Department of Earth Sciences
City College of San Francisco
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Geology 10 LECTURE

Spring 2022 Workbook

Geology 10 Workbook
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Cover image from *Hetch Hetchy, High Sierra, Yosemite Wilderness*

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CLASS INTRODUCTION

What is Science? Activity

Some of the content within has been borrowed and modified from the University of California's Museum of Paleontology UNDERSTANDING SCIENCE WEBSITE: http://undsci.berkeley.edu/article/coreofscience_01.

- Science is a way of learning about the **natural world** – what is in it, how it works, and how it formed.
- Science relies on testing ideas by making **observations** to find out whether expectations hold true.
- Accepted scientific ideas are subjected to rigorous testing. As new evidence is acquired and new perspectives emerge these ideas are revised.
- Science is a community endeavor with checks and balances for greater accuracy and understanding.

Scientific Inquiry

CURIOSITY – A question arises about an event or situation: why and how does this happen?
OBSERVATIONS, MEASUREMENTS – We observe and measure: What is happening? Under what circumstances? Does there appear to be a dependable cause-and –effect relationship at work?
HYPOTHESES – We make educated guesses about what is causing what we are seeing. A good hypothesis can predict future occurrences under similar circumstances. Creativity plays a BIG role here, as we often have to think outside the box. It also helps greatly if we can bring our understandings in a diverse range of scientific disciplines.
EXPERIMENTS – We plan controlled experiments to prove or disprove potential cause-and-effect relationships. These tests can happen in nature or the lab and permit manipulating and controlling the conditions under which we make future observations.
BEYOND THE HYPOTHESIS – Patterns emerge. If one or more of the relationships hold and acceptance is widespread, the hypothesis becomes a theory or principle.

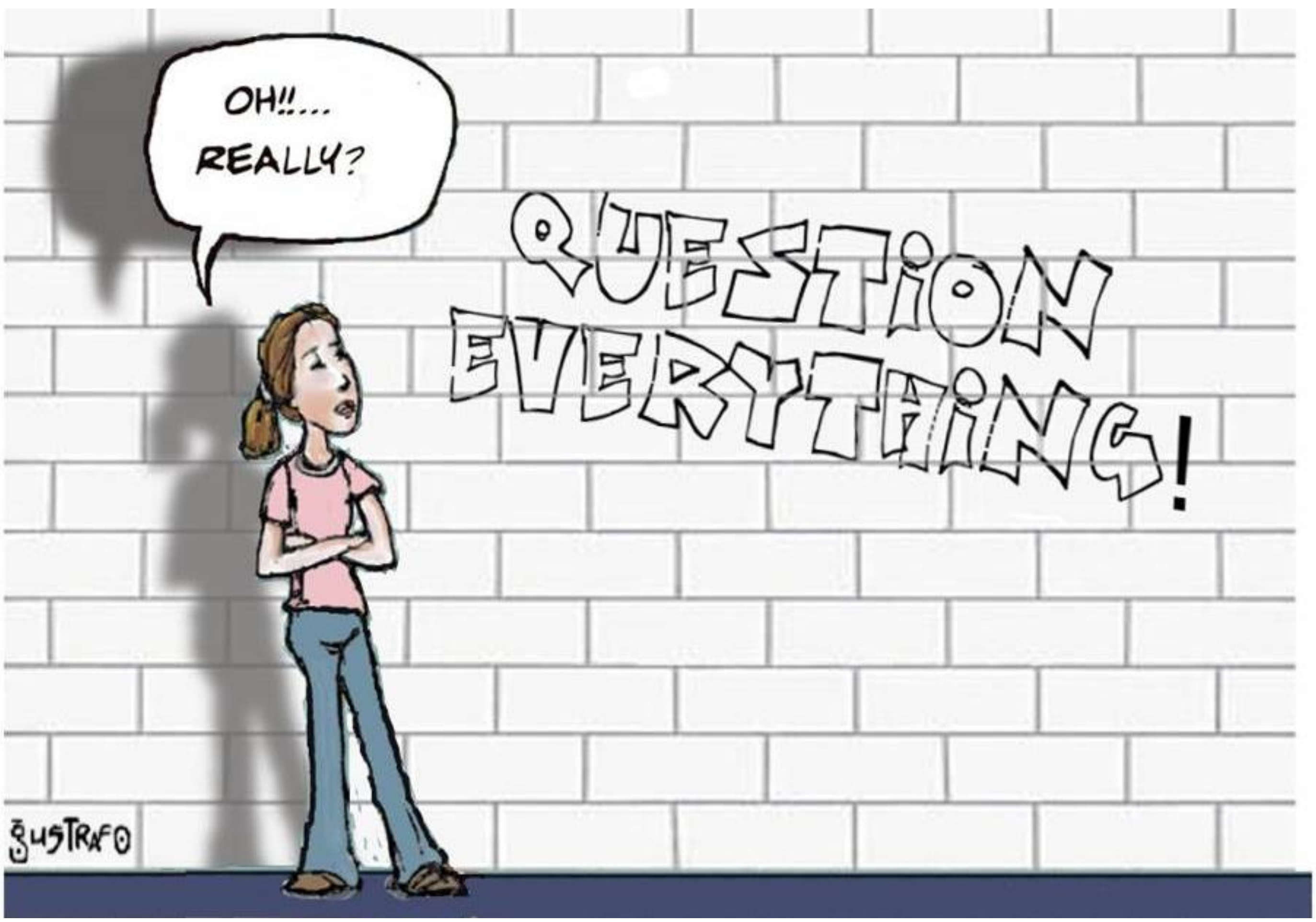

Figure 1. Cartoon: © Gustrafo – used with permission.

BEYOND THE SIMPLIFIED:

- **Scientists engage in many different activities in many different sequences.** Scientific investigations often involve repeating the same steps many times to account for new information and ideas.
- **Science depends on interactions within the scientific community.** Different parts of the process of science may be carried out by different people at different times. Society influences greatly the questions that are researched, and many of the results of scientific investigations become a highly influential part of human culture and civilization.
- **Science relies on creative people thinking outside the box!**
- **Scientific conclusions are always revisable if warranted by the evidence.** Scientific investigations are often ongoing, raising new questions even as old ones are answered.
- **The process of science is iterative.** Science circles back on itself so that useful ideas are built upon and used to learn even more about the natural world. This often means that successive investigations of a topic lead back to the same question, but at deeper and deeper levels.
- **The process of science is not predetermined.** Any point in the process leads to many possible next steps, and where that next step leads could be a surprise.
- **There are many routes into the process**. Research problems and answers come from a variety of inspirations: serendipity (such as being hit on the head by the proverbial apple), concern over a practical problem (such as finding a new treatment for diabetes), a technological development (such as the launch of a more advanced telescope), or plain old poking around: tinkering, brainstorming, making new observations, chatting with colleagues about an idea, or reading.
- **Scientific testing is at the heart of the process.** All ideas are tested with evidence from the natural world — even if that means giving up a favorite hypothesis.
- **Ideas at the cutting edge of research may change rapidly.** In researching new medical procedures or therapies or researching the development of life on earth – making living cells from inorganic materials – scientists test out many possible explanations trying to find the most accurate.
- **The scientific community helps ensure science's accuracy.** Members of the scientific community (such as researchers, technicians, educators, and students) are especially important in generating ideas, scrutinizing ideas, and weighing the evidence for and against them. Through the action of this community, science self-corrects. Note: Authority is NOT a criterion. Just because a scientist has titles or degrees does not mean we must accept their ideas. We apply a healthy dose of skepticism to all.

From Hypotheses to Theories and Principles

The process of science works at multiple levels — from the small scale (such as a comparison of the genes of three closely related North American butterfly species) to the large scale (such as half-century-long series of investigations of the idea that geographic isolation of a population can trigger speciation).

HYPOTHESES are proposed explanations for a fairly narrow set of phenomena. These reasoned explanations are not guesses. When scientists formulate new hypotheses, they are usually based on prior experience, scientific background knowledge, preliminary observations, and logic. *Example hypothesis: a particular butterfly evolved a particular trait to deal with its changing environment.*

LAWS OR SCIENTIFIC PRINCIPLES explain events in nature that occur with unvarying uniformity under identical conditions. These principles are arrived at by fact gathering and experimentation. They may have exceptions, and, like other scientific knowledge, may be modified or rejected based on new evidence and perspectives. *Example principle: Geology's principle of superposition, which states that in an undeformed sequence of rock layers, each laid down through natural processes, the oldest layer is at the bottom.*

THEORIES are broad explanations for a wide range of phenomena. They are concise (generally don't have a long list of exceptions and special rules), coherent, systematic, predictive, and broadly applicable. Theories often integrate and generalize many hypotheses and usually are more involved and complicated than a law or principle, with many more areas of doubt and refinement possible. *For example, the theory of natural selection broadly applies to all populations with some form of inheritance, variation, and differential reproductive success — whether that population is composed of alpine butterflies, fruit flies on a tropical island, a new form of life discovered on Mars, or even bits in a computer's memory. This theory helps us understand a wide range of observations (from the rise of antibiotic-resistant bacteria to the physical match* *between pollinators and their preferred flowers), makes predictions in new situations and has proven itself time and time again in thousands of experiments and observational studies.*

In common usage, the word theory means just a hunch, but in science, a theory is a powerful explanation for a broad set of observations. To be accepted by the scientific community, a theory must be strongly supported by many different lines of evidence. Biological evolution is a theory (it is a well-supported, widely accepted, and powerful explanation for the diversity of life on Earth).

OVER-ARCHING THEORIES are particularly important and reflect broad understandings of a particular part of the natural world. Evolutionary theory, atomic theory, gravity, quantum theory, and plate tectonics are examples of this sort of over-arching theory. These theories have been broadly supported by multiple lines of evidence and help frame our understanding of the world around us. These over-arching theories encompass many subordinate theories and hypotheses. Changes to those smaller theories and hypotheses reflect a refinement (not an overthrow) of the over-arching theory. E*xample over-arching theory: as we learn more about the dynamics of subducting plates in real subduction zones like Japan and Costa Rica, we refine the over-arching theory of Plate Tectonics to reflect that understanding.*

Figure 2. UBC – learningcommons.ubc.ca
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Applying Critical Thinking

There are many places in our daily lives when we apply critical thinking and scientific inquiry to our decision making:

- Something we use stops working, and we try to figure out why so we can fix it.
- We plan a major purchase, and we shop around, check reviews, and test it out first.
- Someone tells us some potentially life-changing news item about our environment or our health or other important societal issue, and we research it and test it and reconsider it continually instead of relying on faith in our story teller.

Gathering Data—Observation versus Evaluation

An important skill for scientists is to be able to distinguish between observations and evaluations. Scientists combine many and continuous observations of natural processes to come up with explanations for how these processes work.

- **Observation—**Something you see or measure. This can include comparisons, as long as they are clearly observed and not related to how someone feels. Example: John is taller than Rick. Taste can be an observation if it involves one our major taste buds: sweet and salty for example. Each of us can measure whether something is sweet or salty and whether one object is sweeter or saltier than another.
- **Evaluation—**Some kind of judgment or explanation of the facts. To determine if something is an evaluation or judgment, ask yourself: is someone trying to explain why something is happening? Or is someone saying how they feel about something? If so, it's an evaluation. Examples: John is happier than Rick. Evaporation is caused by the Sun.

Examples:

- *It's hot outside. (Evaluation)* -- *It's 81°F outside. (Observation)*
- *It's 81°F outside, and this is hotter than the average daily temperature for San Francisco. (Observation)*
- *It's 81°F outside, and this heat is caused by a combination of it being summer season and there being no clouds in the sky. (Evaluation)*

Exercise: For each statement, indicate whether it's an observation or an evaluation. If an evaluation, rewrite as observation.

1. The Arctic Ocean is shallow. **Rewrite?**	CIRCLE: Observation | Evaluation
2. The fastest lava flow measured by scientists moved at 60 km/hr. **Rewrite?**	CIRCLE: Observation | Evaluation
3. The burning of fossil fuels causes global warming. **Rewrite?**	CIRCLE: Observation | Evaluation
4. The halite mineral tastes saltier than the quartz mineral. **Rewrite?**	CIRCLE: Observation | Evaluation
5. Rock falls move faster than soil creep. **Rewrite?**	CIRCLE: Observation | Evaluation
6. The mineral quartz is hard. **Rewrite?**	CIRCLE: Observation | Evaluation
7. The sand at Ocean Beach is produced from cliff erosion. **Rewrite?**	CIRCLE: Observation | Evaluation

When scientists gather data, they have to define a clear method/process and document that process as well as the data. Only when data are gathered in a consistent way over long periods of time (or again, and again, and again), can we rely on the results. Some measurements must be taken directly. Others can be taken remotely. For example, satellites can accurately measure sea surface height. Some measurements happen by stationing an instrument in a single location – it doesn't move, but it measures the changing environment around it. Other instruments in the oceans are designed to move through the water (remotely operated vehicles or submarines or autonomous underwater vehicles) – measuring changing environments they travel through. Still other instruments are designed to drift with the water (drift buoys) – measuring through GPS the transit paths of the water.

The data that scientists gather and record has meaning only if it includes units. If I ask you how long you've been waiting for a phone call, you wouldn't say just 3 – you'd say 3 minutes or 3 hours or 3 weeks. Without the unit, the number has no meaning. As we go further into this class, you'll be reading lots of charts, tables, and graphs – observing and recording data and completing calculations. Be sure to take the time first to really understand the units and what they mean.

8. For each of the units noted below, circle the data type that would use that unit:

Unit	**CIRCLE data that could have this unit:**
Kilometers (km)	Age | Concentration of gas in air | Distance | Mass | Speed | Temperature | Time
Seconds (s)	Age | Concentration of gas in air | Distance | Mass | Speed | Temperature | Time
Meters per minute (m/min)	Age | Concentration of gas in air | Distance | Mass | Speed | Temperature | Time
Parts per thousand (ppt)	Age | Concentration of gas in air | Distance | Mass | Speed | Temperature | Time
Degrees Celsius (°C)	Age | Concentration of gas in air | Distance | Mass | Speed | Temperature | Time
Percent (%)	Age | Concentration of gas in air | Distance | Mass | Speed | Temperature | Time
Grams (g)	Age | Concentration of gas in air | Distance | Mass | Speed | Temperature | Time

RATIOS

Sometimes data are provided as a ratio such as parts per thousand (ppt), parts per million (ppm), percents (%), or just 6 grams per kilogram. These are important ways that we describe information. Examples:

- A glass jar filled with seeds has about 5% sesame seeds. (For every 100 seeds in the jar, 5 are sesame seeds.)
- In the San Francisco Bay Area, the average FLU infection rate is about 3 adults for every 1,000 (fictitious number – here just as an example (parts per thousand).
- For every billion molecules in your drinking water, at most 15 can be lead. That's the maximum amount of lead allowed by the EPA (15 ppb).
- The fee for this transaction is $6 per $1000. (For every $1,000 you receive, $6 will be removed to cover the fee).

How do we work with ratios? Here's an example: If I received $12,000 in funds in a transaction that has a $6/$1000 fee, what was my total fee? $12,000 ÷ $1000 = 12. There are 12 instances of $1,000, and each of those 12 costs $6. $6 x 12 = $72 Total cost.

9. If there are 500 seeds in a jar, and 5% are sesame seeds, how many sesame seeds are there?

10. If there are 200,000 people in a community and the infection rate is 3 ppt, how many people were infected with flu?

11. If a glass of water contains 100 billion molecules of water at maximum lead concentration of 15 ppb, how many lead molecules are there?

Evaluating or Analyzing Data & Formulating and Modifying Hypotheses

Once we have gathered data of any kind – observational or remotely or directly measured – we start thinking about what it means. What does it tell us about the underlying truths of natural process and our human experience? We often find ways to display our data so that it makes those truths easier to see, including graphs, tables, lists, and illustrations. After we begin to formulate a hypothesis, what do we do next? We test it. We design experiments or projects that allow us to gather more data. As new data are evaluated, we confirm or modify our hypothesis as needed.

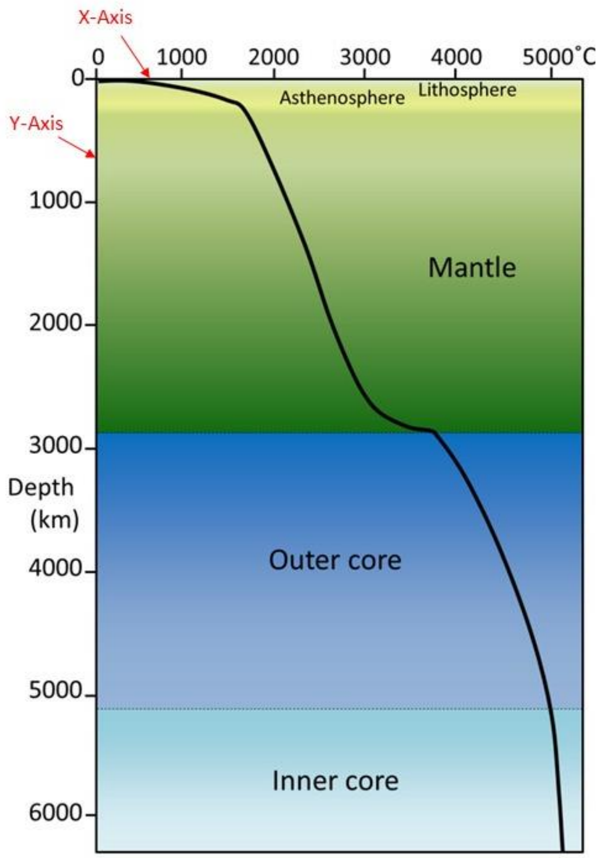


Figure 3. Generalized rate of temperature increase with depth within Earth. Temperature increases to the right, so the flatter the line, the steeper the temperature gradient. Various Earth layers are labeled. Center of Earth is at 6400 km. *(modified from Physical Geology by Steven Earle, CC BY 4.0)*

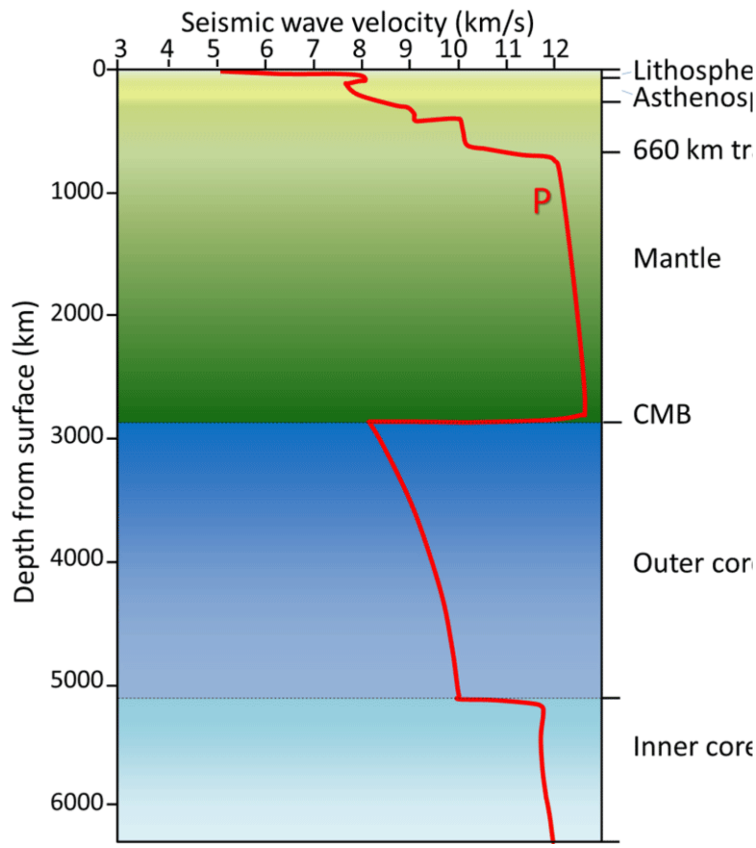


Figure 4. Generalized averaged variation of seismic P wave velocity with depth inside the Earth. Seismic waves are produced during an earthquake near Earth's surface. P waves are compressional, similar to sound waves. This graph shows how their velocity varies with depth as it travels through the Earth. Earth layers are labeled. CMB = Core-Mantle Boundary. Source: Karla Panchuk *(2018) CC BY 4.0, modified from Physical Geology by Steven Earle, CC BY 4.0.*

12. Review figures above and record below **observations** about the data (patterns, values, and more). *Start with captions, review axes (labels and direction of increase), then describe line/curve (using x-axis/y-axis values). **No evaluation or explanation yet!**

	Left Figure	**Right Figure**
Y-axis (Characteristic measured and unit)		
X-axis (Characteristic measured and unit)		
Shape of graphed line (when does it increase, decrease, or stay the same?)		

13. What questions or hypotheses do you have after reviewing and thinking about these data? **Here's the place for evaluation or explanations.**	
Left Figure	**Right Figure**

14. What are the limitations of these data? Are there more data you'd like to collect?	
Left Figure	**Right Figure**

15. Notice there are some data in the different curves that correlate – meaning the trend of the data curve in the figure on the left varies in the same direction over the same depth as the trend of the data curve in the figure on the right. Locate and describe those correlations.

16. It's extremely important to notice correlation because it means there *might* be a relationship between the two characteristics. It might be that one causes the other, or it might mean that the cause of one is also the cause of the other. **CORRELATION ≠ CAUSATION** Look at the correlation described above and indicate below what hypotheses you have about its causation.

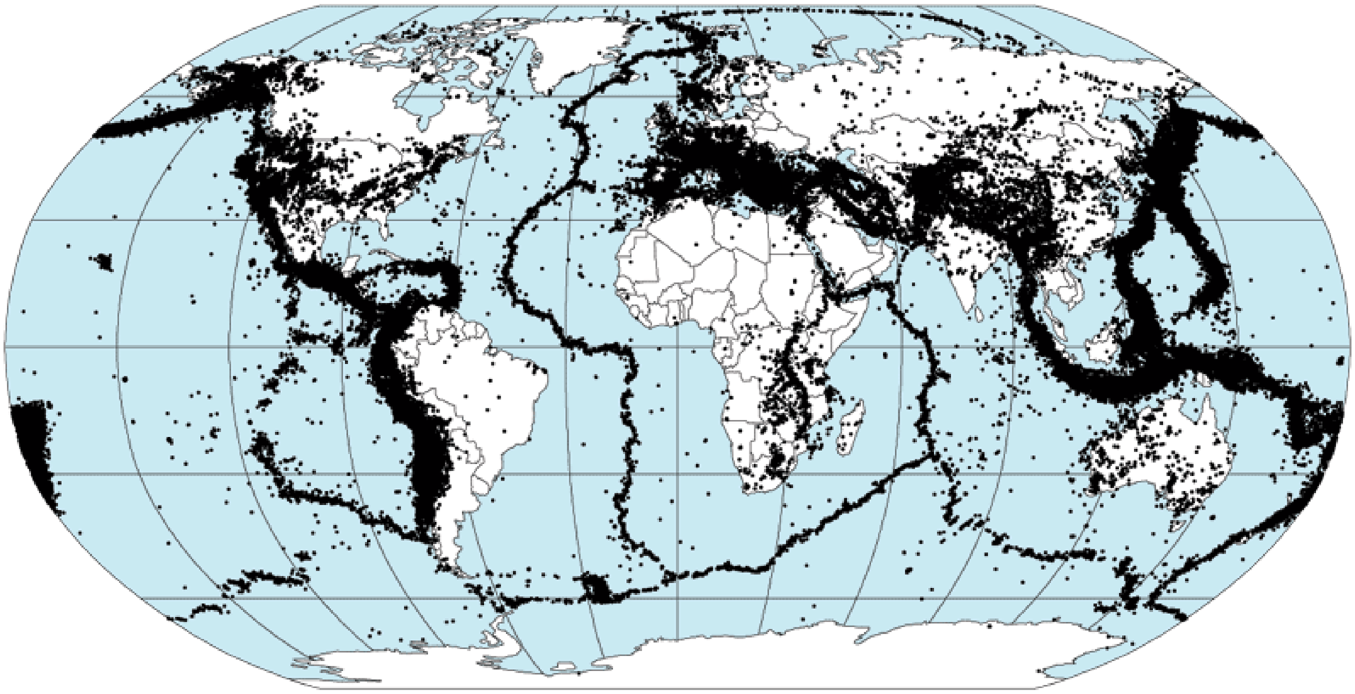


Figure 5. Global earthquake epicenters from 1963 to 1998. NASA, DTAM project team - http://denali.gsfc.nasa.gov/dtam/seismic/

17. Review figure above and record below **observations** about the data (patterns, values, and more). **No evaluation or explanation yet!**
What characteristic/information do the data points represent?
Are the data evenly distributed? If not, are there any patterns or general rules about where they are found?
Do the data outline or concentrate in any shapes? If so, how, where, what shape?
18. What questions or hypotheses do you have after reviewing and thinking about these data? **Here's the place for evaluation or explanations.**
19. What are the limitations of these data? Are there more data you'd like to collect?

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly Objective	**Self-Assessment of Mastery Level**	**Action plan for improvement**
Successfully accessing and navigating the course content and resources.	A | B | C | D | F	
Identifying multiple methods by which you can communicate with your fellow students and instructor.	A | B | C | D | F	
Ensuring you have the right technology and sufficient time to complete class requirements.	A | B | C | D | F	
Comparing and contrasting the basic elements and tools of scientific inquiry, especially observation vs. evaluation.	A | B | C | D | F	
Describing and evaluating patterns in data and graphs and maps.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

INTRODUCTION TO PLANET EARTH AND PLATE TECTONICS

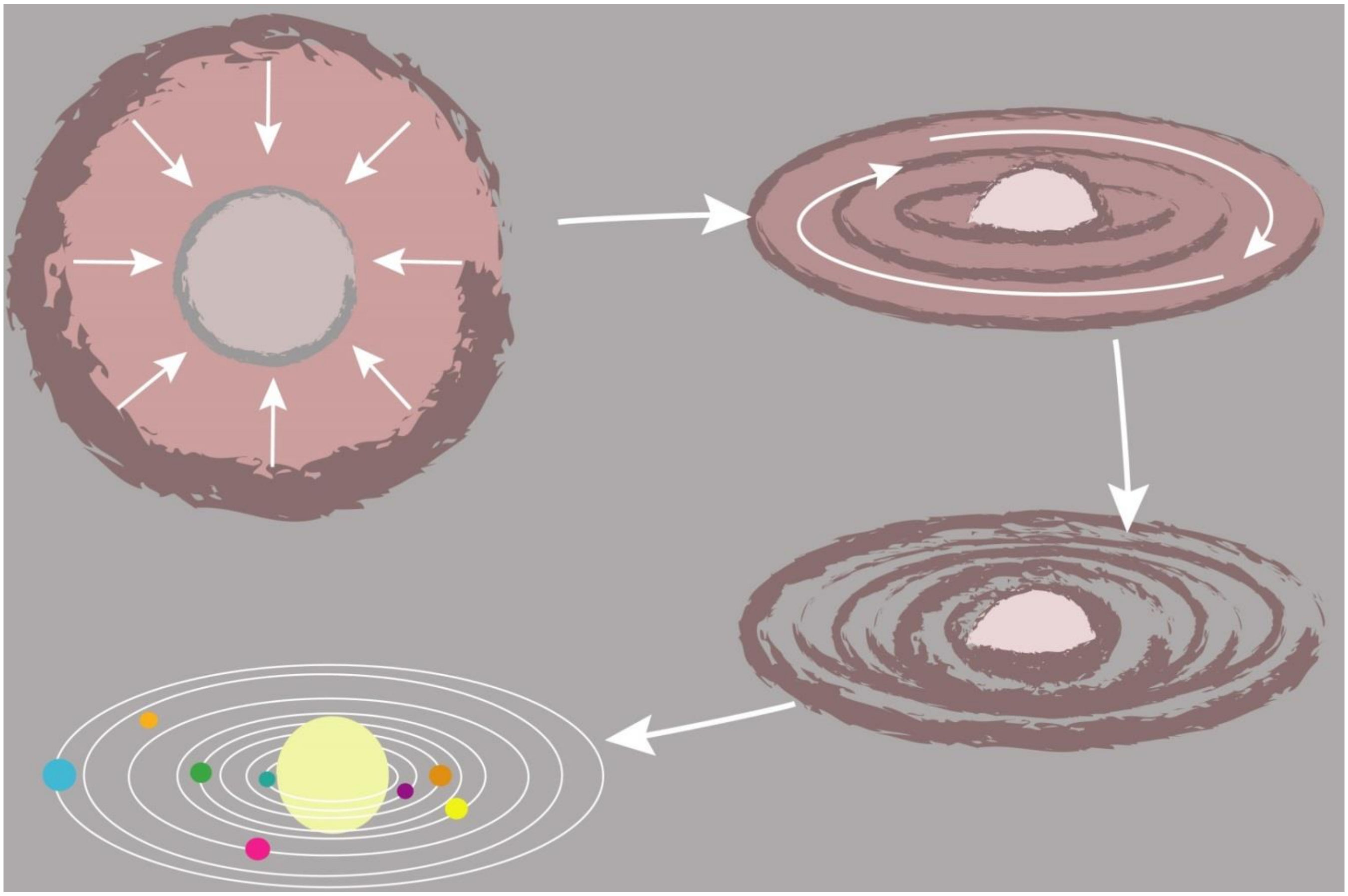


Figure 1. Time-progressive image of the Solar System formation through condensation from a nebula, increasing rotation into a disk, and planetary accretion from debris orbiting the sun.

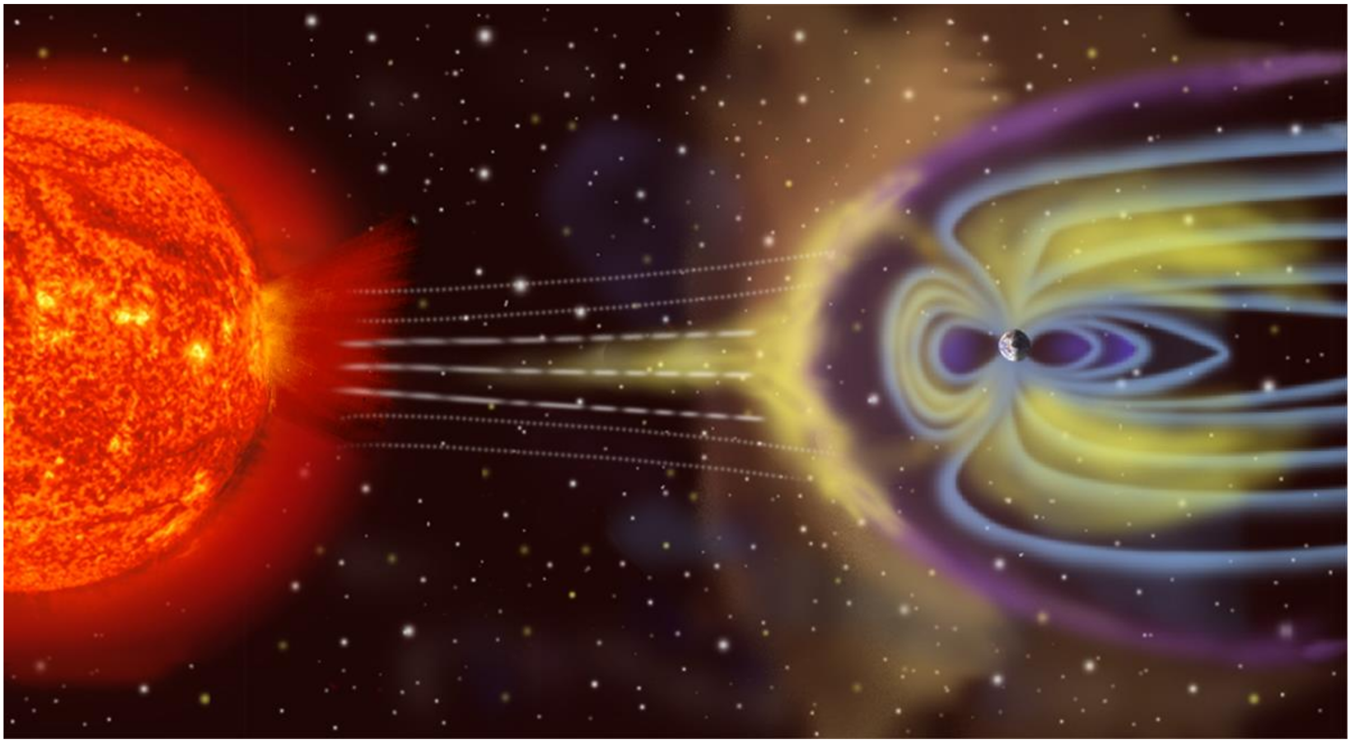


Figure 2. Solar winds blowing towards Earth and deflected by Earth's Magnetic Field. (NASA)

Table 1. Brief History of Earth

Notice that all these events are listed in reverse chronological order – oldest at bottom of table, youngest at top.

10-25 Ka	Wisconsin ice age (most recent one; land bridges form and humans migrate from Asia into North America)
100-300 Ka	Homo Sapiens first appear.
400 Ka	San Francisco Bay forms.
1.6 Ma	Period of frequent ice ages begins and continues to today.
2-4 Ma	Ancient Hominids first appear.
50-25 Ma	San Andreas Fault forms as North American margin stops subducting.
63 Ma	Primates evolve.
65 Ma	Dinosaurs and other organisms go extinct making the way for the Age of Mammals.
145 Ma	First mammals, including platypus, shrews, and opossums.
152 Ma	First birds evolve from small, fast-running dinosaurs.
225 Ma	**Pangaea**, the most recent supercontinent completes its formation, and then begins its breakup (to create the Atlantic Ocean). Two halves: **Gondwanaland** (Australia, India, Africa, S. American, Antarctica) and **Laurasia** (N. America, Greenland, Europe, and Asia).
230 Ma	First dinosaurs, reptiles that distinguished themselves by standing upright on two legs.
240 Ma	First vertebrates to fly – the Pterosaurs, dinosaur cousins.
245 Ma	The largest mass extinction in Earth's history. Over 75% of all marine groups eliminated, making way for the Age of Dinosaurs
350-290 Ma	Giant Swamp Forests thrived in lowlands at the edges of rivers and seas (like today's Louisiana bayous). Tropical climates encouraged dense growth of ferns, tree ferns, and club-mosses. The buried material from these forests eventually became much of the world's current coal resources.
400 Ma	First lungs.
430 Ma	First jawed fish.
438 Ma	First plants move onto land, followed within 10 million years by animals (aquatic scorpions and other arthropods).
480 Ma	Large continent known as **Gondwanaland** forms from the collision of Australia, India, Africa, South America, and Antarctica. Pacific Plate subducts under North America's western margin. The western margin grows through accretion of oceanic rocks and islands (**terranes**).
520 Ma	First vertebrates (cartilaginous fish with tails and fins).
570 Ma	First organisms with hard parts. Beginning of the Age of Trilobites. Also existing early on were brachiopods and ammonites.
670 Ma	First multicelled animals evolve: Ediacaran fauna, soft-bodied marine animals that get their food primarily from small algae.
700 Ma	**Rodinia** breaks up into pieces.
1 Ga	Sexual reproduction begins leading to an increase in the rate of evolution. Red Beds stop forming in large amounts and free oxygen begins to accumulate in the atmosphere. The atmosphere begins to evolve to one closer to today's: 80% Nitrogen, 20% Oxygen. Eventually enough oxygen accumulates in the atmosphere that UV radiation interacted with it in the upper atmosphere to produce **ozone**, a gas that then acts as a UV shield, protecting life on Earth's surface.
1.2 Ga	**Rodinia**, the oldest known supercontinent, forms through collision of Earth's plates. Plate Tectonics has likely been active for billions of years.
2.3 Ga	**Great Oxygenation Event: Red Beds** form on land. These beds are land-based rust piles that take the place of the oceanic banded iron formations as free oxygen now leaves the oceans and enters the atmosphere. The Red Beds absorb most of the available oxygen.
2.5 Ga	**Oxygenic photosynthesis.** $6H_2O + 6CO_2$ + sunlight = $C_6H_{12}O_6$ (sugar) $+6O_2$. Ocean and atmospheric chemistry begins to change as O_2 is added and CO_2 removed. Largest deposit of **Banded Iron Formations (BIFs)**. Earth's oceans would have had a lot of dissolved iron, due to the accumulation of hundreds of millions of years of rock weathering and underwater volcanic eruptions. Oxygenic photosynthesis produced sufficient oxygen gas to readily and quickly combine with the iron to form large deposits of rust.
2.7 Ga	**Eukaryotes** evolve: organisms with a nucleus.

3.7 Ga	Earliest evidence of stromatolites: layered rock mounds formed in shallow oceans as mats of cyanobacteria dome upward to capture energy from sunlight to produce sugar through anoxygenic photosynthesis. Live in mucous layers to avoid UV-radiation damage to the sun.
3.85 Ga	Earliest evidence of microbial activity (carbon isotope ratios). This early life likely lived in the oceans where they were hidden from the sun's ultraviolet rays (no ozone layer yet, because no oxygen in the atmosphere). These early bacteria were known as **prokaryotes**: single celled organisms with no nucleus, otherwise known as bacteria. These early life forms were likely **chemosynthetic**, making food from energy derived from gases emitted at hydrothermal vents on the bottom of the seafloor.
4.4 Ga	Earth's surface cools enough for a solid crust to form. Earth's atmosphere (accumulated gases from **volcanic outgassing** and comets) contains (in decreasing order) carbon dioxide, nitrogen, water vapor, methane, ammonia, carbon monoxide, sulfur dioxide, hydrogen sulfide, and hydrogen cyanide. Because of the solid cooler surface conditions, much of the atmospheric water now rains down and fills in basins to form the first oceans.
4.5 Ga	A Mars-sized object crashes into Earth creating debris that ends up in orbit around the Earth, eventually coalescing through accretion to form the **Moon**.
4.6 Ga	As the solar disk cools down, orbiting material collides and clumps to form larger objects (**accretion**). Continued accretion led to larger bodies with higher gravity that swept up more material within their orbits and ultimately became **planets**. Not all the material got swept up in this process. A large belt of leftover rocky debris – **asteroids** – exists between Mars and Jupiter. A belt of leftover icy debris – **comets** – orbits in the outer solar system. At this point, the interior of the Earth is mostly molten from the heat of accretion. **Density stratification** occurs: dense material, like iron, sinks to form the **core** while less dense material rises to form the **crust**; the remainder becomes the **mantle** layer. All planets are hot from the accretion process. Volcanic activity and continual meteorite collisions dominate the surface. Gases from volcanoes and comets form an early, hot, toxic, atmosphere.
5 Ga	Debris from past supernovas is perturbed, likely by nearby star activity, and starts to clump together to form a new star – a single hot, spinning mass of gas – our proto Sun. The gas giants (Jupiter, Saturn, Neptune, Uranus) began forming soon after the Sun started coalescing, through similar processes. Large clumps of H and He separately coalesced and contracted, increasing in density and attracting material to become gas giant protoplanets. They are not stars because they never grew big enough and hot enough for fusion to occur in their cores. Eventually the material in the proto Sun completely condenses, fusion starts, and our **Sun** forms. As the Sun spins, the surrounding matter flattens into a rotating disk and begins to condense into solids, liquids, and gases – all very hot! It was too hot near the Sun for ices and many gases (like water, ammonia, and methane) to be stable, so condensates near the Sun consisted of iron oxides, aluminum oxides, and silicates – high-density minerals stable at high temperatures. In the cooler outer solar system, all materials were stable and condensed alongside each other. Hence, the inner rocky planets formed from the accretion of rocky material, whereas the moons, comets, and gas giants of the outer solar system formed (or completed their formation) from the accretion of all materials.
12.7-5 Ga	Throughout most of the life of a star, deep in their cores, H nuclei are fused to produce He and energy. Stars "shine" because they are radiating the energy produced from this nuclear fusion. High-mass stars burn the hydrogen fuel in their core rapidly and are short lived—the largest lasting only 10 million years. Low-mass stars burn their fuel slowly—the smallest lasting hundreds of billions of years. (Note: our **Sun** is medium sized and will last 10 billion years.) Once the H is nearly used up, He atoms begin to fuse, and the core temperature of the star rises dramatically. As temperatures rise higher, elements of successively higher mass—like carbon, nitrogen, and oxygen—are produced through fusion. Stars that are ten times more massive than the Sun can create elements as heavy as iron. Eventually the energy produced can't be shed fast enough; a high-mass star explodes in a **supernova** event, ejecting much, if not all of its matter, and producing a **supernova remnant**. Elements up to uranium can form in the supernova's blast waves. New stars eventually form from supernova remnants. Through repeated generations of star birth and death by supernova, these remnants can be enriched enough in heavy elements to form planets. *(Based on the abundance of heavy elements in our solar system, our Sun is likely a third- or fourth-generation star.)*

12.7 Ga	The universe is no longer smooth and uniform. High-density regions of H and He gas generate gravitational fields – the more mass, the more gravity. The more gravity, the more mass from surrounding areas is pulled in. Eventually localized regions condense under their own weight. Gravitational energy is converted into heat – temperature rises. Once the size of this dense spinning sphere of gas is great enough, and its core temperature rises above 10^6 K, nuclear fusion begins – primarily the fusion of H to produce He and energy. As this newly created energy radiates outward, a shining **star** is born. When billions of stars orbit a shared center of gravity, we call them a **galaxy**. There are hundreds of billions of galaxies in the observable Universe.
13.7 Ga	**Big Bang**: the universe is born in an instant in time and expands outwards from one infinitesimally small point. Original material = very high energy (hot) subatomic particles. Universe inflates and cools until protons, neutrons, and electrons form, and matter is governed by the laws of physics as we know them. 380 m.y. later, the universe is 75% Hydrogen (H) and 25% Helium (He) gas.

*Age is when division begins.

Ka = kilo annum = thousand years ago | Ma = Mega annum = million years ago | Ga = Giga annum = billion years ago
my = million of years | My BP = Millions of years before present

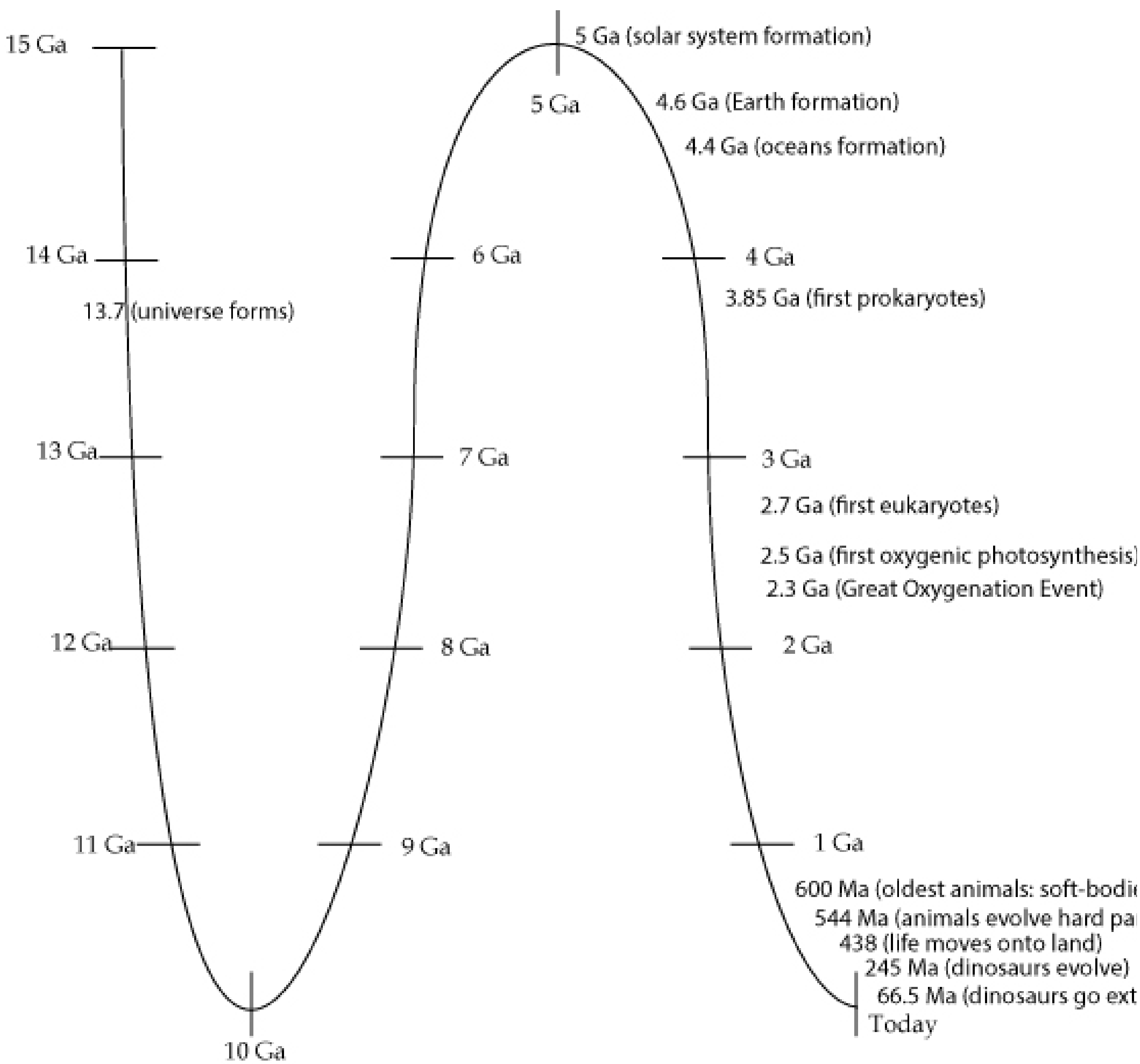


Figure 3. Scaled timeline of the history of the Universe from 13.7 Ga to today.

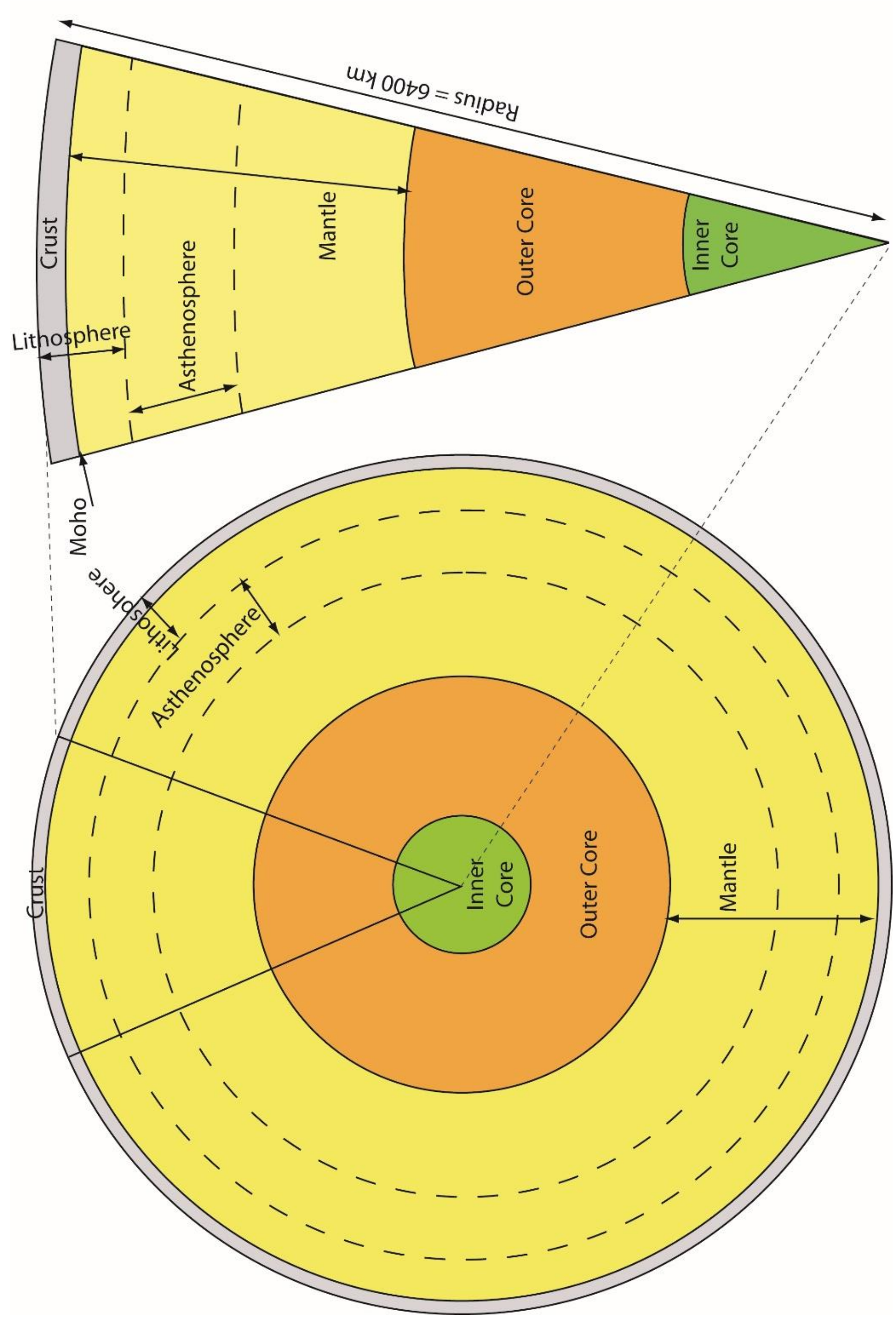


Figure 4. Cross-section of Earth showing its layers (to scale, except for greatly exaggerated crust)
Note: the MOHO is the name given to the boundary between the crust and the mantle.

