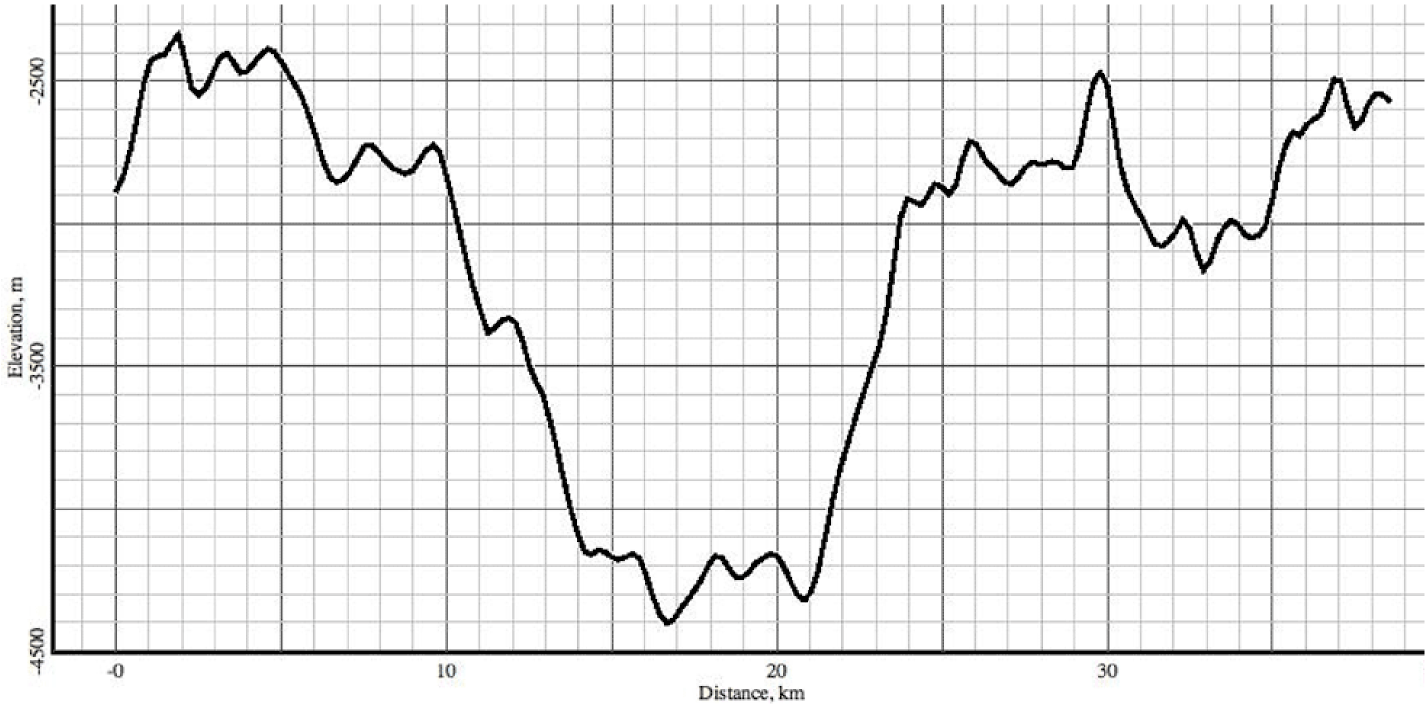


Figure 2.9.7. A bathymetric profile across the slowly spreading ridge which clearly shows the faulted trench or basin with tapering ridges on either side.

Explain how hydrothermal circulation at spreading centers occurs.

Hydrothermal circulation leads to chemical exchange between oceanic lithosphere and hot ocean water. Below is a photograph of a black smoker located along a ridge axis. The "smoke" in the image below is the result of mineral-rich fluid that has been heated to nearly 400ºC (!!) coming into contact with cold seawater and precipitating both sulfides and oxides.