Table 2. Earth Layers – Compositional and Physical Characteristics

Layers	Thickness	Composition	Density/State
Crust: Oceanic	3-10 km	Si, O, Fe, Mg, Al = Basalt	2.9 g/cc SOLID
Crust: Continental	30-50 km	Si, O, Al = Granite	2.7 g/cc SOLID
Mantle	2900 km	Mg, Fe, Si, O	4.5 g/cc SOLID
Outer core	2200 km	Fe, Ni (S, Si)	11 g/cc LIQUID
Inner core	1300 km	Fe, Ni (S, Si)	16 g/cc SOLID

Overlaid layers:

Lithosphere	100-200 km	100% Crust + Upper Mantle	Rigid, solid, brittle: breaks into pieces: plates
Asthenosphere	100-350 km	Portion of mantle	Plastic (flows), but solid

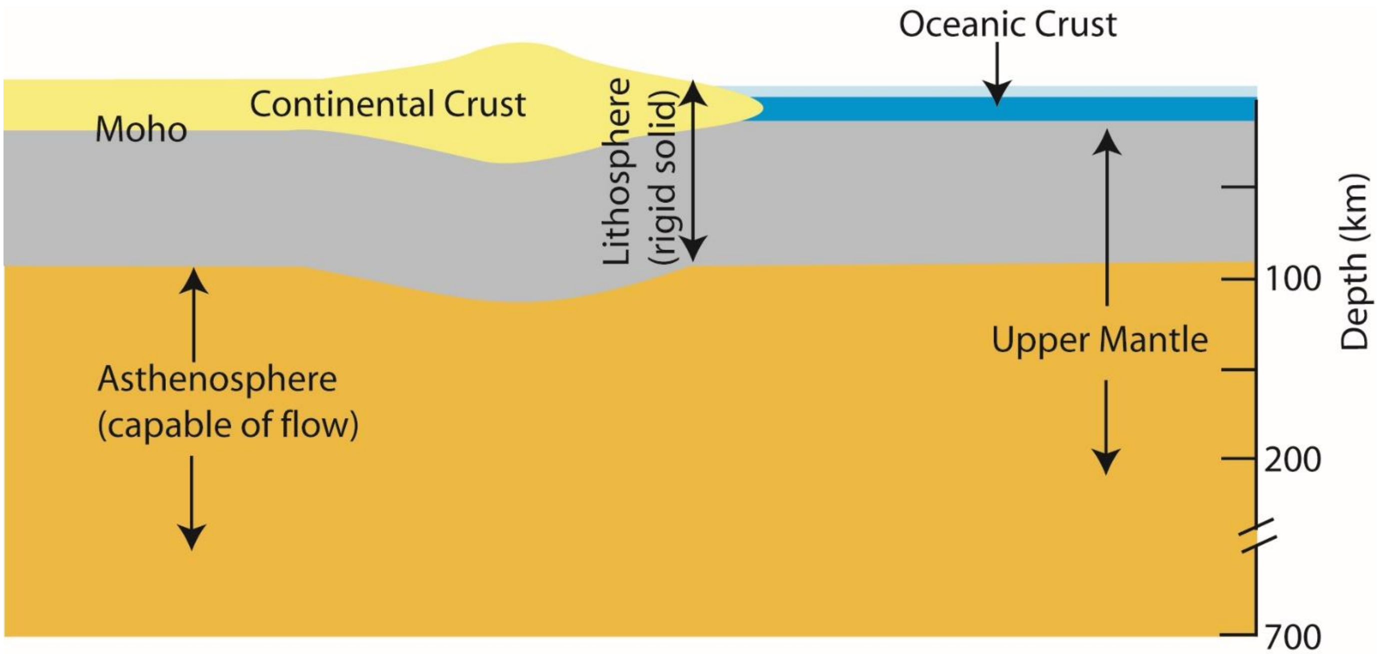


Figure 5. Close-up view of the Earth outer layers. The lithosphere contains ALL the crust plus the uppermost portion of the mantle; it is solid and breaks into pieces called plates, which then move around atop the underlying plastic mantle layer known as the asthenosphere. Convection of the hot plastic asthenosphere directs the motion of the plates above. The MOHO is the boundary between the crust and the mantle underneath. NOTE: The grey layer above has no name.

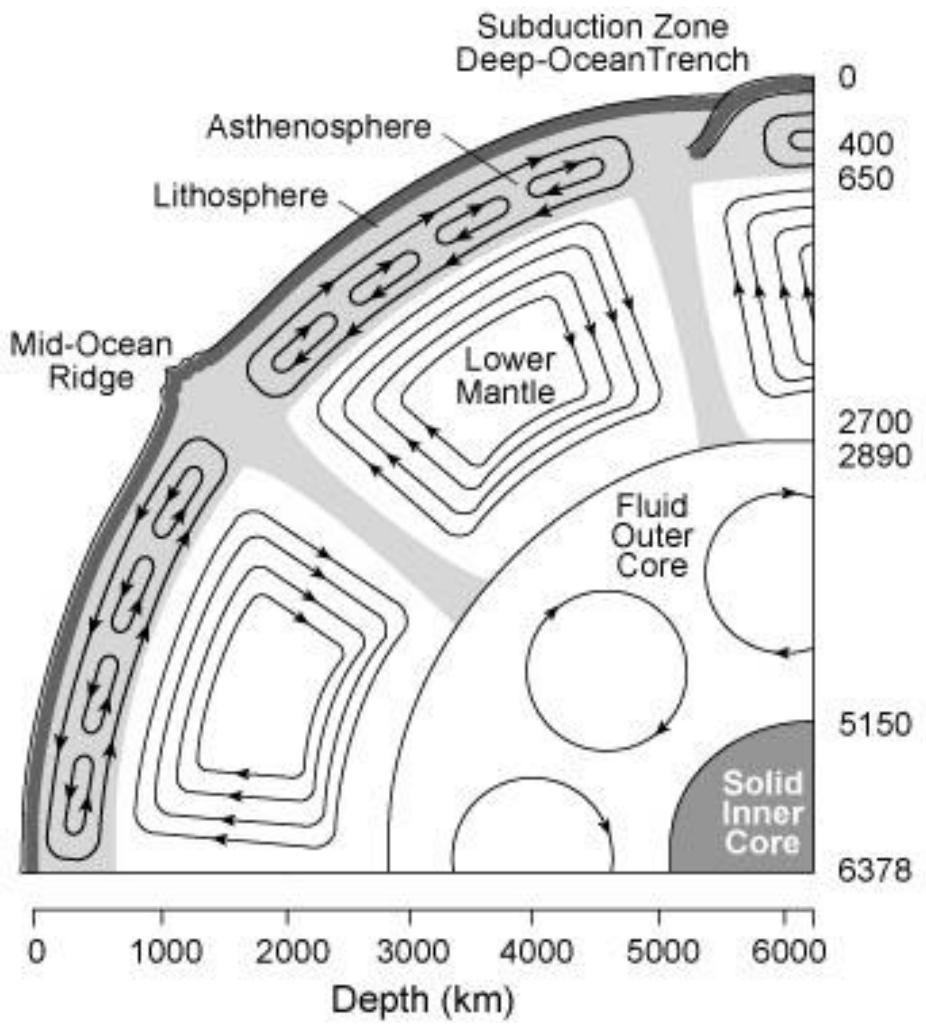


Figure 6. Convection of Earth's mantle, in asthenosphere and lower mantle. Also note the convection of the outer iron core. Note: the convection shown in the lower mantle is different from the rest because the material there is considered solid. The arrows represent the fact that lithospheric plates in subduction zones can descend all the way to the core-mantle boundary and that hotspot plumes can rise up from the core to the crust.
Image from Kenneth R. Lang's book The Cambridge Guide to the Solar System, Second Edition 2011.

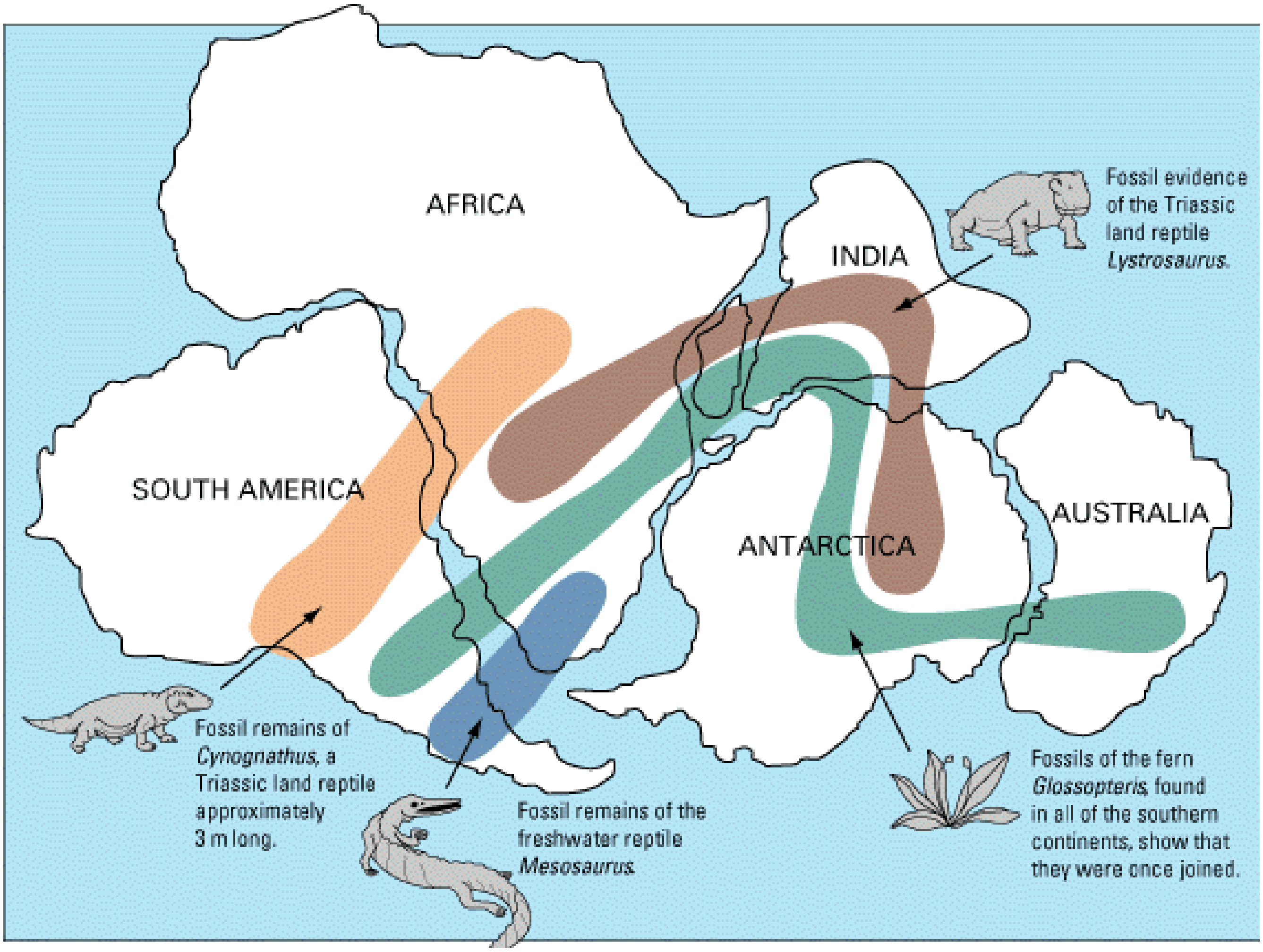


Figure 7. Fossil evidence for continental drift: fossils of the above organisms are found today on continents separated by oceans. When we return the continents to their original Pangaea configuration (225 Ma), the locations mark contiguous habitat for each organism. At the time they lived, they roamed freely over this area of connected land masses. USGS.

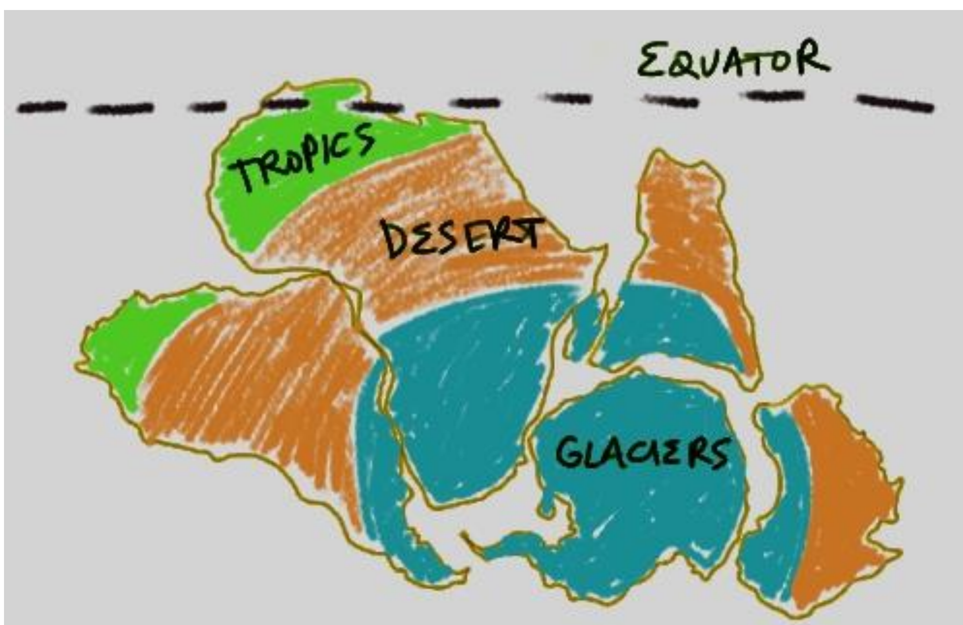


Figure 8. 225-Ma fossil glacial-boundary ferns and glacial striations in the rocks now found on separate continents piece back together to a massive continent with a southern Ice cap in the Pangaea configuration of continents. Eliza Richardson Creative Commons BY-SA-NC-3.0.

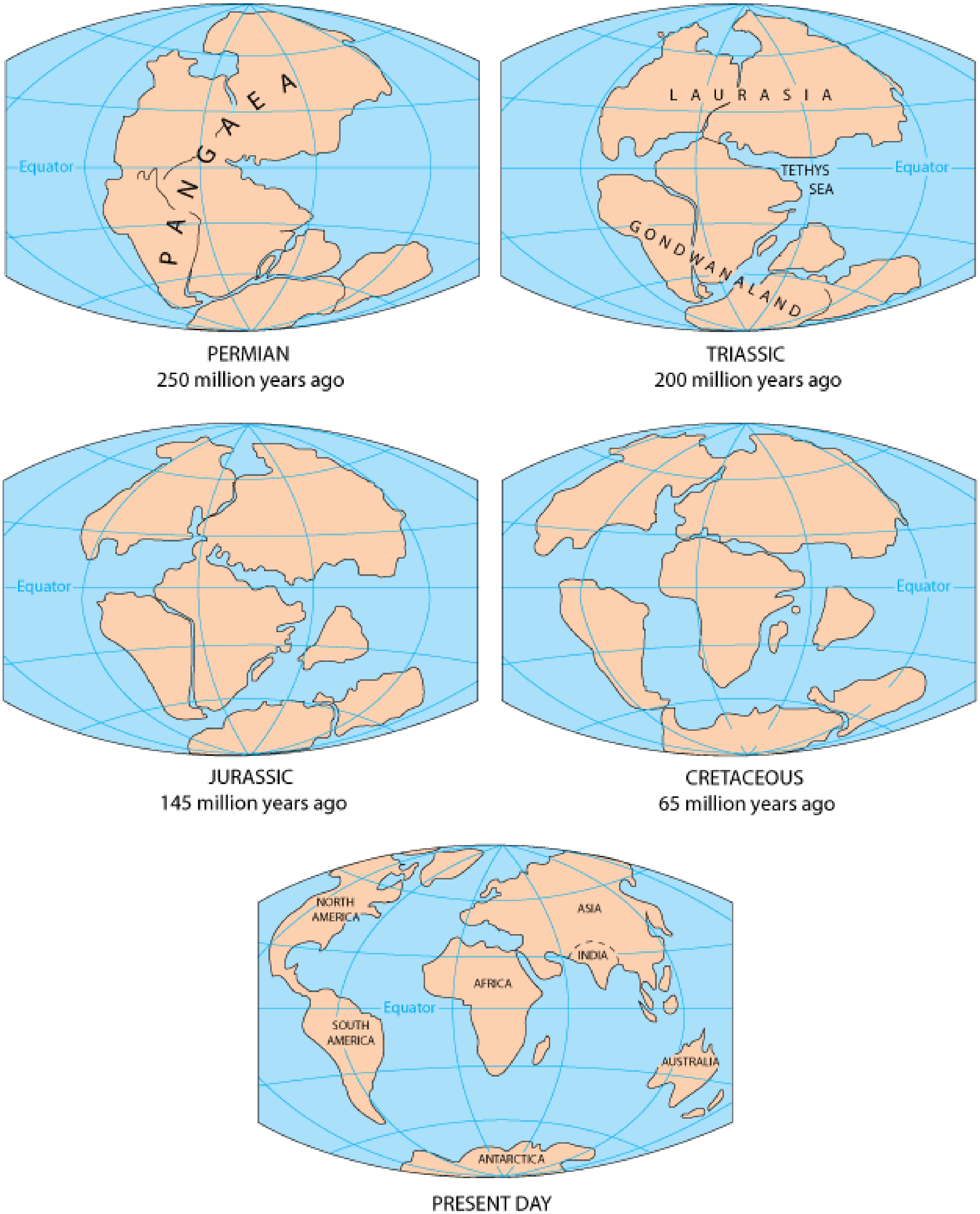


Figure 9. Pangaea breakup. USGS.

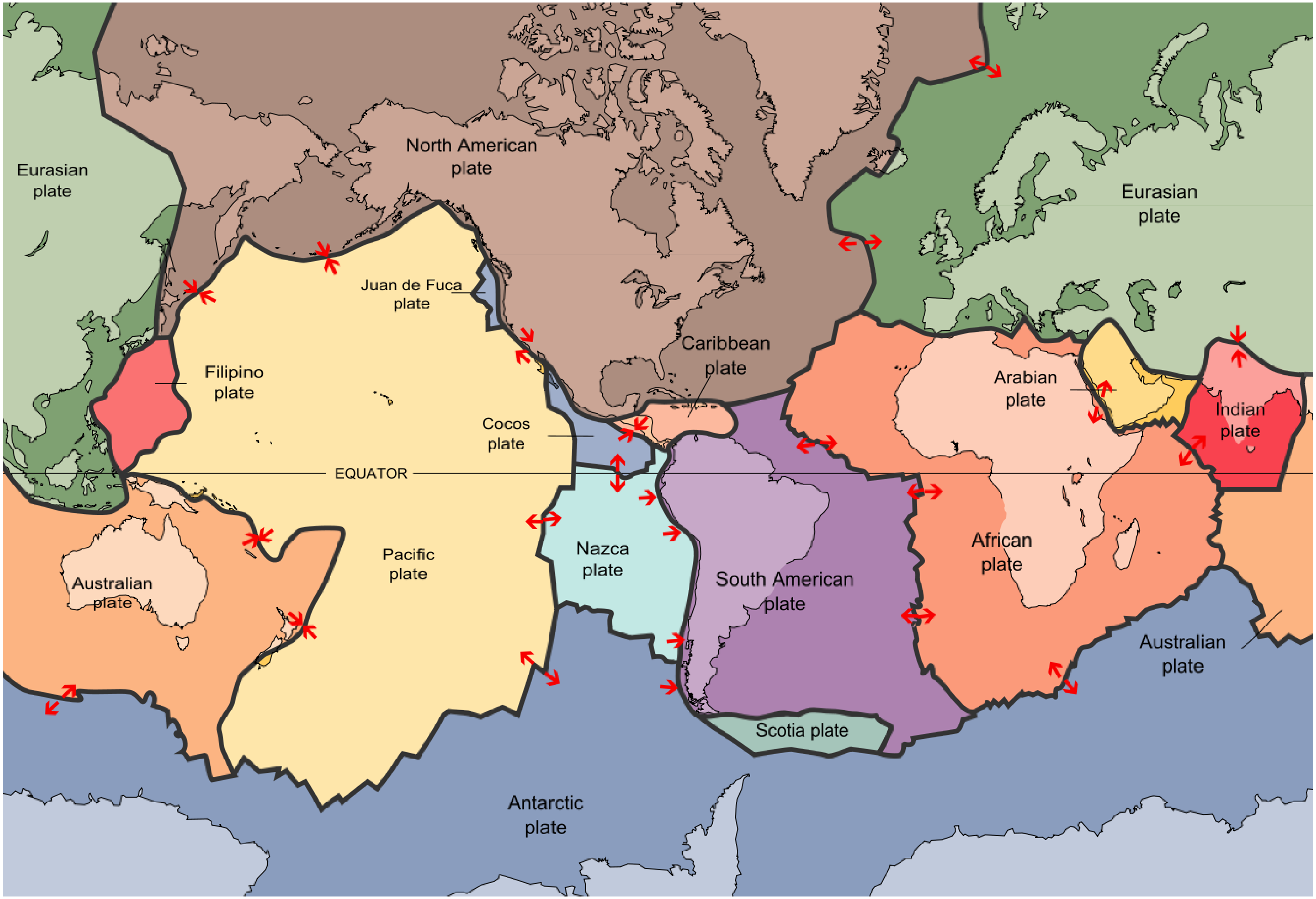


Figure 10. Global Plate Boundaries, USGS

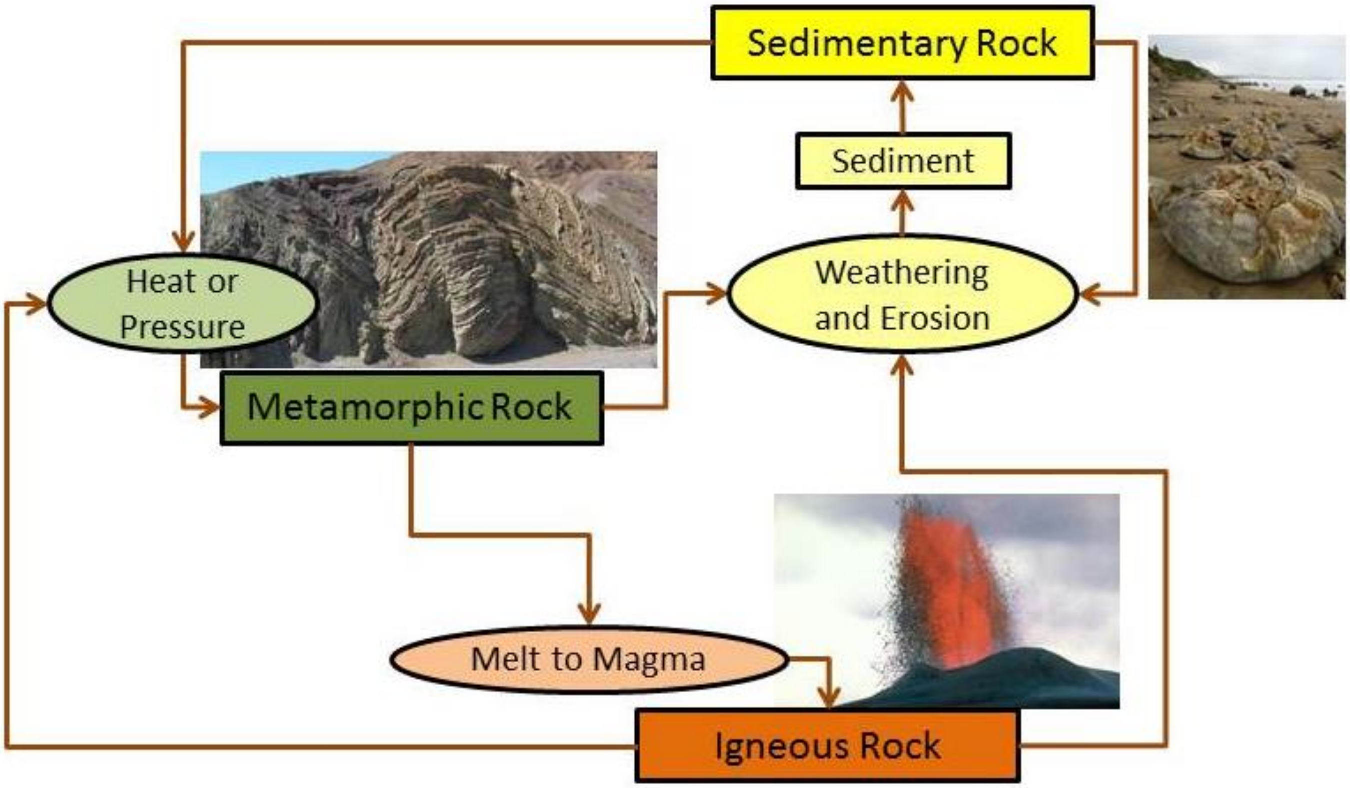


Figure 11. Rock Cycle

Some more useful definitions:

Supernova	The explosion of a high-mass star, which ejects much, if not all of its matter, producing a supernova remnant.
Accretion	The process of growth or increase, typically by the gradual accumulation of additional layers or matter.
Density	density = the quantity of mass per unit volume (see image below); If two objects have equal mass: the one with smaller volume is more dense. If two objects have equal volume: the one with larger mass is more dense.
Convection	A method for transferring heat in a liquid or gas (or plastic solid). The region near the heat source expands as it heats up, making it less dense, so it rises up, displacing the colder material atop it, which sinks and gets heated up, repeating the cycle and transporting heat from bottom to top.
Moho	Short for Mohoroviçic discontinuity - the boundary layer between the earth's crust and mantle whose depth varies from about (3 to 5 kilometers) beneath the ocean floor to about (50 meters) beneath the highest mountains/continent.
Plate Tectonics	Global dynamics having to do with the movement of a small number of semirigid sections of earth's crust, with seismic activity and volcanism occurring primarily at the margins of some of these sections. This movement has resulted in changes in the geographic positions of the continents and the shape and size of the ocean basins.
Divergent Plate Boundary	Boundary between two plates, where the two plates are spreading away from each other. When it happens on land it can break a continent apart (such as the East African Rift Zone) eventually creating an ocean seafloor spreading center.
Transform Plate Boundary	When two plates slide past each other in opposite directions against one another (no subduction occurs).
Convergent Plate Boundary	Boundary between two plates, where the two plates move towards each other. When the crust on the boundary are both continents, a large mountain range forms. When one side of the boundary has ocean crust, and the other continental crust, then ocean crust subducts under the continental crust. When both sides are ocean crust, the oldest densest side subducts under the other side.
Oceanic lithosphere	Ocean plate. Oceanic plates or lithosphere form at seafloor spreading centers. The age of the lithosphere is the age of the rock that first erupts at the ocean ridge and then is pushed sideways to make room for new seafloor. Over time, sediments will collect on top of that rock, and thus sediment age will decrease from the age of the lavas it covered to today, when the most recent grain of sediment settled. The age of the lithosphere is still the age of the rock that underlays the sediment. That's when this new crust formed and when the mantle underneath attached to it and together they became new ocean plate (lithosphere). So... if I look at lithosphere that is 100 Ma -- that means 100 million years ago, its crust (minus the sediment) formed at a seafloor spreading center. Since then, sediment has settled on top and mantle has attached to the bottom -- with the whole plate getting thicker and denser over the past 100 Ma. The sediment that covers the 100 Ma basalt goes from 100 Ma sediment immediately atop the basalt surface to 0 Ma at the top of the sediment layers.
Igneous rocks	Rocks formed through the cooling and solidification of magma.
Sedimentary rocks	Rocks formed through the cementation or compaction of debris (rock and mineral and organic debris) that has collected on Earth’s surface; also rock that is formed through minerals precipitated from waters found at Earth’s surface, usually through evaporation. (NOT hot fluids).
Metamorphic rocks	Rocks formed through the application of intense heat and/or pressure, accompanied by physical and chemical changes that transform the rock into a new one stable at the new temperature and pressure.

Introduction to Planet Earth and Plate Tectonics Chapter Worksheet

1. The term used to describe the formation of the Universe from a single point is:
2. Age of Universe?
3. How do we know the age of the Universe?
4. Earth's formation: CIRCLE ALL THAT APPLY:
   Processes/Characteristics: Accretion | Collisions | Gravity pulled | Hot
   Materials: Gas | Comets | Asteroids
5. Age of Earth?
6. How do we know when Earth formed?
7. Define **density**. Explain how objects of different density behave with each other when free to move in a liquid or gas.
8. What behavior do all liquid or plastic solids near a heat source exhibit?
9. What drives the behavior?
10. What major process formed Earth's layers? (Describe) When?
11. Which ONE layer **within** the Earth is **liquid**?
12. What results?
13. Which ONE layer **within** the Earth is **plastic**?
14. What results?

Review Table 2: Earth's interior compositional and physical layers. While you do not need to memorize thicknesses or densities, you should memorize composition and state, and be able to draw a picture, to scale, of all of Earth's layers. Be sure you understand how oceanic and continental crust compare.

15. What is Earth's radius? (in kilometers, please!)
16. How far from Earth's center is the outer edge of the outer core? (in kilometers, please, or a percentage!)
17. The Moho is the boundary between which two layers?
18. How does the MOHO relate to the asthenosphere, lithosphere?

19. CIRCLE ALL THAT APPLY: Which of natural processes cause the lithosphere to **rise** isostatically? *Basalt lava flows | Thinning/stretching of the crust | Thickening/compression of the crust* *Deposition of sediment | Erosion of rock and sediment* *Glacial advance (more glaciers) | Glacial retreat*	20. CIRCLE ALL THAT APPLY: Which of natural processes cause the lithosphere to **sink** isostatically? *Basalt lava flows | Thinning/stretching of the crust | Thickening/compression of the crust* *Deposition of sediment | Erosion of rock and sediment* *Glacial advance (more glaciers) | Glacial retreat*
21. In what parts of the planet is the moho deepest (closest to the center of the Earth)? CIRCLE: *Mountains | Middle of Ocean | Coastal Plains*	*22.* In what parts of the planet is the moho shallowest (furthest from the center of the Earth)? CIRCLE: *Mountains | Middle of Ocean | Coastal Plains*

23. Sources of water to the early atmosphere of Earth:
CIRCLE ALL THAT APPLY: original nebula | comets | asteroids | volcanoes)

24. When did these sources of water and other gases start collecting in the atmosphere (first atmosphere)?	25. When did first oceans form? (time when planet cooled enough and water in atmosphere finally **precipitated**):

26. What's a simple but complete definition of an **<u>igneous</u>** **<u>rock</u>** (in your own words)?

27. What's a simple but complete definition of a **<u>sedimentary rock</u>** (in your own words)?

28. What's a simple but complete definition of a **<u>metamorphic rock</u>** (in your own words)?

29. How does a **<u>Sedimentary or Metamorphic Rock turn into an Igneous Rock</u>**?

30. How does **<u>an Igneous or Sedimentary Rock turn into a Metamorphic Rock</u>**?

31. How does a **Metamorphic or Igneous Rock turn into a Sedimentary Rock**?

32. List at least 4 lines of evidence that Wegener and others used to prove continental drift. *(Be specific and detailed with at least 4 different lines of evidence.)*

33. What was the name of the most recent supercontinent?
When did it form?

34. **OCEAN CRUST** CIRCLE most appropriate terms:	35. **CONTINENTAL CRUST** CIRCLE appropriate terms:
NEW ROCKS FORMING | OLDEST ROCKS ON PLANET	NEW ROCKS FORMING | OLDEST ROCKS ON PLANET
NEVER OLDER THAN 200 Ma	NEVER OLDER THAN 200 Ma
BASALT | GRANITE	BASALT | GRANITE
THICKNESS: 3-10 km | THICKNESS: 30-50 km	THICKNESS: 3-10 km | THICKNESS: 30-50 km
DENSEST | LEAST DENSE | SUBDUCTS	DENSEST | LEAST DENSE | SUBDUCTS

36. Draw arrows in map-view boxes below to indicate directions of plate motion at these **plate boundaries**: (| is boundary)

Divergent	**Transform**	**Convergent (ocean-ocean)**	**Convergent (ocean-cont)**	**Convergent (cont-cont)**
|	|	|	|	|

Scale Activity

1 kilometer = 1000 meters 1 meter = 100 centimeters

1.	5000 meters = how many kilometers?	
2.	11 kilometers = how many meters?	
3.	5000 meters = how many centimeters?	
4.	What, on your body, is 1 cm wide? (Pick something you can regularly reference.)	
5.	What, on your body, is 10 cm wide or long or tall? (Pick something you can regularly reference.)	
6.	What, on your body, is 100 cm or 1 m wide or tall or long? (Pick something you can regularly reference.)	
7.	If you travelled 1000 meters or 1 km west from the CCSF Science Building, where would you be? ***(Use* Google Maps *and note the scale bar in the lower right corner. Click on it to change it to kilometers) https://www.google.com/maps***	
8.	What is the length/distance in kilometers of some key landmarks in the surroundings? *(Use Google Maps)*	
9.	How **tall is the CCSF Science Building**? *Try to reason this out for yourself. Think about how many floors it has (5) and how tall one floor is. See online tips for more suggestions.*	
10.	What is the **radius** of planet Earth (in km)?	
11.	What is the **circumference** of planet Earth (in km)?	
12.	What is the **deepest hole** ever drilled (in km)? *Follow online links for this answer.*	
13.	What is the **average thickness of continental crust** (in km)?	
14.	What is the **average thickness of oceanic crust** (in km)?	
15.	What is the depth of the ocean's **deepest trench** (in km)?	
16.	What is the elevation of the continents' **tallest mountain** (in km)?	
17.	What is the **average depth of the oceans** (in km)?	
18.	The lowest sea level would drop during an ice age is about 120 m, which exposes the currently flooded edges of the continents, known as the c**ontinental shelves**. 120m is what percent of the average depth of the oceans?	
19.	What is the **average elevation of the land** (in km)?	

Continue on to next page…

20. Draw **Earth's layers** to scale (include asthenosphere, crust, core (inner + outer), lithosphere, mantle, and moho).

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Describe how **Earth formed** and evaluate the evidence that supports it.	A | B | C | D | F	
Define and distinguish among the different **rock types**, including how they form and how they change from one type into another.	A | B | C | D | F	
Diagram and distinguish among **Earth's layers**.	A | B | C | D | F	
Compare and contrast **scales for time and distance**.	A | B | C | D | F	
Explain the process of **isostasy** and evaluate how it produces vertical adjustments in the Earth's crust and lithosphere.	A | B | C | D | F	
Evaluate the **evidence for plate tectonics**.	A | B | C | D | F	
Compare and contrast **plate boundaries and the landforms** and **processes** found associated with them.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

PLATE TECTONICS &
ORIGIN OF OCEANS & CONTINENTS

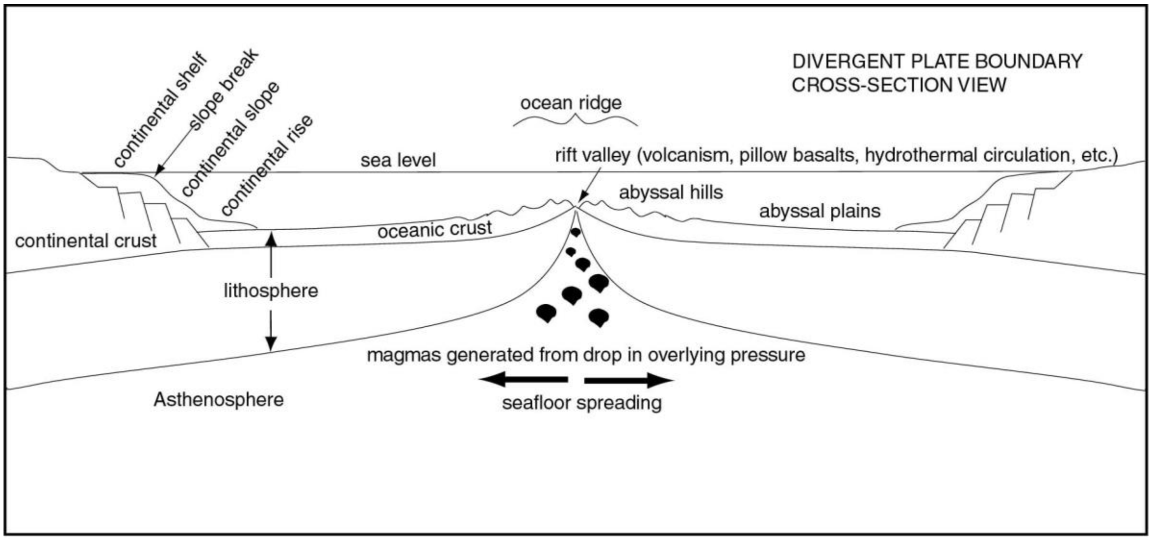


Figure 1.
DIVERGENT MOTION: *Apart*
FEATURES: *Oceanic ridges. Seafloor spreading. Melted mantle rock due to reduced overlying pressure. Rift valleys with volcanism, pillow basalts, hydrothermal vents, and hydrothermal circulation. Serpentinites form at depth in mantle rocks that are undergoing hydrothermal alteration. Transform faults (associated with transform plate boundaries) break up divergent boundaries into small sections offset from one another.*
WORLD EXAMPLES: Mid-Atlantic Ridge, Iceland.

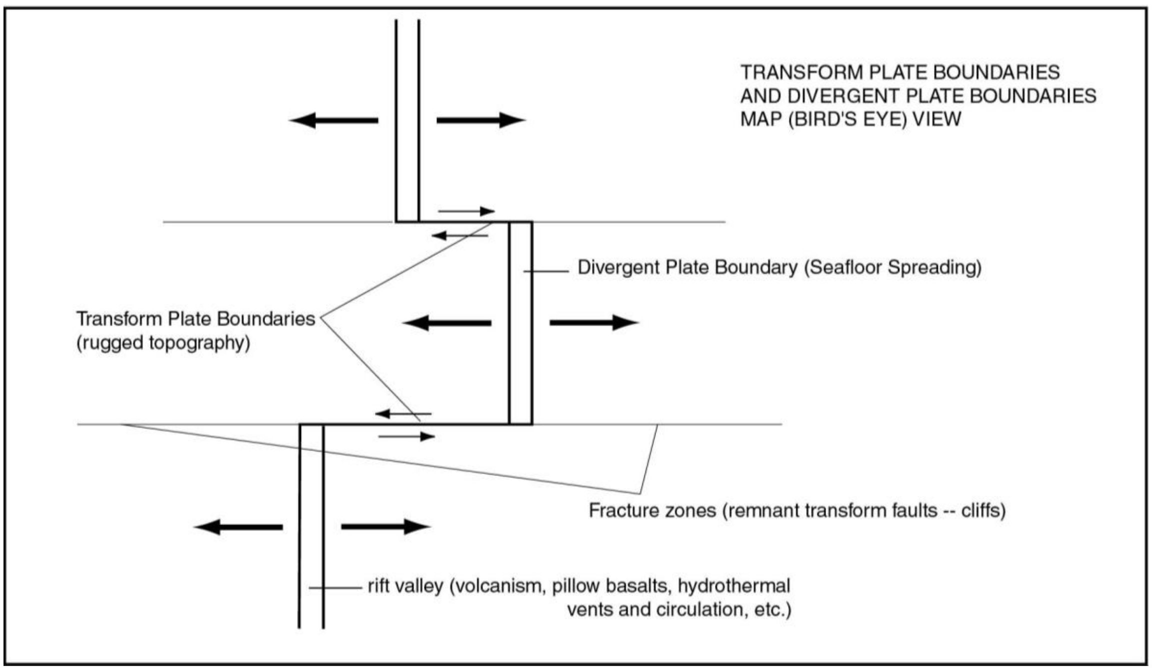


Figure 2.
TRANSFORM MOTION: *side by side*
FEATURES: *Fracture zones (old transform faults, no longer active, because lithosphere on both sides are part of the same plate). Rough topography (cliffs where ridges offset. Oceanic ridges and spreading centers on both sides.*
WORLD EXAMPLES: California, Iceland

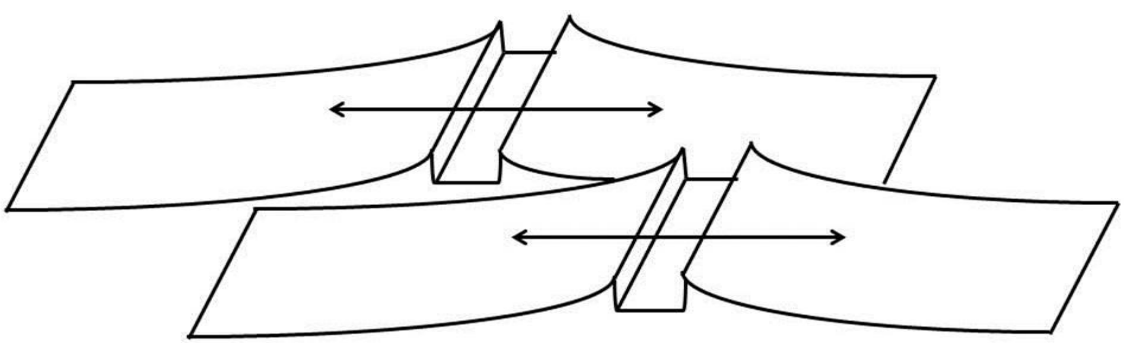


Figure 3. Oblique view of seafloor spreading centers and transform boundaries.

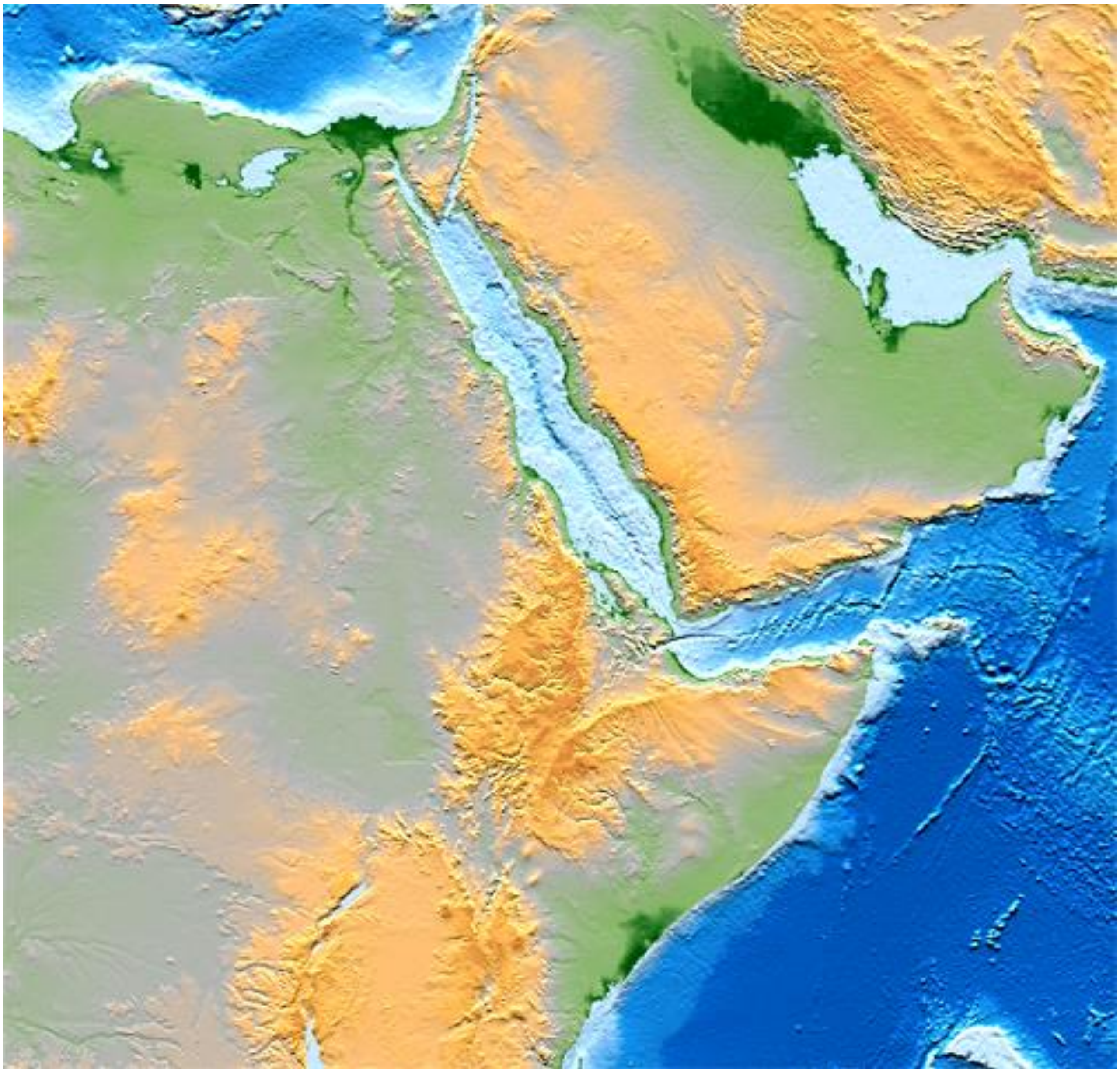


Figure 4. Red Sea, East African Rift Zone, NW Indian Ocean, Arabian Peninsula—triple junction of divergent plate boundaries.

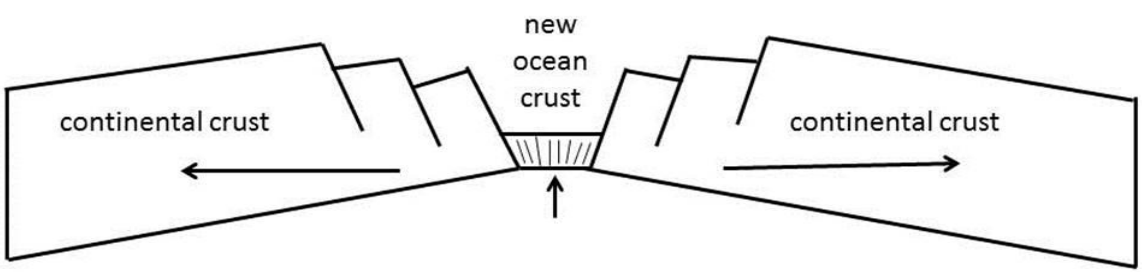


Figure 5. Rift valley in the center of a divergent plate boundary where the continental crust is ripping apart.

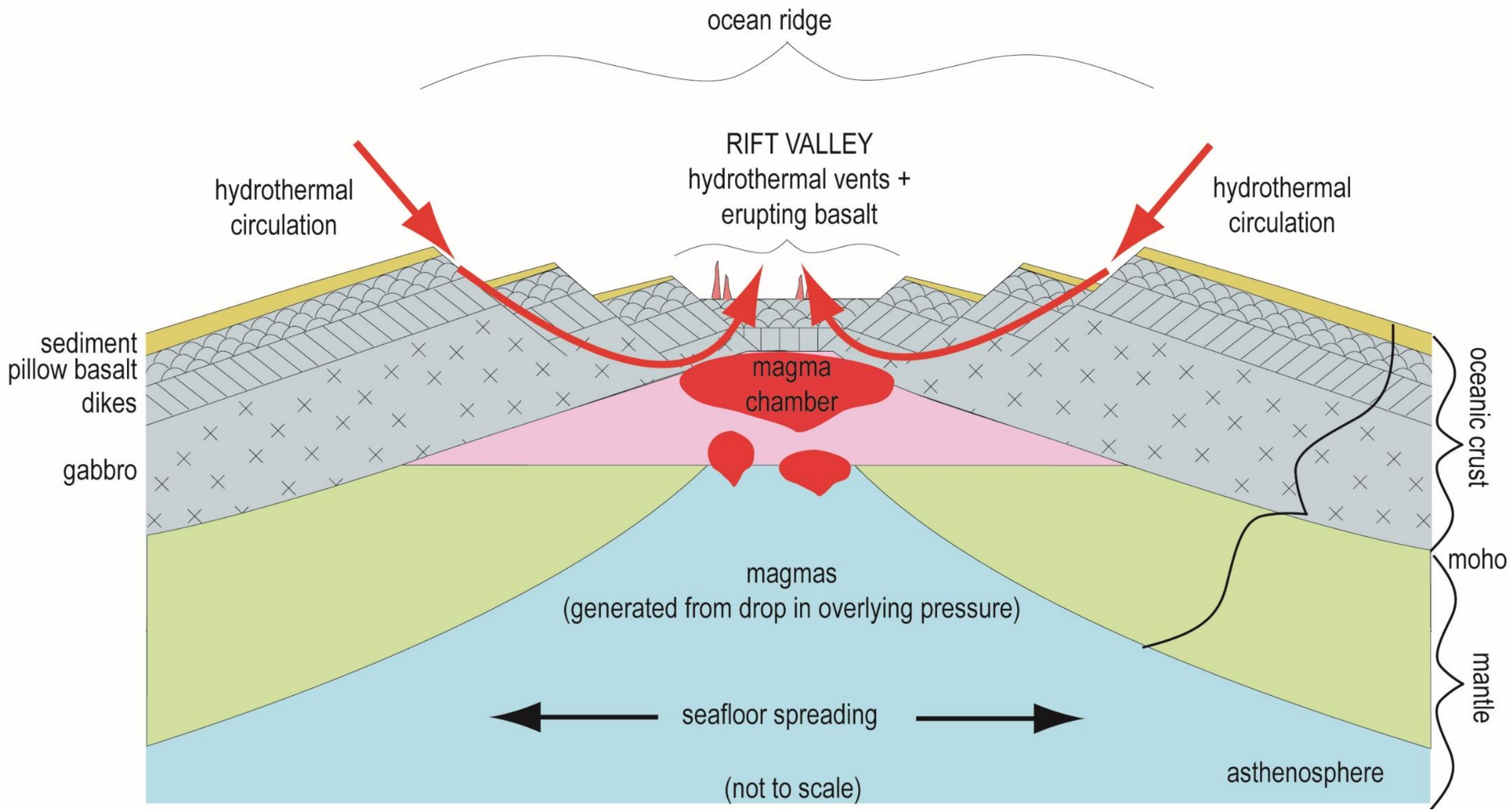
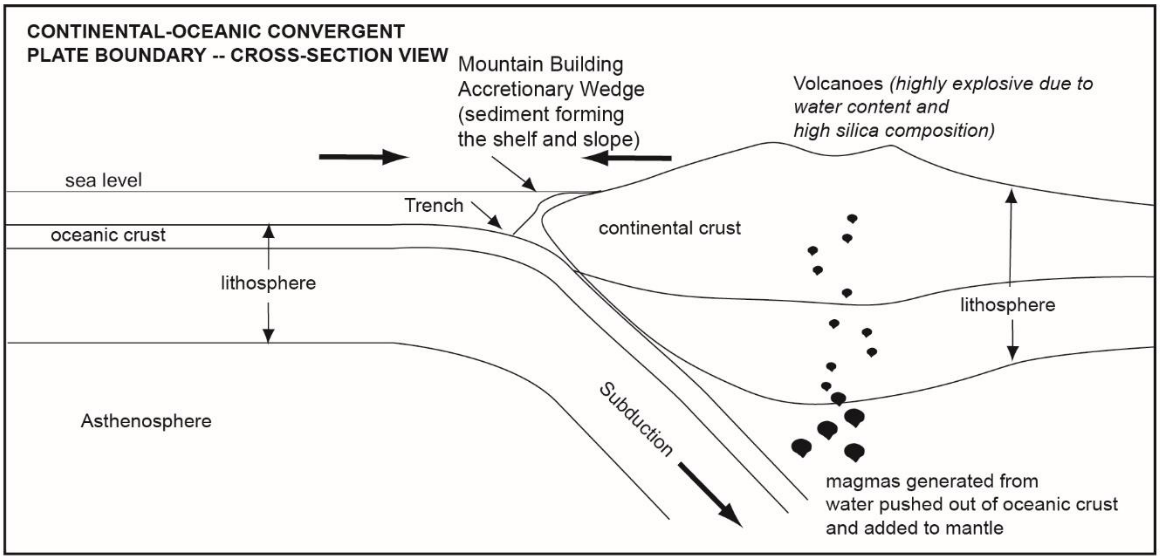
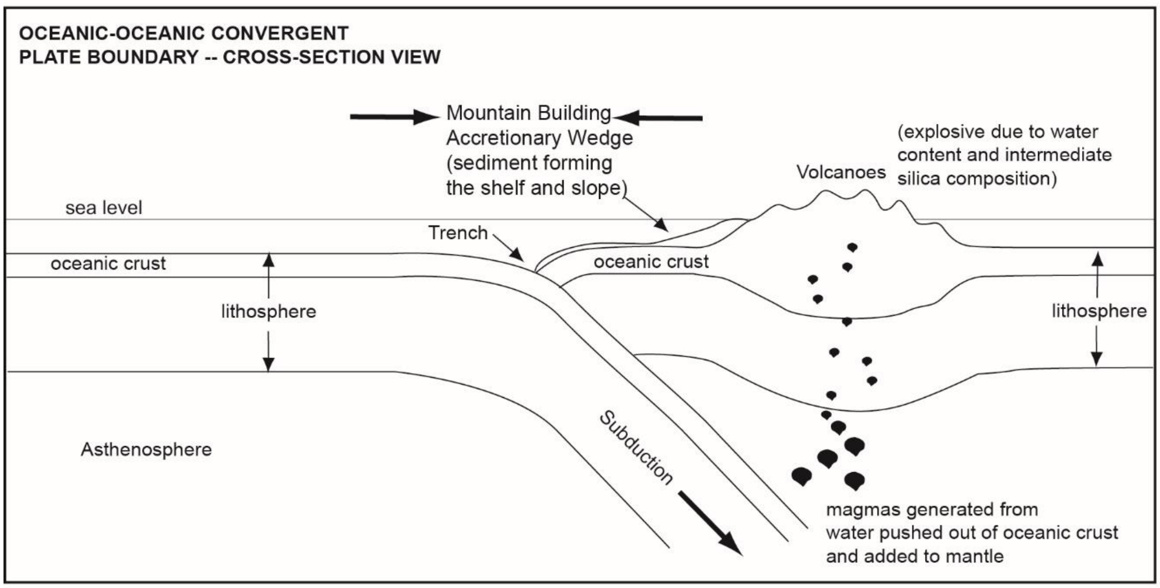
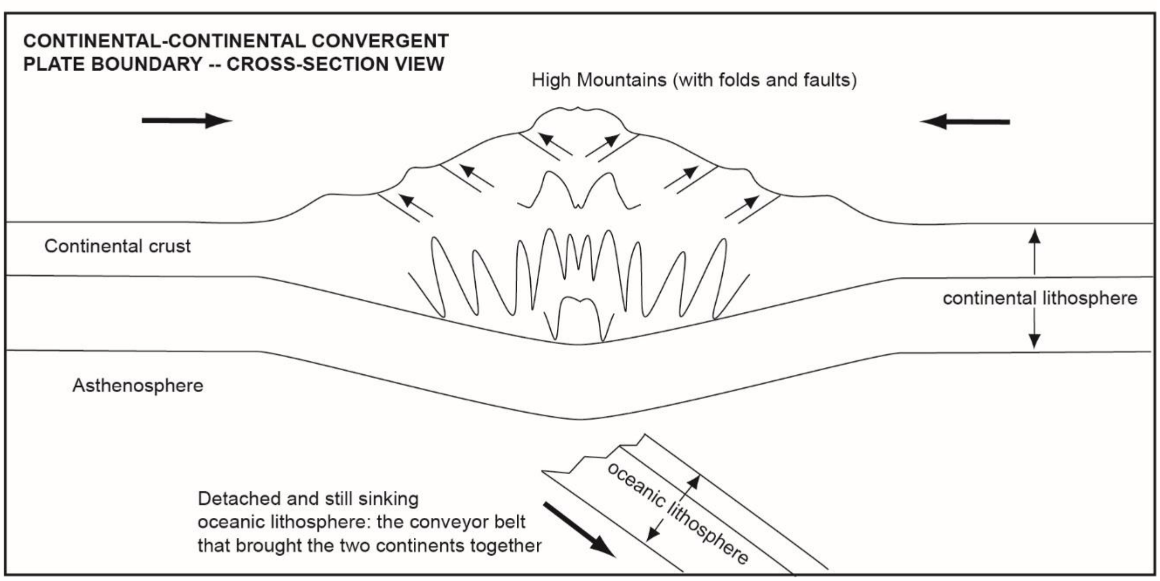


Figure 6. At seafloor spreading centers, magmas form as mantle melts under the thinned crust (a drop in pressure causes melting). Magmas rise to the surface and erupt under water as pillow basalts. The vertical cracks that formed between the top of the magma chamber and the bottom of the seafloor to allow the basalt through will then solidify under the pillows and form basalt dikes. Both of these are spread aside to make room for the next series of pillow basalts and dikes, and as they spread away from the rift valley, they collect sediment on their top and beneath, the edges of the magma chambers cool slowly underground to form gabbro. Seawater will descend through the cracks formed from spreading, leach elements from the ocean crust, get heated by the magma chamber and rise back up in the center of the rift valleys producing hydrothermal vents made of chimneys of metal sulfides precipitated from the hot fluids as they exit the ground and enter the cold ocean (much like mineral deposits that form on the inside of plumbing pipes).







CONVERGENT MOTION:
Towards each other
FEATURES:

Figure 7. Continent-Ocean
Subduction zones (ocean crust sinks back into mantle). Melted mantle rock due to addition of water, which drops the melting point of the underlying mantle. Volcanoes above subduction zone where magmas move upward. Trenches on ocean floor where ocean crust begins subducting. Volcanism is granitic mostly, because it moves through thicker continental crust.
WORLD EXAMPLES:
W. coast S. America
Pacific Northwest

Figure 8. Ocean-Ocean
Subduction zones (ocean crust sinks back into mantle). Melted mantle rock due to addition of water, which drops the melting point of the underlying mantle. Volcanoes above subduction zone where magmas move upward. Trenches on ocean floor where ocean crust begins subducting. Volcanism is basaltic mostly, because it moves through thinner oceanic crust.
WORLD EXAMPLES:
Japan, Philippines, Aleutian Islands

Figure 9. Continent-Continent
Fold and thrust mountains, thickened lithosphere.
WORLD EXAMPLES:
Himalayas (India)
Alps (Europe)

Figure 10. Satellite image showing relief of India and surroundings. NOAA

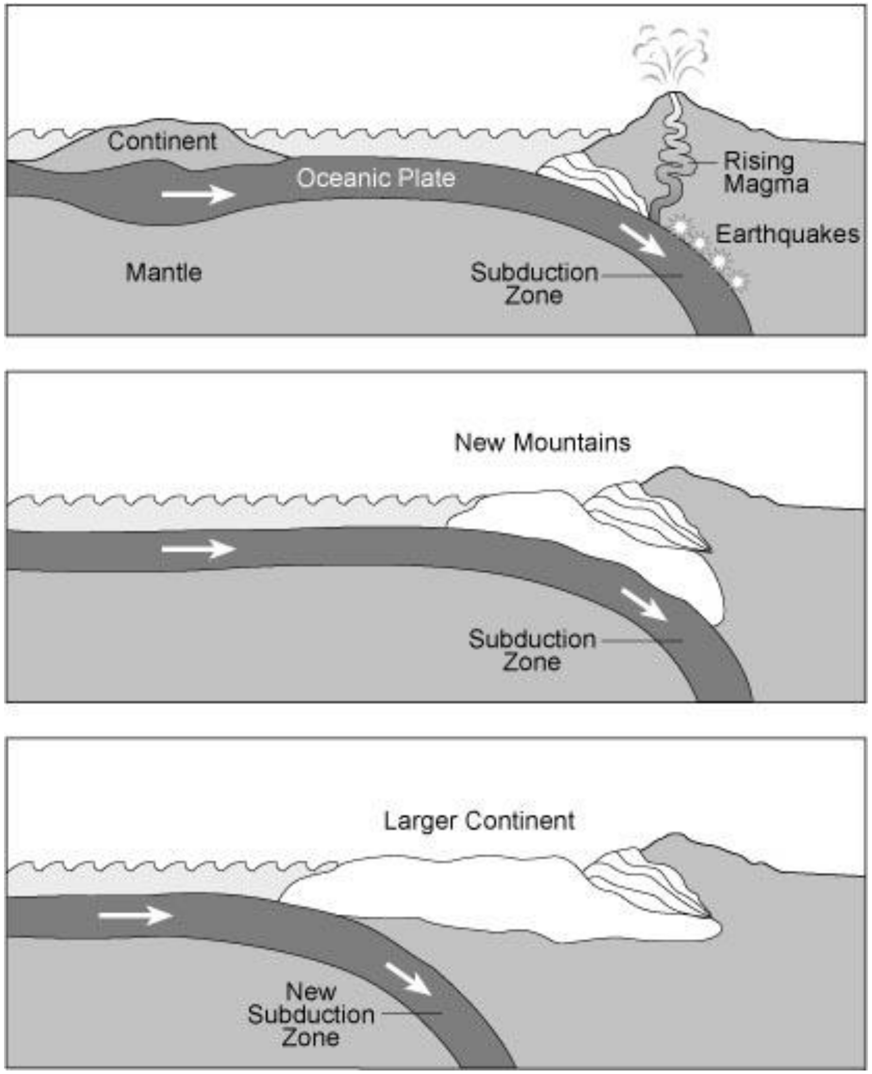


Figure 11. Terrane accretion. Image from Kenneth R. Lang's book The Cambridge Guide to the Solar System, Second Edition 2011.

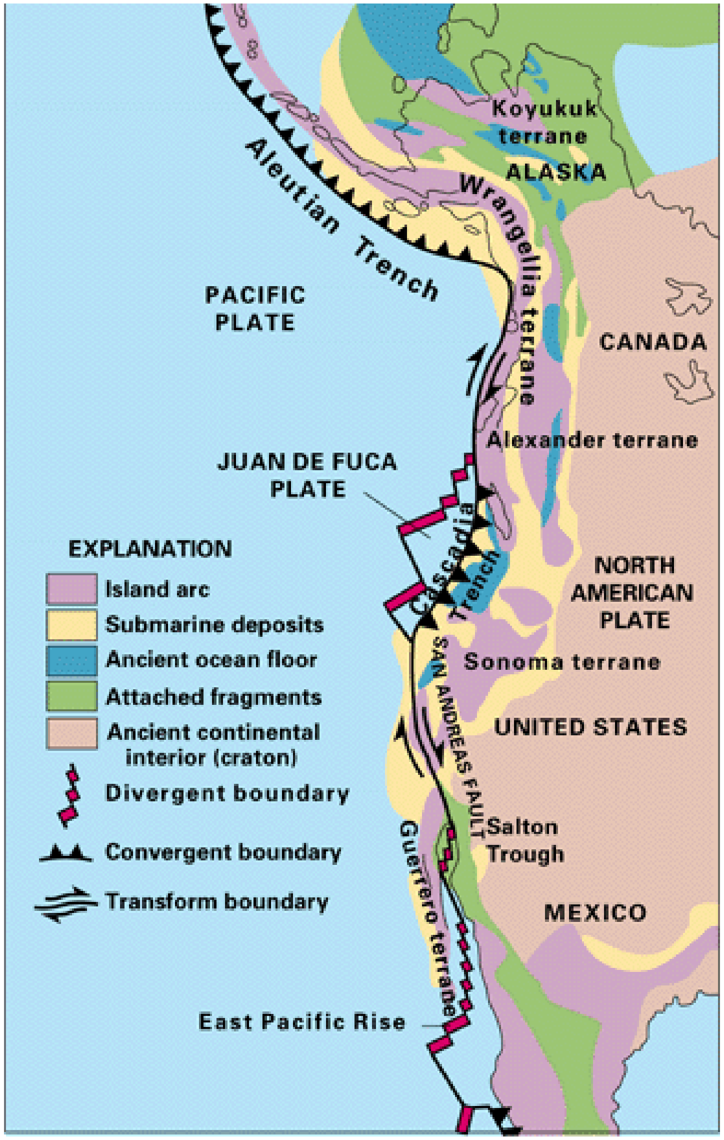


Figure 12. Terrane accretion along the western margin of North America. USGS.

An **accretionary wedge** is a mass of sediment that derives from two sources: 1) sediment that is scraped off a subducting oceanic plate (might include pieces of ocean lithosphere as well), and 2) sediment that erodes off the volcanic arc behind the subduction zone (land). This thick sequence of sediment is folded and compressed between the trench and the volcanic arc, often creating compressional mountain ranges. A **terrane** is anything that has been accreted to the continent and is now a hardened attachment. Terranes include ophiolites (sections of complete ocean lithosphere), accretionary wedges, continental fragments.

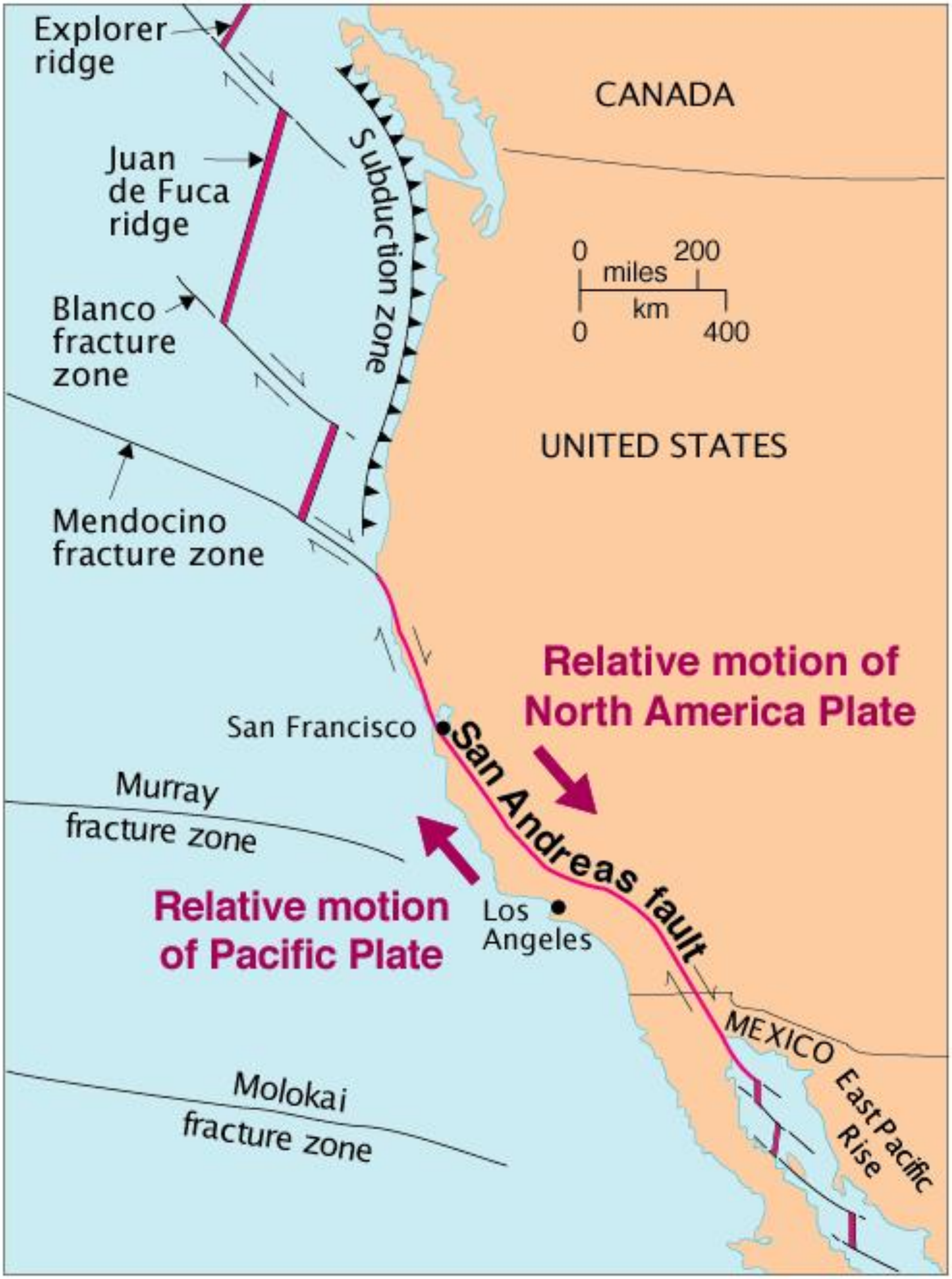
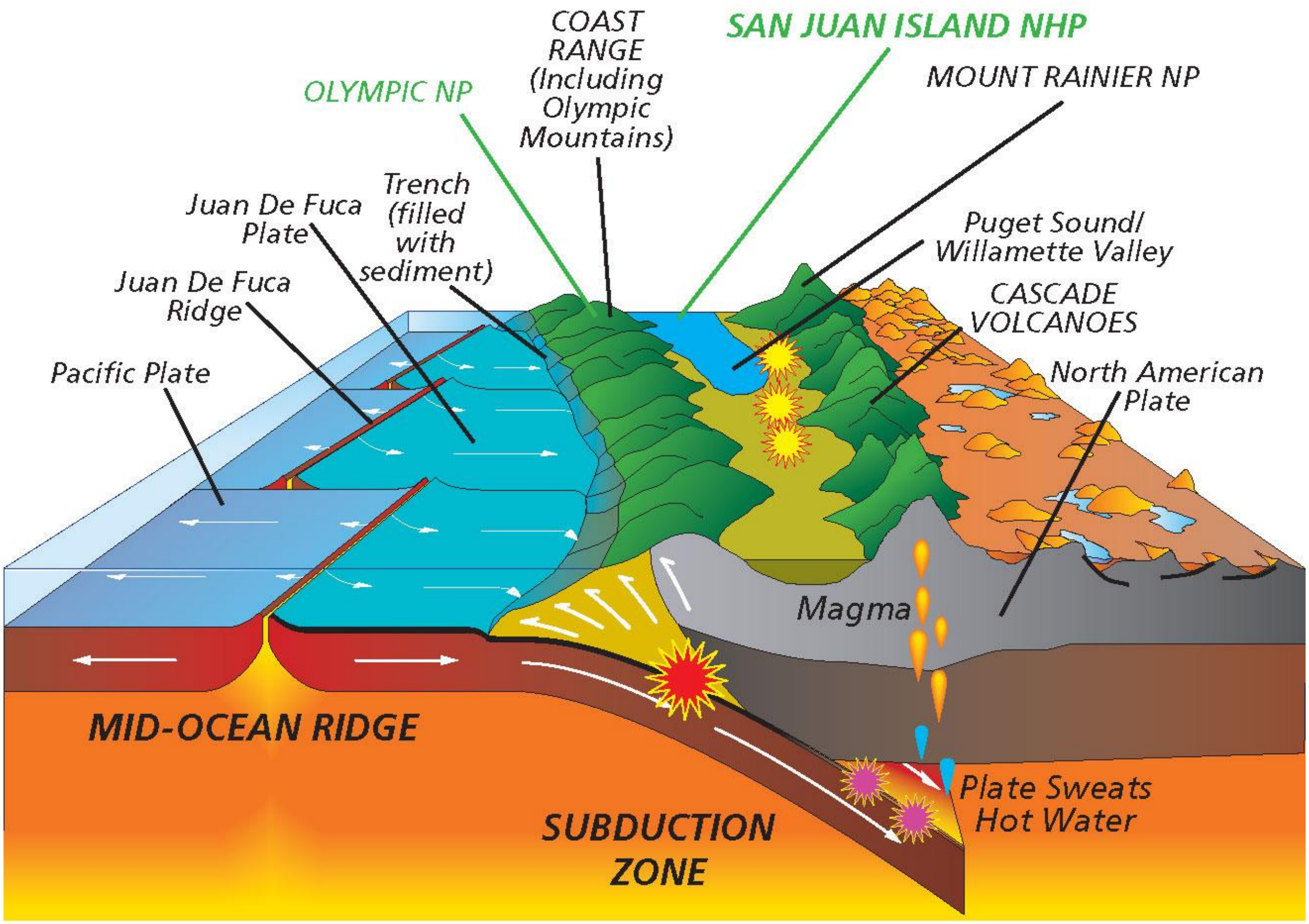


Figure 13. Map view showing plate boundaries along the western margin of North America, with subduction in northern california, oregon, and washington; seafloor spreading off the coast of this same area and in the sea of cortez; transform motion between northern California and Los Angeles. Image from USGS modified from This Dynamic Earth by Stoffer, 2006.



Cascadia earthquake sources

Source	Affected area	Max. size	Recurrence
Subduction Zone	West. WA, OR, CA	M 9	500-600 years (1700)
Deep Juan De Fuca Plate	West. WA, OR	M 7+	30-50 years (1949, 1965, 2001)
Crustal faults	WA, OR, CA	M 7+	hundreds of years? (CE 900, 1872)

Figure 14. Cross-section through the western margin of North America in the region of the Pacific Northwest – Washington, Oregon, and Northern California. Image from National Park Service

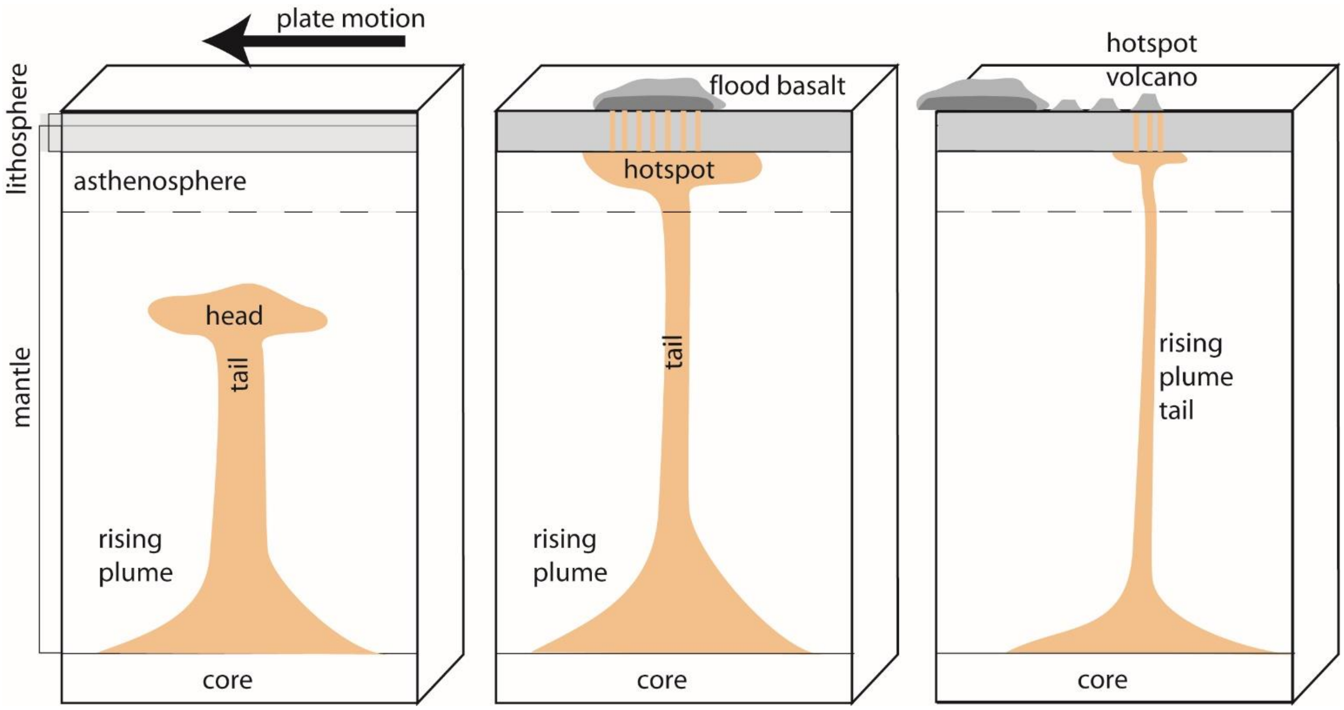


Figure 15. Depiction of the formation of a particular type of deeply formed hotspot, from when it first rises from the base of the mantle, to when it breaks through the lithosphere with a massive eruption of flood basalts, to its continued eruption over time as plate tectonics moves the older volcanic structures away and new volcanoes form .

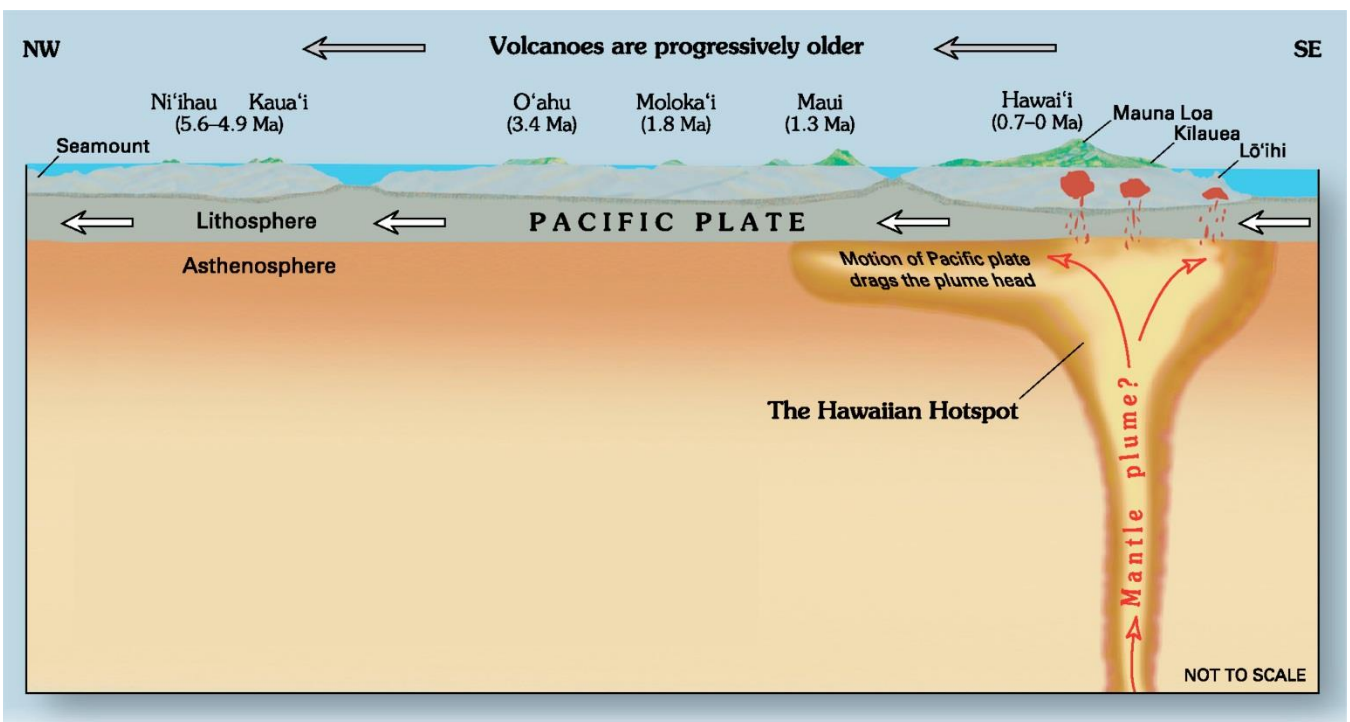


Figure 16. Cross-section through Hawaiian Hotspot – USGS.

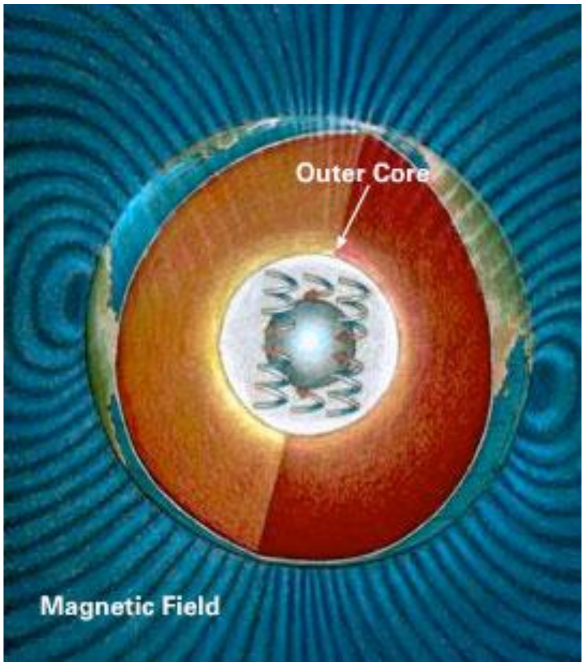


Figure 17. Earth's magnetic field and the proposed source: a magnetic dynamo created by convection of liquid iron in the outer core. This convecting iron acts like a current moving in a loop and creates a magnet. Image from Smithsonian National Museum of Natural History

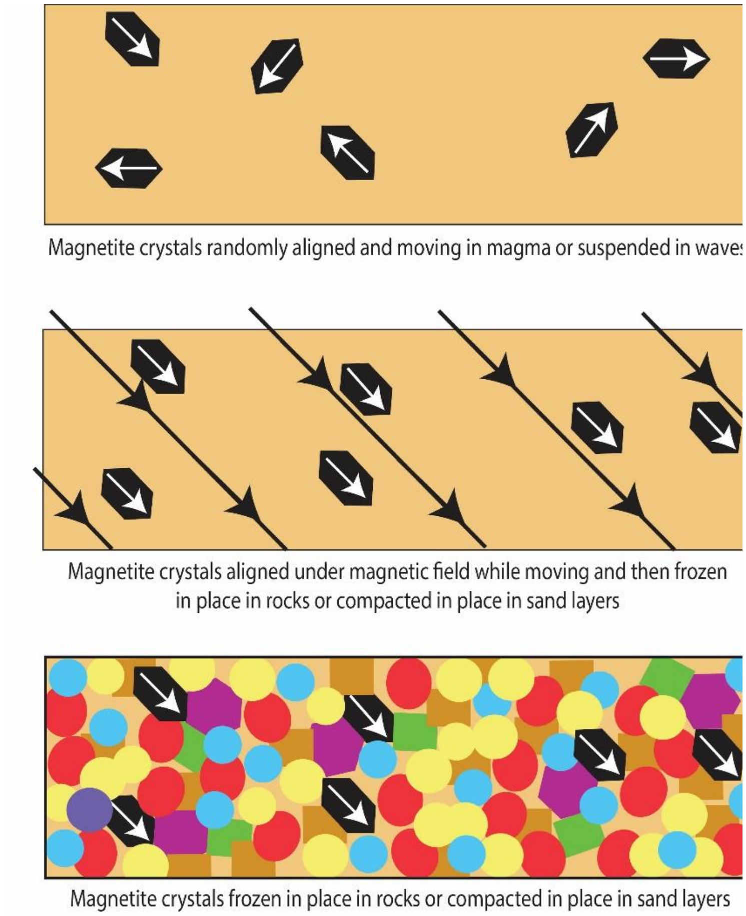


Figure 18. Magnetite crystals aligning with earth's magnetic field while a pile of sand packs together or igneous rock crystallizes.

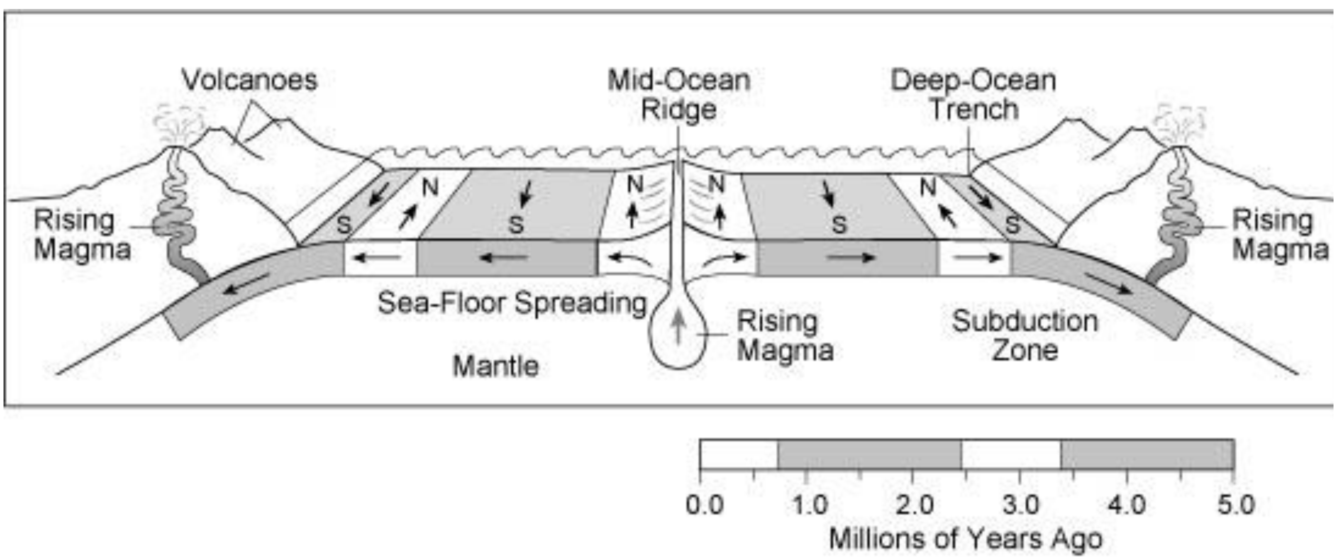


Figure 19. Magnetic anomalies forming on the seafloor during seafloor spreading. Kenneth R. Lang's book The Cambridge Guide to the Solar System, Second Edition 2011.

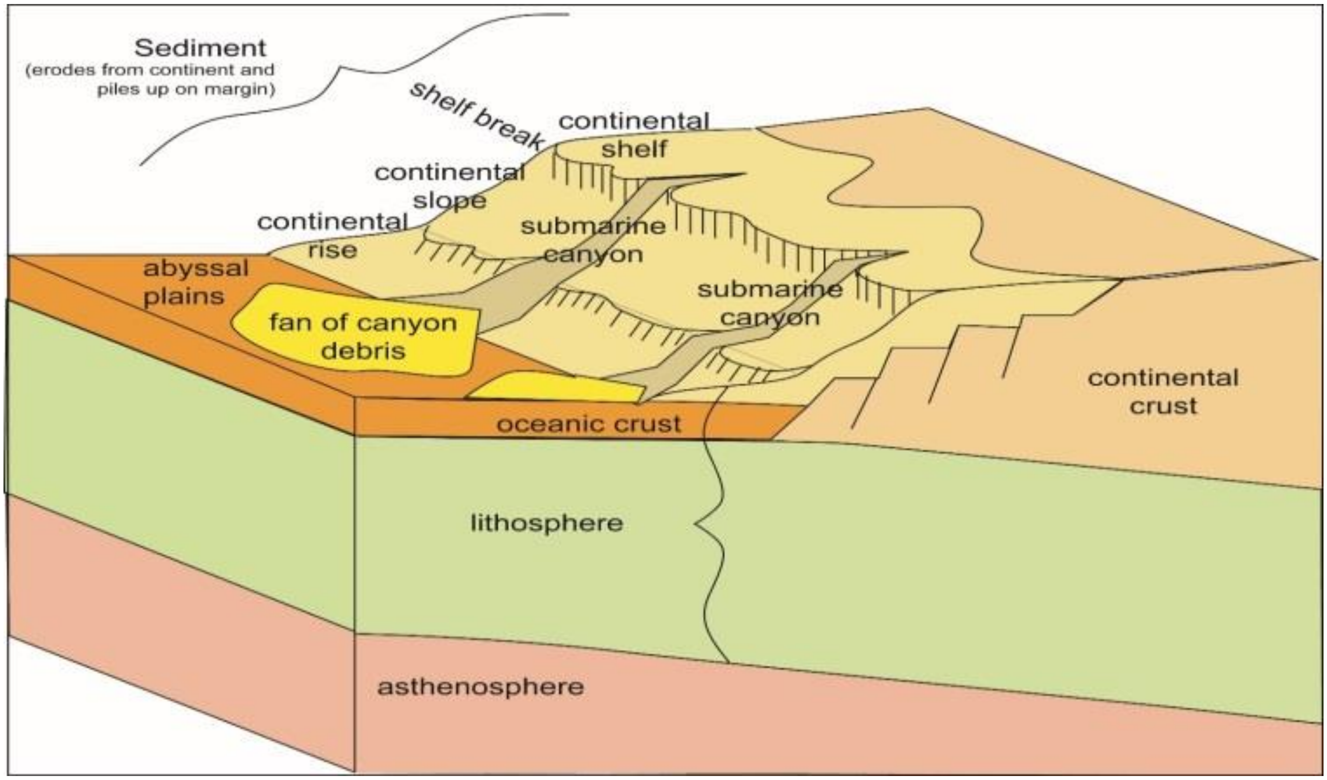


Figure 20. Continental Shelf – not to scale. Submarine canyons carved out of shelf by turbidity currents (avalanches of sediment). {Continental Shelf Break: ~120 m below sea level; Abyssal Plain depth at base of Cont. Rise: ~6,000m}

Table 1. Seafloor depressions

Feature	Depth	Shape	Location & Cause
Rift Valley	1-2 km	Linear valley. Square cross section	At the center of divergent plate boundaries (usually atop ocean ridges, unless in center of continent), caused by divergence.
Submarine Canyon	20 m to 2 km	V-shaped cross-section. Sinuous canyon, like river canyons in the mountains.	Carved out of continental shelves by **turbidity currents** – extend out perpendicular to the shoreline.
Deep-sea trench	> 2 km (6-11 km)	Arc-shaped from above. Deep, wide depression, with steep sides and a flat floor (covered with sediment).	Above subduction zones, caused by subducting oceanic lithosphere.

Some more useful definitions:

Terrane Accretion	When island, continental fragments, ocean crust and sediments scrape off and accumulate on to continents during subduction.
Magnetite	A type of rock component (a mineral) which is found in almost all other rocks, as a crystal that freezes, being aligned based on the magnetism of the Earth's poles. Because of this, magnetometers and other tools have been able to discover much about the seafloor's age pattern, as well as other features' ages and the polarity of Earth, which reverses at times throughout all of Earth's existence.
Isochron	"Iso" = same "Chron" = age "Isochrons" are lines that connect rocks of the same age.
Trench	Deep, arc-shaped depression on the bottom of the seafloor caused when an ocean plate subducts.
Hotspots	Deep plumes of mantle heat that extend, often, from as deep as the core-mantle boundary and that are visible at the surface as high-volume erupting volcanoes. These plumes stay fixed in location while plates move across them. (Only one spot at any time has active volcanism.)
Active Margin	Edge of the continent where ocean and continental crust meet, but they are in separate plates, with ocean plate subducting under the continent plate.
Passive Margin	Oceanic and continental crust are fused together without subduction. The full name is "passive continental margin" -- so we're talking about continental margins -- where ocean crust and continental crust meet. Subduction zone at continental margin = active ; all other continental margins are passive and share similar traits (ocean and continental crust are part of one plate moving together and allowing for large shelf build up).
Volcanic Arc	The chain of active volcanoes that sit above a subduction zone. They can be on land if ocean subducts under continent, or a chain of ocean islands if ocean is subducting under ocean. Because they are caused by subduction, the entire chain is active (as opposed to hostpot chains where only the volcanoes over the hotspot are active). Because of Earth's spherical shape, subduction zones tend to have arc shapes (like crescent moons), and thus these volcanic chains are often also in the shape of a curved arc, hence VOLCANIC ARC.
Abyssal plain	Flattest parts of the ocean created through sediment covering the rough topography of the seafloor.
Continental Shelf	Flat extension of the continent under current sea level. The edges of the shelves (shelf break) represent the true edges of the continent and sea level during ice ages. These edges are about 120 m deep at most.
Continental Slope	The steep edge of the continent where it connects continental crust to ocean crust.
Continental Rise	The apron of sediment that collects at the base of the continental slope and covers the point where it meets the abyssal plain.
Rift valley	Down-dropped depression on the top of mid-ocean ridges, formed as plates diverge.
Submarine Canyon	Canyon carved underwater by the erosion of turbidity currents: avalanches of sediments that fall down from the shelf to the abyssal plains.
Compressional Mountains	Mountains formed when you have two plate converging -- stress or pressure applied here is called compression.
Landform	Landforms are forms or shapes of the land -- features that display particular shapes and sizes. Examples: trench, rift valley, submarine canyon, volcano, dome, cliff, flat plain, etc.

Plate Tectonics & Origin of the Oceans and Continents – Chapter Worksheet

1.	Which of the following plate boundaries produces **earthquakes**? CIRCLE ALL THAT APPLY: Convergent (Ocean-Ocean) | Convergent (Cont-Ocean) | Convergent (Cont-Cont) | Divergent | Transform
2.	Which of the following plate boundaries produces **volcanism**? CIRCLE ALL THAT APPLY: Convergent (Ocean-Ocean) | Convergent (Cont-Ocean) | Convergent (Cont-Cont) | Divergent | Transform
3.	Which of the following plate boundaries produces a **fracture zones**? Convergent (Ocean-Ocean) | Convergent (Cont-Ocean) | Convergent (Cont-Cont) | Divergent | Transform
4.	Which of the following plate boundaries produces a **mid-ocean ridge**? Convergent (Ocean-Ocean) | Convergent (Cont-Ocean) | Convergent (Cont-Cont) | Divergent | Transform
5.	Which of the following plate boundaries produces a **compressional mountain range** (small or large)? Convergent (Ocean-Ocean) | Convergent (Cont-Ocean) | Convergent (Cont-Cont) | Divergent | Transform
6.	What kinds of seafloor features indicate **divergence** is happening? CIRCLE: volcanic activity | trench | rift valley | ocean ridge or rise | fracture zone | flat plain | earthquakes | linear scar/cliff | compressional mountains | offset mid-ocean ridge/rise | submarine canyons
7.	What kinds of seafloor and land features indicate **subduction** is happening? CIRCLE: volcanic activity | trench | rift valley | ocean ridge or rise | fracture zone | flat plain | earthquakes | linear scar/cliff | compressional mountains | offset mid-ocean ridge/rise | submarine canyons
8.	What kinds of seafloor features indicate **transform** motion is happening? CIRCLE: volcanic activity | trench | rift valley | ocean ridge or rise | fracture zone | flat plain | earthquakes | linear scar/cliff | compressional mountains | offset mid-ocean ridge/rise | submarine canyons
9.	**Abyssal Plains:** CIRCLE ALL THAT APPLY: flattest place on Earth | rough topography | the deepest parts of the ocean (after trenches) | shallowest parts of ocean | most of ocean seafloor
10.	What causes **submarine canyons** and where are they found in general?
11.	Circle the locations below that are **subduction zones**: EAST COAST US | NORTHWEST COAST US | SOUTHWEST COAST US | EAST COAST SOUTH AMERICA | WEST COAST SOUTH AMERICA | EAST COAST AFRICA | WEST COAST OF AFRICA | AUSTRALIA | INDIA | ALEUTIAN ISLANDS | PHILIPPINES | JAPAN | INDONESIA
12.	Where does all new ocean crust form? CIRCLE: trenches | passive continental margins | abyssal plains |mid-ocean ridges | varies (no one place)
13.	What is the age of the oldest ocean crust currently found in the world's oceans? Where in general in the world's oceans are the oldest rocks? CIRCLE: trenches | passive continental margins | abyssal plains |mid-ocean ridges | varies (no one place)
14.	What kind of plate boundary do we live on or near in San Francisco?
15.	Which of the following is true of **Earth's Magnetic Field**? CIRCLE ALL THAT APPLY: Poles reverse | Poles wander | Strength changes with time | Has four poles | Attracts magnets | Direction fluctuates based on latitude
16.	If a 10-my-old pillow basalt is 1200 km west of the nearest seafloor spreading center, how fast has its plate been moving since its formation? And what direction has the plate been moving? *(the unit "my" = millions of years. Note: calculate as km/my then convert to cm/yr by dividing by 10.)*
17.	Which of the following is true of **hotspots**? CIRCLE: Can originate from as deep as core-mantle boundary | produce flood basalts and mass extinctions when first break through crust | can last over 200 million years | move with the plate | found in Iceland |found in Yellowstone | found in Hawaii
18.	On the North Pacific bathymetry map that follows this text, locate the HAWAIIAN and YELLOWSTONE hotspot tracks. For each, draw an arrow indicating plate motion (away from active hotspot. **(**REFER TO HOTSPOT VIDEO TUTORIAL **)**

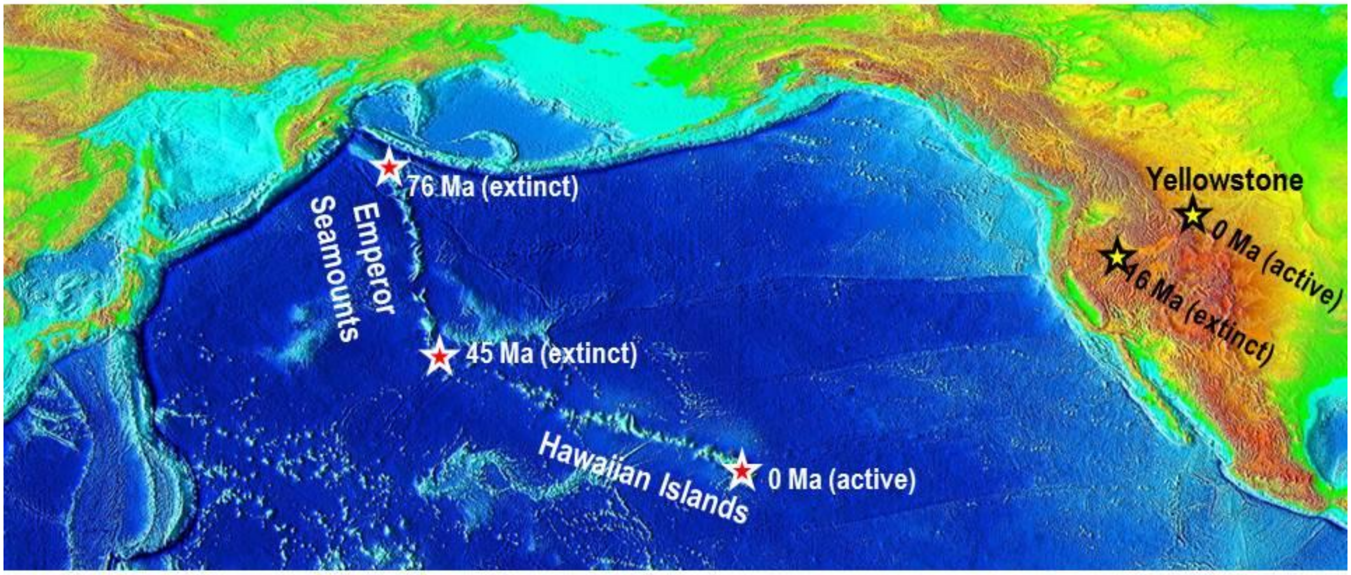


Figure 21. Northern Pacific. Base Map: NOAA.

19.	If a 5-my-old island that formed at a hotspot is now 500 km northwest of the hotspot, how fast has the plate been moving since its formation? And what direction has the plate been moving? *(the unit "my" = millions of years. Note: calculate as km/my then convert to cm/yr by dividing by 10.)*
20.	The light blue areas in the image above are **continental shelves**—currently flooded portion of the continents. During Ice Ages, these shelves are exposed and can be used for land bridges. The edge of the shelves (**continental break**), about 120 m below sea level, represent the true edge of the continents, and thus the shapes produced mostly through breakup of Pangaea. With what features, in general, are the narrowest continental shelves associated in this image?
21.	What happens to oceanic lithosphere over time, as it ages? (Be specific and thorough.)
22.	Stack the following layers found in ocean lithosphere vertically as they'd be found in a hole drilled through the ocean crust and describe how each is formed: BASALTIC DIKES | DEPLETED MANTLE | GABBRO | PILLOW BASALT | SEDIMENT
23.	Which types of chemical, physical, and biological processes occur at or under **hydrothermal vents**? CIRCLE: CHEMOSYNTHESIS | PHOTOSYNTHESIS | DISSOLUTION | PRECIPITATION | EXTREMOPHILE ECOSYSTEMS | ALTERED OCEAN CRUST | PILLOW BASALTS | EARTHQUAKES | HOT AND COLD WATERS MIXING | SUBDUCTION | SPREADING | TRANSFORM MOTION
24.	How hot is the water coming out of a hydrothermal vent?
25.	Where do the water and associated dissolved ions in a hydrothermal vent come from?

26. **Serpentinite**, the California state rock, forms when ocean water gets heated by magma chambers under seafloor spreading centers, and metamorphoses mantle rock. Serpentinite is less dense than crustal material and uses cracks in the crust to make its way from the base of the ocean crust to the top of it. Eventually it ends up in California. How?

27. The continents are ~20 times older than the oldest ocean basins. Why?
    Where are the oldest rocks in the continents?
    Through what two methods do continents grow?