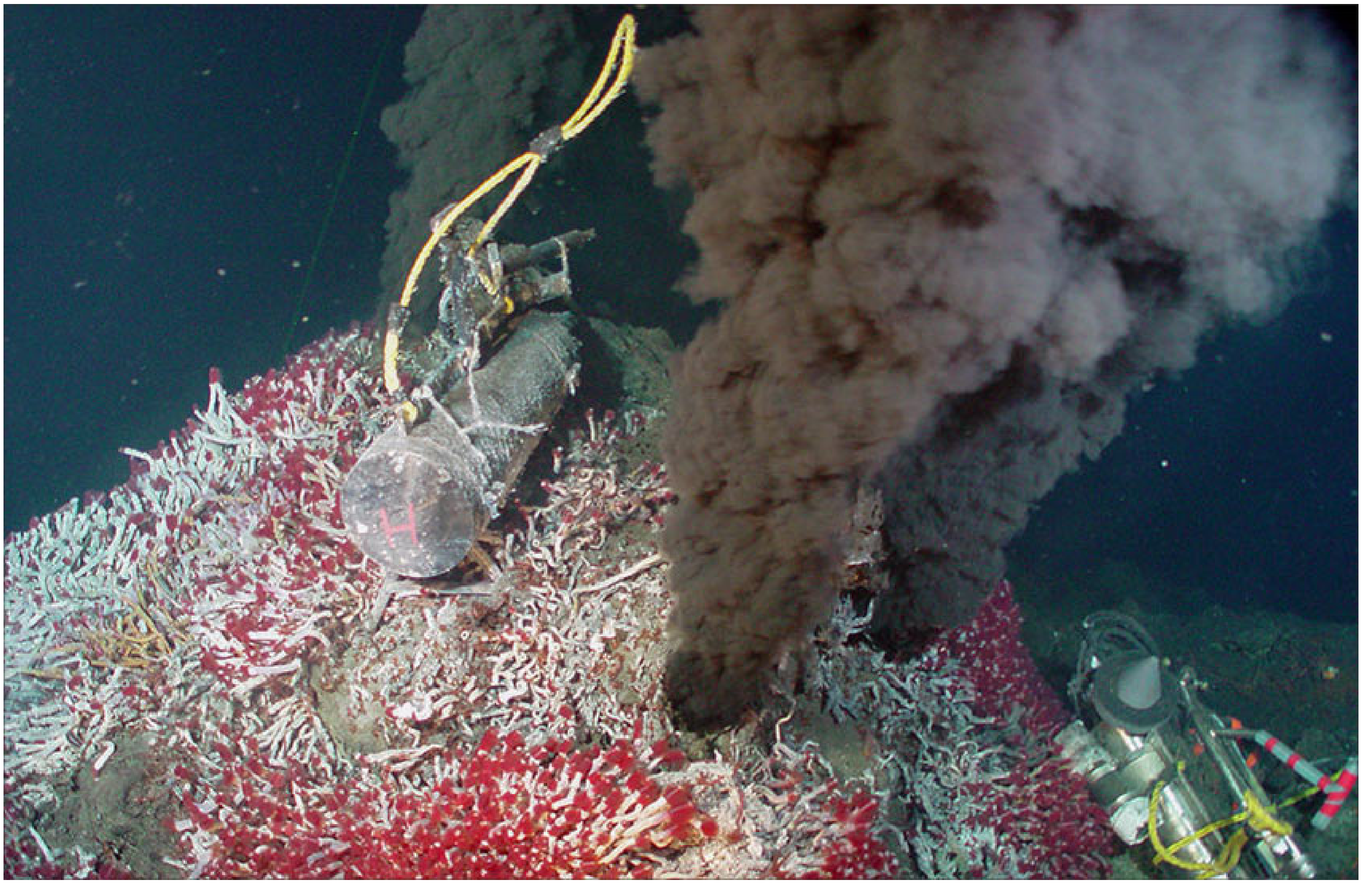


Figure 2.9.8. A photo showing hydro-thermal vents at a mid-ocean ridge which are known as "black smokers." The black smoke like clouds which billow out of this cone shaped vent are really hot, mineral rich water. Upon contact with the cold sea water sulfide and oxide minerals precipitate out of the hydrothermal fluids and form the black clouds. Around the black smokers giant tube worms (*Riftia pachyptila*), with white stems and red heads, carpet the seafloor.

Below is a cartoon that nicely illustrates these hydrothermal plumes. Specifically, where seawater infiltrates oceanic crust and is heated above an active magma reservoir. You'll also note the temperature in different parts of this system. Where are the hottest temps? What about the coldest?

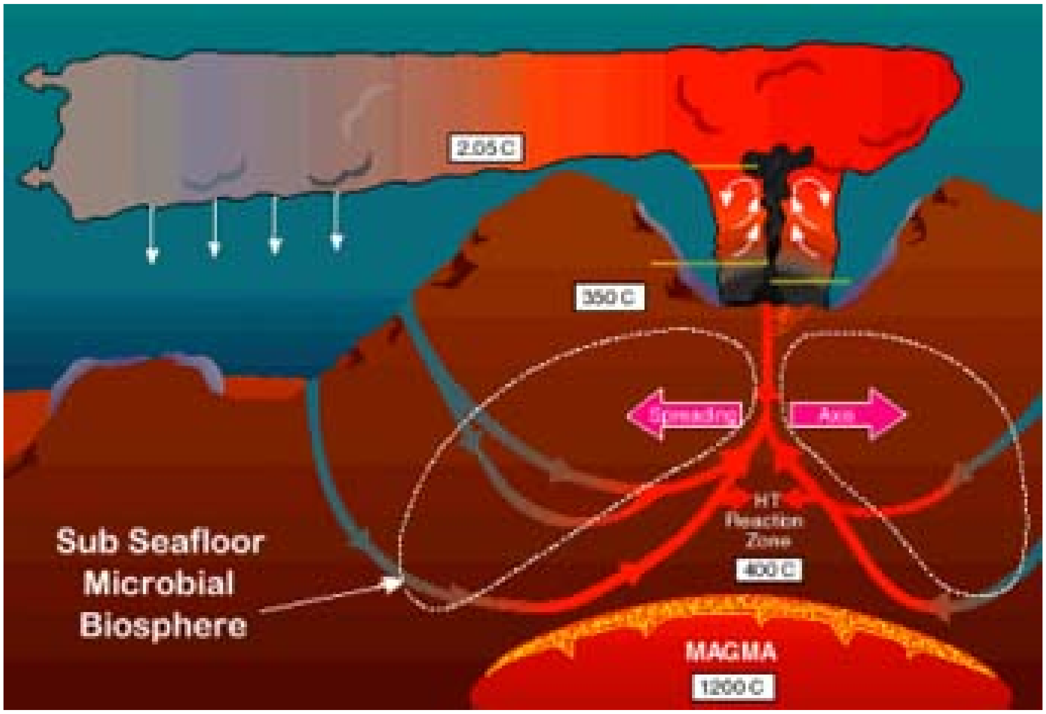


Figure 2.9.9. A cartoon like diagram which shows the elongated hydrothermal plume from a black smoker in the central axis of a slowly spreading ocean ridge. The plume extends vertically upwards due to its thermal buoyancy and is then swept horizontally by ocean currents. As you move away from the vent the hydrothermal water cools rapidly and the suspended minerals begin to fall out of the water column and deposit on the sea floor.

The illustration below shows precisely how cold seawater is mixed into these hydrothermal plumes or black smokers. As well as, you'll notice where mineral precipitate along the margins of the vent forming a chimney—e.g. chalcopyrite (copper iron sulfide).

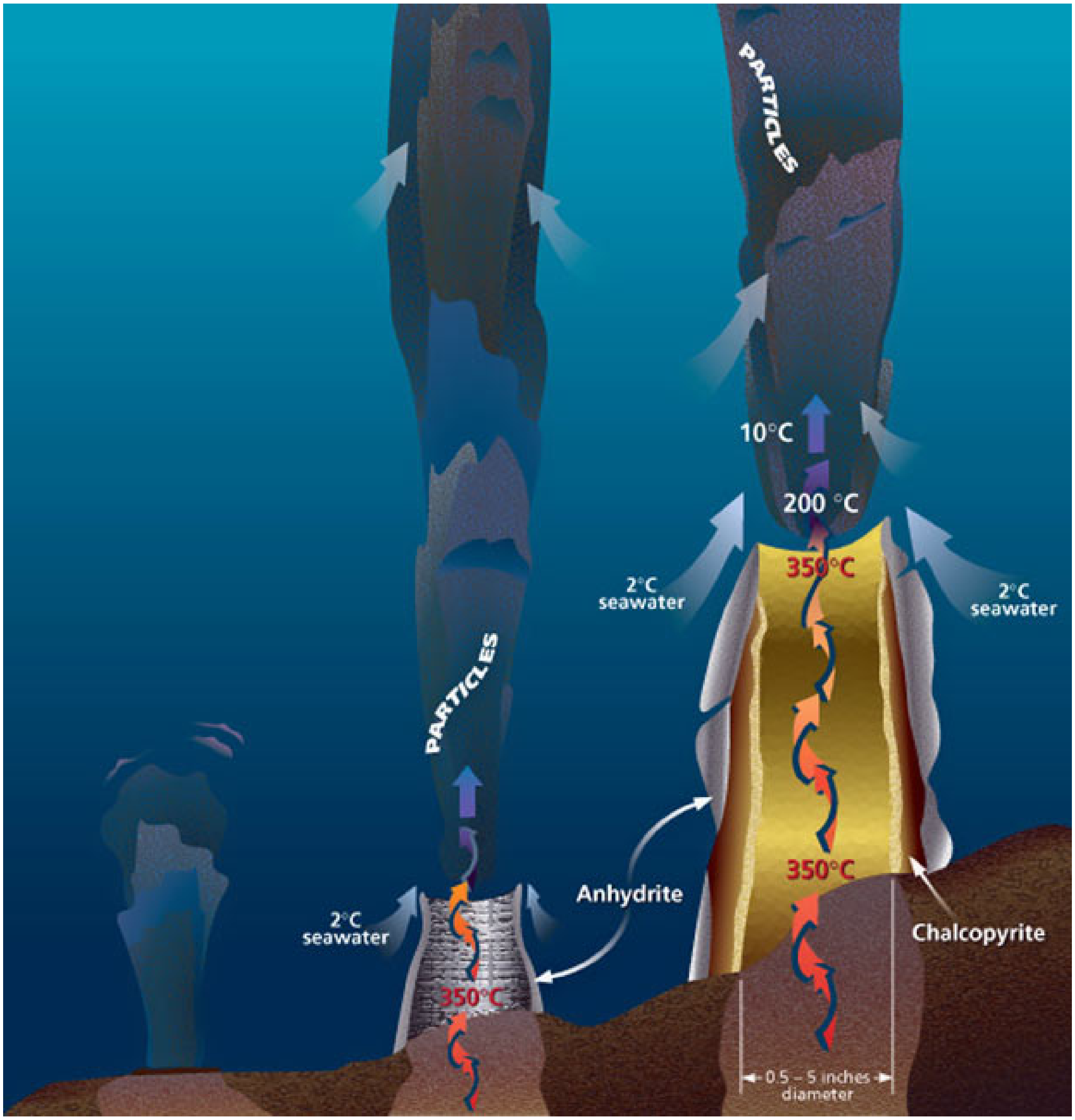


Figure 2.9.10. A cross sectional diagram showing the internal structure of a hydrothermal vent. Most vents form cone like structures of Chalcopyrite which are 0.5 to 5 inches in diameter. Anhydrite deposits often form on the outside of these vents. The hydrothermal waters leave the vent at temperatures around 350 - 400ºC but are rapidly cooled as they mix with the sea water which is typically around 2ºC. As the hydrothermal water cools sulfide and oxide minerals precipitate to form a black cloud of suspended particles.

Below is a depth profile that shows the distribution of ^{3}He in the Pacific Ocean. Why is the ^{3}He isotope a good marker for hydrothermal circulation at spreading ridges?

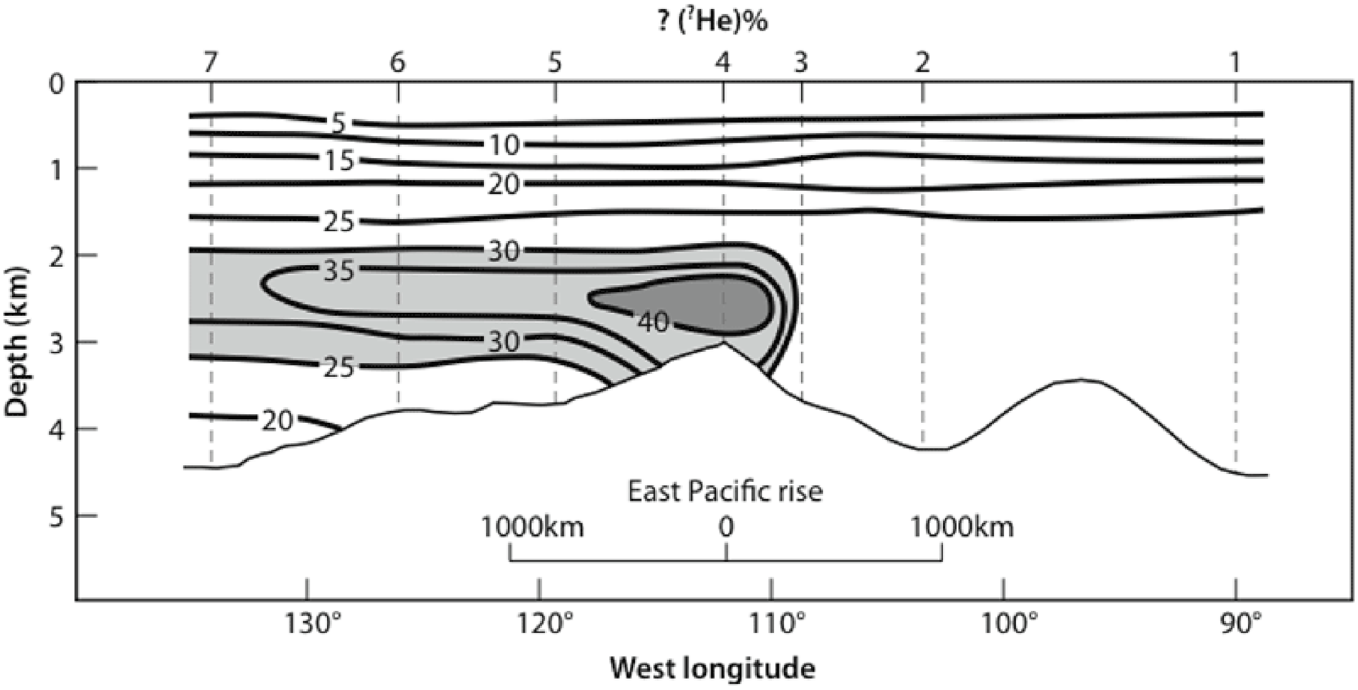


Figure 2.9.11. A contour plot showing concentrations of ^{3}He as a function of depth and longitude along a profile from west to east across the Pacific Ocean. The highest concentrations of ^{3}He lie just above the East Pacific rise as a result of its high hydrothermal activity. As this plume of ^{3}He diffuses into the seawater it is swept westwards by ocean currents.

Gasses released from basalt that erupted from ocean ridge volcanoes contain ^{3}He, which becomes part of the hydrothermal plume and eventually diffuses from the ocean into the atmosphere. ^{3}He typically forms during nucleosynthesis and all old helium has already escaped the atmosphere. Any ^{3}He present in Earth's oceans comes from hydrothermal vents at ocean ridges. Hence, ^{3}He is an excellent tracer for the distribution of hydrothermal fluids throughout the ocean.

One of the most interesting discoveries near these hydrothermal vent systems was the abundance of life at such depths in the ocean! We typically think of life as needing energy from the sun to survive. However, life near hydrothermal vents relies on energy from Earth's interior through volcanic openings at ocean ridges.

Figure 2.9.12. A thriving ecosystem near a hydrothermal vent. Giant tube worms (*Riftia pachyptila*), with white stems and red heads abound and provide cover for animals such as the hydrothermal vent crab (*Bythograea thermydron*).

Discuss how plate tectonics and thus ocean ridges are central to habitability on Earth.

There are 4 key features of ocean ridge formation and recirculation that are particularly important for habitability on Earth.