28. What is the difference between an **accretionary wedge** and a **terrane**? How do they form?

29. Describe the process of **rifting of a continent**. Where in the world is such activity happening today?

30. Central and Southern California is a **passive margin**. What does that mean and why is it one?

31. Which of the following is TRUE of **paleomagnetism**? CIRCLE: ancient record of magnetic pole locations|
requires magnetic material to align and freeze in place in a rock | can form from magnetite crystals forming from lava |
can form with magnetite grains settling on a beach and being buried | can be used to determine latitude of original rock |
can be used to see the symmetry of seafloor spreading | can be studied only in rocks found on the seafloor |
can be studied only in rocks found on land | can be studied in ALL rocks found anywhere

32. Review the figure that shows the **age of the ocean crust beneath ocean sediments (next page, Figure 22)**: Which of the following was required to create this map? CIRCLE: Magnetic signature of rocks on seafloor |
Timeline of when Earth's magnetic field has switched polarities historically (gathered by land-based volcanic rock layers)|
Sampling of individual rocks collected from the seafloor | Dating seafloor rock samples in a laboratory |
Ships travelling back and forth across the sea surface dragging a magnetometer | Satellites

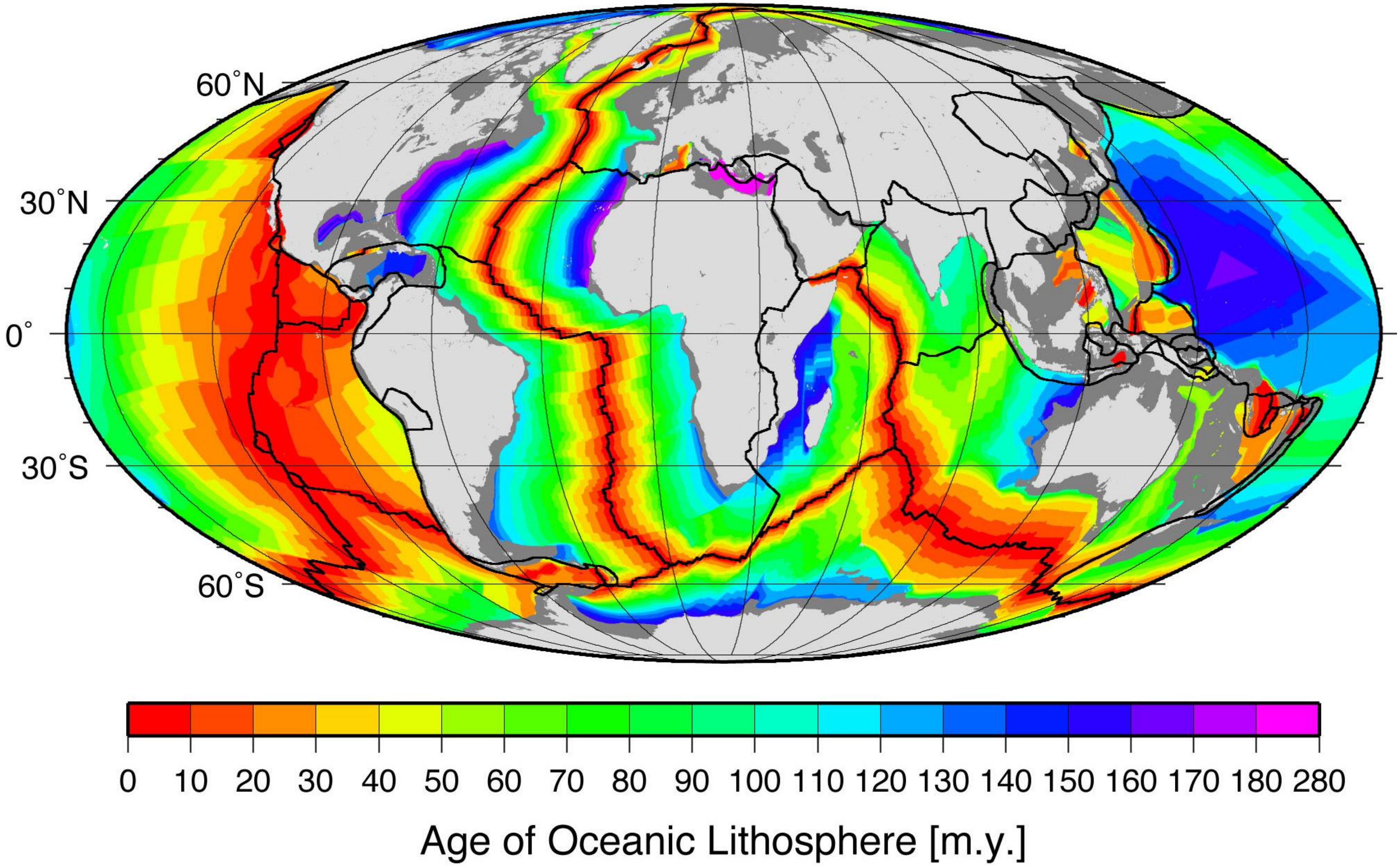


Figure 22. ISOCHRON Map (lines of a particular color represent equal lithosphere age ranges) For example. All areas in yellow are lithosphere from 40 to 50 million years old. NOAA

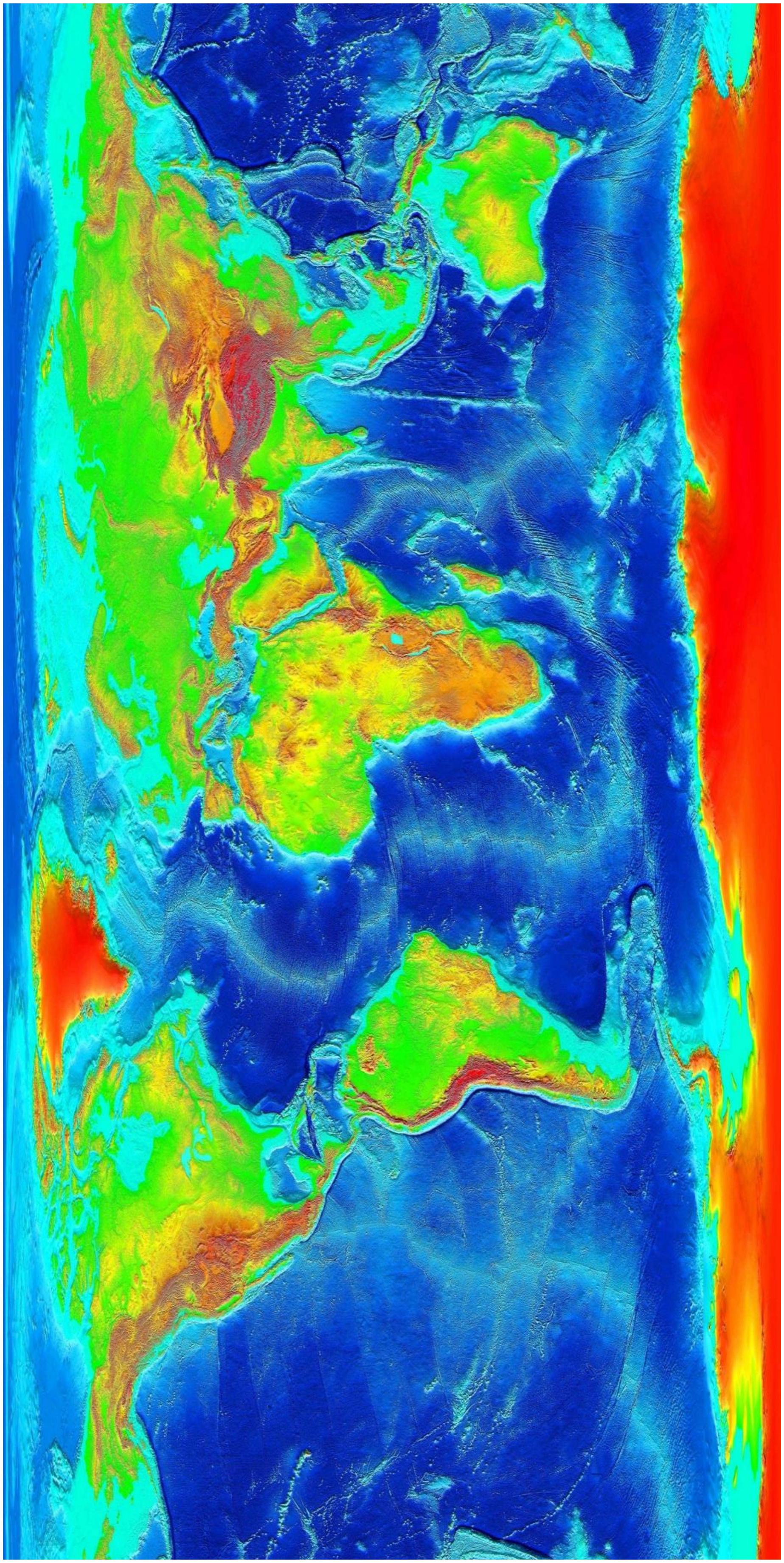


Figure 23. Seafloor Bathymetry and Continental Topography – World Relief Map – NOAA

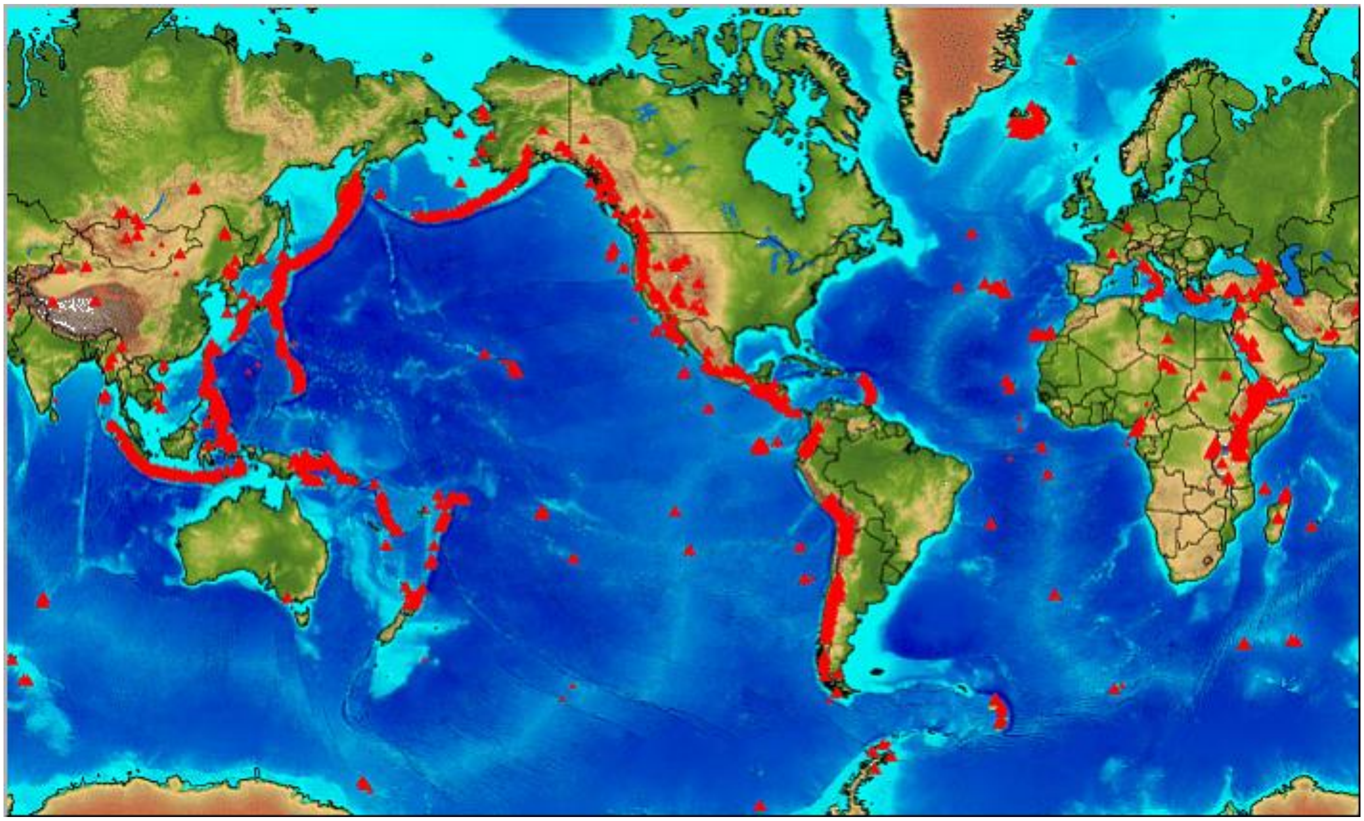


Figure 24. Location of the world's primary active volcanic centers. Image from Smithsonian Institution Global Volcanism Project

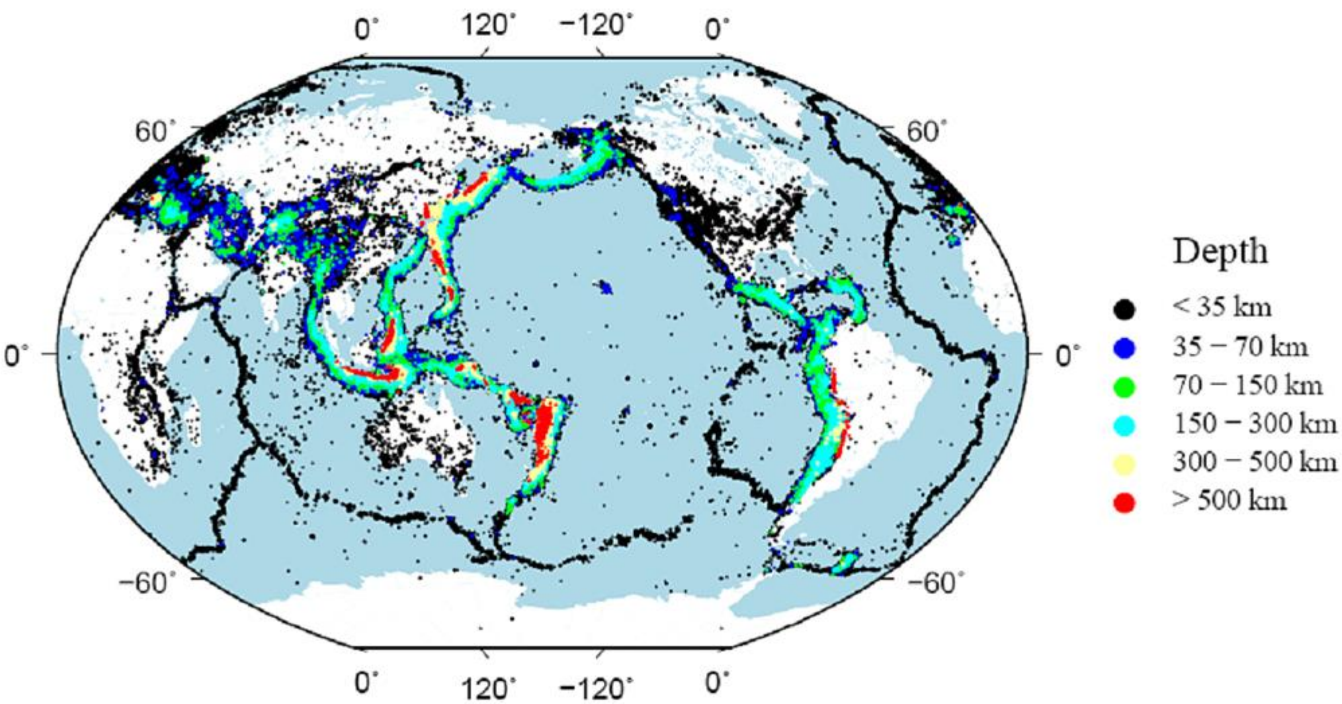


Figure 25. Earthquakes around the world color coded by depth (Image produced by NORSAR using USGS data.

Plate Motions Activity

World Ocean Comparison (Isochron Map)

1.	The fastest spreading center in the world spreads at a rate of 18 cm/yr. How do you recognize it? Where is it located?
2.	The slowest spreading center in the world spreads at a rate of 2 cm/yr. How do you recognize it? Where is it located?
3.	What are some possible reasons for the differences?

Atlantic Ocean (Isochron Map)

4.	What is the age of the youngest rock in the Atlantic Ocean? Where is it?
5.	What is the age of the oldest rock in the Atlantic Ocean? Where is it?
6.	When and where did the Atlantic Ocean first start to open?
7.	Did the entire Atlantic Ocean open at the same time? What's the evidence?

World Ocean (Bathymetry, Volcanoes, and Earthquakes Map)

8. How do the **volcanic landforms** that are produced vary among the three geologic settings for volcanism? (How can you recognize which is which?) Give world examples of each.

	Volcanic Landforms (shapes and behaviors) – CIRCLE	**World Examples**
Hotspots	Curved arc of active large volcanoes Line of active volcanism (eruption sites) but rarely volcanoes Line of inactive volcanoes leading away from active zone	
Subduction Zone Volcanic Arcs	Curved arc of active large volcanoes Line of active volcanism (eruption sites) but rarely volcanoes Line of inactive volcanoes leading away from active zone	
Divergent Plate Boundaries	Curved arc of active large volcanoes Line of active volcanism (eruption sites) but rarely volcanoes Line of inactive volcanoes leading away from active zone	

9. How do you distinguish between **active and passive margins**? For each characteristic below, circle the margin type(s) that are associated with that characteristic.

Characteristics	**CIRCLE**
Edge of the continent (where continental crust meets ocean crust)	Active margin | Passive margin
Subduction	Active margin | Passive margin
Plate boundary	Active margin | Passive margin
Large earthquakes	Active margin | Passive margin
Volcanism	Active margin | Passive margin

10. Look over all the world's oceans and circle below those that are **ACTIVE MARGINS**.

Atlantic Ocean	**Pacific Ocean**	**Indian Ocean**	**Other**
East coast of North America East coast of South America West coast of Europe West coast of Africa Greenland (all coasts)	West coast of South America Most of California (mid and south) Pacific Northwest (northern CA + OR + WA) Aleutian Islands New Zealand Japan Australia	East coast of Africa India coastline Indonesia Australia	Antarctic Peninsula *(near south tip of South America)* Rest of Antarctica

Review locations and types of **plate boundaries (Figure 20 from Earth Formation chapter)**. Based on what you know about where these boundaries appear and the types of features they are associated with, look for patterns that would help you identify them in the preceding figures: Isochron Map (age of seafloor rocks – Figure 22), Global Ocean Bathymetry and Land Topography Map (relief of Earth's surface – Figure 23), Volcanoes Map (Figure 24), and Earthquake Map (Figure 25).

11. Observe the **Isochron Map** (age of seafloor rocks – Figure 22) and describe shapes and patterns of each of the following plate boundaries. **Observations only!**
Divergent plate boundary
Transform plate boundary
Convergent plate boundary (ocean-ocean or ocean-continent with subduction)
Convergent plate boundary (continent-continent: no subduction)
12. Observe the **Global Ocean Bathymetry and Land Topography Map** (relief of Earth's surface – Figure 23) and describe shapes and patterns of each of the following plate boundaries. **Observations only!**
Divergent plate boundary
Transform plate boundary
Convergent plate boundary (ocean-ocean or ocean-continent with subduction)
Convergent plate boundary (continent-continent: no subduction)
13. Observe the **Volcanoes Map** (Figure 24) and describe shapes and patterns of each of the following plate boundaries. **Observations only!**
Divergent plate boundary
Transform plate boundary
Convergent plate boundary (ocean-ocean or ocean-continent with subduction)
Convergent plate boundary (continent-continent: no subduction)
14. Observe the **Earthquakes Map** (Figure 25) and describe shapes and patterns of each of the following plate boundaries. **Observations only!**
Divergent plate boundary
Transform plate boundary
Convergent plate boundary (ocean-ocean or ocean-continent with subduction)
Convergent plate boundary (continent-continent: no subduction)

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	Self-assessment of mastery level	Action plan for improvement
Evaluate the **evidence for plate tectonics**.	A | B | C | D | F	
Compare and contrast **plate boundaries and the landforms** and **processes** found associated with them.	A | B | C | D | F	
Identify global examples of all **plate boundaries and the landforms** and **processes** associated with them.	A | B | C | D | F	
Apply plate tectonics theory to the **origin and evolution of oceanic and continental crust**	A | B | C | D | F	
Describe the causes and behaviors of Earth's magnetic field.	A | B | C | D | F	
Compare and contrast terranes and explain their significance in continental crust formation and evolution.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

CRUSTAL DEFORMATION & MOUNTAINS

Faults

Faults are breaks in rock units along which movement has occurred. Faults form when brittle rocks undergo stress: **tension** (pulling apart or lengthening), **compression** (pushing together, compacting, and shortening), or **shear** (smearing or tearing). Faults can have horizontal slip (along strike – called **strike-slip faults**), vertical slip (along dip – called **dip-slip faults**), or a combination of the two (called oblique-slip faults).

Faults are classified by the motion of rocks on one side of the fault relative to the other. For dip-slip faults, the top surface of the fault is the **hanging wall**. (Think of this as the block of rock that is hanging over the fault surface.) The bottom surface of the fault is the **footwall**. The hanging wall rocks sit on top of the footwall rocks.

Normal faults are caused by tension (rock lengthening). As tensional stress pulls the rocks apart, gravity pulls down the hanging block. Therefore, normal faulting gets its name because it is a normal response to gravity. If the hanging wall has moved downward in relation to the footwall, then the fault is a normal fault.

Reverse faults are caused by compression (rock shortening). As stress pushes rocks together, one rock block rides up atop another. If the hanging wall has moved upward relative to the footwall, the fault is a reverse fault. **Thrust faults** are reverse faults that develop at a very low angle and may be difficult to recognize.

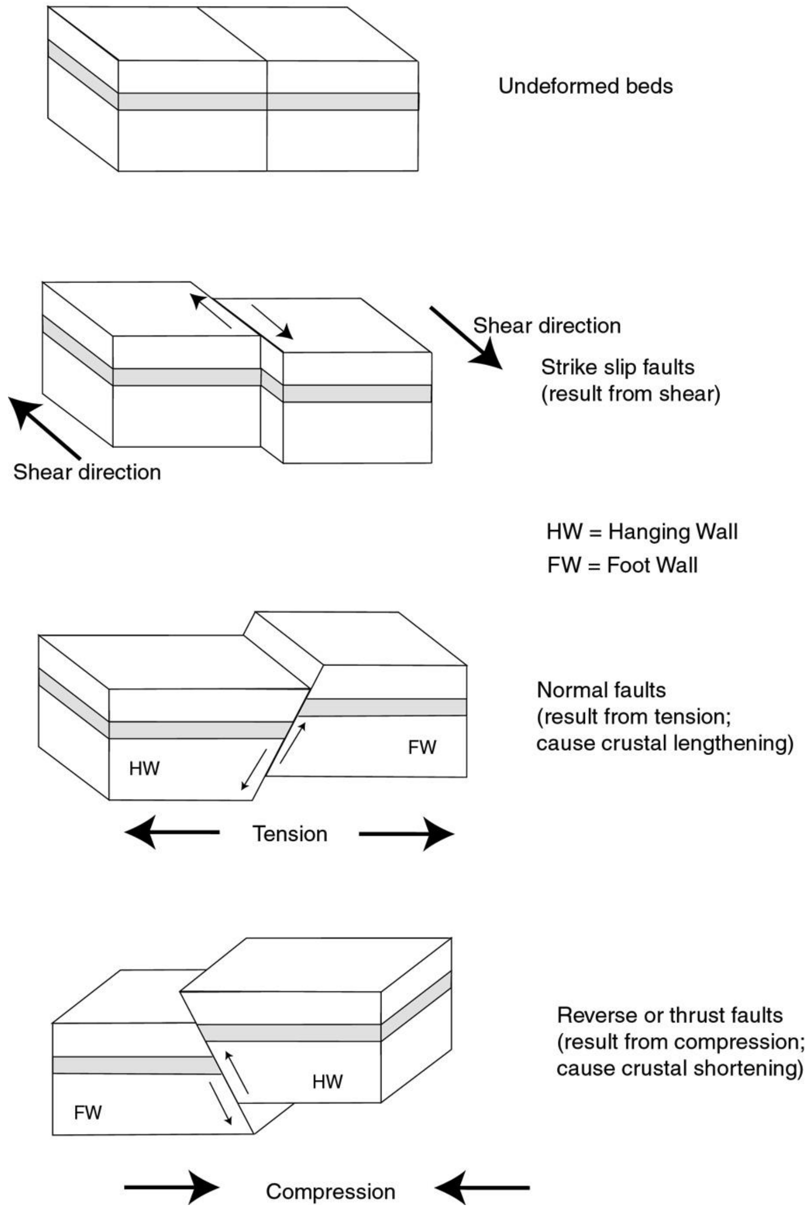


Figure 1. Fault types and how they deform rock layers.

Strike-slip faults are caused by shear and involve horizontal motions of rocks. Along a **right-lateral** strike-slip fault, rocks on one side of the fault appear to have slipped right relative to those on the other side. Along a **left-lateral** strike-slip fault, rocks appear to have slipped left.

Folds

Folds are bends in originally horizontal rock layers. Synclines are U-shaped. Anticlines are opposite: A-shaped. An imaginary plane, called an **axial plane**, can be drawn that bisects the fold. The **hinge line** is an imaginary line that is formed if you could take any layer in the fold and show the way it hangs or "hinges" at the axial plane (like the location of a door hinge where a door meets its frame). If the axial plane is vertical then the hinge line is a horizontal line, and the fold is upright. If the axial plane is NOT vertical, but instead tilted, we call it a tilted fold and usually give the dip angle of the axial plane. For example, in the left-most image on the next page, the left-most anticline is upright (untilted), but both the syncline and anticline have axial planes dipping eastward (if we assume that north is towards the top of the image). The angle looks to be at roughly 60°E, so we call the right-most folds a syncline and anticline with hinge axes dipping 60°E.

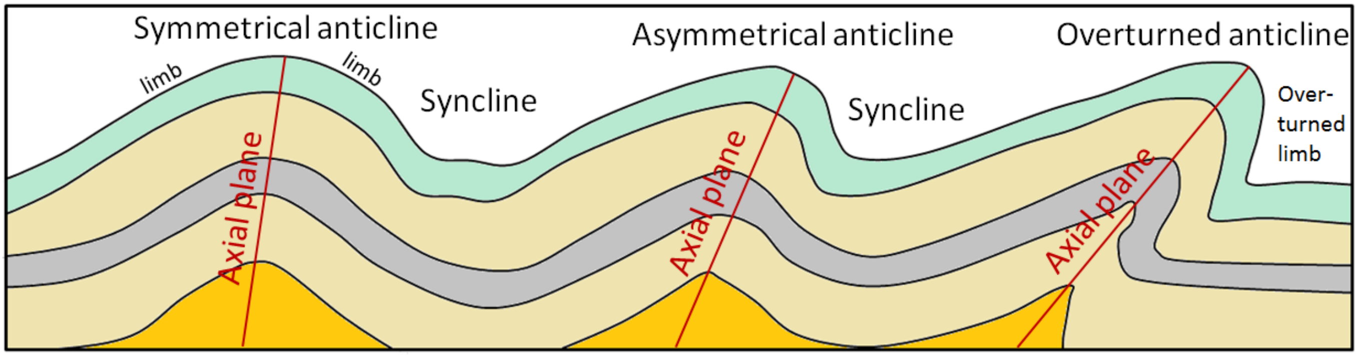


Figure 2. Cross-section. Examples of different types of folds and fold nomenclature. Axial planes are only shown for the anticlines, but synclines also have axial planes. Steven Earle, Physical Geology, CC Attribution 4.0 International License

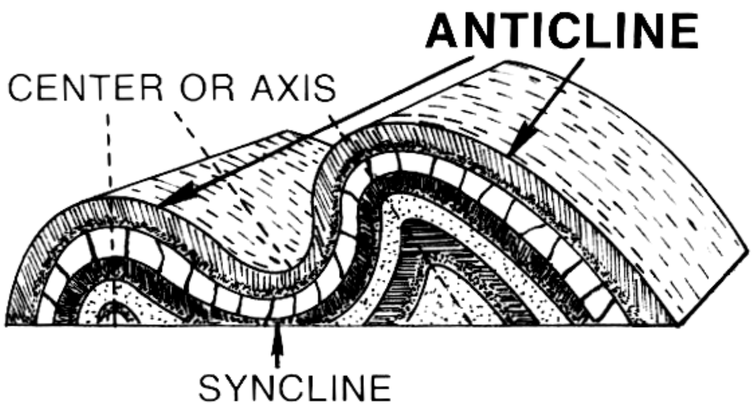


Figure 3.
Left structure: Anticline with Vertical Hinge Axis.
Center structure: Syncline with titled hinge axis (dips toward east, IF the structure is aligned with North at the top).
Right structure: anticline with tilted hinge axis (same dip as syncline).
Image: Public domain.

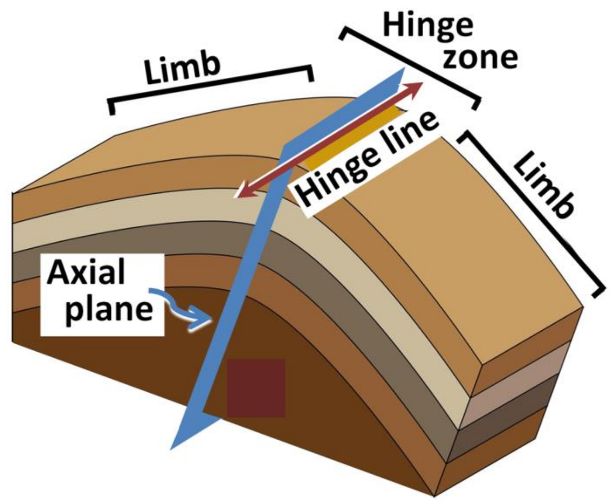


Figure 4. Anticline (oblique view), with hinge axis labeled. Brews Ohare – Creative Commons – BY-SA 3.0

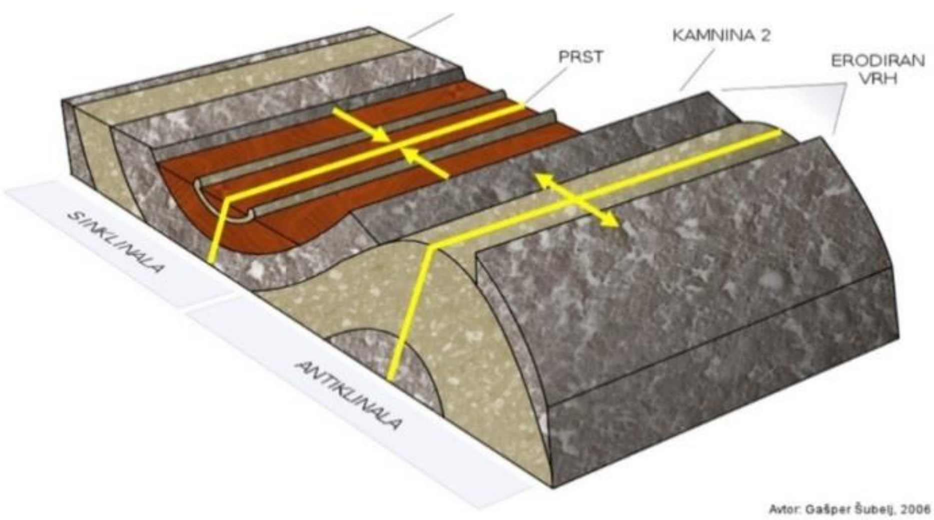


Figure 5. In this picture of an eroded syncline and anticline, we can see that the youngest rocks, which originally were on the top, are now visible along the inside of the eroded syncline and the edge of the eroded anticline. The oldest rocks are on the edge of the eroded syncline and the center of the eroded anticline. Modified from image by Gašper Šubelj – Creative Commons – BY-SA 3.0

A fold can also plunge into the ground, then the axial plane might still be vertical, but the hingeline will also plunge. The fold is called a **plunging fold. Plunge** (similar to dip) is the angle between the hinge line and a horizontal line. **Trend** (similar to strike) is the orientation of the hinge line. For example, a plunging anticline with a hingeline plunge of 20°N, and a trend of due north (or N0W) would be lined up N-S, and the entire structure would plunge into the ground towards the north.

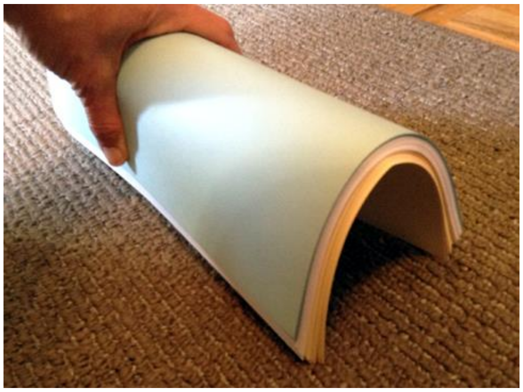


Figure 6. Nonplunging Anticline

Figure 7. Plunging Anticline (plunge direction is to left in this image)

Plunging synclines and anticlines show horseshoe-shaped outcrop patterns on eroded surfaces. For anticlines, the horseshoe bends in the plunge direction. For synclines, the open side of the horseshoe is in the plunge direction. The oldest rocks appear in the center of anticlines and the edges of synclines.

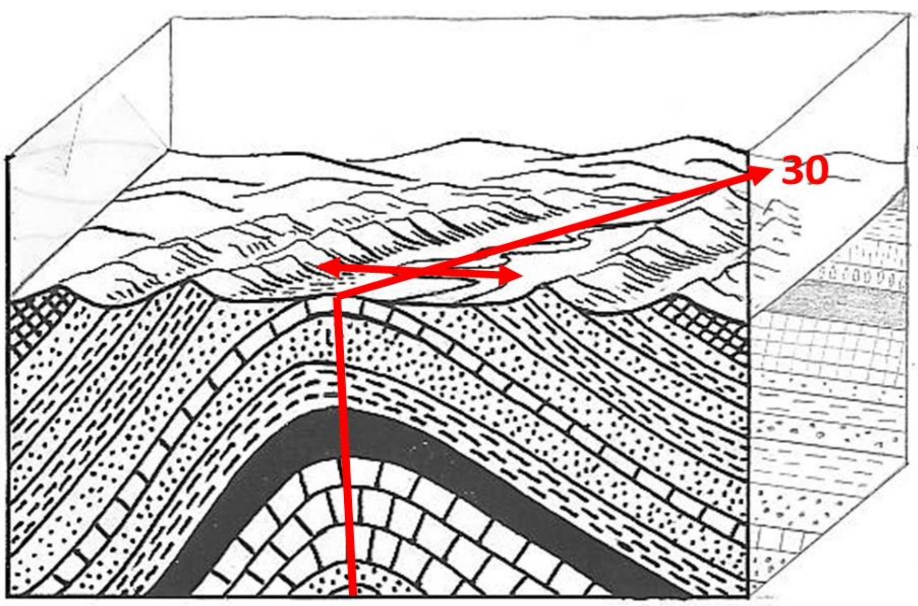


Figure 8. 30NE Plunging Anticline (assuming North is the top of the image). Image modified from public domain.

Domes and basins are large, somewhat circular structures formed when strata are warped upward (domes) or downward (basins). Strata are oldest at the center of a dome, and youngest at the center of a basin.

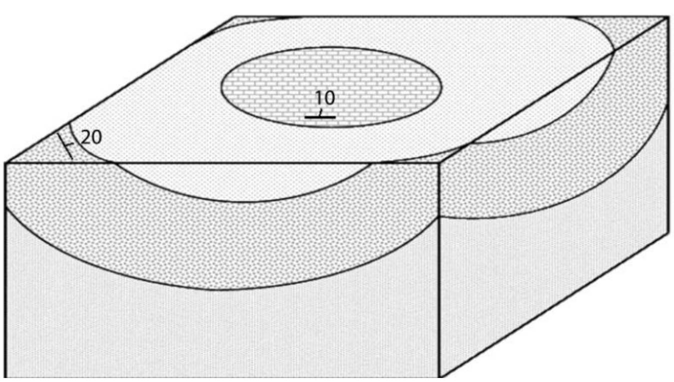


Figure 9. Basin
Modified from Ralph Dawes and Cheryl Dawes –CC BY-SA-3.0

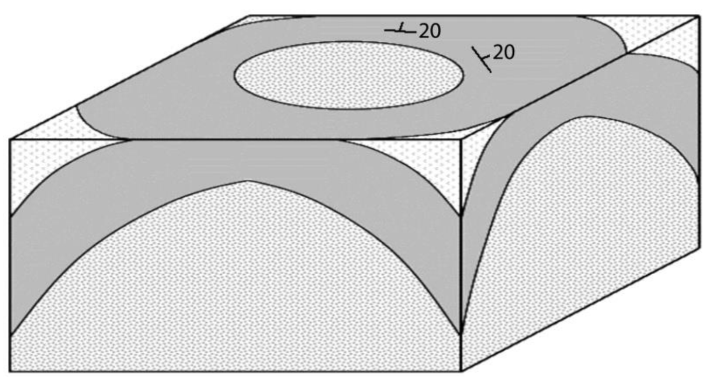


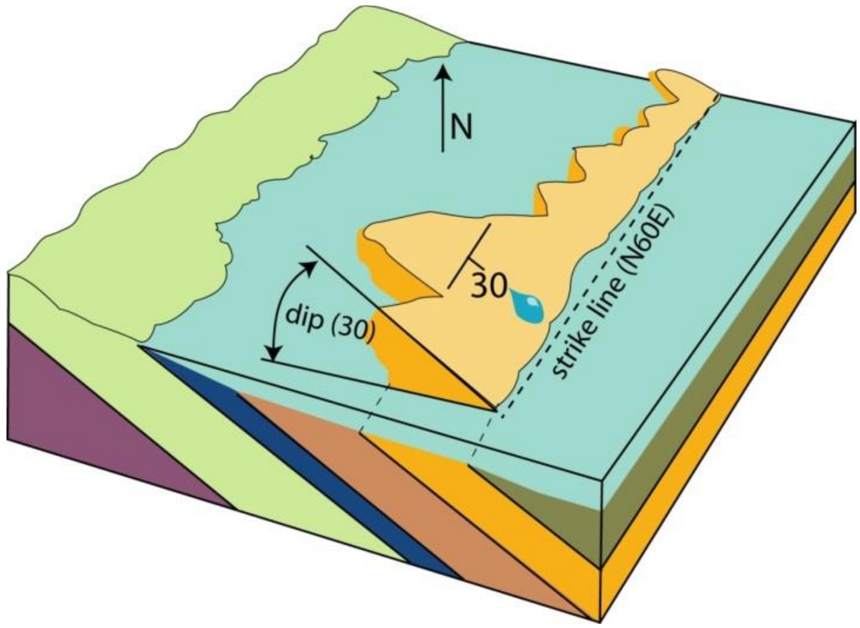
Figure 10. Dome
Modified from Ralph Dawes and Cheryl Dawes – CC BY-SA-3.0

Measuring the attitude of rock units

Attitude is orientation of the surface of any mappable geologic structural feature, such as a fault or a contact between two rock layers. Attitudes consist of two components:

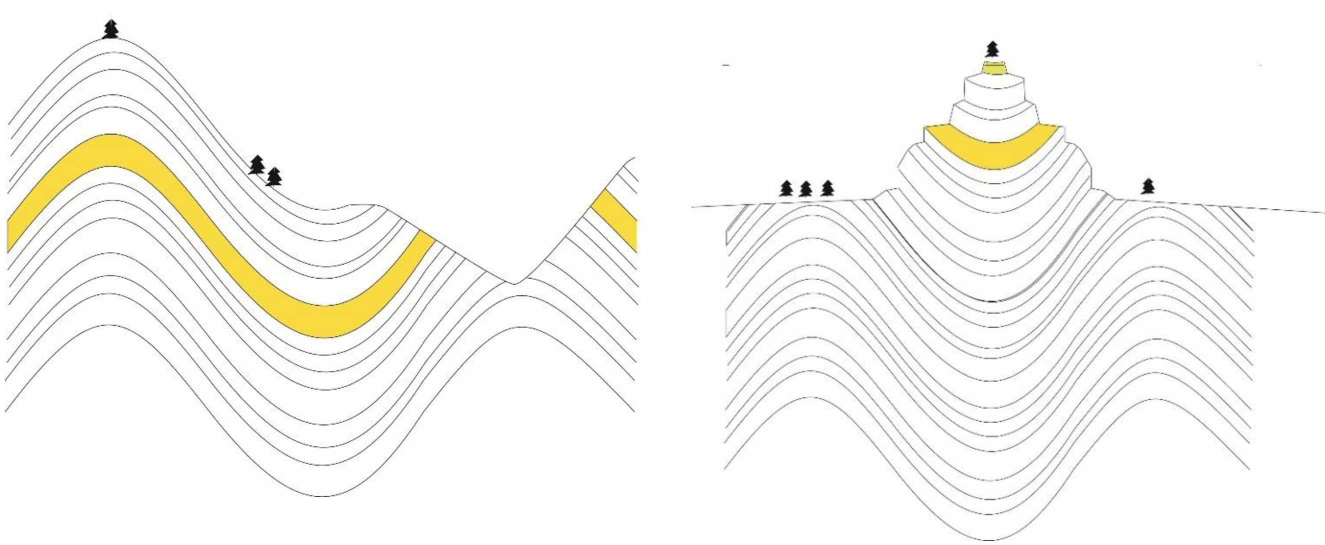
- **Strike** is the orientation of the line that forms when the surface being measured is intersected by a horizontal plane. You can find this line by laying a carpentry level across the bed surface. When level, the line where the surface and level meet is the strike line. Because strike is the orientation of a line, it is expressed relative to north like we have been doing in the first few labs. (NXE or NXW where X £ 90°; example: N15W.)
- **Dip** is the angle formed between a horizontal surface and the surface being measured. A thin stream of water poured onto the bedding surface always runs down the surface in the exact dip direction, which is always perpendicular to strike line. Dip is expressed as an angle and the direction water would flow. Example: 30°SW means the bed is dipping at a 30° angle into the ground towards the southwest.

Figure 11. The water-on-the-rock method for finding the direction and angle of dip is very useful. Because strike is perpendicular to dip, finding one helps you find the other. Strike and dip are shown on maps with T-shaped symbols. The long line shows strike direction; the short line shows dip direction. Dip is always drawn perpendicular to the strike line. The short line points downdip. Dip angle in degrees is written under the dip line. Note: True dip angles can be seen only in cross section if the cross section is perpendicular to the fault, to the strike of the beds, or to the hinge axes of folds.



Topography ≠ Geology

Topography and underlying geology are separate characteristics of a region. For example, in the images below, you can see that, for the image on the left, rivers can carve a valley INTO a geologic anticline or dome. Similarly, for the image on the right, as resistant beds are less easily eroded, it's possible to erode around a resistant bed creating a hilltop or mesa topographically, while geologically, it's a syncline or basin.



Figures 12 and 13. Anticlines and synclines eroded by rivers. On left, we see a river "valley" eroded into an anticline. On right, we see an erosional remnant carved out of a syncline.

Figure 14. North America Relief satellite image.

Table 1: Deformation types—causes and effects

Deformation type	Causes	Results
Elastic – temporary deformation	Stress not greater than elastic limit of rock	Strain released and shape returns to normal
Brittle – permanent break	Stress greater than yield point or elastic limit of rock (usually colder temperatures – nearer surface – rapid stress application)	Strain released with break in rock (faulting)
Plastic – permanent ductile deformation	Stress greater than yield point or elastic limit of rock (usually higher temperatures – deeper underground – stress applied slowly over long time)	Strain is permanent (folding or deformation of rock)

Table 2: Stress types and their associated causes and consequences

Stress types	Plate boundaries	Fault types	Crustal thickening or thinning or both/none?	Mountain types (if any)
Compression	*Convergent*	*Reverse (+ thrust)*	*Thickening*	*Fold and Thrust*
Tension	*Divergent*	*Normal*	*Thinning*	*Fault-Block*
Shear	*Transform*	*Strike-slip*	*None*	*None*

Table 3: Mountain types

Mountain type	Formed by	World examples	California examples
Fold and Thrust	*Compressive stress (usually at convergent plate boundaries)*	*Himalayas*	*Transverse Mountain Range (Santa Barbara and eastward)*
Fault-Block	*Tensile stress (usually at divergent plate boundaries)*	*East African Rift Zone Basin and Range*	*Sierra Nevadas*
Domes	*Single point of pressure pushing up from inside Earth (salt dome rising or magma rising, but not erupting)*	*Adirondacks (NY), Black Hills (S. Dakota)*	*Mt. Diablo*
Erosional Remnant	*Resistant rock that sticks out from surroundings, because they eroded more quickly and easily*	*Devil's Tower, Wyoming*	*Twin Peaks*
Volcanic	*Volcanic activity associated with hotspot, divergent plate boundary, or subduction zone*	*Cascade Mountains, Andes Mountains*	*Mt. Shasta, Glass Mountain, Mammoth Mountain*

Some more useful definitions:

Cross-section	A **cross-section** is what you see when you slice into the earth (like a cake) and look at it from the side (seeing the layers).
Map View	A **map view** is what a bird or satellite sees when flying across the surface.
Oblique view	An **oblique view** tries to show both and is very difficult to draw.
Anticline	Fold that is shaped like an upside-down U -- rocks bend upwards around a hinge line (like towels draped over a clothes line)
Syncline	Fold that is shaped like an U -- rocks bend downwards around a hinge line
Dome	Fold that looks like an anticline in cross-section (upside-down U), but has no hinge axis, because all the rocks are pushed up in center relative to those on sides (like upside down nested bowls).
Basin	Fold that looks like a syncline in cross-section (U), but has no hinge axis, because all the rocks are pushed down in center relative to those on sides (like nested bowls).
Stress	Pressure applied to a rock (pressure = force applied over a surface area)
Strain	Deformation -- change of shape of a rock undergoing various stress.

Crustal Deformation & Mountain Building – Chapter Worksheet

1. **Pressure = Force applied over a given area.** Give real world examples of high pressure vs low pressure. *(Be sure you examples demonstrate an understanding of the formula/definition of pressure).*

2. Provide definitions for stress, shear, and strain that clearly differentiate between them.

Stress

Shear

Strain

3. What are the three types of **stress**? (Use arrows to indicate the motion that causes each.)

4. CIRCLE: Which kind of deformation returns object back to its original shape after stress removed? Brittle | Elastic | Plastic
5. CIRCLE: Which kind of deformation happens at the surface where temperatures are cold? Brittle | Elastic | Plastic
6. CIRCLE: Which kind of deformation happens when stress is applied quickly? Brittle | Elastic | Plastic
7. CIRCLE: Which kind of deformation happens at depth where temperatures are hot and stresses are applied slowly? Brittle | Elastic | Plastic
8. CIRCLE: Which kind of deformation is associated with earthquakes? Brittle | Elastic | Plastic
9. What is **yield point** or **elastic limit**? What does it mean?

10. CIRCLE: Which type of fold(s) is associated with **plastic deformation**? anticlines | basins | domes | synclines
11. CIRCLE: Which type of fold(s) **pushes old rocks up in the center**? anticlines | basins | domes | synclines
12. CIRCLE: Which type of fold(s) has beds **dipping down into the center**? anticlines | basins | domes | synclines

Imagine these folds were eroded to a flat top and you were looking down on them from above.

13. CIRCLE: Which type of fold(s) displays a **bullseye pattern of beds** on the surface when eroded?
basins | domes | plunging anticline | plunging syncline | nonplunging anticlines | nonplunging synclines
14. CIRCLE: Which type of fold(s) displays a **parallel-lines pattern of beds** on the surface when eroded?
basins | domes | plunging anticline | plunging syncline | nonplunging anticlines | nonplunging synclines
15. CIRCLE: Which type of fold(s) displays a **nested horseshoe pattern of beds** on the surface when eroded?
basins | domes | plunging anticline | plunging syncline | nonplunging anticlines | nonplunging synclines
16. Draw a map-view (bird's-eye) picture of what a **south-plunging syncline** would look like when a flat surface is eroded. Make the top of the page north (add a north arrow). Draw a hinge axis and arrows to show direction of dipping beds and plunge.

17. What are the differences and similarities between **dip-slip** and **strike-slip** faults?

Similarities

Differences

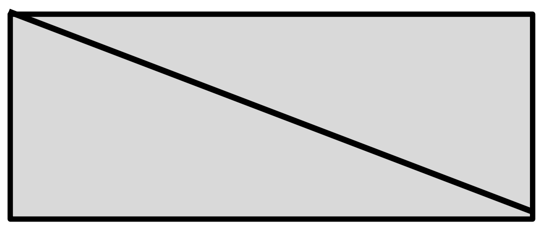
18. How can you tell the difference between **right-lateral** and **left-lateral strike-slip faults**?

19. CIRCLE: What kind of the fault is the **San Andreas Fault**?
normal | reverse | right-lateral strike-slip | left-lateral strike slip

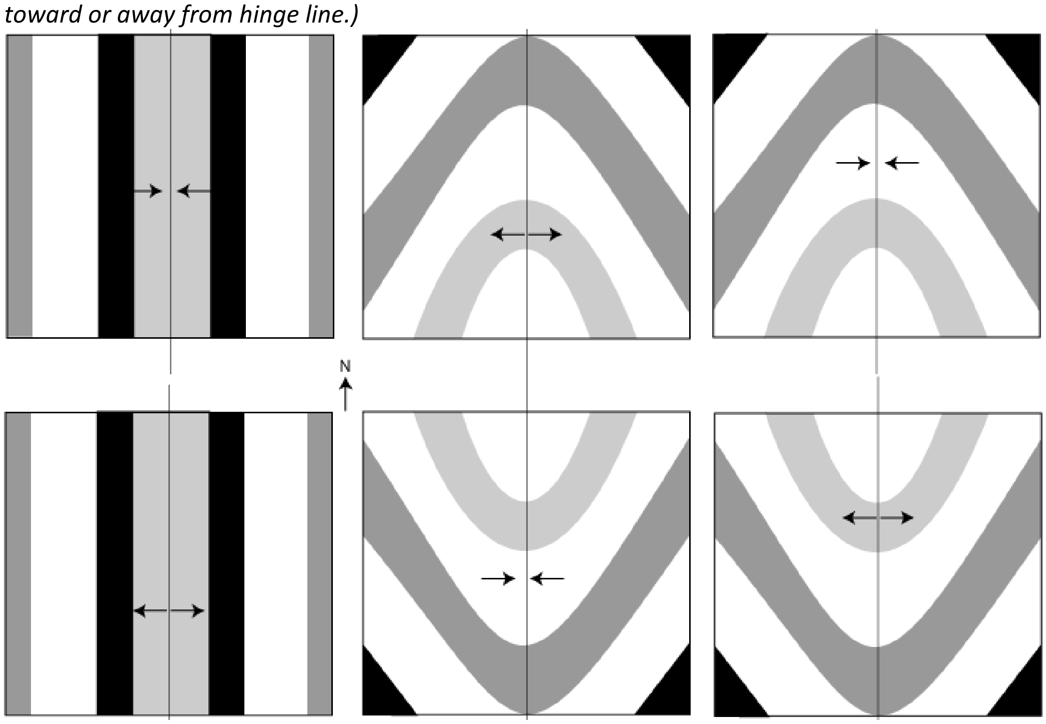
20. CIRCLE what traits are true for a **normal** fault: Strike-slip | Dip-slip |caused by Tension | Caused by Compression | Caused by shear | Hanging wall moves up | Hanging wall moves down

21. CIRCLE what traits are true for a **reverse** fault: Strike-slip | Dip-slip |caused by Tension | Caused by Compression | Caused by shear | Hanging wall moves up | Hanging wall moves down

22. Label **hanging wall** and **footwall** for the following cross-sectional fault image. NOTE: There is no stress direction indicated. Is that necessary for answering this question?