1. Geochemical processes at ocean ridges that maintain the ocean's chemical composition
2. The storage and movement of water and other elements into subduction systems that allow volcanism and the growth of continents.
3. Important for water and carbon cycles for long-term stability of Earth's climate.
4. Important role in the origin of life on Earth!

Summarize the composition of seawater and describe the inputs and output that lead to the steady state composition

of the ocean.

How does seawater maintain its composition through time? The hydrothermal cycle explains habitable aspects of the Earth system—e.g. maintaining seawater composition.

Figure 2.9.13. An underwater photo of the black Chalcopyrite shells of 2 inactive hydrothermal vents.

Table 12-1: Compositions of Earth's Water [&]

Element	Rain*	Rivers#	Seawater*	Hydrothermal^ fluid	Hydrothermal^ River	Hydrotherm flux
Ca	0.65	13.3	412	1200.0	90.0	0.0675

Mg	0.14	3.1	1290	0	0	0
Na	0.56	5.3	10770	—	—	—
K	0.11	1.5	380	975.0	650.0	0.4875
Sulfate	2.2	8.9	2688	28.0	3.15	0.00
Cl	0.57	6.0	19000	—	—	—
Si	0.3	4.5	2	504.0	112.0	0.08
Fe	0	0.03	0.002	168.0	5600.0	4.20
Mn	0	0.007	0.0002	41.0	5857.0	4.39
Li	0	0.002	0.18	5.0	2500.0	1.88
H_2S	0	0	0	255.0	Infinite	Infinite
Mg/Na	0.25	0.58	0.12	0.00	—	—
Ca/K	5.91	8.87	1.08	1.23	—	—
Si/K	2.73	3.00	0.01	0.52	—	—
Flux to ocean		$4 \cdot 10^{16}$Kg/yr		$3 \cdot 10^{13}$Kg/yr	—	—

& Concentrations in parts per million

* Water encyclopedia encyclopedia

#R. Chester, *Marine Geochemistry* (2000) Oxford: Blackwell Science, 2000; and H Elderfield and A. Schultz, *Annu Rev. Earth Planent Sci*. 24:191-224, 1996

^ ElderfieLd and Schultz (1996); hydrothermal fluids have a considerable range in compositio

You'll notice in the table above that element ratios in seawater are much different than river water—shouldn't they be the same? (see discussion on page 363-4 in your text). Because these ratios are distinct, there must be active sinks in the ocean that are removing elements almost at the rate in which they are added! We call this a *steady-state disequilibrium* that has been maintained through Earth's past. Sr isotopes tell us that continents are not the only source of material going into the ocean—so there must be other processes at work... Hydrothermal circulation is the missing link here. This cycle helps to maintain the steady composition of seawater. But how?

As the vent fluid reaches the seawater, certain elements are incorporated into the ocean, while others precipitate in the form of chimneys. In the chart above, which shows the compositions of water on Earth, note that the hydrothermal flux dominates the budgets of Fe, Mn, and Li. Why do we not see higher concentrations of these elements in seawater?

Describe the process of element transport at subduction zones.

Oceanic basaltic crust at ocean ridges is made of anhydrous (water-free) minerals (e.g. plagioclase feldspar, olivine, pyroxene). These rocks do not contain any water or volatiles, so what happens when they come into contact with seawater at the ocean floor? Oceanic lithosphere undergoes compositional changes, whereby "dry" minerals transform into hydrous (i.e. "wet) minerals through the addition of water into their mineral structures. Basalt becomes a metamorphic rock (Greenschist or amphibolite). The numbers in the table below show how the altered crust becomes an important repository for H_2O and CO_2 and has the capacity to transport large amounts of volatiles to the mantle via subduction.

Table 12-2.Compositions of mantle, altered mantle, oceanic crust, altered oceanic crust, and global subducting sediment

Wt%	**Primitive mantle** [a]	*** Altered erpentinite** [b]	**Ocean crust**	**** Altered ocean crust (side 801)**[d]	**GLOSS** [e]
SiO_2	45.00	40.14	49.71	49.23	58.57
TiO_2	0.20	0.01	2.02	1.7	0.62
Al_2O_3	4.45	0.79	13.43	12.05	11.91
FeO	8.05	7.46	12.92	12.33	5.21
MnO	0.14	0.12	0.19	0.226	0.32
MgO	37.80	40.83	6.83	6.22	2.48
CaO	3.55	0.97	11.41	13.03	5.95
Na_2O	0.36	0.09	2.56	2.3	2.43
K_2O	0.03	0.00	0.14	0.62	2.04
P_2O_5	0.02		0.17	0.168	0.19
CO_2	<0.1	{8.61	~0.02	{6.31	3.01

H_2O	<0.01		0.20		7.29
ppm					
Rb	0.6	14.56	1.46	13.7	57.2
U	21.8	1.51	0.02	0.39	1.68

Below is a cartoon that showcases the importance of water in subduction zone volcanism. If we look at water content of the different layers of the oceanic lithosphere as it subducts, we have ocean sediments on top (bright yellow layers) with 3-5 wt.% H_2. Directly below this water-rich sediment is the ocean crust (brown layer) (altered basalt) with less than 1-2 wt. % H_2. And below the crust is the upper mantle (purple layer) (peridotite) that may contain some water. As the plate subducts, the water that comes off of the slab is the key for subduction related volcanism.

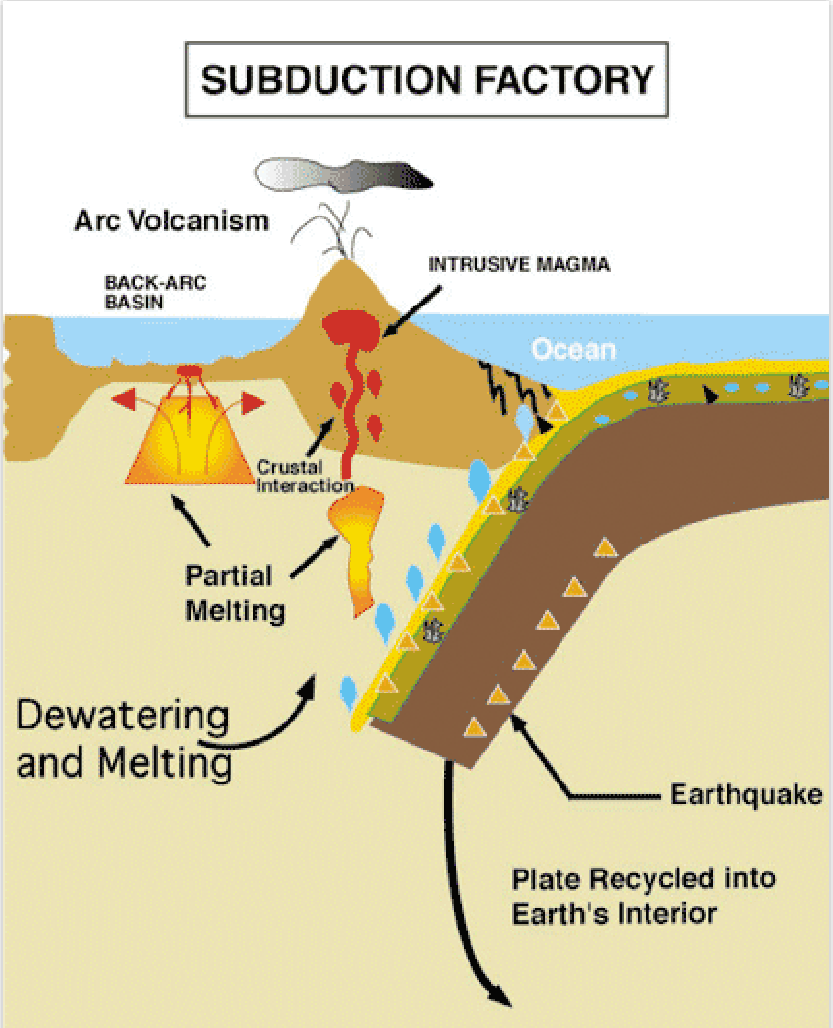


Figure 2.9.14. A cartoon showing the primary components of a subduction zone and its associated volcanism. At oceanic trenches cold, dense oceanic crust is subducted

beneath the continental crust and recycled into the mantle. As the slab is subducted, dewatering and partial melting provides a source of magma for arc volcanism and rifting in the back-arc basin. As the melt rises from the subducting slab through the continental crust it is enriched in silica which decreases its density and increases its viscosity.

Summarize the causes of melting and volcanism at convergent margins and of element transport within Earth's continental crust.

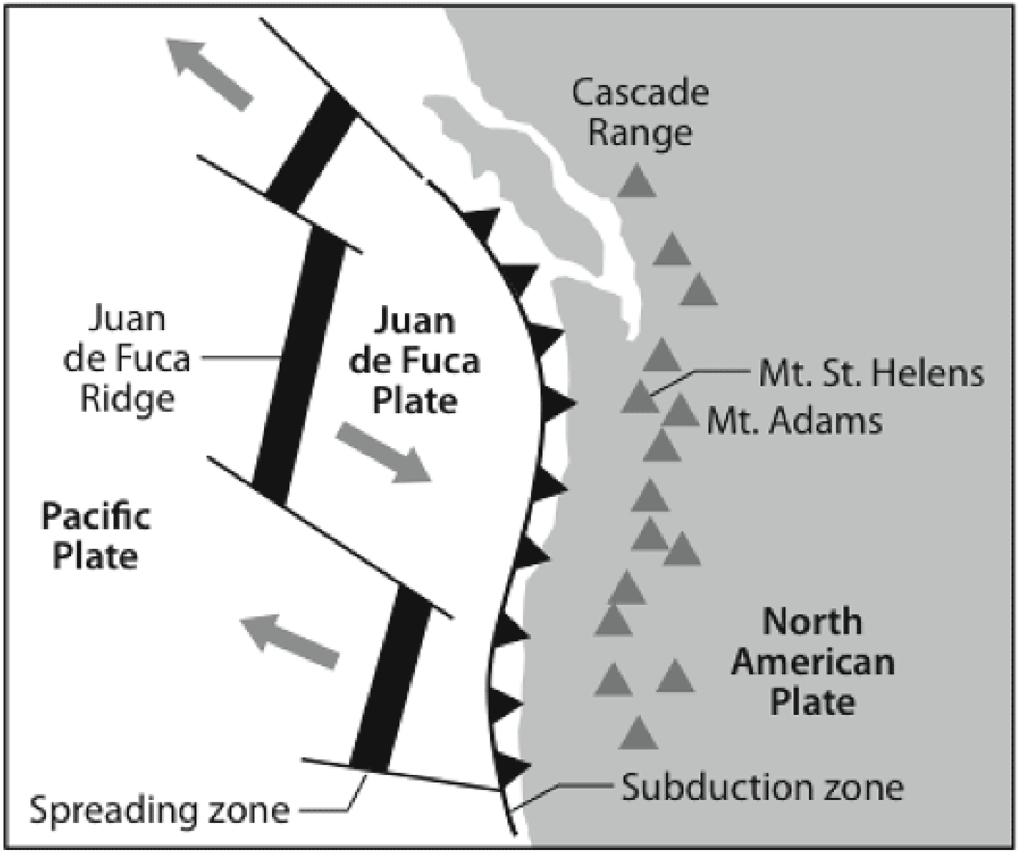


Figure 2.9.15. A map showing the key elements of the Cascadia subduction zone. Just offshore Oregon, Washingtion and British Columbia the remains of the Juan de Fuca Plate are being subducted beneath the North American Plate. Subduction related volcanism has created a created a string volcanoes along the coast. Some of the most prominent volcanoes in the area include: Mt. St. Helens, Mt. Hood, Mt. Rainer, and Mt. Baker.

The map above shows the Cascadia subduction zone. Can you locate Vancouver on this map? Did you know UBC is very close to so many volcanoes?! What do you notice about the relationship between the location f the volcanoes (small gray triangles) to the subduction arc (thick black line with black triangles)? Are they parallel? Perpendicular?

The key to volcanism at subduction zone is water. How do we know? We've analyzed melt compositions (original magma before crystallization) trapped with in erupted magma (called *melt inclusions)* to find that the original magma contained up to 5 wt. % H_20. Volcanoes at subduction zones typically erupt explosively—due to high amount of dissolved gasses trapped within the magma (e.g. water). Magma differentiation in the presence of water produces magmas with higher silica content (e.g. andesite, rhyolite, granite), which are the predominant rock type associated with subduction related volcanoes.

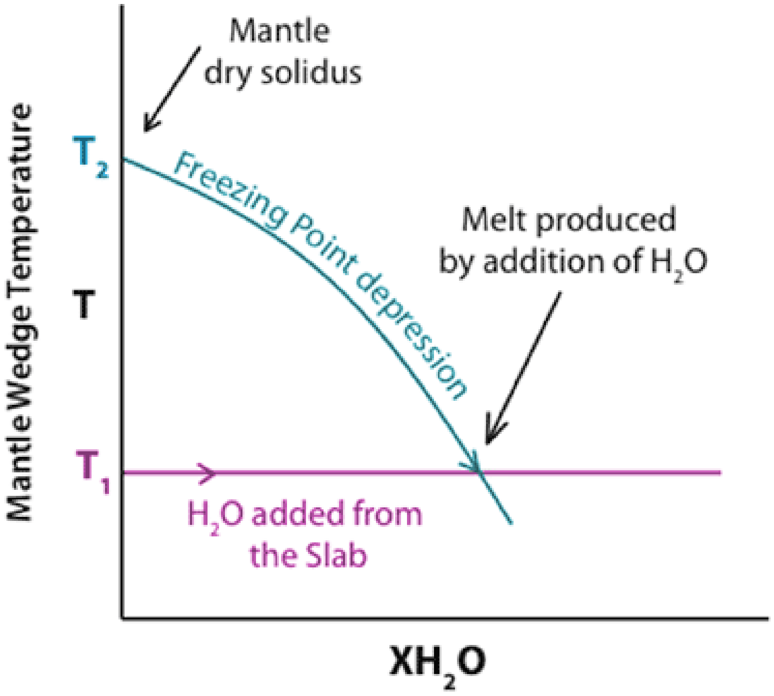


Figure 2.9.16. A plot showing the relationship between melting temperature and water content. Due to the high pressures in the mantle and the high water content of subducted materials the temperature at which rocks within subduction zones begins to melt decreases. This process is known as flux melting and is responsible for most of the melting and volcanism which occurs in subduction zones.