23. NAME THE FOLLOWING FOLDS (fully) BASED ON THESE MAP-VIEW IMAGES OF WHAT THE ROCK LAYERS LOOK LIKE ON THE SURFACE. Put Y on surface where youngest rocks are and O where oldest rocks are. *(*Note: skinny lines are the hinge axes (hinge line over which fold bends); arrows show direction water would flow along folded layers – toward or away from hinge line.)*

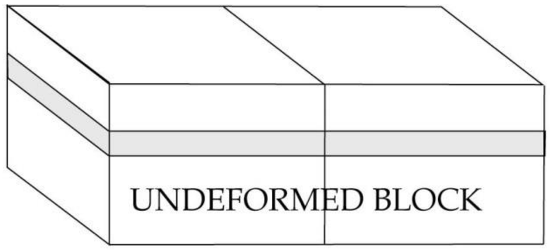


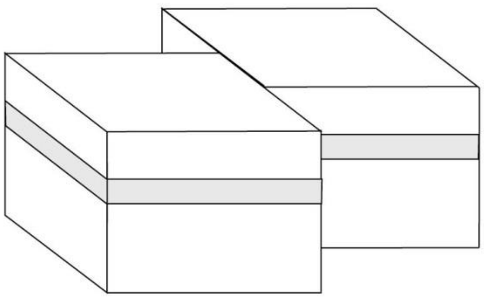
24. Which type of mountain is found in the **East African Rift Zone**? CIRCLE ALL THAT APPLY: Fold and Thrust | Fault-Block | Dome | Erosional Remnant | Volcanic
25. Which type of mountain is associated with **tension and divergent plate boundaries**? CIRCLE ALL THAT APPLY: Fold and Thrust | Fault-Block | Dome | Erosional Remnant | Volcanic
26. Which type of mountain is associated with **compression and all convergent plate boundaries**? CIRCLE ALL THAT APPLY: Fold and Thrust | Fault-Block | Dome | Erosional Remnant | Volcanic
27. Which type of mountain is created by hard rock layers that resist break down while the rocks around them are broken down and removed? CIRCLE ALL THAT APPLY: Fold and Thrust | Fault-Block | Dome | Erosional Remnant | Volcanic
28. Which type of mountain is formed when something from deep in the crust **pushes upwards** but not all the way to the surface? CIRCLE ALL THAT APPLY: Fold and Thrust | Fault-Block | Dome | Erosional Remnant | Volcanic
29. Which type of mountain is **NOT associated with tectonic movements**? CIRCLE ALL THAT APPLY: Fold and Thrust | Fault-Block | Dome | Erosional Remnant | Volcanic
30. Which type of mountain is associated with the **thinning of the crust**? CIRCLE ALL THAT APPLY: Fold and Thrust | Fault-Block | Dome | Erosional Remnant | Volcanic
31. Provide world examples of the following types of mountains:

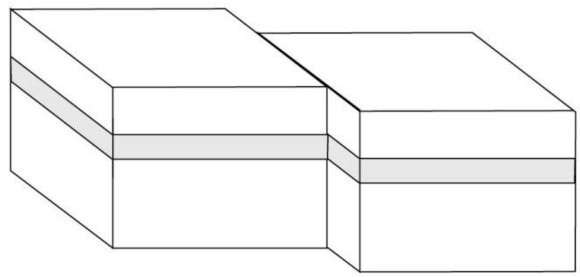
Feature	**Locations**
Fold and Thrust	
Fault-Block	
Dome	
Erosional Remnant	
Volcanic	

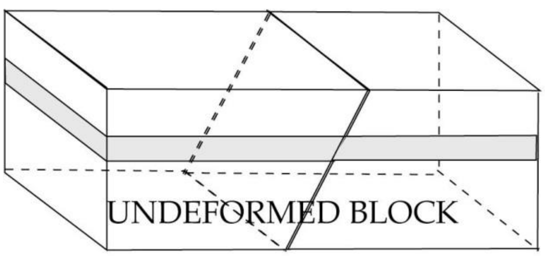
Folds & Faults ACTIVITY

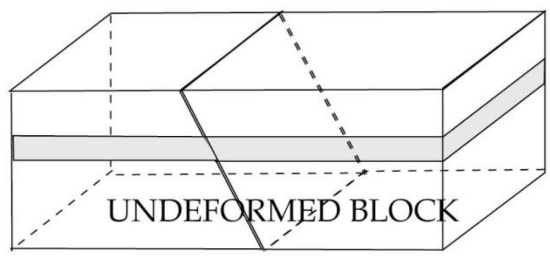
Complete the deformed blocks below by drawing relative motion arrows alongside the fault plane, determining and labeling stress name and direction, and naming the faults. Also indicate which wall in each dip-slip fault is the hanging wall.

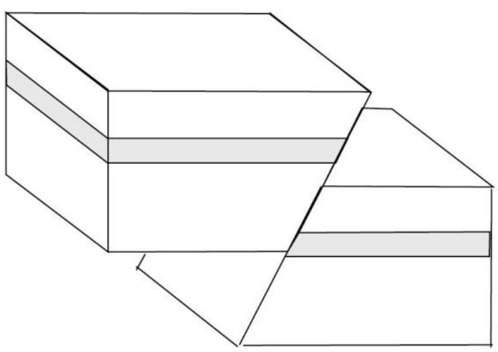


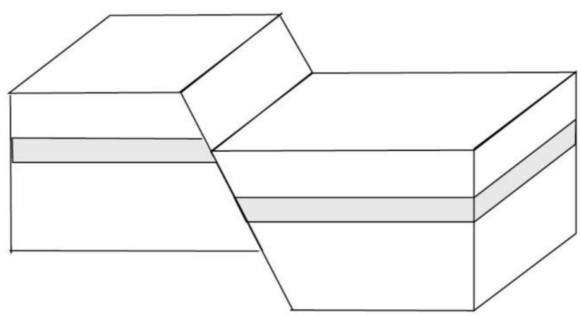


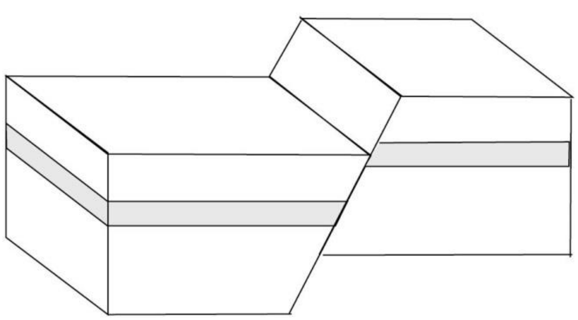


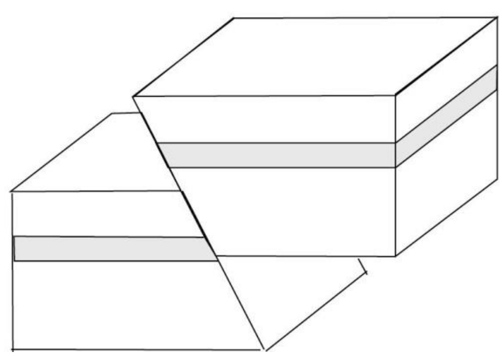


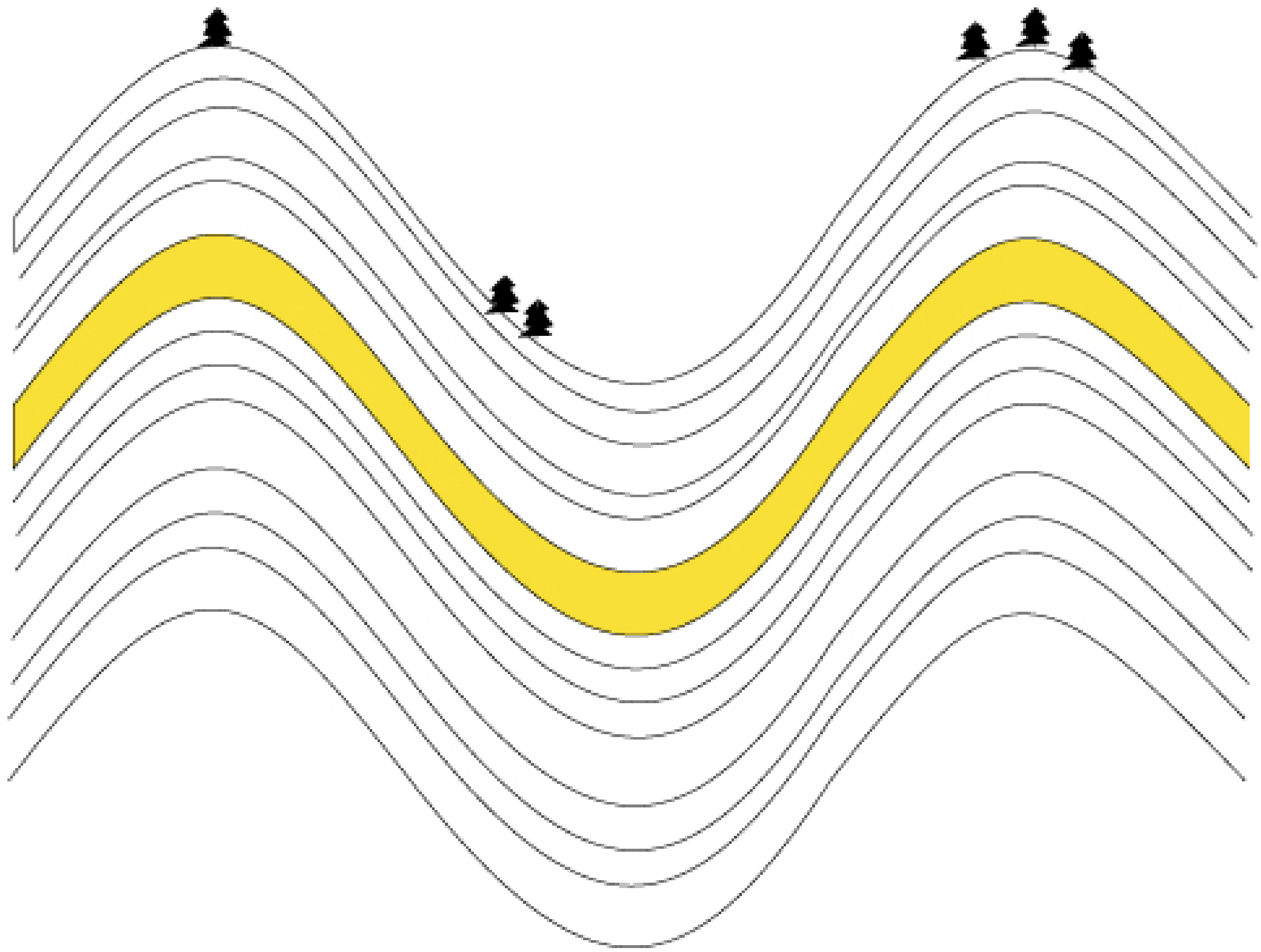












QUESTION FOR CROSS-SECTION ABOVE:
In the picture above, you are seeing the cross-section view of perfectly vertical and symmetrical anticlines and synclines.

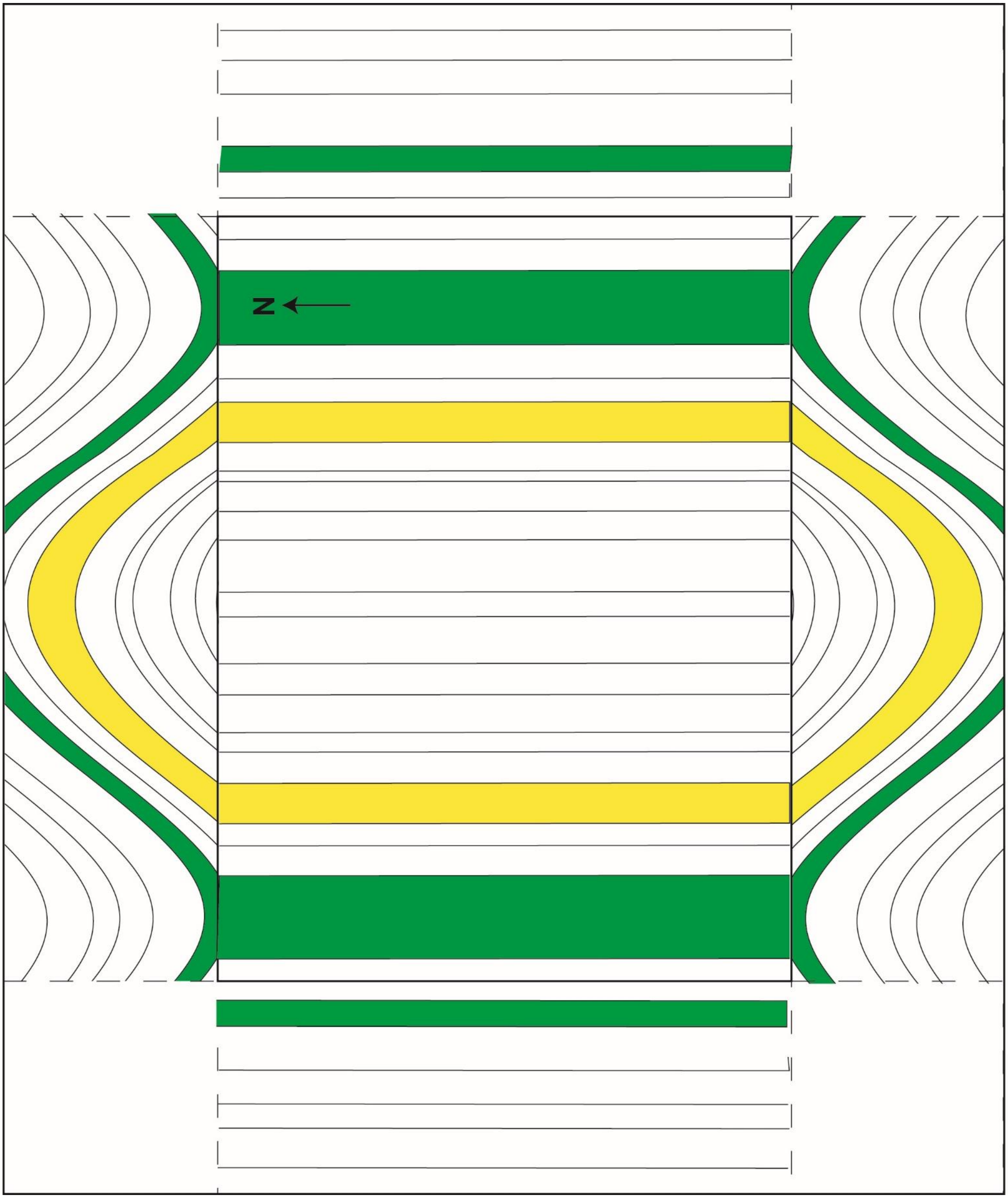
- **Label which structures are anticlines and which are synclines.**
- **Label each layer from youngest (1) to oldest (13).**

QUESTIONS FOR BOX DIAGRAM:
The box diagram on the next page shows you what the structure would look like if about half the exposed rocks were eroded. Build the box diagram to help you visualize these folds in 3-D.

1. Get scissors and cut out the box diagram along its outer border.
2. For the corners, just cut one of the dotted lines on the corner, not both!
3. Fold on all the edges and turn into a 3-D block.

- If the sandstone layer (yellow) contained Gold, and all the surface exposures of that gold layer already had their mining rights purchased, is there anywhere else you could get to the gold? on what surface parcels (in the box diagram) would you buy mining rights? **LABEL with a star and brief explanation.**
- If there were a visible fault line that ran from the northwest corner to the southeast corner straight through the middle of this area, and the fault dipped underground at a 45° angle (goes under to the NE), on which side of the fault would you build your house? **LABEL with a house and brief explanation.**
- **Take a photo and add it to your assignment.**

Ani



(blank page for printing purposes – so you can build the 3-D model on the other page)

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Evaluate the causes and landforms associated with the different types of mountain building processes globally.	A | B | C | D | F	
Distinguish causes and consequences of the different types of stress and strain.	A | B | C | D | F	
Compare and contrast brittle, ductile, and elastic deformation – causes and results.	A | B | C | D | F	
Classify and distinguish among the different types of folds.	A | B | C | D | F	
Classify and distinguish among the different types of faults.	A | B | C | D | F	
Interpret expected relative ages for rock layers exposed at the surface of a fold.	A | B | C | D | F	
Use dip and hinge axes markers to identify folds shown on geologic maps.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

EARTHQUAKES & EARTH'S INTERIOR

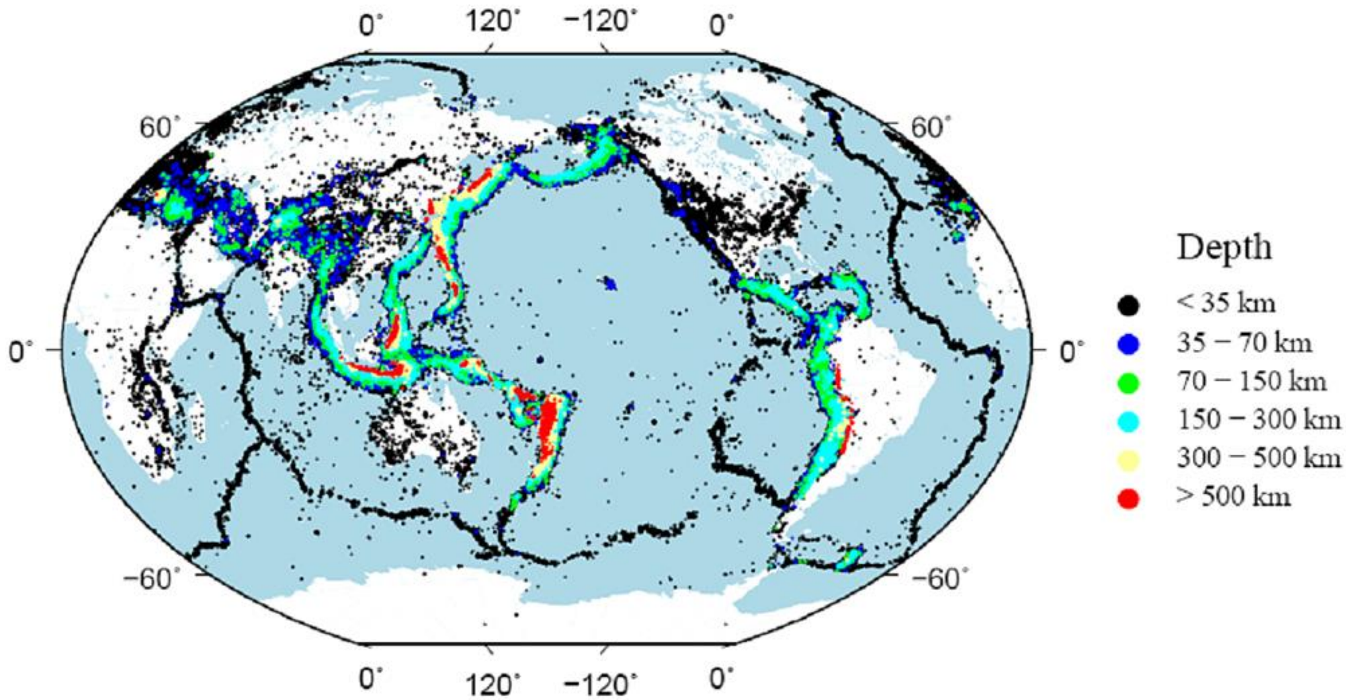


Figure 1. Earthquakes around the world color coded by depth (Image produced by NORSAR using USGS data.

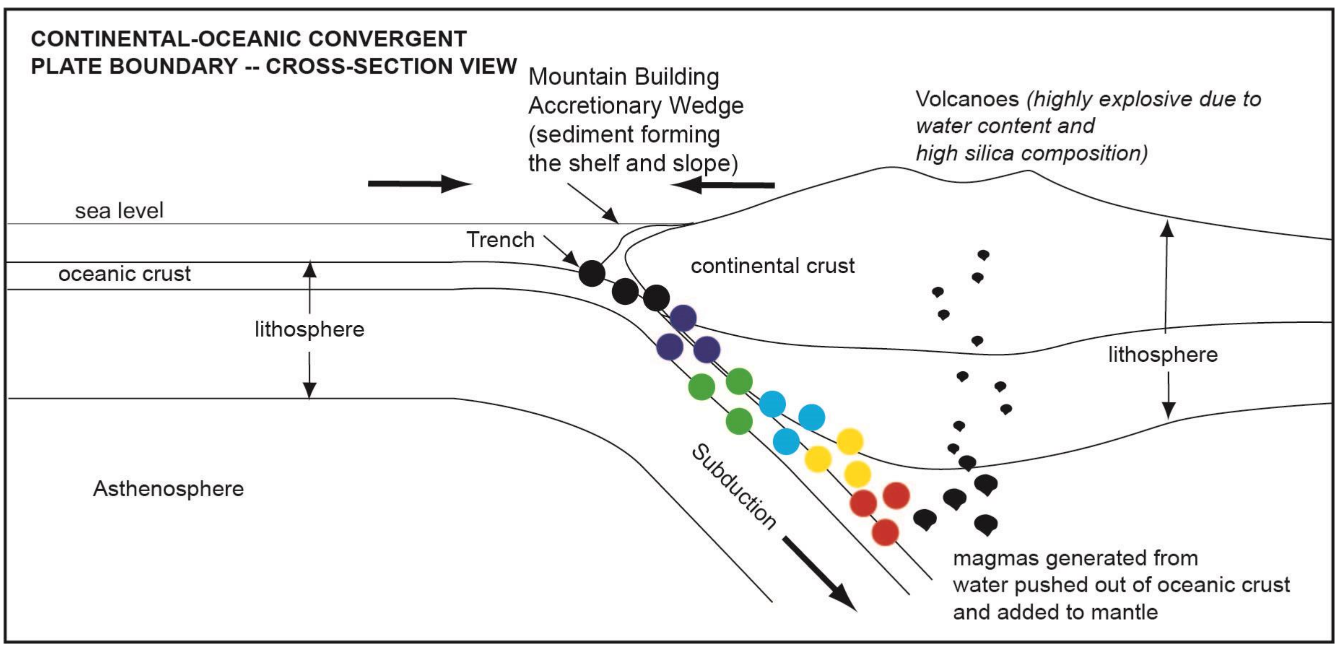


Figure 2. Circles represent focal points for deeper and deeper earthquakes. The locations directly above these earthquakes are known as epicenters and that's where the quakes are felt first.

Table 1. Seismic wave speeds

	P wave	**S wave**
Speed	7 km/s	3.5 km/s
Arrival time	First!	Second
Motion type	Compressional (push-pull)	Transverse (side to side)
Materials wave can travel through?	All	Solids only

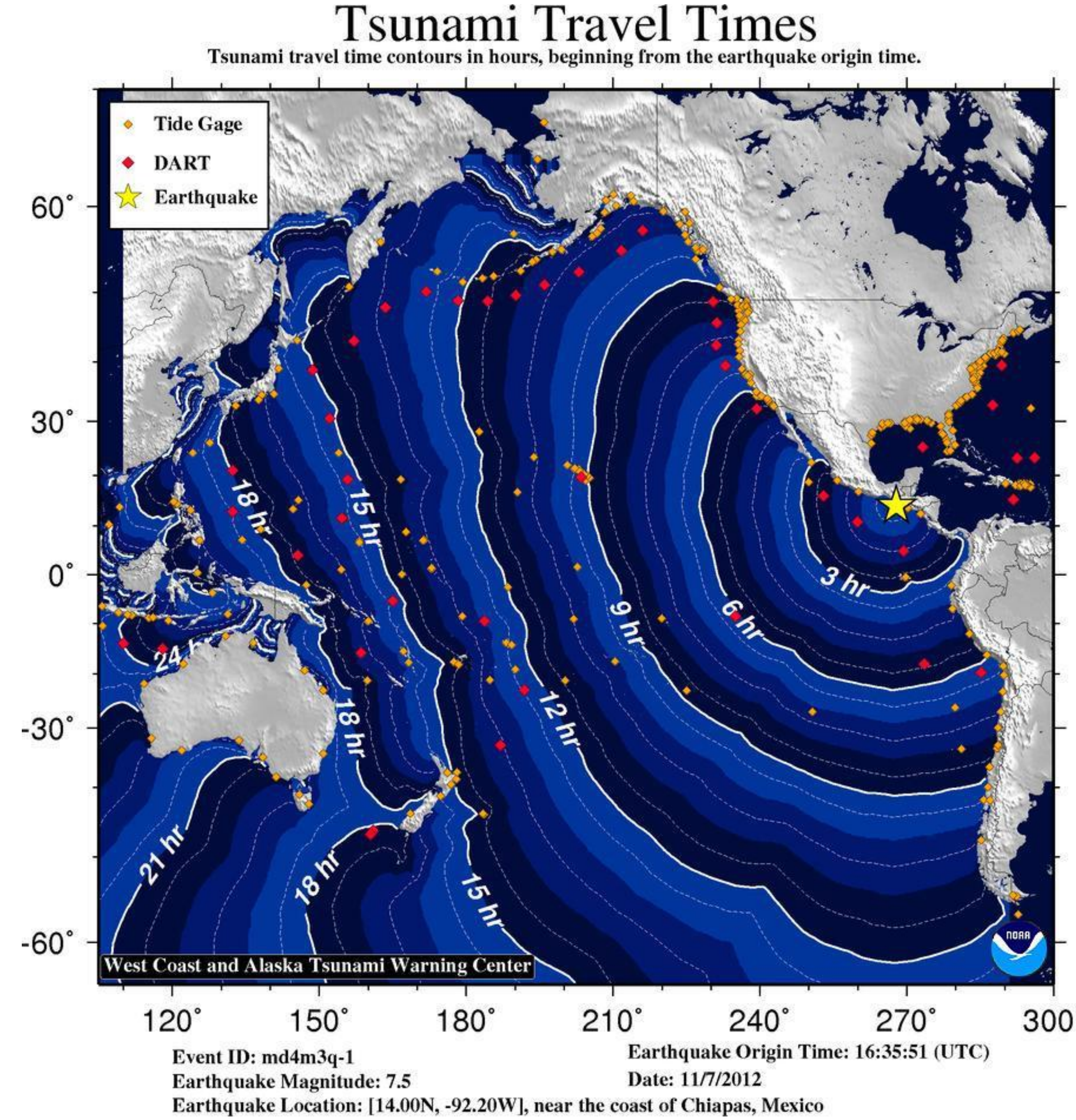


Figure 3. Tsunami Travel Times (travel time contours every 30 mins, beginning from Chiapas 2012 earthquake origin time). NOAA

Figure 4. Interference is the meeting of two waves arriving from opposite directions. When the two waves meet, they add to each other. If they meet crest to crest, or trough to trough (in phase), they increase the wave height. For earthquakes, that increase means more shaking. When the two waves meet crest to trough (out of phase), they decrease the wave height. That decrease means less shaking. Interference happens during an earthquake when the seismic waves bounce off a hard object underground, like the edge of a basin, or the side of a granite intrusion. Areas between the epicenter and the reflection surface will experience two waves from opposite directions – the original earthquake waves and the reflected waves. The pattern that interference makes on the surface is similar to a chessboard – in black squares waves meet out of phase and shaking is reduced; in white squares waves meet in phase and shaking is increased. In the center of black squares people may not feel any shaking at all. In the center of white squares, shaking may be so intense that structures fail. Evidence that interference has occurred can be seen when you view this checkerboard pattern of destruction in an area, like a housing development, where all structures and ground material are similar. Be sure you understand this process: its causes, effects, and what evidence is found after an earthquake to indicate it occurred.

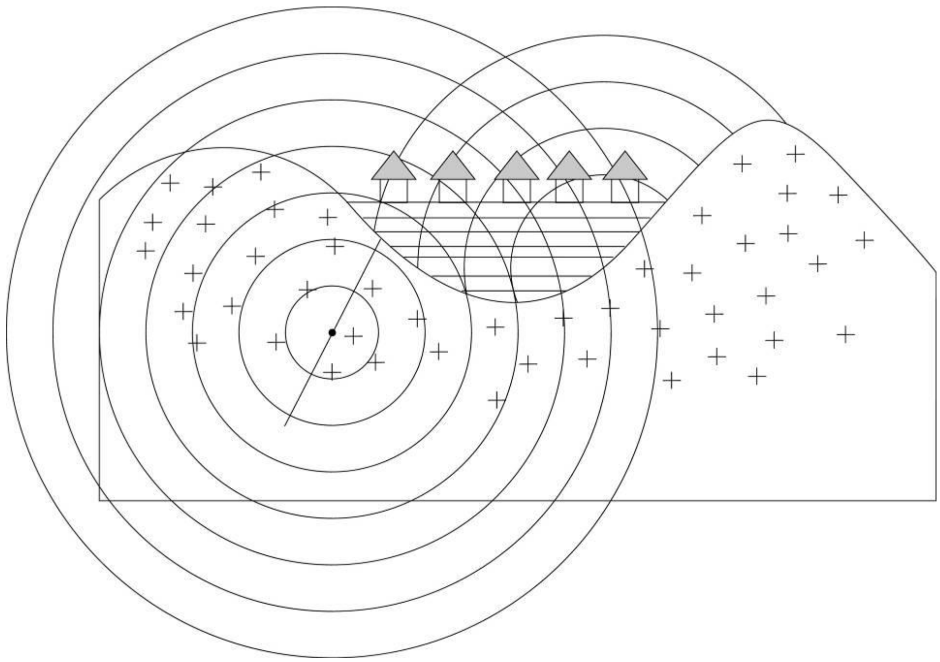
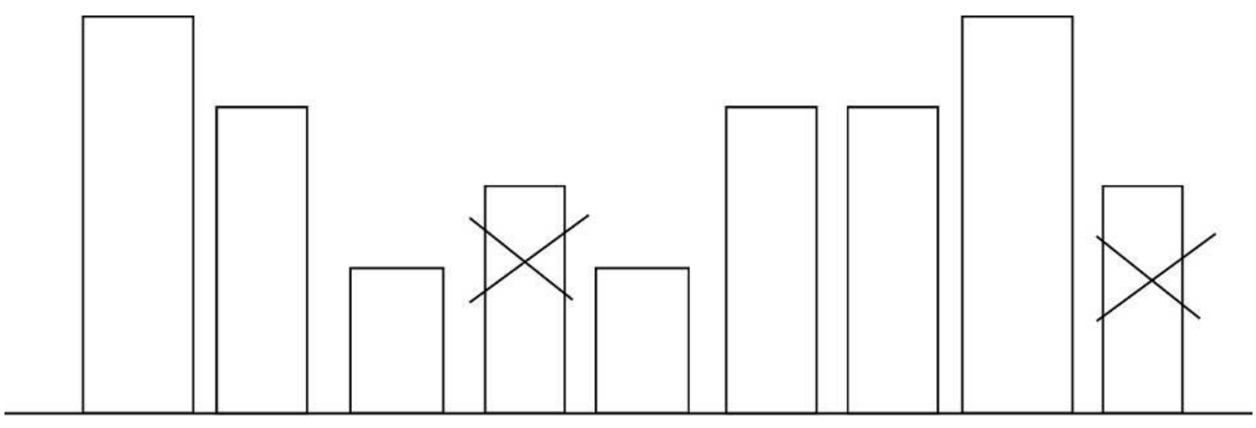


Figure 5. Resonance is the matching of the period (or frequency) of an earthquake wave with the natural vibrational period (or frequency) of an object, like a building. All buildings vibrate at a period (number of seconds per vibration) that depends mainly on the height of the building. If the period of an earthquake is the same as the natural period of the object, shaking increases more and more with each wave's arrival, until the object falls apart. You can see examples of resonance when you push a child on a swing (if your pushing period matches the child's swinging period, the child will swing higher and higher) or when an opera singer makes a glass shatter. After an earthquake, you would see evidence of resonance if you noticed that all buildings of a particular height experienced more damage than other buildings, shorter or taller than it. Be sure you understand this process: its causes, effects, and what evidence is found after an earthquake to indicate it occurred.



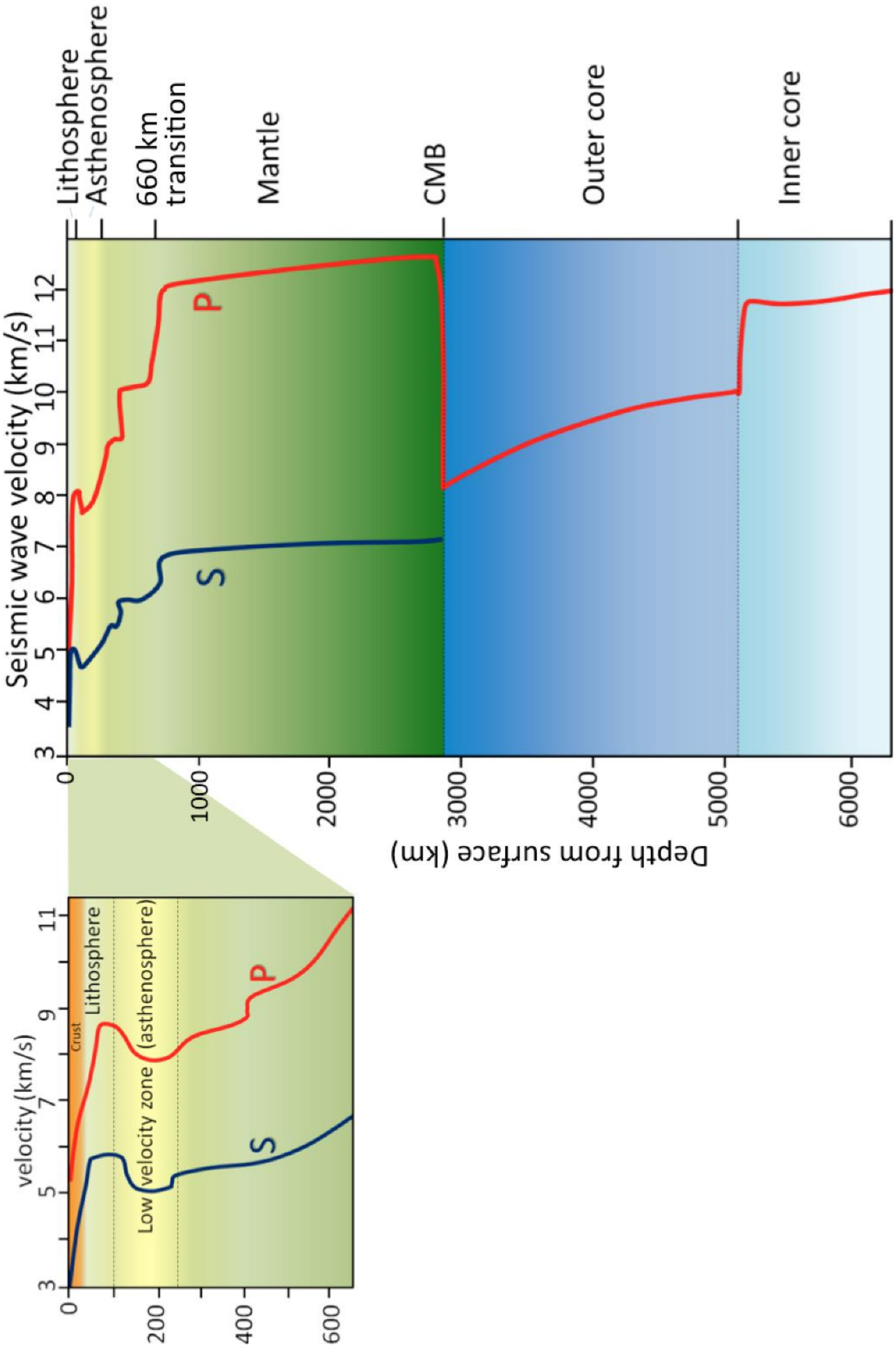


Figure 6. P-wave and S-wave velocity variations with depth from the crust through the upper mantle (left) and from the crust through to the core (right). CMB = Core-Mantle Boundary.

Karla Panchuk (2018) CC BY 4.0, modified after Steven Earle (2016) CC BY 4.0

What causes an earthquake?

1. Stress (pressure) is continually applied to rocks or pre-existing faults.
   This stress most likely comes from plate tectonics and is at a plate boundary.
2. Stress builds where strong rocks or locked faults withstand it.
   (Friction is the internal force that locks a fault, making its two sides stick together.)
3. Rocks and faults deform elastically (strain) in response to the building stress.
4. Stress finally builds higher than rock strength or fault's friction and rock breaks or fault slips.
5. Stress is released in the form of energy waves that move outward in all directions.
6. The rocks or faults elastically rebound and strain energy is released.
7. After the rocks or faults have settled back into place, the stress begins building again.

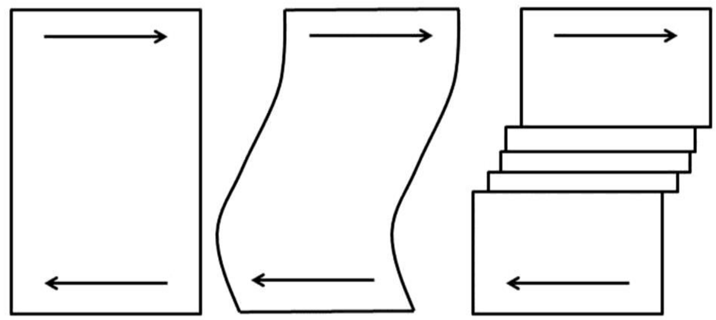


Figure 7. Map view of an undeformed surface as stress builds and it breaks due to shear.

Some more useful definitions:

Fault	Planar surface along which a rock or sequence of rocks breaks and movement happens
Focus	Location along a fault where the break first occurs or for existing faults where friction is overcome by built-up stress, and the fault slips
Epicenter	Point on the surface directly above the focus of an earthquake.
Surface waves vs Body waves	Surface waves are those that move along the surface of Earth (boundary of rock and atmosphere). Body waves emanate out from focus of earthquake and travel through rocks (not along boundaries). When body waves hit a surface, they generate waves that propagate along that surface. All surface waves are produced by body waves. Does that help?

Earthquakes and Earth's Interior Chapter Worksheet

1. **REVIEW:** Where do most earthquakes occur globally?

2. Review the seven-part explanation of what causes an earthquake. Explain how **friction** is involved.

3. Review the seven-part explanation of what causes an earthquake *(on previous page)*. Explain what is meant by **elastic rebound**.

4. Faults that are experiencing no active creep may be considered "safe." Rebut or defend this statement.

5. How are faults, foci, and epicenters related?

Faults

Foci

Epicenters

6. Distinguish between **surface waves** and **body waves**.

7. CIRCLE which is true for **P-Waves**: body wave | surface wave | fastest | arrives first | arrives second | arrives last
shear wave | compressional wave | moves through all materials (solid, liquid, gas) | moves only through solids

8. CIRCLE which is true for **S-Waves**: body wave | surface wave | fastest | arrives first | arrives second | arrives last
shear wave | compressional wave | moves through all materials (solid, liquid, gas) | moves only through solids

9. Which type of seismic wave causes the greatest destruction to buildings? Why?

10. Distinguish between the Mercalli Intensity, Richter, and Moment-Magnitude scale. What does each measure?

Mercalli Intensity

Richter

Moment Magnitude

11. An earthquake measuring 7 on the Richter scale has an **amplitude** on the seismograph how many times taller than a size 6 earthquake? How many times more **energy** released?

Amplitude increase:

Energy increase:

12. An 8 compared to a 6?

Amplitude increase:

Energy increase:

13. Describe the principle of a **seismograph**. What's the difference between energy and amplitude?

14. Approximately how many earthquakes occur for the following magnitudes each year?

magnitude <4.0	magnitude 4-6	magnitude > 6.0

15. What are specific characteristics of an area, structure, and earthquake that can increase the amount of destruction caused by earthquakes.

16. What is a **tsunami**? How is one generated?

17. How can you recognize a **subduction zone plate boundary** from the earthquake map *(see the first page of figures for this section)*?

18. What happens to seismic waves as they travel from more rigid material into less rigid material? Vice versa?

19. Graph the velocity changes that happen to P-waves as they travel through planet Earth. (Start with a dot in the upper left of the first cell in the “Graph” column. Make that starting velocity at Earth’s surface. Then as you descend, draw from that point a line moving right and down if velocity increases and left and down if velocity decreases with depth. At boundaries, draw the line right or left across the line.) In the right-most column, describe the chemical and physical properties of each layer *(review Introduction to Geology chapter’s Earth Layer’s image and table).*

Depth (base of layer)	**Layer (starting at Earth’s surface)**	**Graph (velocity increases Þ)**	**Chemical and Physical properties**
8-70 km	**CRUST** Lithosphere		
100 km	**MANTLE** Lithosphere		
350 km	Asthenosphere		
400 km			
700 km	Transition Zone		
2900 km	Lower Mantle (Mesosphere)		
5270 km	**OUTER CORE**		
6370 km	**INNER CORE**		

20. How can we use **P and S wave shadow zones** to conclusively prove that Earth's outer core is molten?

Earthquake Activity: Locating the Epicenter and Time of Earthquake

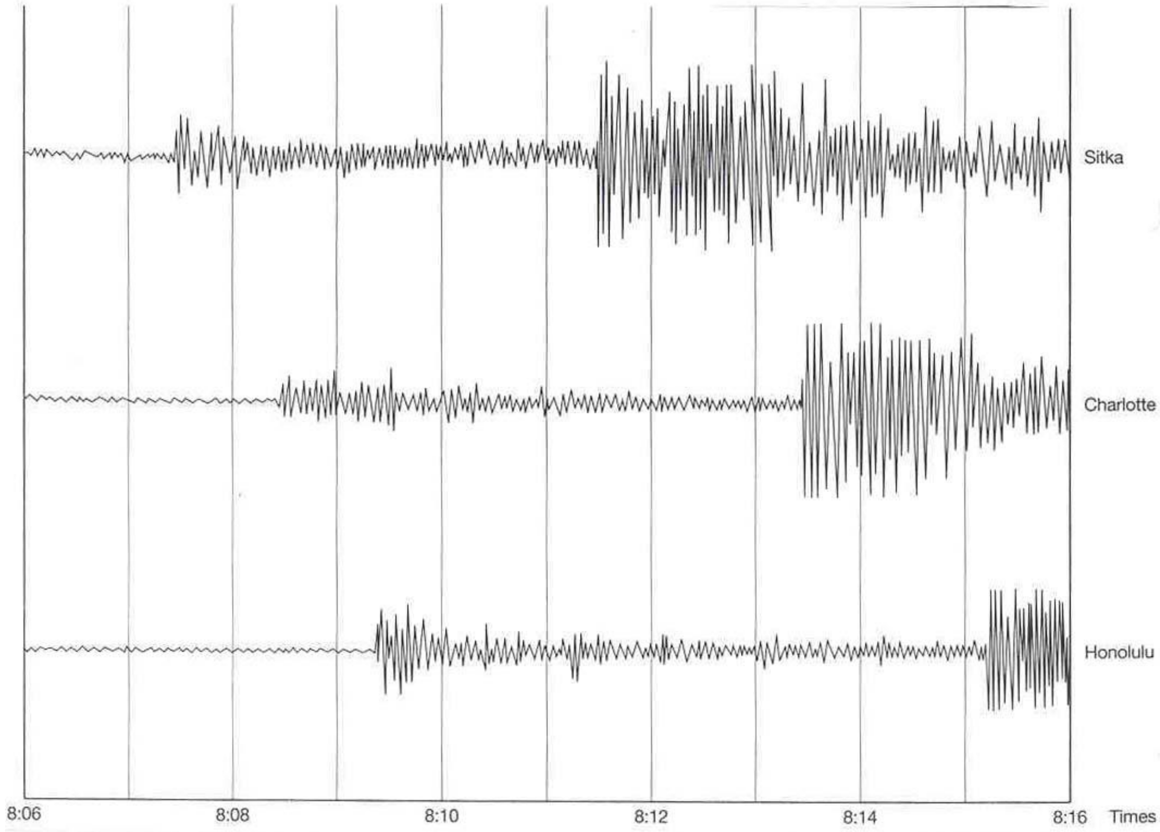


Figure 8. Seismograms from three different locations
Time on x-axis is in hours:minutes. Example: 8:06 is 8:06 am

STEP 1 – Determining time difference between P- and S-wave arrivals at station

Lay a strip of paper along the time axis of one of the above **seismograms**. Mark a dot where the P wave first appears and then one where the S wave first appears. Move the first dot to a specific, known time on the time axis and approximate the total time difference between the two dots. Write the time difference below. Repeat for each station.

Station	**Time difference between P and S arrival** *(calculate using step 1 instructions above)*	**Distance from earthquake** *(calculate using step 2 instructions on next page)*
Sitka, Alaska		
Charlotte, North Carolina		
Honolulu, Hawaii		

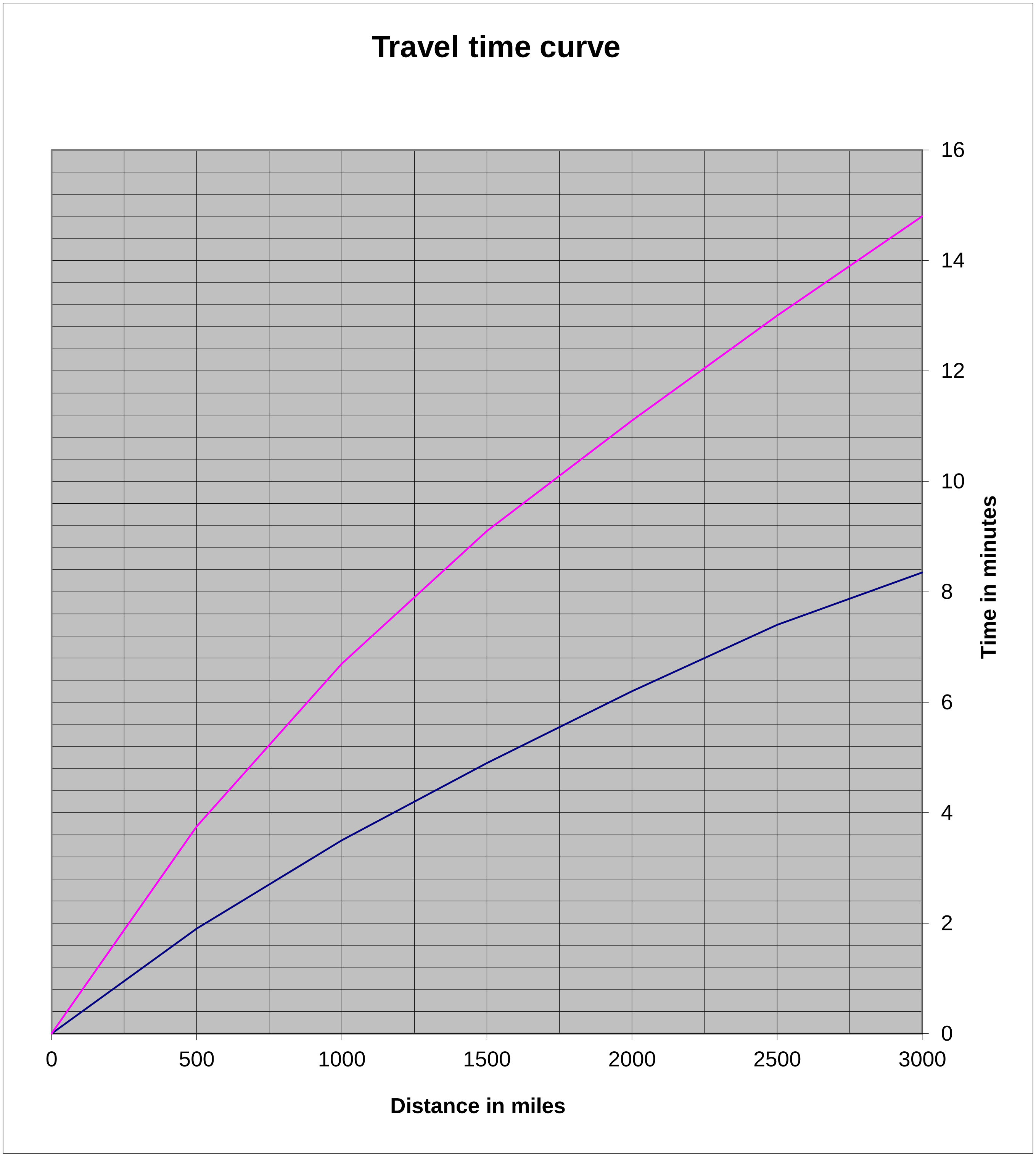


Figure 9. P-Wave curve on bottom; S-Wave curve on top. Travel Time Curve – how long to travel various distances.

STEP 2 – Determining distance from station to earthquake

THE TIME SCALE ON THIS GRAPH IS DIFFERENT THAN PREVIOUS ONE so you will have to remeasure your time intervals. Lay a strip of paper along the time axis of the **travel-time curve above (Y axis). Mark a dot at t=0; Mark a second dot when t = the time that you determined in step 1 for the first station.

Keeping the strip of paper vertical, place the bottom dot on the P curve. Move the strip across the travel-time curve, keeping the bottom dot always on the P curve, and keeping the strip vertical. When the top dot intersects the top S curve (the bottom dot still on the P curve), stop. Draw a vertical line down to the x-axis and that is the distance that station is away from the earthquake! Write that distance down in table on preceding page. Repeat for each station.

STEP 3 – Finding the location of the earthquake

Using the latitude and longitude information below, locate and draw a dot for each station.

Sitka: 57N, 135W | Charlotte: 35N, 81W | Honolulu: 21N, 158W

For each station, take a compass and, using the scale bar above, open it up to the exact distance you calculated already between the earthquake and that station. Then draw a circle around that dot of that distance/radius. The earthquake is somewhere on that circle. Repeat for all stations.

Where the three circles, intersect, that is the location of the earthquake. (Put an X above at that location.)

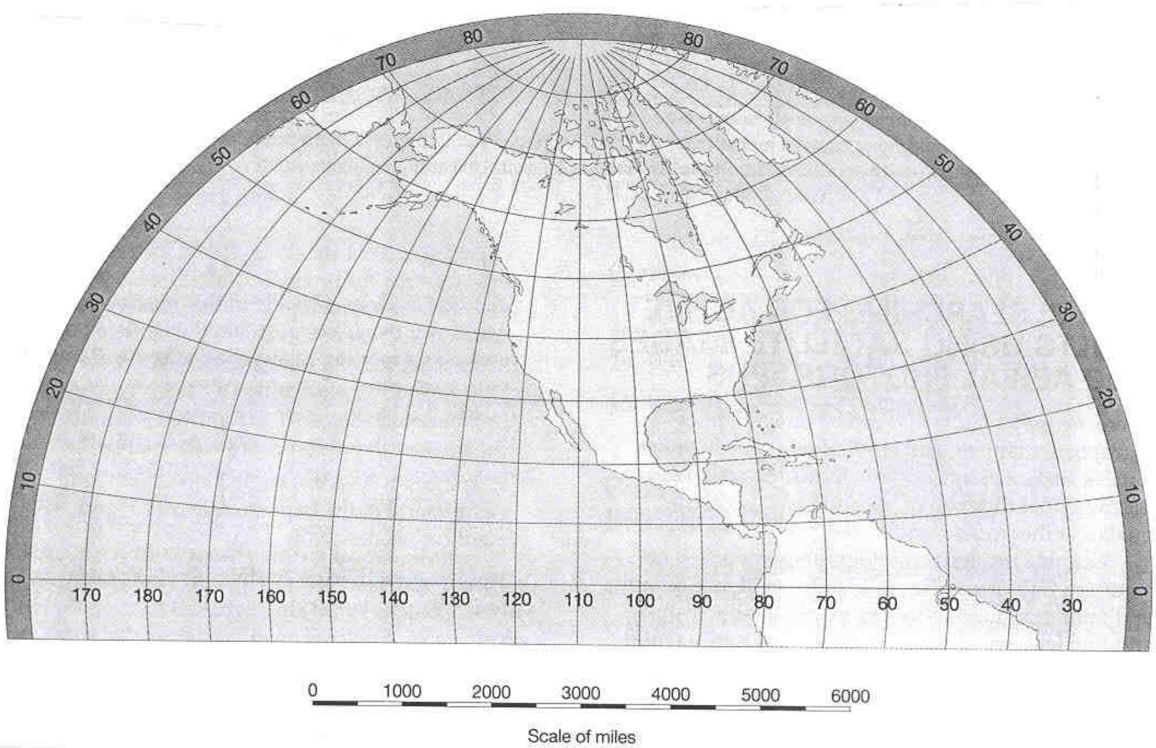


Figure 10. World map with latitude and longitude lines

STEP 4 – When did the earthquake occur?

Go back to the seismogram images on the first page of this assignment and for a particular station, determine the time of arrival of the P wave. Then go back to the Time-Travel curve (Step 2 – Figure 9) and based on the distance this station was from the earthquake, how much time would it take for a P-wave to travel that distance? Subtract that number from the arrival time, and you'll get the departure time! Repeat for all stations and compare answers.