Water acts to lower the melting point of a magma (see diagram above), such that the mantle will melt at a lower temperature that it otherwise would at a given depth below Earth's surface.

YouTube video
Title: Behind the science 2011 - Subduction zone volcanoes
Duration: 1:54 minutes
Source: ***https://www.youtube.com/watch?v=pq-JVocLiCQ*** ***(https://www.youtube.com/watch?v=pq-JVocLiCQ%20target=)***

BEHIND THE SCIENCE 2011 | Subduction Zone Volcanoes

Figure 2.9.17. Mt. St. Helens (top) before and (bottom) after the famous 1980 eruption.

Describe how Earth's crust is recycled through plate tectonics.

Subduction introduces water to the mantle → water lowers mantle viscosity (imagine mixing water into a bowl of sticky peanut butter... would the PB get more/less sticky?) → a lower viscosity leads to an increased Rayleigh number → Higher Ra means more vigorous convection → increased volcanism at ocean ridges → increased volcanism at subduction zones → major consequences for Earth's climate and life at the surface.

Why doesn't Venus have plate tectonics? –no water on Venus! There is volcanism, but no plate tectonics.

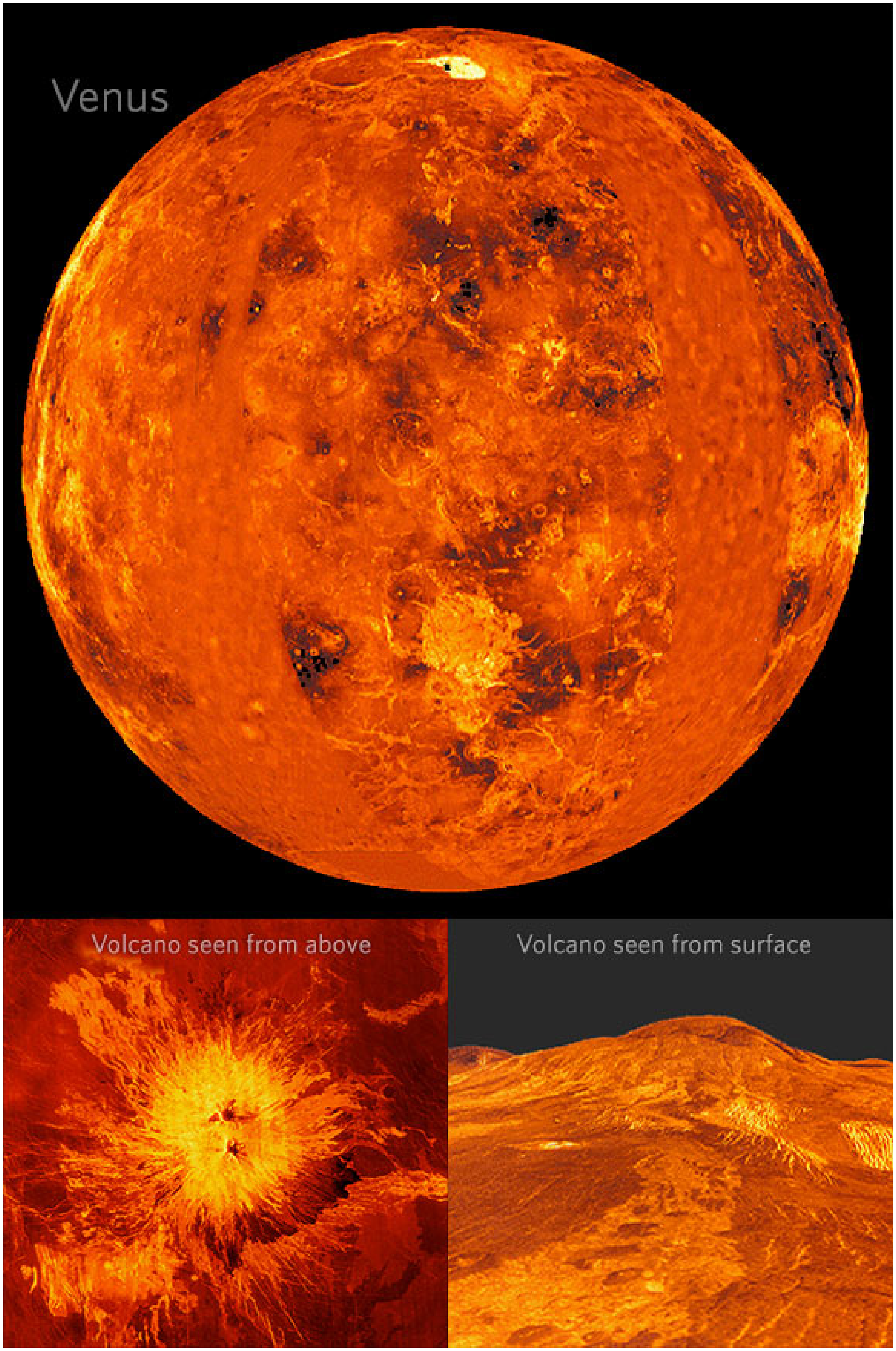


Figure 2.9.18. Images of Venus which show evidence of extensive volcanism. Examples include satellite imagery of a volcano with multiple layers of finger like lava flows radiating outwards in all directions.

The processes described above lead to slow mixing of thick mantle material –imagine a marble cake! The mantle therefore becomes more heterogeneous as a result of this increased mixing.

Figure 2.9.19. A photo of swirled chocolate and vanilla marble cake which is often used as an analogy for how increased mixing of the mantle increases its heterogeneity.

Volcanism and the Carbon Cycle: This is Earth’s Climate Thermostat. Carbon cycles continuously among the solid earth, ocean, atmosphere, and life. CO_2 removed from atmosphere by chemical weathering, deposited in ocean sediments, subducted and returned by volcanism.