Station	**Arrival time of P wave**	**Distance from earthquake**	**Time it takes P wave to travel that distance** **Measured from Step 2, Fig. 9*	**Departure time (time of earthquake)**
Sitka				
Charlotte				
Honolulu				

OPTIONAL ACTIVITY: Calculating Earthquake Magnitude

The Richter scale was developed by Charles Richter in the 1930s as a quick method of classifying the size of southern California earthquakes. To determine the Richter magnitude, you need to use a particular type of seismogram (one recorded on a Woods-Anderson seismograph), which is particularly sensitive to high-frequency earth vibrations. The seismogram must be recorded within 600 km of the epicenter. The figure on the next page provides a method for calculating earthquake magnitude based on the distance to the epicenter and the maximum amplitude of the seismogram. (Amplitude is the height above the center line of the largest wave on the seismogram.)

How large is the seismogram amplitude if the earthquake has a magnitude of 2 and the seismograph is 100 km from the epicenter? Draw a straight line from 100 on the distance scale to 2 on the magnitude scale. Extend your line to the amplitude scale.

1. Per example above, draw lines on next page between scales to match the data below, and then based on line result, determine amplitude and complete this table:

Distance from epicenter (km)	**Magnitude**	**Amplitude (mm)**
100	2	
100	3	
100	4	
100	5	

2. Based on your measurements, complete this sentence:

An increase of 1 on the magnitude scale increases the amplitude of the seismic waves by a factor of _____.

Estimating Energy Release (requires scientific calculator)

When slip occurs on a fault, elastic energy is released in much the same way that elastic energy is released when a rubber band is snapped. Some of this energy escapes in the form of seismic waves. There is a rough correlation between the amount of energy released during an earthquake and the magnitude of the earthquake:

Energy (joules) = 10 to the power of (5.24 + (1.44 x Magnitude)) $E = 10^{(5.24 + (1.44 \times M))}$

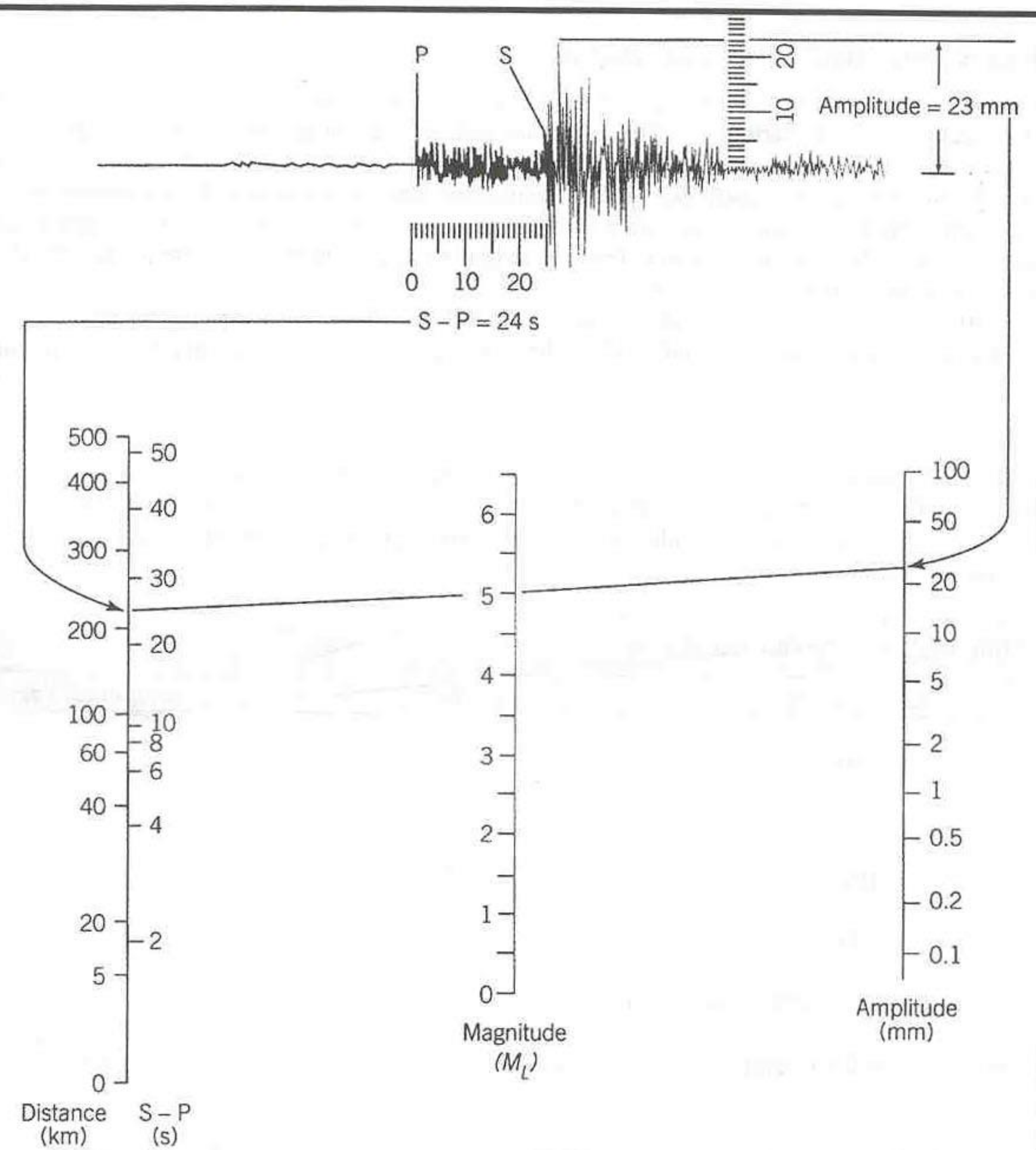
3. Modern seismographs can measure earthquakes with Richter magnitudes as small as –2. How much energy is released by an M=-2 earthquake?

4. How much energy is released by an M=-1 earthquake?

5. How much energy is released by an M=0 earthquake?

6. How much of an energy increase occurs as Richter magnitude increases by 1? What's the factor? (Divide the two numbers.)

As comparison, the energy released in an M=-2 earthquake is the same amount as released when a 23 kg (10.4 lb) weight is dropped from 1 meter. To make similar comparisons for other energy values, simply divide the energy released in the earthquake by 10, and you'll calculate the size weight that must be dropped from 1 meter to produce the same amount of energy.



Procedure for calculating the local magnitude, M_L

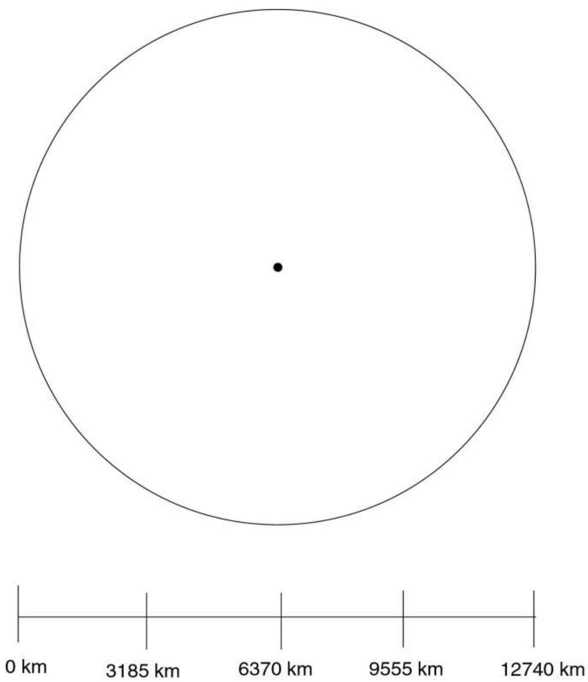
1. Measure the distance to the focus using the time interval between the S and the P waves (S – P = 24 s).
2. Measure the height of the maximum wave motion on the seismogram (23 mm).
3. Place a straight edge between appropriate points on the distance (left) and amplitude (right) scales to obtain magnitude $M_L = 5.0$.

Figure 11. Richter Scale

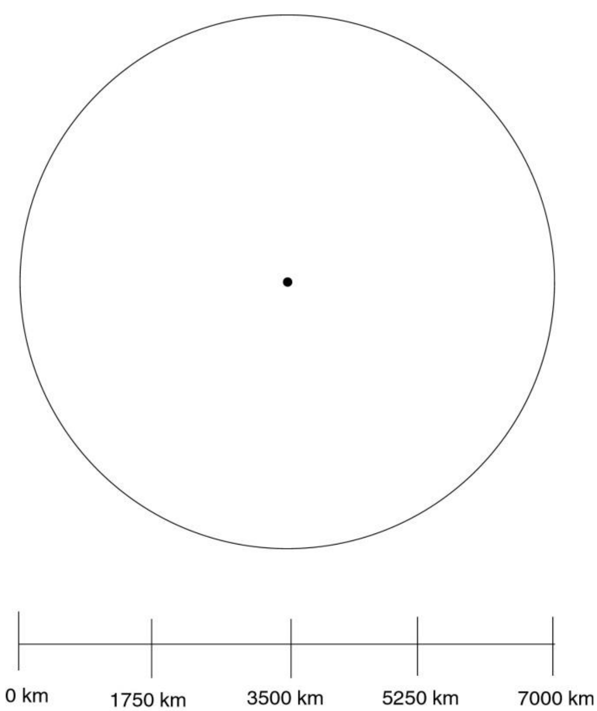
OPTIONAL ACTIVITY: Calculating the Radius of Earth's Core

EARTH CROSS-SECTION THROUGH EQUATOR

The circle IS the surface of the Earth. The dot is the center of the core.



MARS CROSS-SECTION THROUGH EQUATOR



Instructions

1. Pick a point on the Earth surface and make that the epicenter of the earthquake. Draw a dashed line between this surface and the center dot of core.
2. With a protractor, measure a 103° arc right and left of this line. Put a dot at the location on Earth's surface 103° away on each side. (Place protractor's center spot on Earth's center. Line up protractor's bottom line along radial line you just drew. Measure 103° in one direction, then flip the protractor and do the same again in the other direction.)
3. Draw a slightly curved line (seismic ray) from the earthquake epicenter through the Earth to the points 103° away (bend it slightly, as shown in the book, to represent the refraction through some of Earth's layers—don't worry if not precise, just be consistent).The area within the ray will receive S waves; the area outside is the shadow zone.
4. Repeat this procedure for 3 other random epicenters around and on the planet surface.
5. Use a compass to draw a circle that lies just below the bottom arcs of each seismic ray you drew. This is in Earth's core/mantle boundary, off which the rays deflect.
6. Measure the radius of the circle you just drew (compare with scale).
7. The correct answer for the radius of the Earth's core is 3370km. How close is your answer to the correct one? Why are there differences?

8. Use the same general procedure to determine the radius of Mars' core, if the planet has a radius of 3400 km, and an S-wave shadow zone that begins 7000 km or 118° away on the surface.

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Evaluate the causes and consequences of earthquakes globally.	A | B | C | D | F	
Analyze the factors that contribute to increased damage during an earthquake.	A | B | C | D | F	
Compare and contrast the physical and chemical properties of the various layers of planet Earth.	A | B | C | D | F	
Evaluate the evidence supporting the properties and thicknesses of Earth's layers.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

MINERALS

A **mineral** is a naturally occurring, inorganic solid with a characteristic chemical composition, distinctive physical properties, and a definite internal atomic arrangement (crystal structure). A **rock** is an aggregation of crystals or grains of one or more minerals. Examples:

- **Granite** is an **igneous rock** that contains these minerals: Quartz, Micas (Biotite or Muscovite), and Potassium Feldspar
- Liquid mercury (Hg), or **quicksilver**, is NOT a mineral. It becomes a mineral when it freezes at -40°C.
- **Sugar** ($C_6H_{12}O_6$) is organic (contains C, H, and O), so sugar is NOT a mineral.
- Salt (NaCl) is inorganic. Salt is a mineral called **Halite**.
- **Glass** (Si + O, not bonded in a crystalline structure) is NOT a mineral.

Minerals have chemical formulas, which indicate the relative proportions of atoms that make up the mineral. These atoms bond to each other in a specific geometric arrangement (making them **crystalline**). For example, *Galena* – PbS – has equal amounts of Lead (Pb) and Sulfur (S) atoms. The way that these atoms bond and arrange themselves determines the shape of the crystals that form. Some minerals can have a range of options. For example, *Olivine* – $(Mg,Fe)_2SiO_4$ – has 7 types of atom sites; 1 of every 7 is held by Silicon (Si), 4 by Oxygen (O), and 2 by either Magnesium (Mg) or Iron (Fe). The amount of Mg or Fe can vary, which does change the shape and color of the mineral to some extent, but leaves it still as the Olivine mineral.

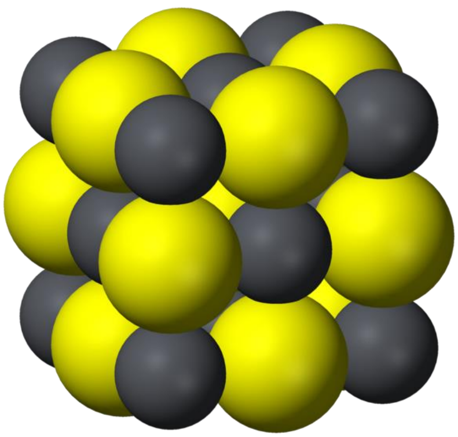


Figure 1. Crystalline shape and atomic bonding of Galena, PbS. Image: Ben Mills – Public Domain.

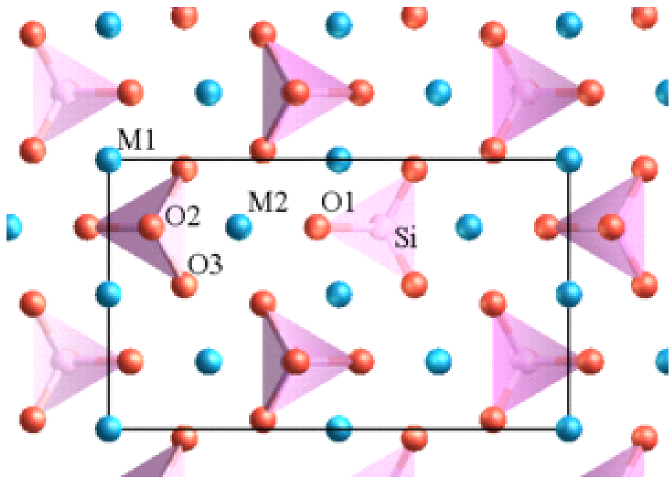


Figure 2. Underlying crystalline shape and atomic bonding of olivine. Image: Matanya – Public Domain.

Table 1: Bonding types

	Covalent bonds	Ionic bonds	Hydrogen bonds
Description	Shared electrons to complete outer shell.	Atoms exchange electrons to complete outer shell. Now atoms are ions that are oppositely charged and attracted to each other.	Water molecules (because of shape) have a slightly positive end and slightly negative end. These molecules are attracted to each other and to other ions.
Relative strength	Strongest	Medium	Weakest
Example	Diamond Quartz Water (between H and O atoms)	Halite (salt)	Water (between water molecules – how they stick to each other)

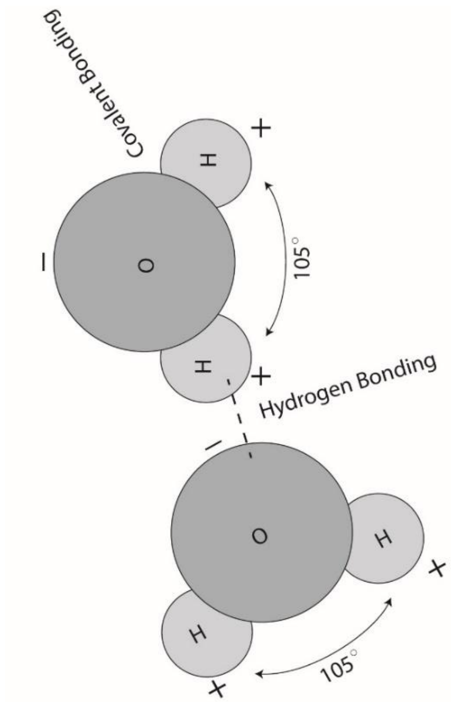


Figure 3. Two water molecules bonded loosely through a hydrogen bond.

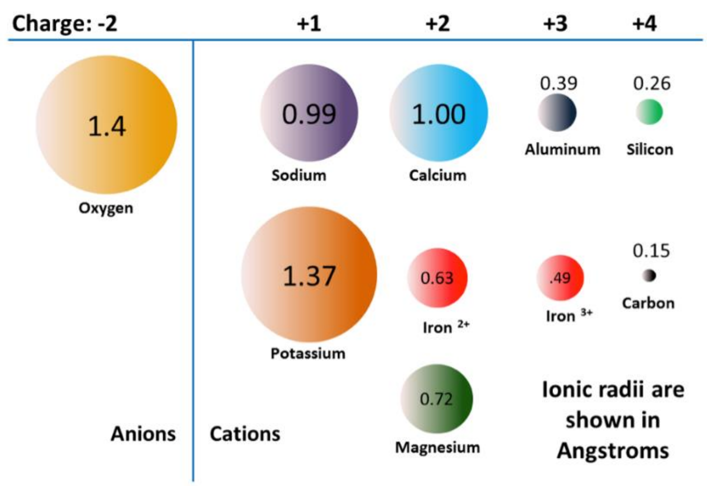


Figure 4. The ionic radii (effective sizes) in angstroms, of some of the common ions in silicate minerals. When atoms not part of the chemical formula slip into a crystal structure and substitute for one of the main atoms, it skews the crystal shape in that location (because of the different size and charge of the substituting atom). Result: light interacts differently with the crystal structure and different colors can result.

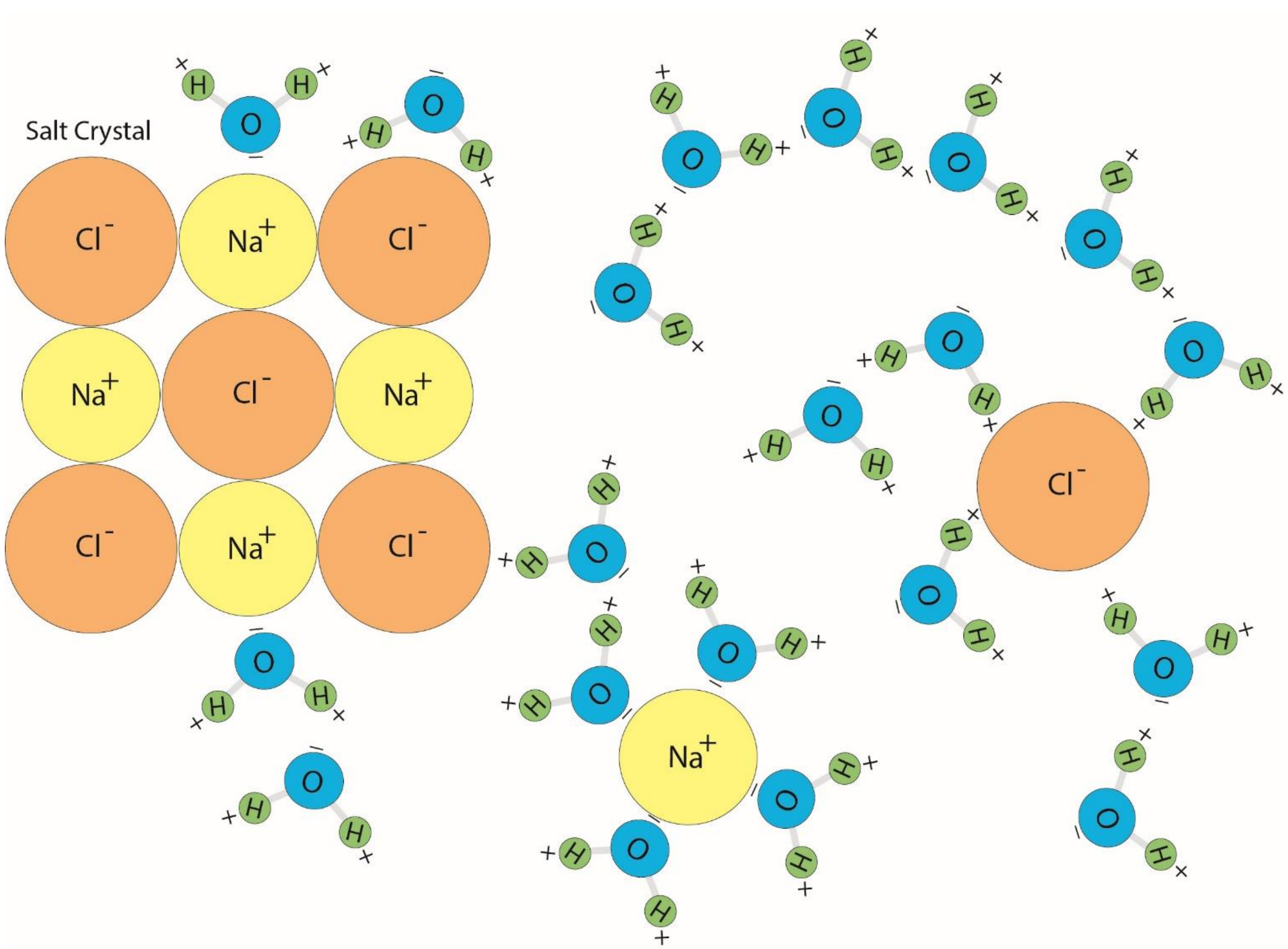


Figure 5. Salt (NaCl) crystal with IONIC BONDING between Na+ and Cl-. Image shows dissolution of salt by hydrogen bonding water.

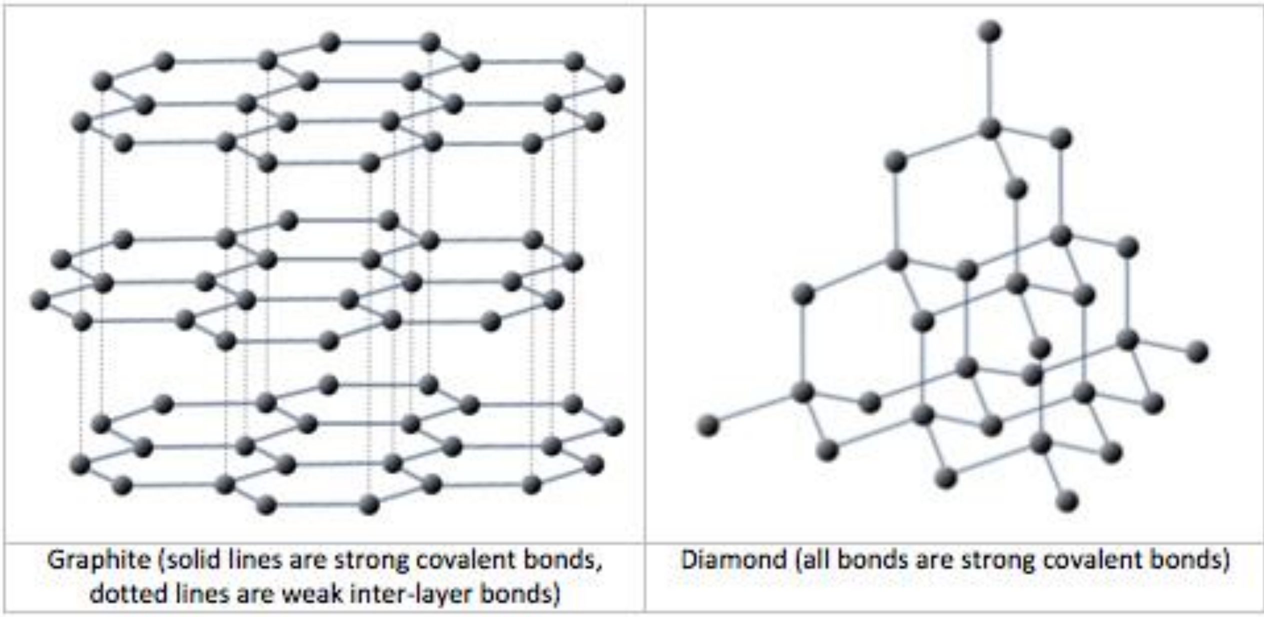


Figure 6. Polymorphs Graphite and Diamond – they share a chemical formula—C—but have different crystalline arrangements and hence are different minerals. Steven Earle, Physical Geology, CC Attribution 4.0 International License

WHAT PHYSICAL PROPERTIES HELP US IDENTIFY MINERALS?

CRYSTAL SHAPE OR HABIT

If a crystal grows without obstruction, it can develop flat edges called crystal faces, which reflect the internal crystal structure. Most minerals do not display perfect crystal shape, because they did not have enough space to grow. (Crystals are common in caves and rock cavities.) Sample crystal shapes: cubic, rhombohedral, prism that comes to point.

HARDNESS

Hardness is a mineral's ability to resist scratching. Moh's hardness scale consists of 10 minerals arranged in order of increasing hardness from 1 (softest) to 10 (hardest). Hardness is a relative property, not absolute. If mineral A scratches mineral B, then the scratched mineral (B) is softer.

Table 2. Moh's Hardness Scale

1. Talc	**Other items:**
2. Gypsum	
3. Calcite	2.5 fingernail or copper, including pennies *(post 1900 pennies)*
4. Fluorite	3.5 brass
5. Apatite	4.5 iron wire or nail
6. Orthoclase	5.5 glass or masonry nail or knife blade
7. Quartz	6.5 streak plate
8. Topaz	
9. Corundum	
10. Diamond	

COLOR

Color is often the least useful diagnostic tool, as many minerals appear in a large range of colors. Why? **Ionic substitution**. When atoms substitute in small amounts for main elements in a mineral's crystal structure (too small a substitution to impact overall chemical formula), the atomic structure is deformed in the area of the substitution, and light will absorb or refract/reflect differently in that area. These small substitutions can be enough to change the color of the mineral. For example, the mineral corundum (Al_2O_3) is brown. With a little titanium and iron substitution for aluminum corundum will turn blue (and is called sapphire); with a little chromium substitution for aluminum, corundum turns red (and is called ruby). Note: If the substitution is significant enough to change the chemical formula, it's a new mineral. There are a few minerals, however, that are associated with one particular color. Color clarity is defined as **transparent** (clear like window glass), **translucent** (foggy, like looking through sanded glass), or **opaque** (doesn't transmit light – like metals). **Streak** is the color of the mineral when ground to a powder. You determine streak by scratching the mineral across a streak plate and viewing the powdered material left behind. Streak is a much better diagnostic tool than color, as streak does not usually vary for a mineral.

LUSTER

Luster is the appearance (quality and intensity) of light reflected from a mineral surface. Minerals are separated into two categories: those with metallic luster and those without. We can further classify luster as silky, resinous, glassy, greasy, pearly, dull, and earthy.

CLEAVAGE & FRACTURE

Cleavage describes the tendency of a mineral to break along flat surfaces (planes). These surfaces correspond to planes of weak bonds in the mineral's crystal structure. For example, micas are sheet silicates, which means they are made up primarily of strong sheets of silicon and oxygen atoms. These individual sheets are bonded to each other through weak bonds made with atoms like Fe, Mg, Ca, etc. When micas are hit, they break most easily between sheets.

We describe cleavage by the number of unique cleavage planes (parallel planes are not unique) and the angle between those planes. Since micas cleave in sheets, they exhibit one direction of cleavage (no angle measurement between different cleavage surfaces, because there's only one surface). Note: Sometimes it is difficult to tell the difference between cleavage faces and crystal faces. Look at the edges of the surface to see if it looks broken or if it looks like it grew that way. Broken surfaces tend to have a step-like look on their corners or edges. Crystal faces are more regular and smooth. Note: in many cases cleavage planes are the same planes as crystal faces.

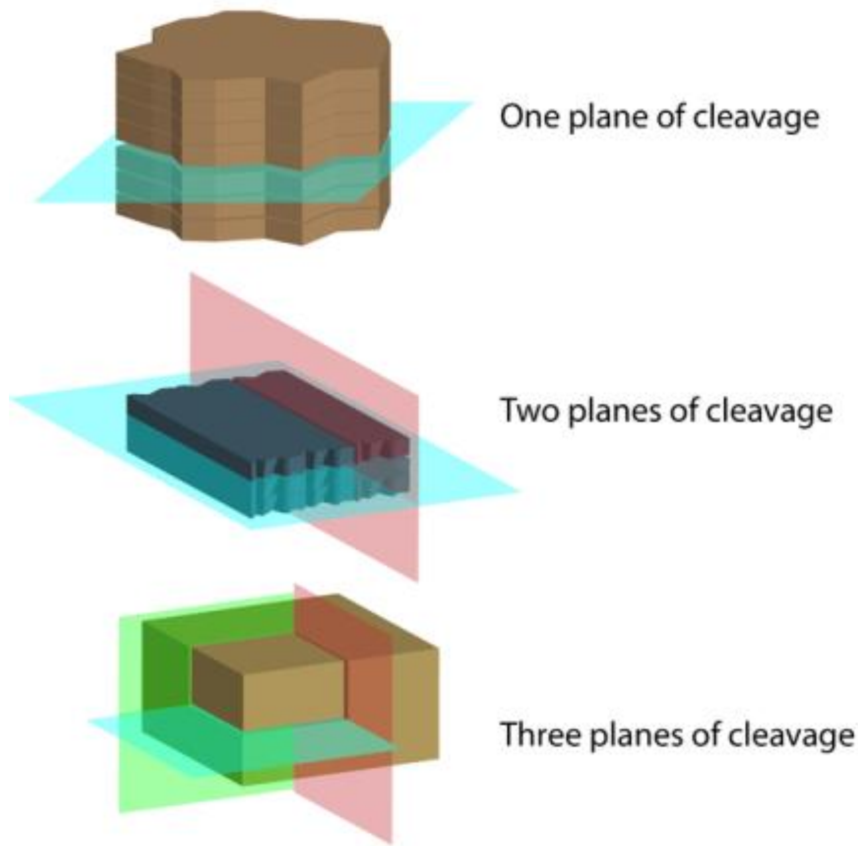


Figure 7. Cleavage planes in 3D.: Jillcurie – Creative Commons – CC BY-SA 3.0

Fracture is a description of how a rock breaks when it doesn't cleave along a plane. Most fractures are irregular and nondiagnostic, but some, like conchoidal, even, and splintery fracture can be helpful in identifying minerals.

Olivine, garnet, and quartz are well known for their conchoidal fracture (which is the typical fracture pattern you see when you break nontempered glass – a clamshell-like appearance).

Mineral types

Although there are 1000s of minerals known on Earth's surface (and new ones being discovered yearly), only a few are considered common rock-forming minerals. Only a few elements make up the majority (99%) of Earth's crust. The mineral made up of these elements, therefore, are the most commonly found. Since Oxygen and Silicon represent over 75% of the Earth's crust (by weight), the minerals made up of Silicon and Oxygen are the most abundant. These minerals are called Silicates. Their basic molecular building block is the Silicon-Oxygen tetrahedron, a molecule that consists of one Silicon atom surrounded by four Oxygens, in the shape of a tetrahedron. These tetrahedron connect to each other and other elements, like Fe and Mg, to create a range of different silicate minerals – all with crystal shapes that reflect their underlying molecular structure. The most abundant elements in Earth's crust (in decreasing weight percent abundance) are Oxygen (O) 47%; Silicon (Si) 28%; Aluminum (Al) 8%; Iron (Fe) 5%; Calcium (Ca) 3.6%; Sodium (Na) 2.8%; Potassium (K) 2.6%; Magnesium (Mg) 2.1%.

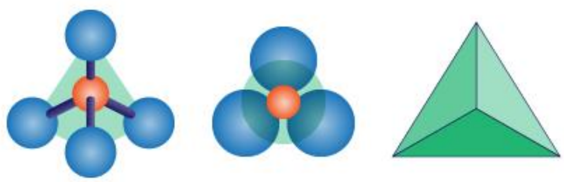


Figure 8. Three ways of drawing the silica tetrahedron: a) At left, a ball & stick model, showing the silicon cation in orange surrounded by 4 oxygen anions in blue; b) At center, a space filling model; c) At right, a geometric shorthand.
Image: Anne E. Egger, Ph.D. "The Silicate Minerals" Visionlearning Vol. EAS-2 (9), 2006

Table 3. Mineral Groups and Chemical Formulas (Summary)

Silicates

Amphibole family: Hornblende $(Ca,Na)_{2\text{-}3}(Fe,Mg,Al)_5Si_6(Si,Al)_2O_{22}(OH)_2$

Feldspar family:

- Plagiociase Feldspars: $CaAl_2Si_2O_8$ to $NaAlSi_3O_8$
- Potassium Feldspars: $KAlSi_3O_8$

Garnet $X_3Y_2(SiO_4)_3$ where X and Y are combinations of Ca, Mg, Fe, and Al

Mica family:

- Biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$
- Muscovite $KAl_3Si_3O_{10}(OH)_2$

Olivine $(Mg,Fe)_2SiO_4$

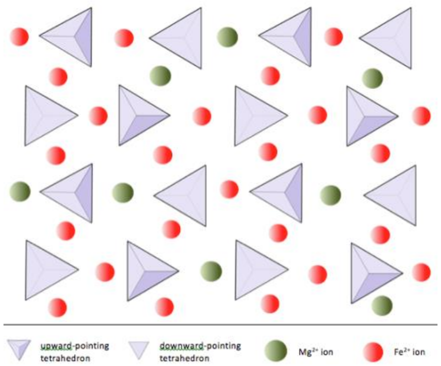
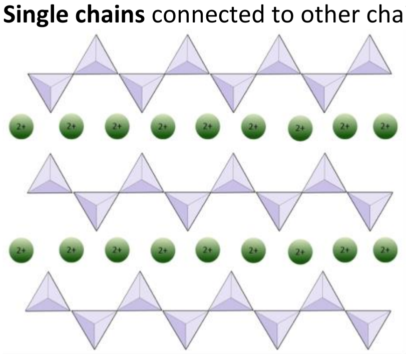
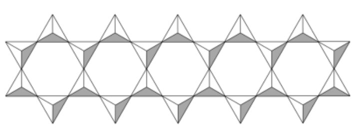
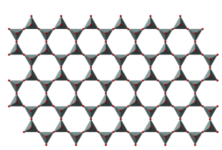
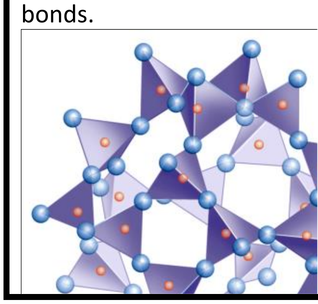
Pyroxene family: *Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$

Quartz SiO_2

Serpentine $Mg_6Si_4O_{10}(OH)_8$

Talc $Mg_3Si_4O_{10}(OH)_2$

Carbonates	**Sulfates**	**Native elements**
Calcite $CaCO_3$	Gypsum $CaSO_4 \cdot 2(H_20)$	Graphite C
Sulfides	**Halides**	**Oxides**
Galena PbS	Fluorite CaF_2	Hematite Fe_2O_3
Pyrite FeS_2	Halite NaCl	Magnetite Fe_3O_4

Table 4. Silicate structure	Cleavage type	Examples	Si:O ratio
Single Si-O tetrahedron connected to other tetrahedron by ionic bonds.  *Steven Earle, Physical Geology, CC Attribution 4.0 International License*	None	**Olivine** $(Mg,Fe)_2SiO_4$ **Cleavage:** None	1:4
Single chains connected to other chains by ionic bonds.  *Steven Earle, Physical Geology, CC Attribution 4.0 International License*	2 planes at 90° (square columns) or hairs/fibers	**Pyroxene** family: Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$	1:3
Double chains connected to other chains by ionic bonds. 	2 planes at 60 and 120° (sheared columns) or hairs/fibers	Amphibole family: **Hornblende** $(Ca,Na)_{2-3}(Fe,Mg,Al)_5Si_6(Si,Al)_2O_{22}(OH)_2$	1:2.75
Sheets connected to other sheets by ionic bonds. 	1 plane	Mica family: **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$ **Muscovite** $KAl_3Si_3O_{10}(OH)_2$	1:2.5
Three dimensional framework of Si-O tetrahedrons with Aluminum tetrahedron substituting for Silicon tetrahedron in 25-50% of the sites (leaves excess charges that require ionic bonding with other cations within the structure).	2 planes at 90° (square tablets)	**Feldspar** family: $CaAl_2Si_2O_8$ AND $NaAlSi_3O_8$ AND $KAlSi_3O_8$	1:2
Three dimensional framework of Si-O tetrahedrons only with no ionic bonds. 	None	**Quartz** SiO_2	1:2

Mineral Identification Tables

Review and be able to distinguish diagnostic characteristics of each of the minerals listed in the following tables (if these descriptions showed up in a multiple-choice exam, you could match them to the correct mineral.)

Table 5. NONMETALLIC MINERALS (listed in decreasing hardness) Review mineral formula to connect to family! H=Hardness; SG = specific gravity (density)

Mineral	H	SG	Streak	Color (and/or luster)	Form	Cleavage/Fracture	Diagnostic properties
Garnet $X_3Y_2(SiO_4)_3$ *where X and Y are combinations of Ca, Mg, Fe, Al*	7	3.5-4.3	White	Red, black, or brown; can be yellow, green, pink. Glassy. Translucent.	Dodecahedrons (12-sided polygons)	No cleavage. Brittle. Conchoidal fracture.	Dodecahedron form, red, glassy, conchoidal fracture, H=7.
Olivine $(Mg,Fe)_2SiO_4$	7	3.3-3.4	White	Pale or dark olive green to yellow-green or brown-green. Glassy. Transparent.	Short prisms (usually too small to see).	Conchoidal fracture. Brittle.	Green, conchoidal fracture, glassy, H=7. Usually granular.
Quartz SiO_2	7	2.7	White	Colorless, white, or gray; can occur in all colors. Glassy and/or greasy.	Massive; or hexagonal prisms that end in a point.	Conchoidal fracture.	Glassy, conchoidal fracture, H=7. Hex. prism with point end.
Plagioclase Feldspar family: Anorthite and Labradorite $CaAl_2Si_2O_8$ to Oligoclase and Albite $NaAlSi_3O_8$	6	2.6-2.8	White	Colorless, white, gray, or black; can have iridescent play of color from within. Translucent to opaque.	Tabular crystals or thin needles	2 good cleavage planes at nearly right angles.	Twinning. Irridescent colors (blues and greens). 2 cleavages at 90°. H = 6.
Potassium Feldspar family: Orthoclase and Microcline $KAlSi_3O_8$	6	2.5-2.6	White	Pink. Or white, orange, brown, gray, green. Translucent to opaque.	Tabular crystals	2 good cleavage planes at nearly right angles.	Subparallel exsolution lamellae. 2 cleavages at 90°. Pink color.
Pyroxene family: Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$	5.5-6	3.2-3.5	White, pale grey	Green to black; opaque.	Short, 8-sided prisms (if visible).	2 good cleavage planes at nearly right angles.	H=5.5. Dark green or black. 2 cleavages at 90°. (Looks like HB.)
Amphibole family: **Hornblende** $Ca(Mg,Fe)_4Al(Si_7Al)O_{22}(OH)_2$	5.5	3-3.3	Grey-green, white	Dark green to black. Opaque.	Long, perfect prisms.	2 cleavages planes. Angles: 60° and 120°. Brittle. Splintery fracture.	H=5.5. Dark green or black. 2 cleavages at 60° & 120°. Splintery fracture. Long prisms.
Serpentine $Mg_6Si_4O_{10}(OH)_8$	2-5	2.2-2.6	White	Pale or dark green, yellow, grey. Opaque. Dull or silky.	Smooth, rounded masses.	No cleavage.	Mottled green color. Smooth, curved surfaces. No cleavage. Waxy luster. H: 2-5
Fluorite CaF_2	4	3-3.3	White	Colorless, purple, blue, grey, green, or yellow. Glassy. Opaque to transparent. Rainbow luster in places.	Usually cubes or octahedrons.	4 excellent cleavage directions. Gives crystal shape triangular faces. Brittle.	Cubic or octahedral form. 4 directions of cleavage. Triangular faces. Rainbow luster in places.

Mineral	H	SG	Streak	Color (and/or luster)	Form	Cleavage/Fracture	Diagnostic properties
Calcite $CaCO_3$	3	2.7	White	Usually colorless, white, or yellow, can be green, brown, or pink. Glassy. Opaque to transparent.	Rhombohedrons.	3 excellent cleavage planes. Angles: < 90° and > 90°.	Bubbles in HCL. Double refraction (2 images visible through clear sample). Rhombs, 3 cleavage planes (not 90°), H=3.
Mica family: **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	2.5-3	2.7-3.1	Grey-brown	Black, green-black, brown-black. Transparent to opaque.	Short tablets. Like a tablet of paper.	1 excellent cleavage – splits easily into thin, flexible sheets.	1 flexible cleavage plane (sheet), dark colored; brown streak.
Mica family: **Muscovite** $KAl_3Si_3O_{10}(OH)_2$	2-2.5	2.7-3	White	Colorless, yellow, brown, or red-brown. Transparent to opaque.	Short tablets. Like a tablet of paper.	1 excellent cleavage – splits easily into thin, flexible sheets.	1 flexible cleavage plane (sheet), light colored; white streak.
Halite NaCl	2.5	2.1-2.6	White	Colorless, white, yellow, blue, brown, or red. Glassy.	Cubes.	Brittle. 3 excellent cleavage planes: cubes.	Salty taste. H=2.5. Cubic form and cleavage. Usually clear.
Gypsum $CaSO_4*2(H_20)$	2	2.3	White	Colorless, white, or grey. Translucent to transparent.	Tabular, prisms, blades, or needles.	1 good cleavage plane.	H=2. 1 cleavage plane. Translucent.
Talc $Mg_3Si_4O_{10}(OH)_2$	1	2.7-2.8	White	White, grey, pale green, or brown. Opaque. Greasy or silky luster.	Shapeless masses (if no cleavage visible) or tabular.	1 poor cleavage plane (may not be visible).	Feels greasy or soapy. H=1. Opaque.

Table 6. METALLIC MINERALS (listed in decreasing hardness) Review mineral formula to connect to family! H=Hardness; SG = specific gravity (density)

Mineral	H	SG	Streak	Color	Form	Cleavage/Fracture	Diagnostic properties
Pyrite FeS_2	6-6.5	5	Dark grey	Brass yellow; tarnishes brown.	Cubes or octahedrons	Brittle. No cleavage.	Cubic form, brassy color, and SG=5.
Magnetite Fe_3O_4	6	5.2	Dark grey	Silvery grey to black. Tarnishes grey. Opaque.	Octahedrons	No cleavage.	Attracted to a magnet. SG=5.2. No cleavage.
Hematite Fe_2O_3	1.5-6	2.1-2.6	Red to red-brown	Silvery grey, black, or brick red. Luster can also be nonmetallic.	Thin tabular crystals or shapeless masses.	No cleavage.	Red streak. Metallic + nonmetallic. Earthy red.
Galena PbS	2.5	7.6	Grey to dark grey	Silvery grey. Tarnishes dull grey.	Cubes and octahedrons	Brittle. 3 good cleavage planes (cubes).	SG=8. Dense! Silver cubes (form and cleavage).
Graphite C	1	2.1-2.3	Dark grey	Silvery grey to black.	Flakes, short hexagonal prisms, and masses.	1 excellent cleavage plane.	Dark grey. H=1. Greasy. Dark grey streak.

MINERAL RESOURCES

The following excerpt is from the USGS Mineral Resources website: https://minerals.usgs.gov

"Did you know that the average automobile contains more than a ton of iron and steel, 240 lbs of aluminum, 50 lbs of carbon, 42 lbs of copper, 41 lbs of silicon, 22 lbs of zinc, and more than thirty other mineral commodities, including titanium, platinum, and gold? Do you know the cost of a pound of copper or an ounce of platinum? Though you are constantly reminded of the importance of gasoline, and its cost, to keep the car running, do you ever think about the importance and cost of the mineral materials that make up the car? Do we take minerals for granted?"

"When the power goes out, few of us give a second thought about the copper and aluminum needed to carry electricity from the power plant to our homes or offices. When the battery dies, you do not automatically think about the lead, nickel, cadmium, or lithium used to make the batteries that store power for our cell phones, MP3 players, or hybrid cars, because you do not buy minerals, you buy products that have been manufactured using mineral materials. But without these nonfuel mineral commodities, many things that we take for granted would not work."

"Minerals in the environment and products manufactured from mineral materials are all around us and we use and encounter them every day. They impact our way of life and the health of all that lives. Minerals are critical to the Nation's economy and knowing where future mineral resources will come from is important for sustaining the Nation's economy and national security."

"Our homes and office buildings contain many mineral materials:

- Drywall is made from gypsum,
- Concrete in the foundation is made with limestone and aggregate reinforced with steel rebar,
- Bricks are made from clay,
- Titanium oxide is used to make paint,
- Silica is used to make windows,
- Electrical wiring is made from copper,
- Iron and copper are used to make pipes for plumbing, and
- Faucets contain various combinations of iron, chromium, nickel, and molybdenum combined to make stainless steel."

"Bicycling, baseball, and horse racing are examples of hobbies and recreational activities that rely on a variety of mineral materials. Some things we use for our favorite hobbies and recreation also rely on mineral materials to make them stronger, lighter, and more flexible. Advances in materials science have allowed bicycles, once largely made of steel, to incorporate parts made of aluminum, carbon fiber, magnesium, and titanium that make them lighter and more durable. Aluminum, fiberglass, graphite, titanium, zirconium, beryllium, copper, tungsten, and steel have replaced wood in baseball bats, tennis racquets, and golf clubs to make them lighter and stronger. Race tracks, as well as playing surfaces for baseball and tennis, are a prescribed mixture of clay, sand, and silt. Calcined clay (a clay that has been heated) readily absorbs water to dry wet spots on fields and it is used to reduce soil compaction. It is also used on infield areas of baseball diamonds and on fields and tracks because it does not stick to cleats or hooves."

"We use minerals every day to grow, prepare, and eat our food. Much of our food is grown using fertilizers made from phosphate and potash. Meat and poultry come from animals that eat fodder grown with mineral-based fertilizers that may be supplemented with selenium, phosphorus, or zinc. Modern tools for safe food storage and preparation (such as, refrigerators and stoves) are made from many mineral commodities and rely on copper wires for electric power or copper pipe for natural gas. At the table, salt is used for seasoning, cutlery is made from stainless steel or may be silver plated, plates are made from clays, and glassware is made from silica (or perhaps on special occasions it is lead crystal)."

"Many of the minerals that our bodies require for good health, such as calcium, magnesium, iron, potassium, and zinc, we get from food. And while we need an adequate supply of many different minerals, there are negative health consequences resulting from exposure to some mineral materials or elevated levels of otherwise good minerals. Some of these minerals come from our everyday contact with the air, water, and ground in our surroundings. Some of them we are exposed to by man-made disturbances to the natural environment or as a result of a wide range of natural disasters."

"As standards of living rise around the world, there is greater demand for durable goods and products manufactured from mineral materials. As large emerging economies, such as China and India, increase their participation in the global economy, demand for critical mineral resources is increasing at a rapid rate. That means that we are depleting our known mineral deposits at an increasing rate, requiring that new deposits be found and put into production."

"Every year, each person in the U.S requires more than 25,000 pounds of new nonfuel minerals to make the items we use every day. "

Table 7. Every American born in 2008 is estimated to use the following amounts of nonfuel mineral commodities in their lifetime for their necessities, lifestyles, and health.

Mineral commodity	Amount required over a lifetime
Aluminum (bauxite)	5,677 pounds
Cement	65,480 pounds
Clays	19,245 pounds
Copper	1,309 pounds
Gold	1,576 ounces
Iron ore	29,608 pounds
Lead	928 pounds
Phosphate rock	19,815 pounds
Stone, sand, and gravel	1.61 million pounds
Zinc	671 pounds

Data from U.S. Geological Survey and U.S. Energy Information Administration; statistical analysis by National Mining Association. Source of information:

Table 8. Some select resources and their uses:

Resource	Use
Limesone	Cement, steelmaking, soil amendments, chemical, building stone
Diamonds	Gemstones, saws and sanding
Bauxite (Al)	Canning, foils, tools, window frames, vehicle and building parts, Alloy with other metals
Platinum	Jewelry, catalytic converters (chemical catalyst), computer/electrical, dental fillins, spark plugs
Quartz	Sand paper, Glass
Gold	Jewelry, Currency, Dentistry, Computers/Electronics

Table 9. Some selected formation process for minerals (we will review many of these over the next few weeks)

Formation process	Minerals produced
Pegmatite formation: Intrusive igneous process – late stage water-rich, low viscosity felsic magma emplacement and slow cooling to form minerals rich in water and rare elements not part of commonly formed igneous minerals.	Quartz, Feldspar, Muscovite, Beryl, Topaz, Tourmaline
Hydrothermal deposits: High-temperature metal-rich fluids surrounding magma chambers crack surrounding rock and penetrate into these cracks precipitating minerals in veins. They can also disseminate through surrounding rock depositing leached metals across an entire rock formation.	Lead, Zinc, Gold, Silver, Copper, Mercury,
Kimberlite pipes: Violent, rapid eruptions of gas-rich mantle pockets, forming 150 to 450 km depth. These typically inject themselves into the base of the crust and bring along trapped foreign rock and mineral fragments stable in the deep mantle.	Diamonds
Contact metamorphism High-temperature transformation of minerals in proximity to magma chambers.	Sphalerite (Zinc), Galena (Lead), Chalcopyrite (Copper), Magnetite (Iron), Bornite (Copper), Garnet, Corundum
Regional metamorphism High-temperature and high-pressure transformation of minerals due to deep burial or being trapped between converging continents.	Talc, Graphite
Chemical weathering Chemical transformation of minerals on Earth's surface in contact with atmosphere and water.	Bauxite (the principle aluminum ore), some copper and silver
Placer deposits: Sediments that collect in areas along a river where velocity slows and heavier grains drop out.	Gold, Platinum, Diamonds, Tin
Evaporation: Minerals that precipitate out of supersaturated waters rich in dissolved salts (either in the ocean or inland salt lakes). Typically the supersaturation happens as water evaportes under hot weather conditions.	Halite, Gypsum, Potassium
Sedimentary processes: Precipitation of crystals from ion-rich surface fluids.	Limestone, Chert

CASE STUDY—GARNET

Garnet—An Essential Industrial Mineral and January's Birthstone

By James G. Evans, Phillip R. Moyle, David G. Frank, and Donald W. Olson—2006

Garnet is one of the most common minerals in the world. Occurring in almost any color, it is most widely known for its beauty as a gem stone. Because of its hardness and other properties, garnet is also an essential industrial mineral used in abrasive products, non-slip surfaces, and filtration. To help manage our Nation's resources of such essential minerals, the U.S. Geological Survey (USGS) provides crucial data and scientific information to industry, policymakers, and the public.