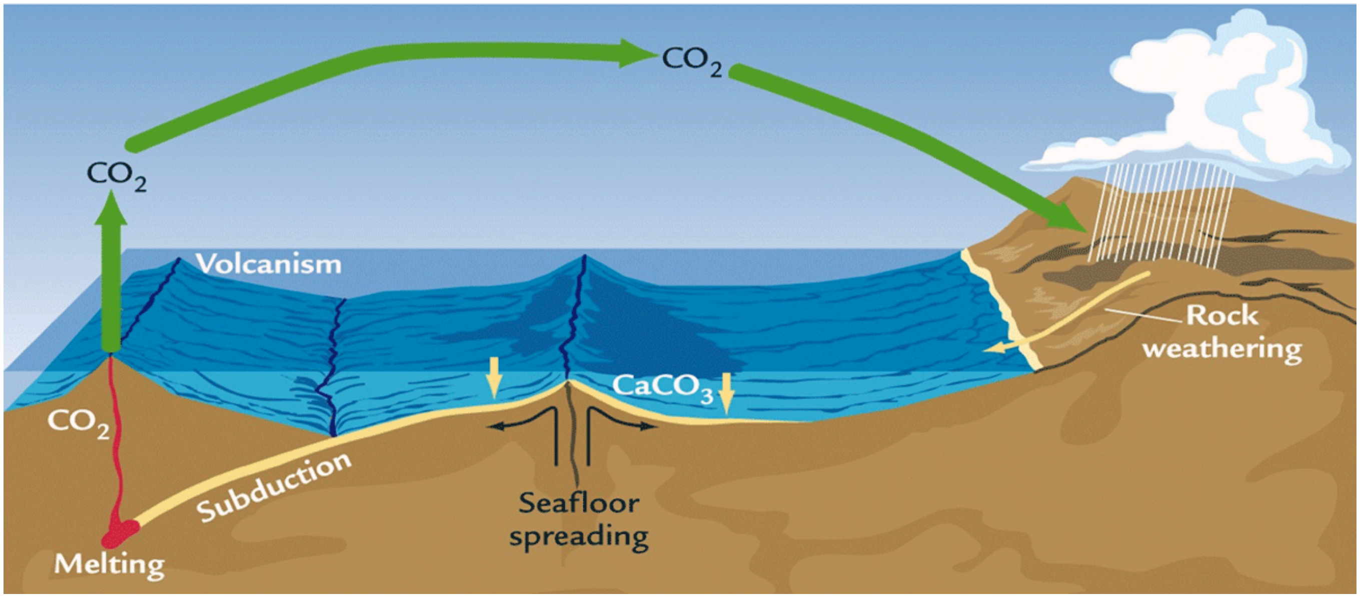


Figure 2.9.20. A basic diagram of the Carbon Cycle which shows how CO_2 is removed from atmosphere by chemical weathering, deposited in ocean sediments, subducted into the mantle, and then returned to the atmosphere by volcanism.

Cycling of carbonate, and release or CO_2 to the atmosphere at subduction zones is critical to long term climate stability. This does not happen without ocean ridges and plate tectonics. This cycle is what maintains Earth’s oceans. The ocean is needed to lead to PT geochemical cycle, and PT geochemical cycle is needed for the climate stability that maintains the oceanà it’s one big cycle!