Figure 9. Photograph of a mineral specimen containing large crystals of the garnet mineral spessartine (red), showing the distinctive "euhedral isometric" crystal form of garnet. Used since ancient times for jewelry, the first industrial use of garnet was probably in coated sandpaper manufactured in the United States by Henry Hudson Barton in 1878. The United States currently consumes about 16 percent of the global production of industrial garnet. (Copyrighted photo by Stan Celestian/courtesy of Glendale Community College).

Garnet as a Gem Stone

Garnet is familiar to many people as January's birthstone and as the New York State gem stone. It has been used as a gem stone since prehistoric times. Most recognizable in a deep shade of red, garnet occurs in the greatest variety of color of any mineral, except for blue. Some types of garnet even change color when exposed to artificial light. Unlike many other gem stones, garnet is almost never treated using heat, chemicals, or other methods to enhance appearance and value. The value of gem-stone garnets involves a complex combination of factors, including color, clarity, scarcity, durability, type of cut, and fashion. Larger garnets are popular both as gems and as collectable mineral specimens. Star garnets, found in Idaho, India, and Madagascar, contain inclusions of the fibrous mineral rutile that reflect light in two, four, or six rays when the stones are cut and polished.

Garnet as an Industrial Mineral

The first industrial use of garnet appears to have been in coated sandpaper manufactured in the United States by Henry Hudson Barton in 1878. Garnet is an important industrial mineral because it is relatively hard, rating 6 to about 8 on the "Mohs scale of hardness," where diamond is the hardest at 10. Consequently, garnet is an excellent abrasive for applications such as sand- or air-blasting, water-jet cutting, and sandpaper. Garnet is now used for some blast-cleaning applications that previously used common sand. Common sand contains crystalline silica (SiO_2) that in the form of dust produced during blasting can cause lung damage if inhaled. There are many additional industrial applications of garnet, including conditioning aluminum and other soft metals for use in aircraft and ships; deburring welds and grinding and polishing optical lenses; producing high-quality, scratch-free semiconductor materials; finishing hard rubber, plastic, and wood products; and making nonskid paints and coatings. The U.S. petroleum industry is one of the leading garnetconsuming industries, using garnet for cleaning drill pipes and well casings. Garnet is also chemically inert and recyclable, making it an ideal filtration medium. Garnet can also be used in mining exploration as an indicator to help locate diamond deposits. Diamonds only form at great pressure and temperature and are associated with kimberlite, an intrusive igneous rock that comes from deep within the Earth. As the molten rock (magma) that cools to form a kimberlite rises toward the Earth's surface, it incorporates fragments of rocks and minerals, including garnets with distinct color and composition that form under the same conditions as diamonds. If these distinct types of garnet are found in sediments, they may indicate the presence of nearby diamond-bearing kimberlites.

How do Garnets Form?

Garnet crystals form in rocks of appropriate chemical composition that have been modified by heat and pressure deep within the Earth's crust. These are "metamorphic" rocks, such as gneiss, amphibolite, and schist. Less frequently, garnets form in "calcareous" rocks that have been heated by nearby intrusions of magma. Garnets can be recovered using either surface or underground mining methods. Most garnets are found in and recovered from alluvium (unconsolidated or poorly consolidated combinations of clay, silt, sand, and gravel) derived from metamorphic rocks that have undergone weathering and erosion. Subsequent stream action moves and deposits the garnets, resulting in local concentrations of garnet due to its high specific gravity (its mass relative to an equal volume of water). During the recovery process the specific gravity and magnetic properties of garnet are used to separate it from other material.

Are all Garnets the Same?

Although all garnets possess similar physical properties, including crystal structure, hardness, and specific gravity, there are actually several different types of the mineral. The six most common members of the garnet family are almandine (rich in iron and aluminum), grossular (rich in calcium), pyrope and spessartine (rich in magnesium or manganese), uvarovite (rich in chromium), and andradite (rich in iron) Almandine is the hardest and, together with andradite, is the garnet mineral most commonly used in industrial applications. Tsavorite, a rare green grossularite garnet of exceptional beauty is among the most expensive garnets by weight. At the other extreme are reddish pyrope and abundant almandine garnets that are both common and relatively inexpensive.

Where are Garnet Deposits Found in the United States?

Garnet deposits have been located in 21 different states, including Alaska, Arizona, California, Colorado, Connecticut, Idaho, Montana, Nevada, New Hampshire, New York, North Carolina, Pennsylvania, Utah, and Virginia. However, the only U.S. garnet mines currently active are in northern Idaho, southeastern Montana, and eastern New York. In Idaho, garnet deposits are found adjacent to metamorphic rocks that make up the western Clearwater Range. In Montana, garnet deposits are found in the Ruby Range and southern Tobacco Root Mountains. In both Idaho and Montana, garnets are mined from alluvial deposits that formed from weathering of amphibolite, mica schist, gneiss, or granite. In northeastern New York, garnet is mostly extracted from unweathered gneiss bedrock of the Adirondack Mountains using surface mining methods.

U.S. Industrial Consumption of Garnet

The United States presently consumes about 16 percent of the global production of industrial garnet. In 2005, domestic production of crude industrial garnet was 40,100 metric tons (t), valued at $3.84 million. In the same year, the Nation imported 41,800 t of industrial garnet, valued at $5.91 million, primarily coming from Australia, Canada, India, and China. Meeting the challenge of supplying America's needs for essential minerals such as garnet requires accurate and unbiased scientific data. The ongoing work of scientists with the USGS Mineral Resources Program provides the information crucial to the creation of sound policies that will ensure future supplies of mineral resources.

Some useful definitions not defined above:

Mineral	a naturally occurring, inorganic solid with a characteristic chemical composition, distinctive physical properties, and a definite internal atomic arrangement (crystal structure).
Rock	An aggregation of one or more minerals.
Crystals	Specific geometric pattern and arrangement of atoms

Atoms Review

Table 10. Atomic Particles (amu = atomic mass unit)

Name	Symbol	Charge	Mass	Location
Electron	e-	-1	0	Energy shells surrounding nucleus
Proton	p+	+1	1 amu	Nucleus
Neutron	n	0	1 amu	Nucleus

Atomic mass = total mass of atom = # of protons + # of neutrons
Atomic number = # of protons = designation for element
Energy shells: electrons reside in energy shells surrounding the nucleus of an atom.

- Shell 1 maximum = 2 electrons (no more allowed)
- Shell 2, 3, 4, 5… maximum = 8 electrons (no more allowed)
- Therefore, the first two electrons go into shell 1, the next eight into shell 2, and so on.

Octet rule: All atoms want to completely fill their outermost energy shell: 2 electrons maximum in the first shell and 8 maximum in all other shells.
Valence electrons = the number of electrons residing in the outermost unfilled energy shell
Bonding = Atoms attempts to fill their outermost energy shell by removing, adding, or sharing electrons.

- **Ionic bonding** = Atom A gives up electrons to Atom B, so that both can achieve the octet rule. The result: two ions with equal and opposite charges that now attract each other.
- **Covalent bonding** = Atoms A and B both share one or more of their electrons with each other, thereby effectively gaining one. In such cases, the electrons orbit both nuclei, gluing them together most strongly.
- **Hydrogen bonding** = Hydrogen atoms bonded to oxygen (like in water) act as weak positive ions that can then weakly attract negative ions. This is how water dissolves ions so easily, by surrounding and attacking ionic bonds, pulling the positive and negative ions apart. Hydrogen bonds are weak bonds, and so it take a number of water molecules to pull apart one salt molecule, for example.

Isotopes = atoms with same atomic number (same # protons), but different # of neutrons. Therefore, they are the same element, but with different masses.
Atomic weight = the average atomic mass of a given sample of an element (averaging in all its naturally occurring isotopes).

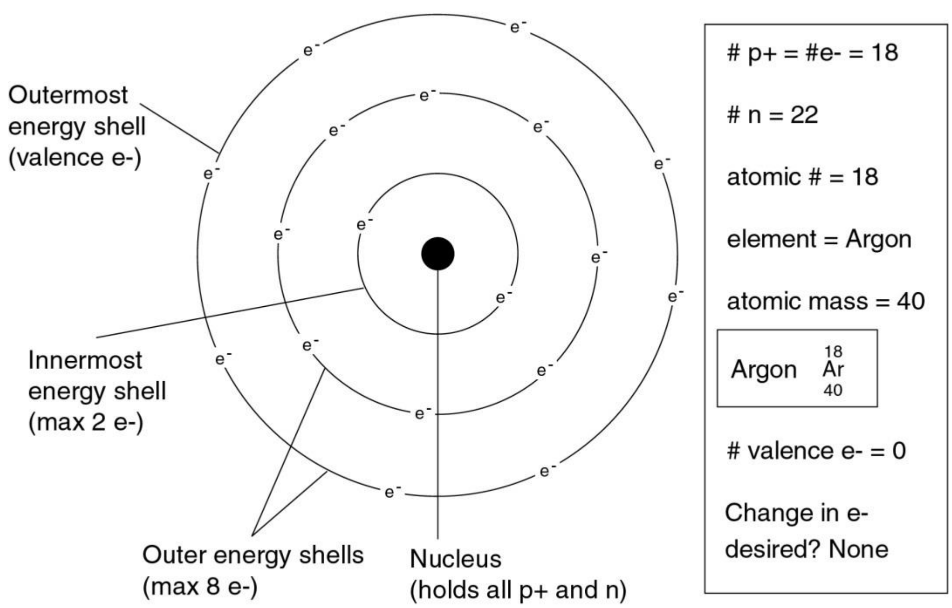


Figure 10. Simplified labeled model of an Argon atom.

Minerals – Chapter Worksheet

1. How do minerals differ from rocks?

2. What are the 5 MAIN requirements of a substance to be called a mineral?

3. CIRCLE: which of these are minerals? gold | glass | sugar | salt | ice

4. Circle which of the following are true for **<u>ionic substitution</u>**?
   CIRCLE: Affects the chemical formula of a mineral | Doesn't affect the chemical formula of a mineral
   Changes the shape of the bonds where the substitution occurs | Doesn't impact bond lengths or shape
   Can change the way light transmits through crystal and thus affect color | Has no impact on color

5. Circle which of the following are true for **<u>cleavage vs fracture</u>**?
   Cleavage = when a crystal breaks along a plane | Cleavage = when a crystal breaks along a nonplanar surface
   Cleavage = classified as even, uneven, regular, or conchoidal
   Cleavage = classified by number of unique planes and angles between planes
   A particular mineral can cleave OR fracture, not both | A particular mineral can both fracture and cleave

6. Circle which of the following is true for **<u>luster</u>**?
   Luster = the exact hue of color seen in a mineral | Luster = the way light reflects off the surface of a mineral
   Luster is independent of color | Luster can be used to distinguish among different minerals
   (circle which of these choices are luster choices): Metallic/ Nonmetallic |Soft/Hard | Waxy/Silky | Smooth/Rough

7. Water has a density (or specific gravity) of 1 g/cm^3. Gold has a density (or specific gravity) of 20 g/cm^3. If a pail of water weighs 2 kg, what does the same size pail of gold weigh? (Show work!)

8. Mineral A is scratched by glass but will itself scratch a fingernail. Using Moh's hardness scale, what do you know about the hardness of Mineral A?

9. What are the three subatomic particles in an atom, and what are the names, charges, and masses?

10. If the number of electrons in an atom is 20, and its atomic mass is 41:

How many protons?	How many neutrons?	What is the atomic number?	What is the element?	How many valence electrons?

11. CIRCLE what is true for **Hydrogen Bonds**:
    Found between Si and O in a silicon-oxygen tetrahedron | Found between water molecules when they're in liquid form
    Found between Na+ and Cl- in a salt crystal | Formed through the sharing of electrons between different atoms
    Formed through the giving up of electrons by one atom to another, thereby making two oppositely charged ions
    Formed through a bent molecule shape that concentrates a partial negative charge on one side and positive on other
    Major bond type used by water molecules to dissolve ionically bonded crystals or polar covalently bonded molecules

12. CIRCLE what is true for **Ionic Bonds**:

Found between Si and O in a silicon-oxygen tetrahedron | Found between water molecules when they're in liquid form
Found between Na+ and Cl- in a salt crystal | Formed through the sharing of electrons between different atoms
Formed through the giving up of electrons by one atom to another, thereby making two oppositely charged ions
Formed through a bent molecule shape that concentrates a partial negative charge on one side and positive on other
Major bond type used by water molecules to dissolve ionically bonded crystals or polar covalently bonded molecules

13. CIRCLE what is true for **Covalent Bonds**:

Found between Si and O in a silicon-oxygen tetrahedron | Found between water molecules when they're in liquid form
Found between Na+ and Cl- in a salt crystal | Formed through the sharing of electrons between different atoms
Formed through the giving up of electrons by one atom to another, thereby making two oppositely charged ions
Formed through a bent molecule shape that concentrates a partial negative charge on one side and positive on other
Major bond type used by water molecules to dissolve ionically bonded crystals or polar covalently bonded molecules

14. CIRCLE what is true for **polymorphs**?

Different crystal structures, same chemical formula | Different chemical formula, same crystal structure
Example: Diamond and Graphite | Example: Kyanite, Andalusite, Sillimanite | Example: Galena and Halite

15. What is the most abundant mineral group?

CIRCLE: Carbonates | Halides | Native Elements | Oxides | Silicates | Sulfates | Sulfides

16. Which silicate mineral has the **lowest Si:O ratio**? Why?

17. Which silicate mineral has the **highest Si:O ratio**? Why?

18. What is the chemical formula for **quartz**?

19. What is the chemical formula for **calcite**?

20. What's the best test for distinguishing calcite from quartz or anything else? (Be specific!)

21. What is the best means of distinguishing between plagioclase and potassium feldspar? (Be specific!)

22. Reviewing the Mineral Resources Review section that precedes this chapter worksheet, what are the primary uses for **garnet** in our society?

23. Which of the minerals you're learning about this week do you use in your life the most and how do you use it?

24. Everything we use in our society is either mined or farmed or made in a laboratory from things mined or farmed. What does this concept mean to you?

25. Review the mineral identification table (Tables 5 and 6) in the preceding pages. You should be able to use this table to identify all the minerals listed by description. (There is a photo album on the class website that shows you images of all these minerals as well, but you will have to identify them in lecture only by their description.) What is the difference between the two tables minerals have been divided into and how are they sorted within?

Minerals Activity: Identifying Minerals

Using the mineral-naming table (Tables 5 and 6) from the preliminary figures and tables for this chapter AND the photo album provided in the class materials, practice distinguishing between and naming the different minerals

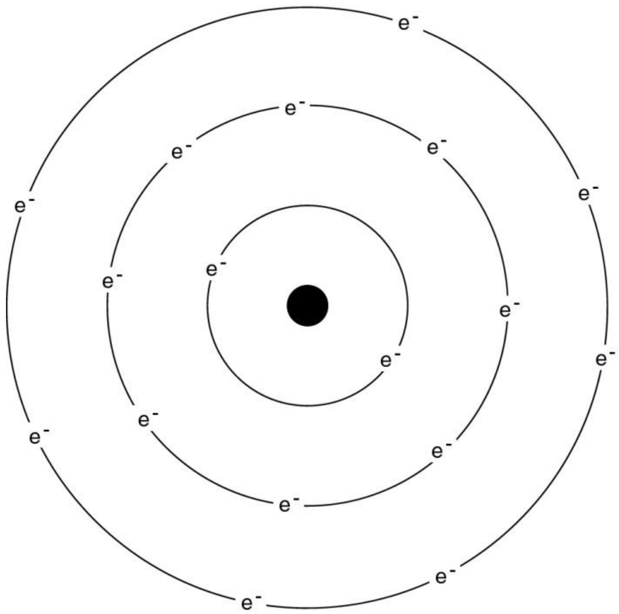
Mineral	Diagnostic properties
Mica family: **Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	
Calcite $CaCO_3$	
Fluorite CaF_2	
Galena PbS	
Garnet $(Ca,Mg,Fe,Mn)_3(Al,Fe,Cr)_2(SiO_4)_3$	
Graphite C	
Gypsum $CaSO_4*2(H_20)$	
Halite NaCl	
Hematite Fe_2O_3	
Amphibole family: **Hornblende** $(Ca,Na)_{2-3}(Fe,Mg,Al)_5$ $Si_6(Si,Al)_2O_{22}(OH)_2$	

Mineral	Diagnostic properties
Magnetite Fe_3O_4	
Mica family: **Muscovite** $KAl_3Si_3O_{10}(OH)_2$	
Olivine $(Mg,Fe)_2SiO_4$	
Plagioclase Feldspar family: Anorthite and Labradorite $CaAl_2Si_2O_8$ to Oligoclase and Albite $NaAlSi_3O_8$	
Potassium Feldspar family: Orthoclase and Microcline $KAlSi_3O_8$	
Pyrite FeS_2	
Pyroxene family: Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$	
Quartz SiO_2	
Serpentine $Mg_6Si_4O_{10}(OH)_8$	
Talc $Mg_3Si_4O_{10}(OH)_2$	

:

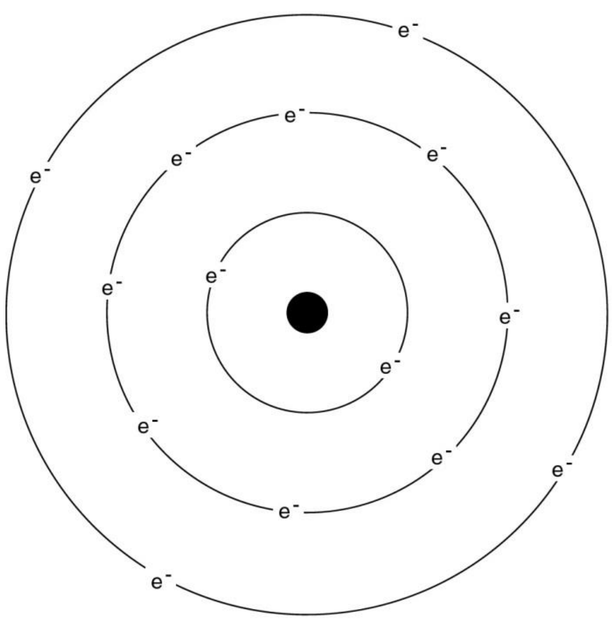
Atomic Particles, Atoms, Isotopes, and Bonding PRACTICE

If you would like some review and practice on basic atoms and bonding, complete these diagrams with all the missing information and then find key online.



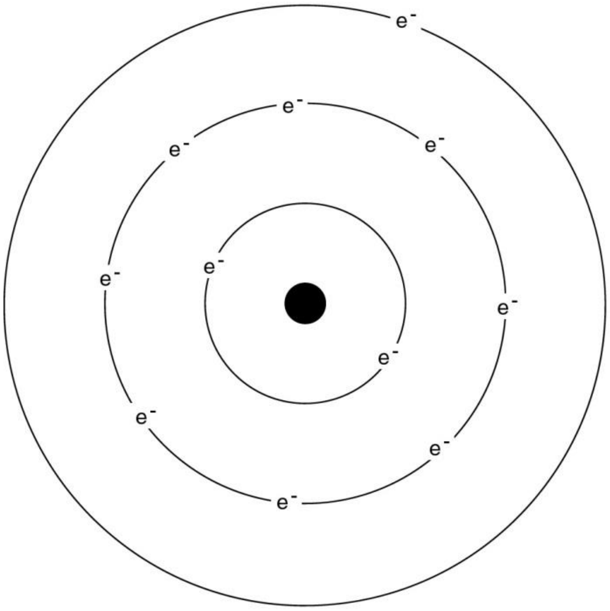
Atomic mass = 36

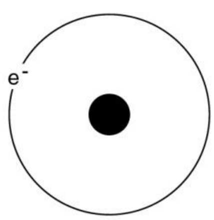
#e-=	
#p+=	
#n=	
Atomic # =	
Element (name and symbol) =	
# Valence e- =	
What change in e- does this element want?	

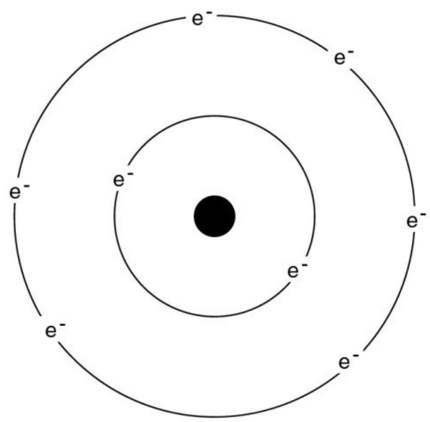


Atomic mass = 28

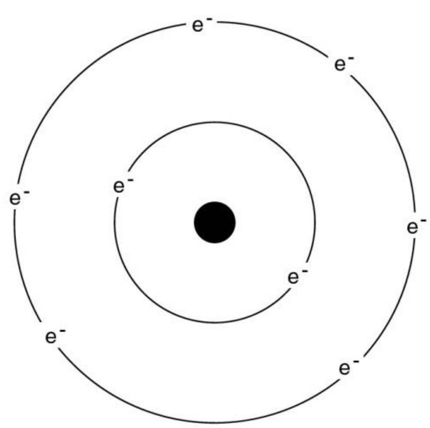
#e-=	
#p+=	
#n=	
Atomic # =	
Element (name and symbol) =	
# Valence e- =	
What change in e- does this element want?	

 **Atomic mass = 23**	#e-=
	#p+=
	#n=
	Atomic # =
	Element (name and symbol) =
	# Valence e- =
	What change in e- does this element want?

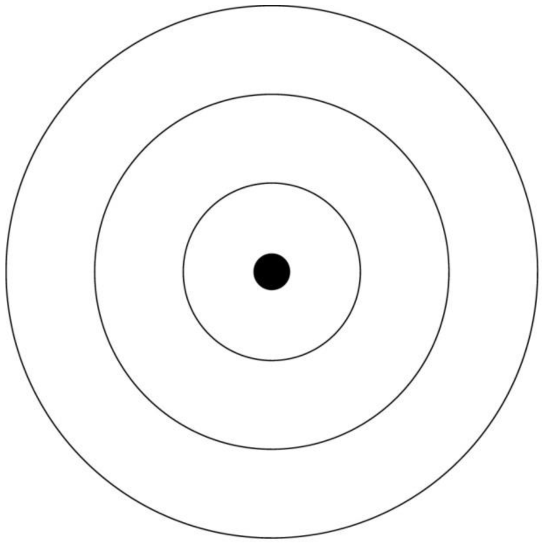
 **Atomic mass = 1**	#e-=
	#p+=
	#n=
	Atomic # =
	Element (name and symbol) =
	# Valence e- =
	What change in e- does this element want?

<table>
<tr><td rowspan="7">

Atomic mass = 16</td><td>#e-=</td></tr>
<tr><td>#p+=</td></tr>
<tr><td>#n=</td></tr>
<tr><td>Atomic # =</td></tr>
<tr><td>Element (name and symbol) =</td></tr>
<tr><td># Valence e- =</td></tr>
<tr><td>What change in e- does this element want?</td></tr>
</table>

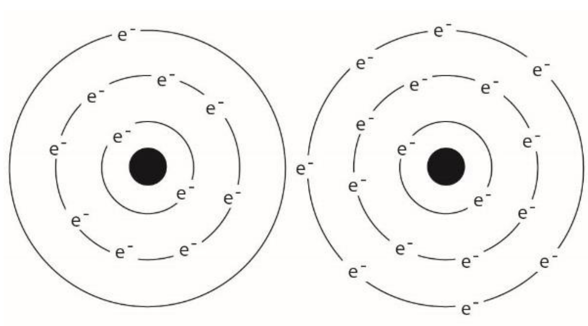
<table>
<tr><td rowspan="7">

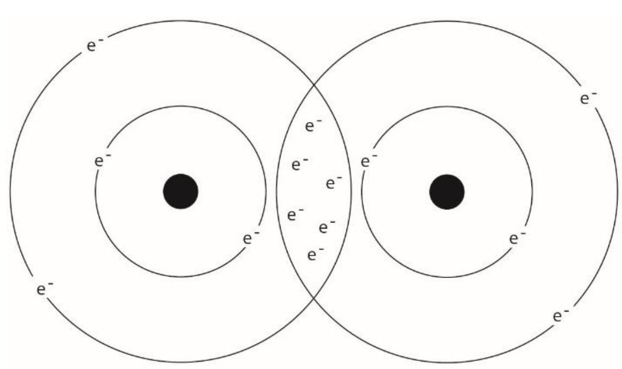
Atomic mass = 18</td><td>#e-=</td></tr>
<tr><td>#p+=</td></tr>
<tr><td>#n=</td></tr>
<tr><td>Atomic # =</td></tr>
<tr><td>Element (name and symbol) =</td></tr>
<tr><td># Valence e- =</td></tr>
<tr><td>What change in e- does this element want?</td></tr>
</table>

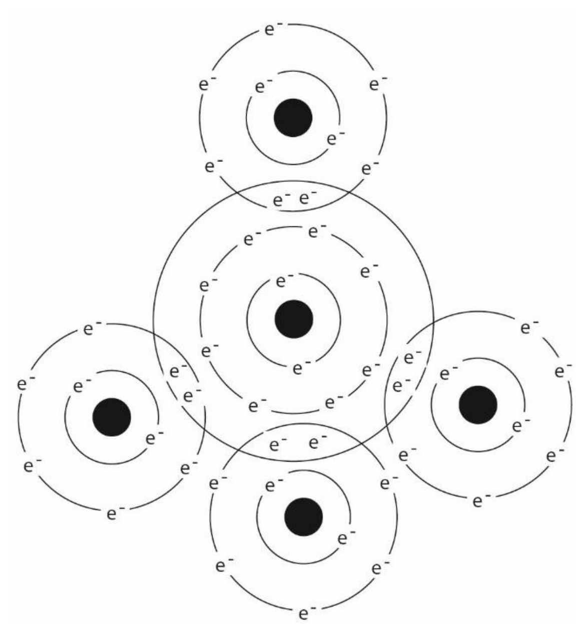


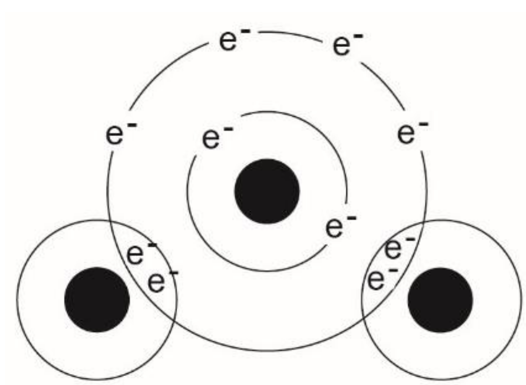
Atomic mass = 27, Element = Aluminum
DRAW ELECTRONS AND ANSWER ITEMS TO RIGHT

#e-=
#p+=
#n=
Atomic # =
Element (name and symbol) =
Valence e- =
What change in e- does this element want?

#e-=		#e-=
#p+=		#p+=
Atomic # =		Atomic # =
Element (name and symbol) = **Sodium (Na)**		Element (name and symbol) = **Chlorine (Cl)**
# Valence e- before bond =		# Valence e- before bond =
What change in e- count this element want?	**Ionic Bonding NaCl**	What change in e- count this element want?

#e-=		#e-=
#p+=		#p+=
Atomic # =		Atomic # =
Element (name and symbol) = **Nitrogen (N)**		Element (name and symbol) = **Nitrogen (N)**
# Valence e- before bond =		# Valence e- before bond =
What change in e- does this element want?	**Covalent Bonding N_2 (gas)**	What change in e- does this element want?

#e-=		#e-=
#p+=		#p+=
Atomic # =		Atomic # =
Element (name and symbol) = **Oxygen (O)**		Element (name and symbol) = **Silicon (Si)**
# Valence e- before bond =		# Valence e- before bond =
What change in e- does this element want?	**Covalent Bonding SiO_4**	What change in e- does this element want?

#e-=		#e-=
#p+=		#p+=
#n=		#n=
Atomic # =		Atomic # =
Element (name and symbol) = **Hydrogen (H)**	**Covalent Bonding H_2O**	Element (name and symbol) = **Oxygen (O)**
# Valence e- before bond =		# Valence e- before bond =
What change in e- does this element want?		What change in e- does this element want?

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Compare and contrast the different chemical and physical properties of minerals and what they indicate about the internal differences among minerals.	A | B | C | D | F	
Classify and name basic rock-forming minerals.	A | B | C | D | F	
Differentiate the most common rock-forming silicate minerals, specifically in regards to their internal crystal structure, Si:O ratios, and external characteristics.	A | B | C | D | F	
Evaluate the chemical formulas of a mineral and what it indicates about the atomic and crystalline structure of a mineral.	A | B | C | D | F	
Explain the formation process of key mineral resources, how they are used, and how they relate to geologic processes at work in the past.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

IGNEOUS ROCKS

Igneous Rocks Review

Magma is molten rock below the surface. **Lava** is molten rock that is now exposed at the surface. **Igneous rocks** are rocks that form from the solidification of magmas. (All igneous rocks were once molten.)

Generating magmas

Most magmas form at great depth when mantle rock partially melts. Mantle rock is ultramafic in composition and solid under its usual pressure and temperature conditions. Its minerals are stable in solid form (like food in an icebox). To melt mantle rock, there must be a change in the normal conditions. If temperature increases for example, some of the minerals in the mantle rock will start to melt (not all, just some – think of increasing the temperature in your freezer – not everything starts to melt at once). If pressure decreases or water is added (or both), the melting point of a mineral actually decreases and it will start to melt. As small amounts of melt migrate and accumulate, they form a magma.

Imagine taking a jar and filling it with marshmallows, water, and syrup. Now freeze it. The composition of the jar is the combined composition of all three ingredients. But if you increase the temperature of the jar slightly, so that some components are still frozen and others not, (say the water melts only), then you get a melt forming that has a different overall composition from the jar's materials. The original composition was marshmallows, water, and syrup. The melt that forms from a slight increase in temperature is pure water. The residual material left behind is marshmallows and syrup (no water).

The same thing happens in the mantle. When ultramafic mantle rock begins to melt, only minerals with the lowest melting temperatures go into the magma phase. Others remain behind. We call this **partial melting**. We can study the composition of mantle rocks and tell if they've produced melts before. (If our jar contains only marshmallows and syrup, then we know it partially melted and lost its water.)

To melt mantle rock, there must be a drop in pressure (which is what happens under oceanic ridges where seafloor spreading occurs), a rise in temperature (which is what happens when plumes migrate from the deep in the Earth, through the mantle and the crust), or an influx of water (which happens where subduction zones reinject water-rich oceanic crust back into the mantle).

Partially melted mantle tends to produce mafic compositions. Fully melted mantle produces ultramafic magmas. After these magmas are produced at depth, they rise because of buoyancy.

Changing magma composition

As magmas rise, they mix with other magmas (**magma mixing**) or melt rocks that they are moving through (**assimilation**), both of which processes will change magma composition. In addition, as magmas rise to the surface, they gradually cool down. When magmas cool, crystals start to form. Bowen's Reaction Series is a graphic representation of the order in which minerals crystallize during the cooling of a typical ultramafic magma (see image ahead). If after a mineral forms it is removed from the magma through gravitational settling or floating or other processes, the magma composition will change. We call this process **crystal fractionation**. Back to our frozen jar example from earlier, imagine that we have a molten goop of chocolate, marshmallows, and water. If the marshmallows are the first to cool and solidify from the goop, and after they solidify, they float to the top, removing themselves from the goop, the goop's composition is now different. It began with 1/3 marshmallow. Now it has none! Magma composition changes when particular elements are removed to form early minerals. Most early minerals like olivine, plagioclase and pyroxene contain high amounts of (iron) Fe, (magnesium) Mg, and (calcium) Ca, and low amounts of silicon. Thus, early crystal fractionation removes iron, magnesium, and calcium from the magma, leaving the magma preferentially enriched in silicon and sodium.

If a high-temperature mineral crystallizes and remains in the melt (as opposed to settling out of the magma due to gravity), it will react with the remaining magma to become a different mineral. There are two types of reaction series for minerals: the Fe-Mg silicates are the discontinuous branch, while the plagioclase feldspars form the continuous branch. In the discontinuous reaction series, as the magma cools each mineral reacts with the remaining more evolved magma to form a different mineral. For example, olivine reacts with an evolving magma to form pyroxene. The continuous branch involves the continuous reaction of plagioclase feldspar with the melt to change its composition only, not its crystal structure. Plagioclase gets more sodium-rich during magma evolution. Bowen's Reaction Series provides a useful way to describe which minerals, because of similar temperatures of crystallization, are found together in a given igneous rock. Draw a horizontal line through the Bowens Reaction Series at any point and you will find the minerals that can coexist in an igneous rock of that specific composition.

Occasionally magmas carry pieces of foreign rocks that are caught up in the magma when it moves through and breaks surrounding rock. Such foreign rocks are called **xenoliths**.

Magma chambers are areas in the crust where magmas accumulate and reside for long periods of time. Magmas in these chambers can erupt at any time – usually when new magmas rise under them and push them out. Since magma compositions can change so easily over time, the composition of erupted lavas or plutons from a single volcano can also vary.

Primitive magmas (ones that haven't experienced much evolution through crystal fractionation) are dominant in seafloor spreading centers (where oceanic crust is thin and so primitive magmas can reach the surface quickly). Evolved magmas dominate in continental volcanism (where continental crust is thick, and magmas take a long time to reach the surface on their journey from the mantle and can undergo changes).

The word *mafic* comes from the abundance of *magnesium* and iron (*Fe*). The world *felsic* comes from the large percentage of *feldspars* and *silicon* in their mineral composition. Bowen's reaction series shows how primitive, **ultramafic** magmas change into evolved, **felsic** magmas, as the Mg- and Fe-rich minerals crystallize first and are removed from the magma. (Along the way, they evolve into first **mafic**, then **intermediate** compositions.) Ultramafic magmas and their solidified rock forms are extremely rare, because their magmas must have undergone no changes on their way to the surface.

You can use Bowen's Reaction Series to see what minerals crystallize in each composition magma. Primitive magmas produce olivine and pyroxene. Evolved magmas produce mostly potassium feldspar and quartz.

Volcanic (or extrusive) igneous rocks

Magmas that reach the surface and erupt as lavas ultimately form **extrusive** rocks. We classify extrusive rocks by the eruption style and the composition of the magmas. **Basalts** are the products of mafic lavas. **Rhyolites** are the products of felsic lavas. **Andesites** are intermediate. (Note: Ultramafic lavas don't exist on Earth anymore, as our crust it too thick, even in the oceans, to allow no evolution to occur during magma transit). When lavas erupt at the surface, they cool too quickly for visible crystals to form (though there are crystals in the rocks, just too small to see). We call the texture of these rocks **aphanitic** (most crystals are too small to see). Note:

Any large crystals found in volcanic rocks were produced at depth in the magma chamber (imagine a few minerals just beginning to slowly form throughout the magma – they'd be scattered, like poppy seeds in a muffin). These crystals are carried to the surface during the eruption. Volcanic rocks that consist of an aphanitic (or small-crystal size) matrix or **groundmass** with larger crystals disseminated throughout that groundmass, like chocolate chips in a cookie are called **porphyritic**. Sticking with the chocolate chip cookie analogy, the chips are called **phenocrysts**; they formed when the magma was still underground (prior to eruption); the rest of the cookie is the groundmass; it formed after eruption. Most volcanic rocks display a porphyritic texture in some form. We name such rocks by preceding the name with the major phenocryst and ending the name with the word, porphyry. Example: olivine basalt porphyry.

The more evolved the magma (felsic), the more silica, and hence the more viscous the fluid. (Viscosity is a measurement of a fluid's resistance to flow: syrup is more viscous than water.) As viscosity increases, it becomes harder to produce crystals (ions have a hard time moving through the melt to find each other). Occasionally, extremely evolved magmas produce lavas that are so viscous that they cool before they can produce any crystals. When no crystals form, we call the substance **glass**. Felsic lavas that cool as glass are called **obsidian**. Glass usually forms when lavas either cool too quickly to form crystals, or when the lava is so viscous that ions can't move to form crystals.

Magmas also can contain a lot of gas (water, sulfur dioxide, carbon dioxide, etc.). When such lavas erupt, a process occurs that is similar to opening the top on a can of shaken soda. The gas immediately wants to get out of the lava. As lavas flow across the surface, these gases rise through the lava. When the lava cools and solidifies around gases, the final rock contains **vesicles**, small round pockets in the rock, where gas was trapped while moving.

When erupted lavas contain more vesicles than rock, they have a **frothy** texture (lightweight – mostly holes – with the actual rock made of glass – no minerals – quickly cooled). Frothy rocks are called **pumice** if they're light colored (and therefore felsic or intermediate in composition) or **scoria** if they're dark colored (and therefore mafic in composition). Because mafic compositions have iron in them, scoria is not light enough to float in water. Pumice, however, does!

Lavas that contain more gas than liquid will erupt violently as **ash**. Ash is just a tiny drop of liquid that adheres to the exsolving gas bubbles and solidifies into glass (no crystals) as soon as it hits the air. Ash (as well as particles pumice, crystals, and other volcanically ejected material – collectively called **pyroclastic** debris) can accumulate on the surface of volcanoes. When this material is compressed or welded together, it forms a rock called **Tuff**. Pyroclastic rocks are made of pieces (*clasts*) of material that came from a volcano or fire (*pyro*).

Plutonic (or intrusive) igneous rocks

Magmas that never reach the surface will cool at depth in a magma chamber or vein or dike. As long as they are deep, they cool slowly and form large crystals (crystal size increases with slower cooling). Slowly cooling mafic magmas produce **gabbro** (the plutonic equivalent of a basalt). Slowly cooling felsic magmas produce **granite** (the plutonic equivalent of rhyolite). Intermediate magmas produce **diorite** (the plutonic equivalent of andesite) . We call the texture of these larger-crystalline rocks **phaneritic** (100% crystals visible to the eye).

We attach the term **pegmatite** to any plutonic rocks with *unusually* large crystals. Pegmatites form because cooling was slow and water content was extremely high, thereby decreasing magma viscosity and allowing ions to migrate quickly. To name such rocks, we append the word, pegmatite, to the end of the rock name. Example: granite pegmatite.

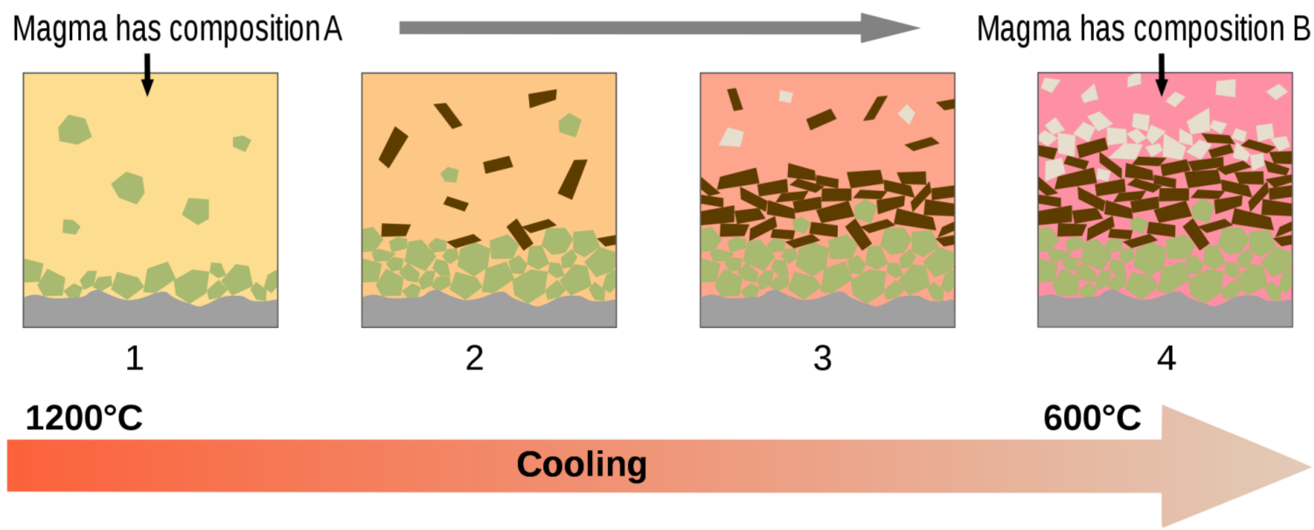


Figure 1. Schematic diagrams showing the principles behind fractional crystallisation in a magma. While cooling, the magma evolves in composition because different minerals crystallize from the melt. 1: olivine crystallizes; 2: olivine and pyroxene crystallize; 3: pyroxene and plagioclase crystallize; 4: plagioclase crystallizes. At the bottom of the magma reservoir, a cumulate rock forms. Image: Woudloper – Creative Commons – CC BY-SA 3.0

Table 1. Pluton types

	Sill	**Dike**	**Batholith**
Parallel to surrounding bedding (concordant) or cross-cutting (discordant)	Parallel	Cross-cutting	Cross-cutting
Shape: tabular or massive	Tabular	Tabular	Massive
Size	5-30 m thick	0.5-30 m thick	100s of km wide

**Tabular means like a flat sheet or wall – for sills, they appear like layers of rock, but have intruded between existing rock layers. For dikes they cut through and across existing rock layers along a near vertical crack so they appear like walls.*

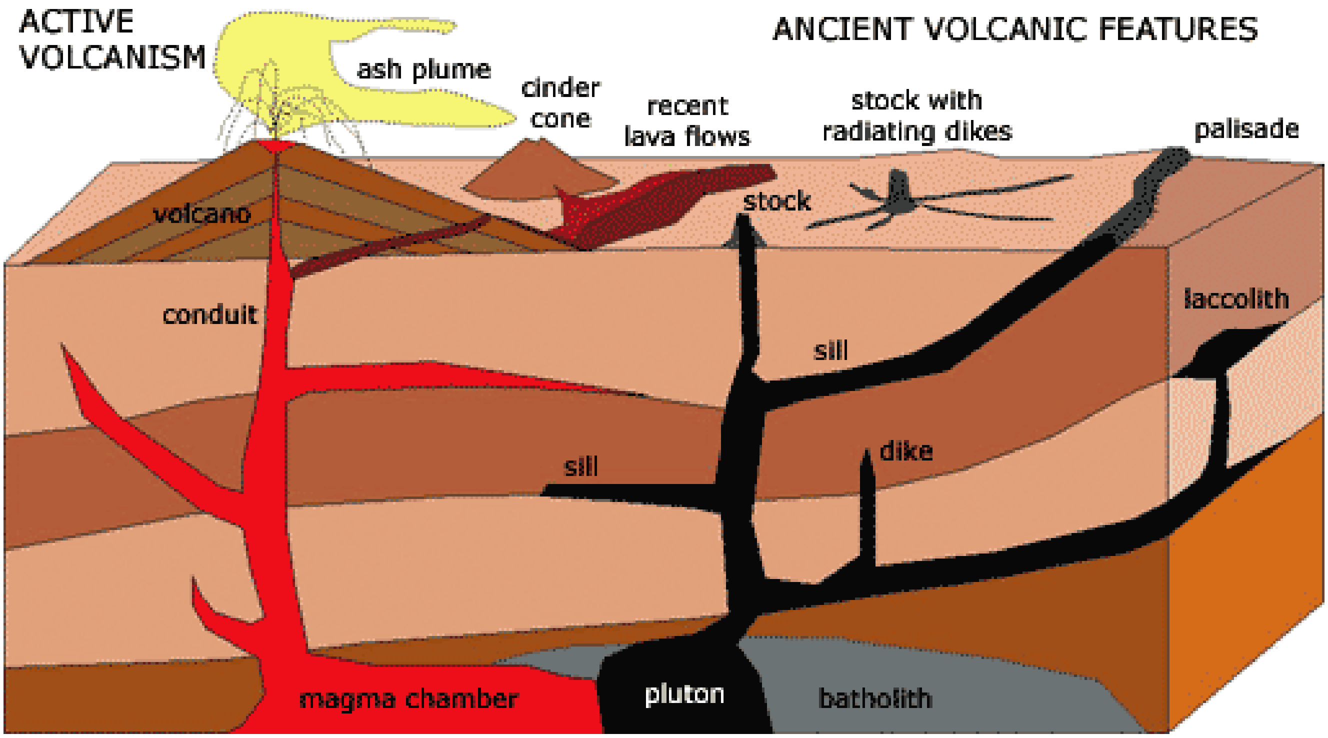


Figure2. Volcanic vs Plutonic landforms/structures – USGS

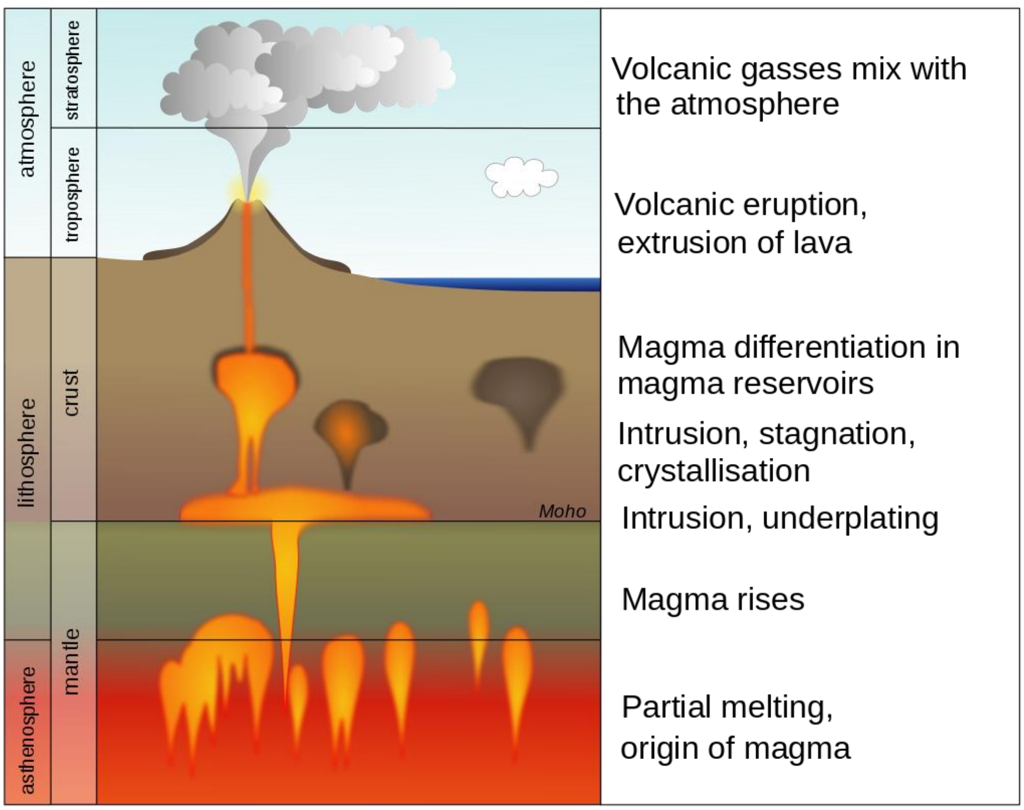


Figure 3. Woudloper –Creative Commons – CC BY-SA 3.0

To identify (name) igneous rocks, you determine two things about the rock: composition and texture. First determine composition, which is based on mineral content or color, if you can't see minerals. Then determine the texture of the rock and based on the two, identify the rock name.

Review and be able to distinguish diagnostic characteristics of each of the rocks listed in the following table (if these descriptions showed up in a multiple-choice exam, you could match them to the correct rock.)

Table 2. Igneous Rock Identification and Naming

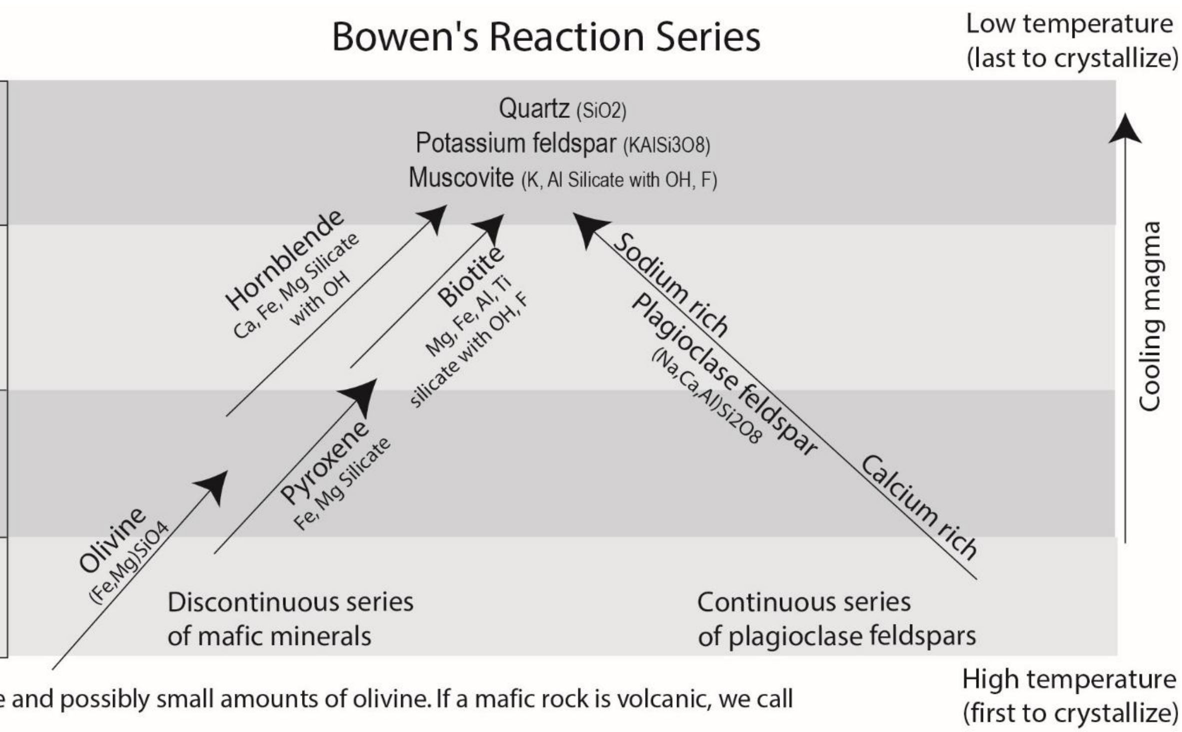
	Texture				
	Phaneritic 100% visible crystals	**Aphanitic** Most crystals too small to see	**Glassy** 100% glass	**Frothy** Greater than 50% vesicles (rest is usually glass-like)	**Pyroclastic** Fragments of ash, crystals, pumice, rocks
Ultramafic	*Peridotite*				
Mafic	*Gabbro*	*Basalt*		*Scoria*	*Volcanic Tuff*
Intermediate	*Diorite*	*Andesite*		*Pumice*	*Volcanic Tuff*
Felsic	*Granite*	*Rhyolite*	*Obsidian*	*Pumice*	*Volcanic Tuff*
	Pegmatitic texture is a subcategory of Phaneritic	*Porphyritic texture is a subcategory of Aphanitic***			

*** Porphyritic rocks can rarely be found in the Phaneritic category as well, where 100% of the crystals are visible, but some formed first and grew larger than the others. For purposes of this class, however, all porphyritic rocks we will see will be aphanitic (background mass of crystals are too small to see).*

Table 3. Igneous Rock Compositions

Composition	**Name**	**Mineral composition**	**Intrusive rock names**	**Extrusive rock names**
< 45% Si	Ultramafic	Major: Olivine Minor: Pyroxene, Plagioclase	Peridotite	NONE EXIST ON PLANET EARTH
45 – 55% Si	Mafic	Major: Pyroxene, Ca-rich Plagioclase Minor: Olivine	Gabbro	Basalt, Scoria
55 – 65% Si	Intermediate	Major: Hornblende, Biotite, Na-rich Plagioclase	Diorite	Andesite, Pumice, Tuff
> 65% Si	Felsic	Major: Quartz, K-Feldspar, Muscovite Minor: Biotite, Hornblende, Na-rich Plagiocl.	Granite	Rhyolite, Pumice, Tuff, Obsidian

COMPOSITION NAME	APHANITIC ROCK NAME	PHANERITIC ROCK NAME
Felsic	Rhyolite	Granite
Intermediate	Andesite	Diorite
Mafic	Basalt	Gabbro
Ultramafic		Peridotite



Example: A mafic rock contains pyroxene and plagioclase and possibly small amounts of olivine. If a mafic rock is volcanic, we call it basalt. If it is plutonic, we call it gabbro.