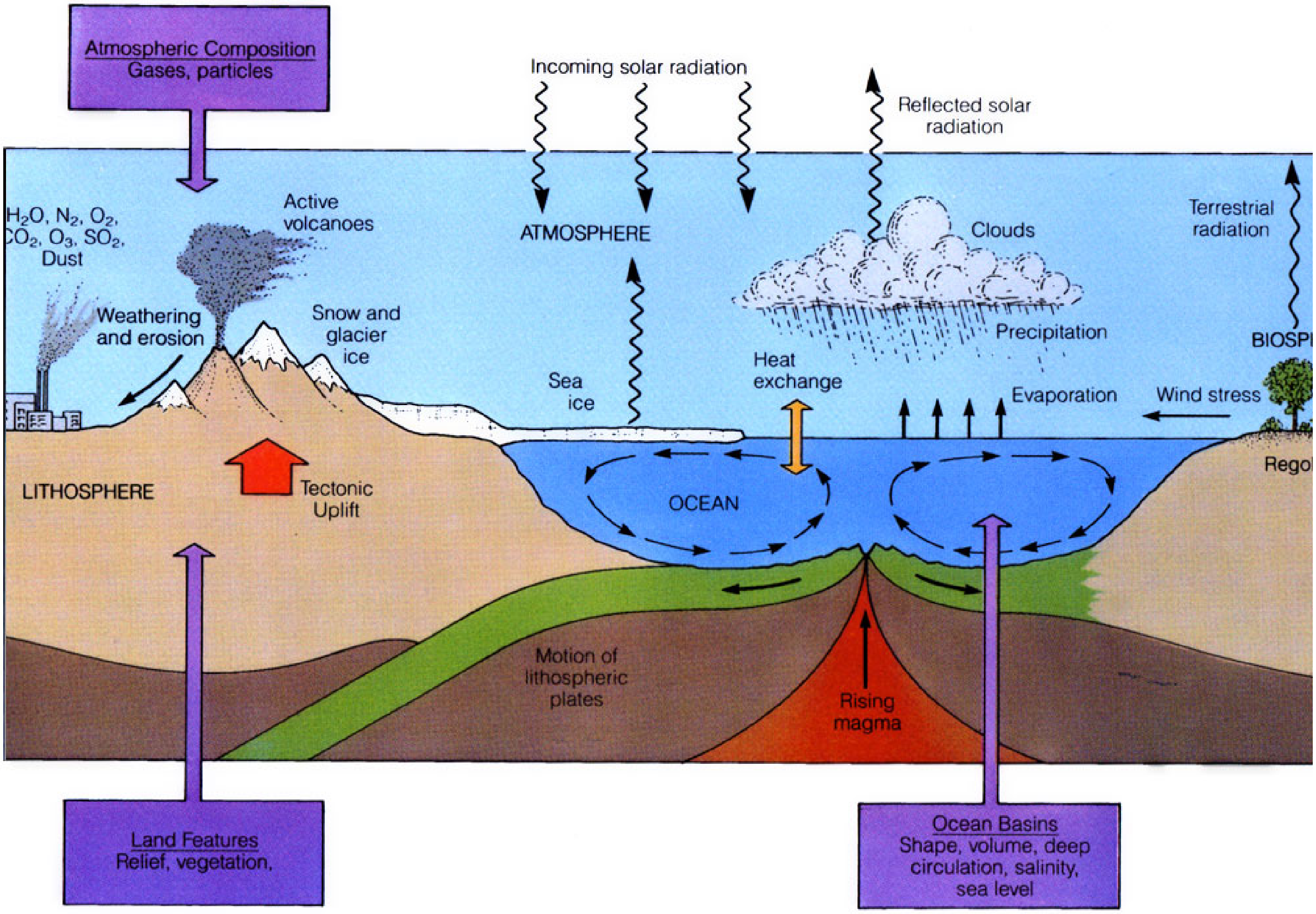


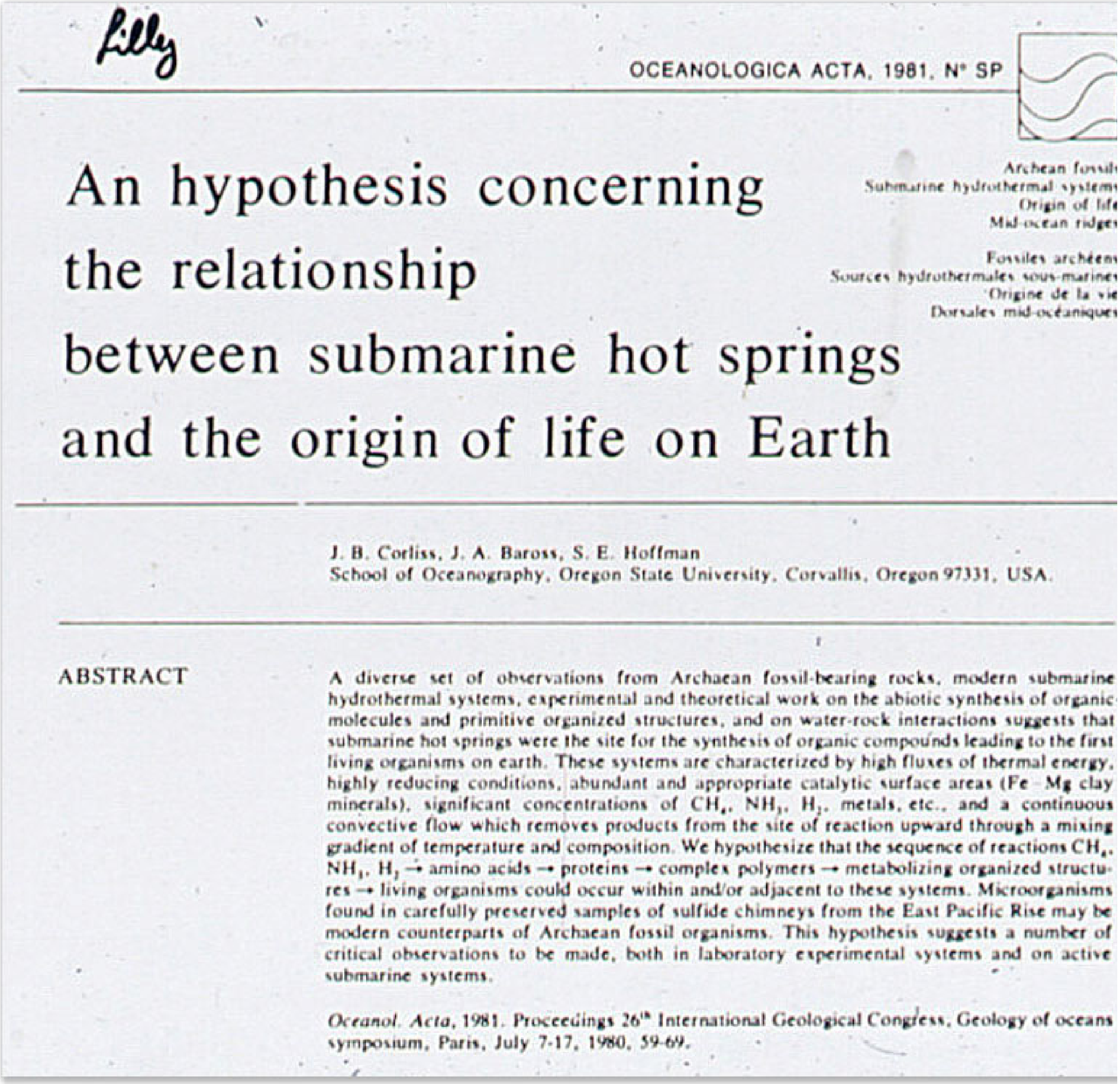
Figure 2.9.21. Cartoon like diagram which is intended to show how the whole earth forms a single interconnected system. Elements of the ocean, biosphere, lithosphere, atmosphere, mantle, and recently human systems can all have an impact on one another.

The whole earth is a linked system, even such apparently disparate phenomena as hot springs at ocean ridges, the existence of continents, the flow of the mantle, the steady state composition of seawater are ALL linked phenomena. IT IS THIS LINKED INTEGRATED SYSTEM THAT PROVIDES THE CONDITIONS FOR AND SUSTAINS A HABITABLE PLANET.

This has lead to a new perspective on planetary life…. Recent evidence indicates a *SUBSEAFLOOR* biosphere of heat-loving microbes living in the rocks supported by volcanic volatiles.

Figure 2.9.22. Plume of microbial particulates from a recently erupted sea-floor volcano.

Perhaps the brittle, water-saturated outer shell of volcanically active planets can harbor (initiate?) diverse microbial biospheres... life on other planets? This is not a new idea...



Lilly

OCEANOLOGICA ACTA, 1981, N° SP

An hypothesis concerning the relationship between submarine hot springs and the origin of life on Earth

Archean fossil
Submarine hydrothermal system
Origin of lif
Mid-ocean ridge

Fossiles archéen
Sources hydrothermales sous-marine
Origine de la vi
Dorsales mid-océanique

J. B. Corliss, J. A. Baross, S. E. Hoffman
School of Oceanography, Oregon State University, Corvallis, Oregon 97331, USA.

ABSTRACT

A diverse set of observations from Archaean fossil-bearing rocks, modern submarine hydrothermal systems, experimental and theoretical work on the abiotic synthesis of organic molecules and primitive organized structures, and on water-rock interactions suggests that submarine hot springs were the site for the synthesis of organic compounds leading to the first living organisms on earth. These systems are characterized by high fluxes of thermal energy, highly reducing conditions, abundant and appropriate catalytic surface areas (Fe–Mg clay minerals), significant concentrations of CH_4, NH_3, H_2, metals, etc., and a continuous convective flow which removes products from the site of reaction upward through a mixing gradient of temperature and composition. We hypothesize that the sequence of reactions CH_4, NH_3, H_2 → amino acids → proteins → complex polymers → metabolizing organized structures → living organisms could occur within and/or adjacent to these systems. Microorganisms found in carefully preserved samples of sulfide chimneys from the East Pacific Rise may be modern counterparts of Archaean fossil organisms. This hypothesis suggests a number of critical observations to be made, both in laboratory experimental systems and on active submarine systems.

Oceanol. Acta, 1981. Proceedings 26th International Geological Congress, Geology of oceans symposium, Paris, July 7-17, 1980, 59-69.

Figure 2.9.23. A copy of an article by Corliss et al from 1981 which shows that researchers have been thinking about the possibility of life to form in harsh environments such as hydrothermal vents at the bottom of the ocean. If life can develop here might it also be capable of developing under harsh conditions in other parts of the universe?