Figure 4. Bowen's Reaction Series – the order in which crystals form as a magma that forms from melting the mantle rises through the crust and cools.

Igneous Processes and Igneous Rocks – Chapter Worksheet

1. How does magma differ from lava?

2. Igneous rocks are divided into four main compositions. How do we distinguish among them?

Name	**Distinguishing characteristics**
Ultramafic	
Mafic	
Intermediate	
Felsic	

3. Igneous rocks are divided into five main textures. Fill out the following table with definitions to distinguish among those five textures. And write in the rock names that go with each texture and composition.

Phaneritic	**Aphanitic**	**Glassy**	**Frothy**	**Pyroclastic**

4. Write in the rock names that go with each texture and composition.

	Phaneritic	**Aphanitic**	**Glassy**	**Frothy**	**Pyroclastic**
Ultramafic					
Mafic					
Intermediate					
Felsic					

5. What is viscosity?

6. CIRCLE in table below physical and chemical characteristics of a magma that would increase its viscosity.

Increase Temperature Decrease Temperature No Impact	Increase Silica % Decrease Silica % No Impact	Increase Water % Decrease Water % No Impact

7. What major factors increase the crystal size of minerals in igneous rocks? How?

8. CIRCLE: Which of the following are true for **pegmatites**?
High silica % -- felsic compositions only | Low silica % -- mafic compositions only | All compositions possible
Unusually large crystals | Unusually small crystals | Two different crystal sizes (big and small)
Requires high water content in magma to reduce viscosity | Must be dry
Often filled with "garbage" elements that have no place in normal rock-forming minerals
Multiple cooling episodes | Erupts on surface | Stays underground and cools slowly

9. Under what circumstances will no crystals form when a melt solidifies?

10. What do we call such a product?

11. CIRCLE: Which of the following are true for **porphyritic rocks**?
High silica % -- felsic compositions only | Low silica % -- mafic compositions only | All compositions possible
Unusually large crystals | Unusually small crystals | Two different crystal sizes (big and small)
Requires high water content in magma to reduce viscosity | Must be dry
Often filled with "garbage" elements that have no place in normal rock-forming minerals
Multiple cooling episodes | Erupts on surface | Stays underground and cools slowly

12. What processes change a magma's composition and lead to the different compositions?

13. CIRCLE correct description of how magmas' physical and chemical characteristics change as they rise to the surface and progress through Bowens Reaction Series:

Temperature Increases | Decreases Stays the same	**Si, K, Na % content** Increases | Decreases Stays the same	**Fe, Mg, Ca % content** Increases | Decreases Stays the same	**Viscosity** Increases | Decreases Stays the same
Water % content Increases | Decreases Stays the same	**Quartz % content** Increases | Decreases Stays the same	**Olivine % content** Increases | Decreases Stays the same	**Plagioclase % content** Increases | Decreases Stays the same

14. According to Bowen's reaction series,
what minerals crystallize first as magmas cool?

15. According to Bowen's reaction series,
what minerals crystallize last as magmas cool?

16. According to Bowen's reaction series,
what minerals will you never find together?

17. According to Bowen's reaction series,
what minerals will you always find together?

18. CIRCLE all the characteristics that match each of these subdivisions of igneous rock

PLUTONIC	**VOLCANIC**
Cools underground only – never erupts | Erupts Phaneritic | Aphanitic | Glassy | Frothy Pyroclastic | Porphyritic | Pegmatite | Vesicles	Cools underground only – never erupts | Erupts Phaneritic | Aphanitic | Glassy | Frothy Pyroclastic | Porphyritic | Pegmatite | Vesicles

19. CIRCLE correct description of each pluton.

Sill	**Dike**	**Batholith**
parallel to existing beds cuts across existing beds tabular shape | massive shape 5-50 m thick | kilometers thick	parallel to existing beds cuts across existing beds tabular shape | massive shape 5-50 m thick | kilometers thick	parallel to existing beds cuts across existing beds tabular shape | massive shape 5-50 m thick | kilometers thick

Igneous Rock Activity: Identifying Igneous Rocks

Using the rock-naming table (Table 2) from the preliminary figures and tables for this chapter AND the photo album provided in the class materials, practice distinguishing between and naming the different igneous rocks:

Igneous rock name	Texture	Composition (if it's a phaneritic rock, be sure to include here the actual minerals present)	INTRUSIVE OR EXTRUSIVE
Andesite			
Basalt			
Diorite			
Gabbro			
Granite			
Obsidian			
Peridotite			
Pumice			
Rhyolite			
Scoria			
Volcanic Tuff			

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Compare and contrast the different chemical and physical properties of igneous rocks and what they indicate about the formation process of each rock.	A | B | C | D | F	
Classify and name basic igneous rocks.	A | B | C | D | F	
Evaluate how Bowen's Reaction Series, assimilation, and magma mixing contribute to the range of igneous rock compositions found on our planet.	A | B | C | D | F	
Compare and contrast plutonic and volcanic igneous processes, structures, and rocks.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

VOLCANOES

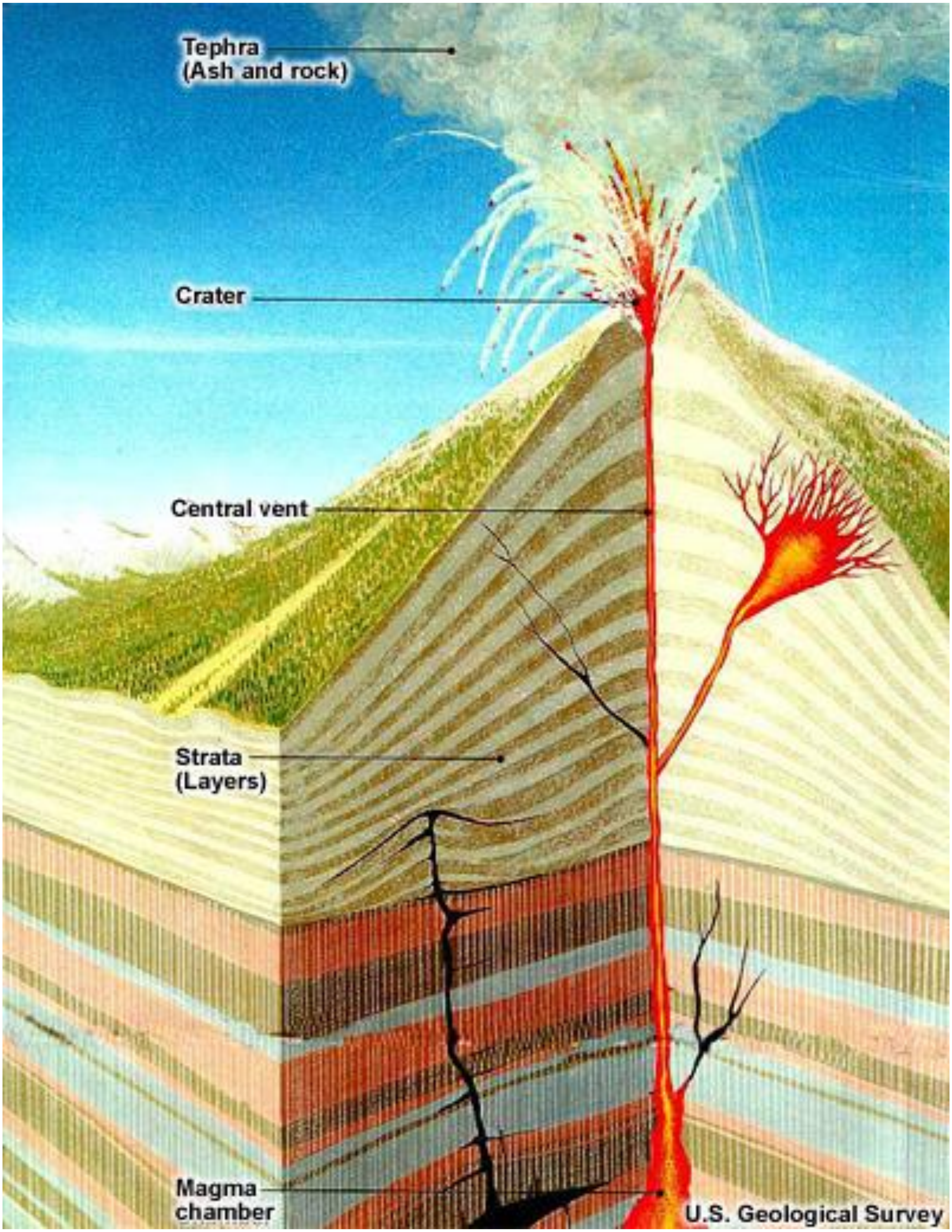


Figure 1. Oblique view of a volcano with a cutaway to show the layers and internal volcanic plumbing. USGS.

Table 1. Geologic Settings for Global Volcanism

Geologic setting for volcanism	Magmas produced by:	World example:
Hotpots	Increased heat	Hawaii, Yellowstone, Iceland
Subduction zones	Addition of water causes melting point of mantle to drop.	Cascade Mtns, Andes Mtns, Indonesia, Aleutian Islands, Japan, Philippines
Divergent plate boundaries	Drop in pressure causes melting point of mantle to drop	Iceland, Oceanic ridges everywhere, East African Rift Zone, Long Valley

Volcanic Hazards Summary

Ashfall

Ash mantles topography. It moves as fast as the wind that carries it. Therefore, it is distributed in the direction the wind is blowing during the eruption, at the same speed as the wind is blowing. For example, with winds of 66 km/hr, if a farm is in the down wind direction during an eruption, and is 66 km away, it will take 1 hour for the ash to arrive, and the farmers have 1 hour to evacuate. Towns and agriculture in the up wind direction are likely to be unaffected by ash during the eruption.

The thickness of ash deposited during eruptions is related to how far away from the summit you are.
For example, in a small eruption, if you are 80 km downwind from the eruption, you get 2 cm of ash falling. In an extreme eruption, you could get as much as 90 cm. Note: if you lived 80 km away in the opposite direction of the wind, you would probably receive nothing. As you get closer to the wind direction, the ash thickness would increase until it reaches the maximums described above.

Much of the volume of ash produced in an eruption will be deposited outside the 1 cm boundary, but such small amounts generally constitute only a mild hazard, significant only under special circumstances, for example for people with severe respiratory disease and for jet engines if ash enters intakes.

- **Zone 1 – Moderate Hazard – Thickness between 1 and 10 cm .** Less than 10 cm thick, ash can cause plenty of damage by clogging machinery, overwhelming sewage treatment plants when it gets into storm drains, causing auto crashes due to sliding and decreased visibility, covering grass that animals normally graze, etc. But less than 10 cm of ash is unlikely to cause much loss of life.
- **Zone 2 – Severe Hazard – Thickness between 10 cm to 100 cm (1 meter).** 10 cm of ash is enough to collapse roofs (crushing the inhabitants), especially if the ash gets wet, which increases load on roofs.
- **Zone 3** – **Extreme Hazard – Thickness exceeds 1 m.** One meter of ash is enough to collapse nearly all roofs, and it would bury vegetation so deeply, recovery would be impossible. The size of the pumice lumps and rocks torn from the vent increases toward the vent (big particles fall out of the column closer to the vent than smaller particles), just as the thickness of the deposit does. Where the deposit is thick, there is also a severe hazard of being clobbered by falling pumice lumps and rocks.

Lava Flows

Lava flows are composed of 100% molten lava, originating from a vent or fissure. They tend to move slowly: the higher the viscosity (higher the silica content) of the lava, the slower the flow. Andesitic lava flows move about 4 km/hr on steep slopes and only about 0.5 km/hr on flat areas. Gravity pulls lava flows downhill, while increased magma supply from above gives them added push. The slower the lava flow, the closer it stays to the vent. Low viscosity pahoehoe lavas can flow thousands of kilometers (if volume is high enough, like in flood basalts). High viscosity rhyolitic lavas never flow more than a kilometer or two. Where magma supply is high (like in hotspots), flow rate increases.

Volcanic Mudflows

Mudflows are composed of ash and usually meteoric water (nonmagmatic) such as melted ice, lake water, sea water, and groundwater. They move rapidly (30 km/hr), pulled downhill by gravity. They stick to river valleys, basins, and lakes. They usually involve such large amounts of water that they cause lakes and rivers to overflow their banks. Mudflows (often referred to as Lahars when they occur on volcanoes) can take out bridges, houses, and cars, and can travel hundreds of kilometers from the vent. Because they flow down existing river valleys, they do most of their damage in the flood plains of rivers. Note: lahars can occur during and after eruptions. Lahars that occur during eruptions usually are the result of hot ash raining down on and melting glaciers, or the combination of hot ash and water breaking through dams. Lahars that occur after eruptions usually result from rains that mobilize recently deposited ash and carry it to streams.

Pyroclastic Flows

Pyroclastic flows form in a variety of ways. Hot ones form by initial collapse of the outside of an ash column. They can also form as colder rock and glass from the front of lava flows falls off, exposing magma underneath that is still full of gases. Another cause is catastrophic depressurization of a hydrothermal system (as in the Mt. St Helens eruption, when the bulge on the side of the mountain slid away, after an earthquake).

Pyroclastic flows are composed of original magmatic material. They are fast because they are light and contain gases, which help reduce friction (75 km/hr). Pyroclastic flows are intensely heated with minute fragments of magma, crystals, gas, ash and any other rocks or sediments they can entrain as they flow from the vent or fissure, much like an avalanche.

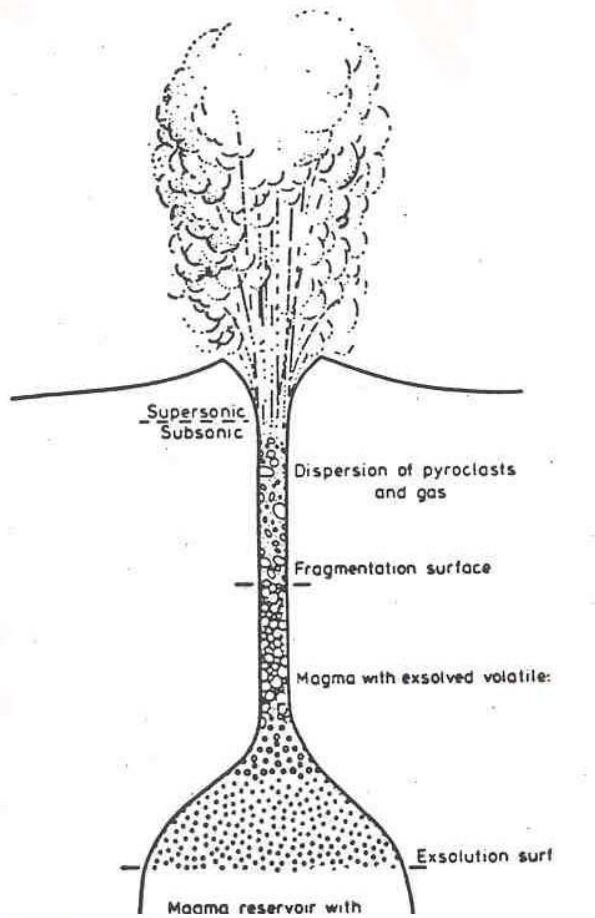


Figure 2. Inside of a magma chamber as gases rise to surface and pressure builds then explodes and causes an ash eruption.

Surges

A surge is the fastest and most dangerous type of pyroclastic flow (200 km/hr). They are sometimes referred to as nuee ardentes. They differ from a more typical pyroclastic flow because of increased volume of gas and the small size of particles they carry. Pyroclastic flows can carry large sizes; surges transport mostly fine-grained material.

Warm to cold surges usually come from nonmagmatic water, such as melted ice, lake water, sea water, and groundwater. This water comes in close contact with magma or hot rock and flashes to steam. Most surges don't go very far, because either they entrain cooler air and rise upwards, or they literally run out of steam. The biggest surges will extend a few kilometers beyond the base of the volcano. Surges mantle topography, but tend to be thick in valleys and thin on ridges. They are powered partly by the initial gas expansion (blast), which gives them a lateral component. (Close the vent, surges cover everything!) But surges also are flowing in response to gravity, so they tend to prefer to go downhill. They can climb topography near the vent if they are going fast enough, just as large snow avalanches can go uphill.

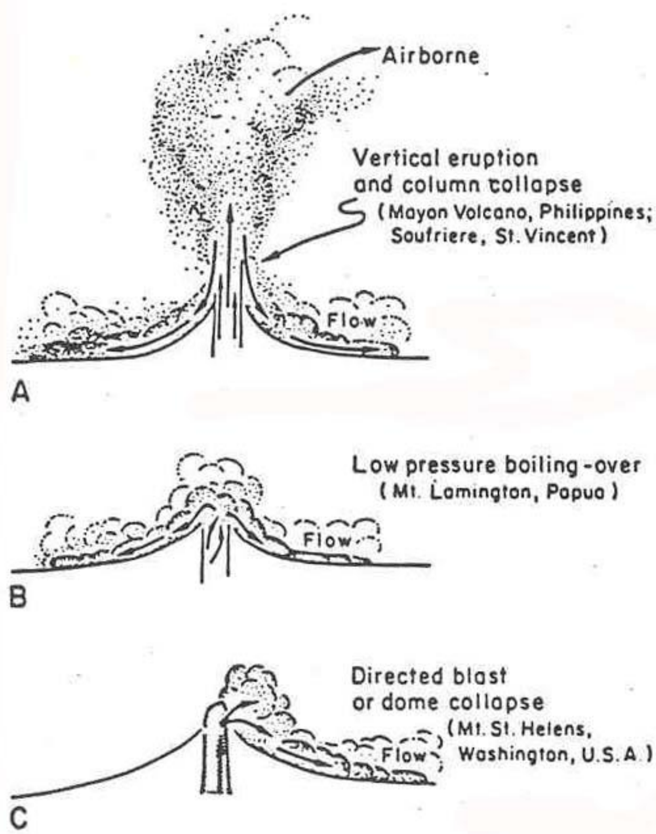


Figure 3. Different ways in which a pyroclastic flow forms.

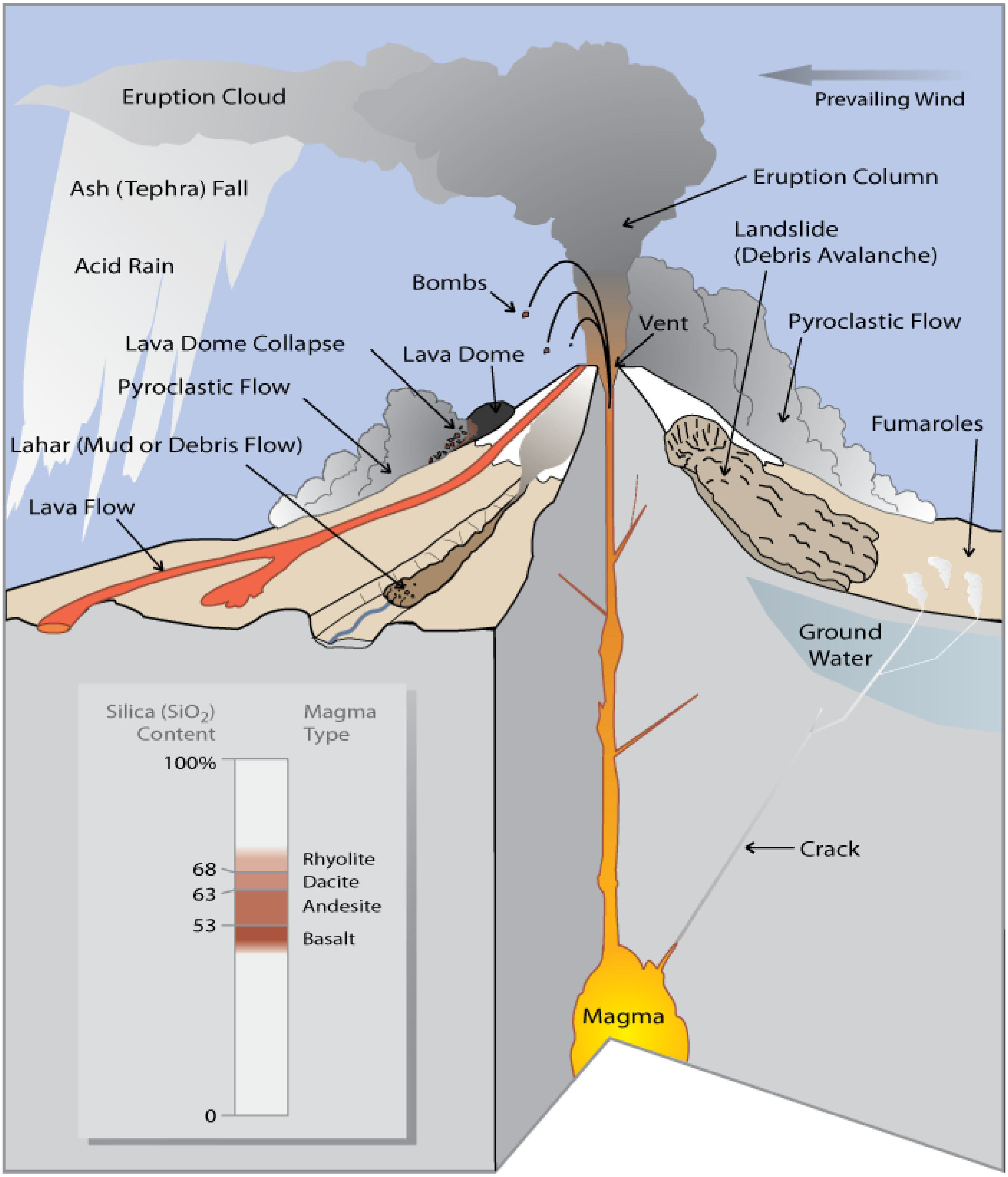


Figure 4. Volcanic Hazards, USGS

Table 2. Volcanic Hazards

Hazard	Definition	Speed	Distance travelled	Dangers
Dust, ash, and pyroclastic bombs	Material thrown from the vent of a volcano	Ash: as fast as wind (20-80 km/h)	Ash: All over world, potentially	Ash: Roof collapse, Asphyxiation, clogged machinery, lost crops, breathing problems increased for asthmatics, Bombs: bodily injury or death
Lahar	Mudflow: ash + water (rain or melted glacier)	Up to 40-50 km/h	100s of km from vent (along river valleys)	Drowning, destruction of all bridges and buildings near water's edge
Pyroclastic flows	Ash, gas, lava, rocks	Up to 200 km/h	10s of km from vent	Death and destruction to any and all in its path.
Lava flows	Flowing molten rock	2-4 km/h	10s of km from vent (if basalt), 1 km if rhyolite	Destruction to property and vegetation. Little hazard to human life.
Gas clouds	High density rolling CO_2 gas.	??	10s of km from vent	Asphyxiation of all life.
Acid rain	SO_2 gas + H_2O creates sulfuric acid.	Same as wind	10s of km from vent	Temporary lull in growth of vegetation and contamination of water.

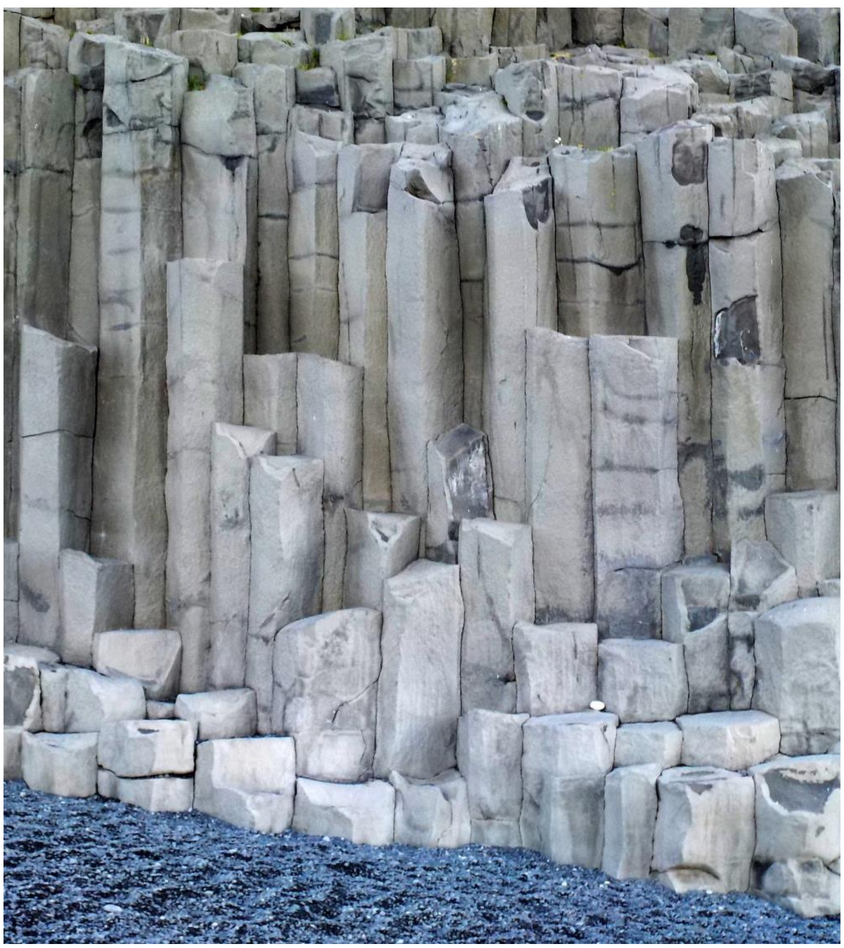


Figure 5. Columnar Jointing, Reynifjara, Iceland (photo: P. Tesler)

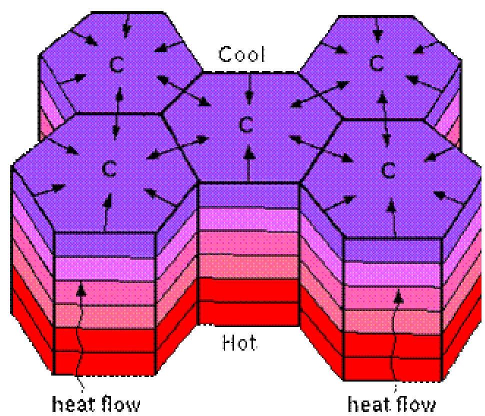


Figure 6. Columnar Jointing forming as lavas cool and shrink. https://www.geocaching.com

Table 3. Volcano Types

	Shield volcano	Stratovolcano or composite cone	Cinder or pyroclastic cone	Volcanic dome
Size	200 km wide 9 km tall	18 km wide 3 km tall	1500 m wide 300 m tall	50 m wide 25 m tall
Shape	Shield	Perfect cone (or composite of many cones)	Perfect cone shape	Dome
Major materials produced	Lavas primarily	Equal: pyroclastics & lavas	Scoria or pumice only (pyroclastics)	Lava only
Magma compositions	Mafic	Intermediate and Felsic	All	Felsic
Eruptive style (relative hazard)	Low	High	Low	Very high
Typical locations	Over hotspots	Subduction zone arcs and continental rifts	Flanks of all volcanoes	Craters of stratovolcanoes

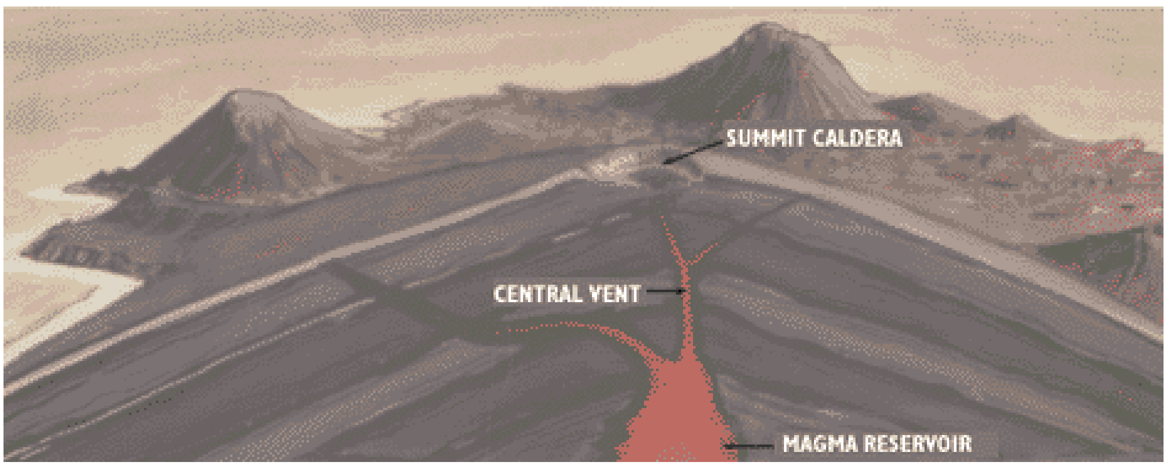


Figure 7. Shield Volcano – USGS – (200 km wide by 9 km tall)

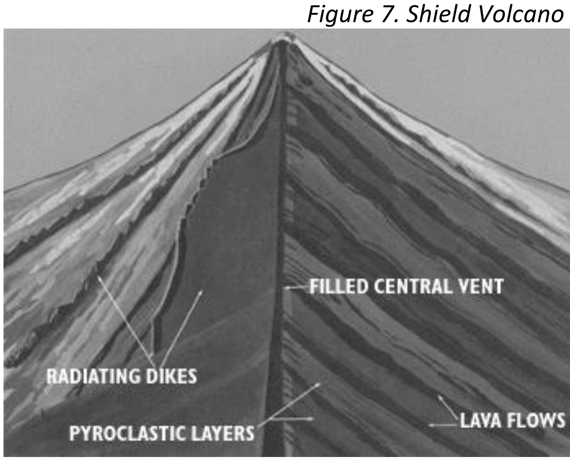


Figure 8. Composite or Stratovolcano – USGS (18 km wide by 3 km tall)

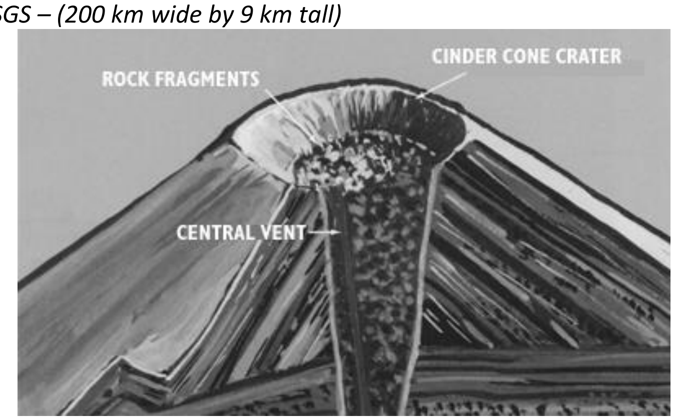


Figure 9. Cinder Cone – USGS – (1.5 km wide by 0.3 km tall)

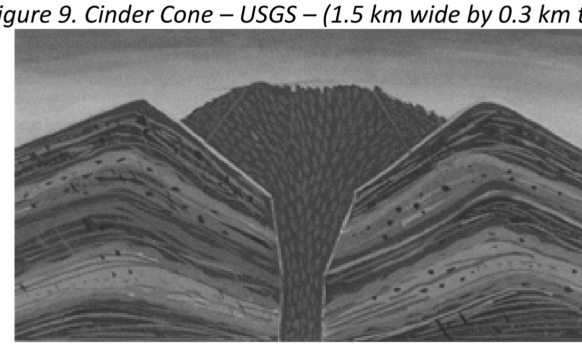


Figure 10. Volcanic Dome – USGS – (0.05 km wide by 0.025 km tall)

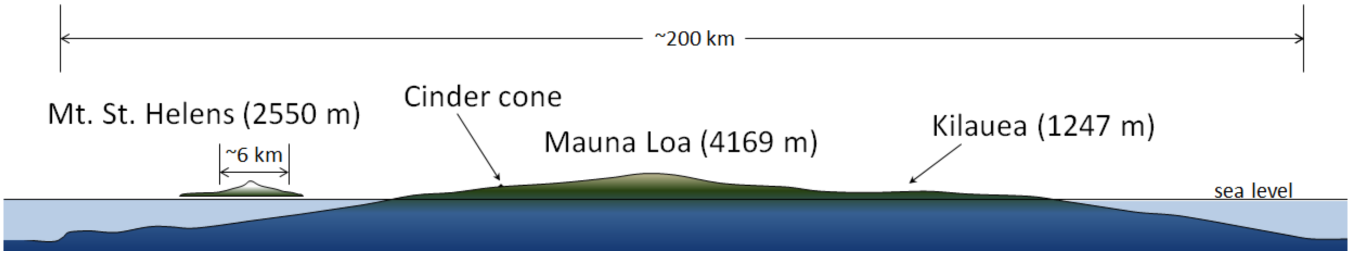


Figure 11. Profiles of Mauna Loa shield volcano, Mt. St. Helens composite volcano, and a large cinder cone. From Physical Geology by Steven Earl—CC 4.0 Attribution Intl. .

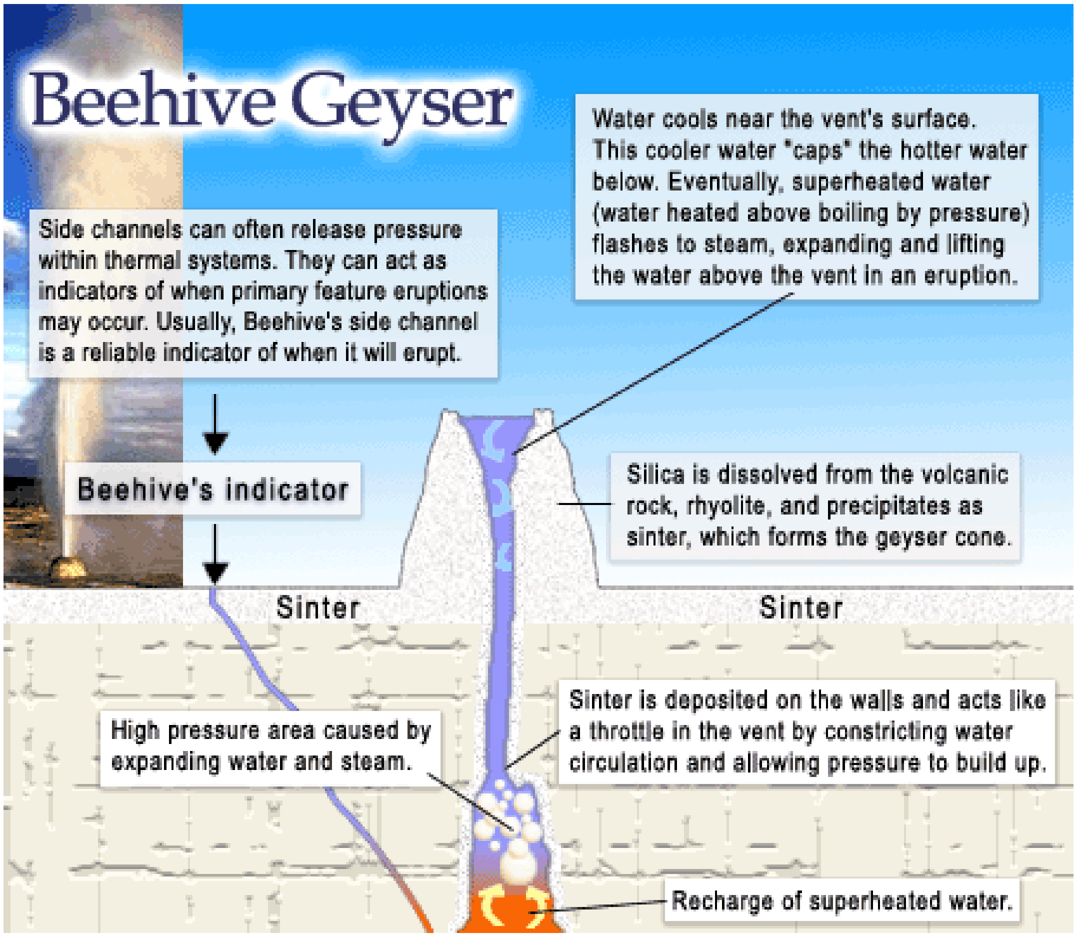


Figure 12. Geysers are hot springs that erupt periodically. In Yellowstone National Park, all of the ingredients needed for geyser activity are present: heat, water, and underground rock hard enough to withstand intense pressures. NPS. gov

Some more useful definitions:

Columnar joints	5-to-7-sided column-shaped cracks that form as lavas cool and shrink.
Shield volcanoes	The tallest and broadest volcanoes -- formed from low-viscosity mafic lavas, usually over hotspots.
Stratovolcanoes	Volcanoes formed from high-viscosity intermediate and felsic lavas alternating with pyroclastic flows or ashfall or lahars, usually over subduction zones or continental divergent plate boundaries.
Volcanic Domes	Felsic magmas that erupt in the craters of stratovolcanoes and form a dome shape because of their high-viscosity. These structures effectively block and cap the vent.
Cinder or pyroclastic cones:	**50-to-300-m tall c**one-shaped piles of pumice or scoria that are found on the flanks of shield or stratovolcanoe and repreasent single eruptions..
Tephra	Any material that was thrown out of (ejected from) a volcano during an eruption -- either liquid lava cooling as it traveled through the air or rock fragments ripped from the vent -- can be as small as a droplet that turns into ash or as big as a volcanic bomb.

Volcanoes and Volcanism – Chapter Worksheet

1. CIRCLE flood basalts are associated with which type of volcanism?
hotspot | subduction zones | divergent plate boundaries

2. What is the effect of flood basalts on global climate and Earth history?

3. CIRCLE which one of the following types of volcanism produces the highest-volume volcanoes (most eruptions from a single location in a given year): **hotspot | subduction zones | divergent plate boundaries**

4. How do magmas form under **hotspots**?

5. How do magmas form under **subduction zones**?

6. How do magmas form under **divergent plate boundaries**?

7. CIRCLE which of the following locations have volcanism due to a **hotspot**?
Aleutian Islands | Andes Mtns | Cascade Mtns | East African Rift Zone | Hawaii | Iceland | Indonesia | Japan | Long Valley Oceanic ridges everywhere | Philippines | Yellowstone

8. CIRCLE which of the following locations have volcanism due to a **subduction zone**?
Aleutian Islands | Andes Mtns | Cascade Mtns | East African Rift Zone | Hawaii | Iceland | Indonesia | Japan | Long Valley Oceanic ridges everywhere | Philippines | Yellowstone

9. CIRCLE which of the following locations have volcanism due to a **divergent plate boundary**?
Aleutian Islands | Andes Mtns | Cascade Mtns | East African Rift Zone | Hawaii | Iceland | Indonesia | Japan | Long Valley Oceanic ridges everywhere | Philippines | Yellowstone

10. **Oceanic volcanism** is mostly what igneous composition? CIRCLE: Mafic | Intermediate | Felsic
What is it about volcanism happening through oceanic crust that produces this composition?

11. **Continental volcanism** is mostly what igneous composition? CIRCLE: Mafic | Intermediate | Felsic
What is it about volcanism happening through continental crust that produces this composition?

12. List the main three gases released in a volcanic eruption.

13. What are the two primary characteristics of a magma sitting in a magma chamber that would make a volcanic eruption more hazardous? Why?

14. What does *tephra* mean?

15. CIRCLE which of the following are considered tephra? Ash | Gas | Lava | Pumice | Rock fragments | Scoria | Tuff

16. What do we call the **texture** and **name** of a rock composed of compacted ash and tephra? Why is such a rock usually **felsic**? (Why would felsic rocks be more likely to produce this texture?)

17. CIRCLE which of the following hazards moves the **furthest from the vent**:
Acid Rain | Ash | Gas Clouds | Lahar | Lava Flows | Pyroclastic Flows

18. CIRCLE which of the following hazards is the **fastest**:
Acid Rain | Ash | Gas Clouds | Lahar | Lava Flows | Pyroclastic Flows

19. CIRCLE which of the following hazards is the **hardest to escape**:
Acid Rain | Ash | Gas Clouds | Lahar | Lava Flows | Pyroclastic Flows

20. CIRCLE which of the following volcanic landforms is the **largest**:
Cinder Cone | Shield Volcano | Stratovolcano | Volcanic Dome

21. CIRCLE which of the following volcanic landforms is made almost entirely of **lavas**:
Cinder Cone | Shield Volcano | Stratovolcano | Volcanic Dome

22. CIRCLE which of the following volcanic landforms is the most **hazardous**:
Cinder Cone | Shield Volcano | Stratovolcano | Volcanic Dome

23. CIRCLE which of the following volcanic landforms is made entirely of **felsic material only**:
Cinder Cone | Shield Volcano | Stratovolcano | Volcanic Dome

24. How do we recognize each of the following geologic settings for volcanism? (Complete table below.)

Geologic Setting for Volcanism	**World Locations**	**Typical Volcanic Landforms found here (see options above)**	**Materials (composition and type)**
Hotspots			
Subduction Zone Volcanic Arcs			
Divergent Plate Boundaries			

Volcanoes Activity: Case Study & Concept Sketch

Case Study: pick a volcano, anywhere in the world, and research it in class materials and online. What is its geologic setting? What kind of volcanic materials and landforms are associated with it? Use the answers to these questions, and your research to draw a concept sketch of the volcano below (with scale!). Describe and label its key characteristics. Add your name and a bibliography of any sources you used. Be sure you include why this particular volcano interested you.

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Explain the various processes at work that make a volcano erupt.	A | B | C | D | F	
Compare and contrast the various geologic settings in which volcanism occurs.	A | B | C | D | F	
Analyze the hazard levels associated with all the different types of volcanic products.	A | B | C | D | F	
Compare and contrast various volcanic landforms including their causes, products, and hazard levels.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

MIDTERM EXAM WORKSHEET

These questions are intended to help you prepare for the exam and thus represent a subset of questions you might be asked on that exam. (To ensure you can answer ALL exam questions correctly, be sure to review all the chapter worksheets and concept sketches/activities).

1. For each of the following objects, place in order from smallest (top) to tallest (bottom) and give depths/thicknesses/etc. in kilometers.

Feature	Depth in km	Depth in km	Depth in km
Average depth of the oceans		Depth sea level would fall during an ice age	
Average thickness of ocean crust		Deepest location in oceans (Marianas Trench)	
Continental shelf break depth		Highest mountain elevation	
Deepest hole ever drilled on the planet		Radius of planet Earth	

2. When and how did Earth form?

3. From what two sources did the water in today's oceans originally come?

4. Where in the oceans is the newest ocean crust found?(general answer)

5. What kind of plate boundary exists in the Pacific Northwest along the coast?

6. What kind of plate boundary does San Francisco sit on?

7. If an extinct 6 m.y.-old hotspot volcano is located 600 km northeast from the current hotspot volcano. What has been the average plate speed and direction during that time in cm/yr?

8. Where are earthquakes concentrated globally? (Where do most occur in general?)

9. What evidence do we have that the outer core is liquid? Be specific and complete

10. Give all the ways that **<u>continental</u>** crust differs from oceanic crust (be SPECIFIC!).

Name the four layers of ocean crust.

11. TOP LAYER:

12. LAYER 2:			
13. LAYER 3:			
14. BOTTOM LAYER:			
Plate Boundary Type	Arrows showing the direction of motion:	Seafloor Feature	Primary cause:
15. Convergent		16. Rift Valley	
17. Divergent		18. Submarine Canyon	
19. Transform		20. Trench	
21. Draw what an anticline looks like from the side and the top when eroded. Where are the oldest rocks? Make the top of the page north (add a north arrow).			
22. What kind of fault is the San Andreas Fault? How can we tell?			
23. An earthquake measuring 5 on the Richter scale has an amplitude on the seismograph how many times taller than a size 2 earthquake?			
24. An earthquake measuring 5 on the Richter scale releases how many times more energy than a size 2 earthquake?			

25. How do earthquakes differ among the different plate boundaries?
26. Where in the world is continental rifting happening today?
27. Which oceans are dominated by ACTIVE MARGINS? CIRCLE: Arctic | Atlantic | Indian | Pacific
28. Which oceans are dominated by PASSIVE MARGINS? CIRCLE: Arctic | Atlantic | Indian | Pacific
29. Where would we find the thickest crust in the world? Why?
30. What would happen to the crust during an ice age? After?
31. Through what methods do continents grow?

32. Where do we usually find the oldest rocks in a continent? Why?

33. How do minerals differ from rocks?

34. If the number of electrons in an atom is 12; its atomic mass is 25.

How many protons?	How many neutrons?	What is the atomic number?	What is the element?	How many valence electrons?

35. Which silicate mineral has the **lowest Si:O ratio**? Why?

36. Which silicate mineral has the **highest Si:O ratio**? Why?

37. What is the chemical formula for **quartz**?

38. What is the chemical formula for **calcite**?

39. What's the best test for distinguishing calcite from quartz or anything else?

40. What is the best means of distinguishing between plagioclase and potassium feldspar?

41. How does magma differ from lava?

42. Write in the rock names that go with each texture and composition and be sure how to distinguish among them.

Texture:	**Phaneritic**	**Aphanitic**	**Glassy**	**Frothy**	**Pyroclastic**
Ultramafic					
Mafic					
Intermediate					
Felsic					

43. List below the minerals that appear in Bowen's Reaction Series, starting with the first on left and last on right.

44. What major factors increase the crystal size of minerals in igneous rocks? How?

45. What is porphyritic texture and what does it mean about a rock's formation history?

46. Under what circumstances will no crystals form when a melt solidifies? What do we call such a product?

47. CIRCLE flood basalts are associated with which type of volcanism?
hotspot | subduction zones | divergent plate boundaries

48. CIRCLE which of the following type of volcanism is the highest volume in a given year:
hotspot | subduction zones | divergent plate boundaries

49. How is mantle melted to create magmas under the three geologic settings for volcanism? (Provide three settings and the mantle melt method.)

50. Oceanic volcanism is mostly what igneous composition? CIRCLE: Mafic | Intermediate | Felsic
Why?

51. Continental volcanism is mostly what igneous composition? CIRCLE: Mafic | Intermediate | Felsic
Why?

52. List the main gases released in a volcanic eruption.

53. What are the two primary ways to make a volcanic eruption more hazardous? Why?

54. Which volcanic hazard is the most difficult to escape? Why?

SEDIMENTARY ROCKS

Sedimentary Rocks Review

Sedimentary rocks form from:

- **Precipitation** of minerals directly from a fluid (example: salt that forms when seawater evaporates).
- **Lithification of sediment** – small particles of rocks, minerals, and organic material, broken up, transported, and deposited in piles, then hardened and turned into rocks through:
  - **Cementation** of sediments usually by aqueous solutions that percolate through sediments and deposit calcite, quartz, or iron oxide glues that then cement the sediments together. Example: sand dunes buried and cemented by percolating waters depositing quartz or calcite between grains to create *sandstone*.
  - **Compaction** of sediments by being buried under layers of other rocks and sediments. Example: old layers of seafloor mud buried under new layers, thereby becoming mudstone and shale.

Classifying sedimentary rocks

Composition and grain size are the primary means for classifying sedimentary rocks. All sedimentary rocks are separated into these main categories:

- **Chemical** – Intergrown crystals precipitated from *aqueous solutions* (water and dissolved ions): gypsum, halite, limonite, hematite, dolomite, some varieties of quartz, calcite.
- **Clastic** – Composed of individual fragments (clasts), usually of varying types of material.
  - **Organic** – Fragments that are mostly the remains of organisms: shells, plant fragments, carbon.
  - **Detrital** – Fragments that are mostly rock fragments and mineral grains that were weathered and transported from their source – broken pieces, of quartz, feldspars, micas, clays, and rocks.

Chemical sedimentary rocks can have a **crystalline** texture (visible crystals) or **microcrystalline** texture (crystals too small to see). We further classify chemical sedimentary rocks by their primary mineral composition. For example, chemical sedimentary rocks of $CaCO_3$ composition (like the mineral Calcite) are called **limestones**. If the composition is mostly SiO_2 (glass), they are called **chert**. Note: a subset of chemical sedimentary rocks are **evaporites**: minerals and the rocks they produce, such as halite and gypsum, that form when water rich in dissolved ions evaporates allowing the dissolved ions to once again combine and precipitate as crystals. Typically these form around the edges of the ocean in warm climates (and in interior lakes in desert climates, such as the Great Salt Lake and the Dead Sea).

Clastic sedimentary rocks are classified by both their composition and their grain size. For example, rocks with mud-sized fragments of calcareous ($CaCO_3$) shells are called **chalk**. Rocks with mud-sized fragments of siliceous (SiO_2) shells are called **diatomite**. Rocks with mud-sized fragments of detritus (rocks, minerals, etc.) are called **mudstones**.

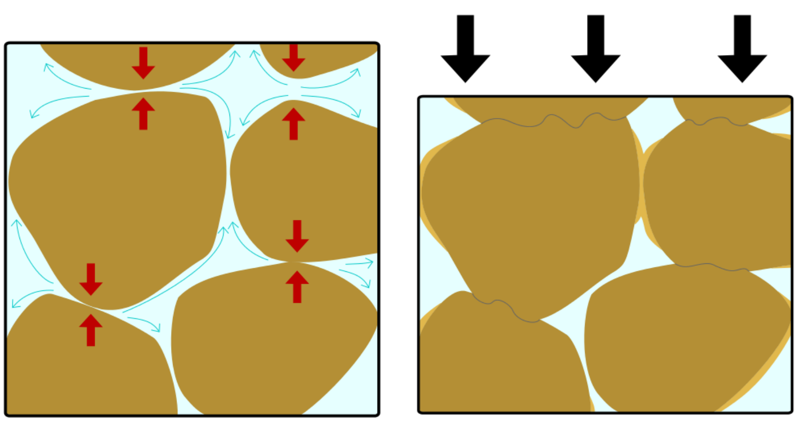


Figure 1. Schematic diagram of pressure solution accommodating compression/compaction in a clastic rock. Left box shows the situation before compaction. Blue arrows indicate the flow of particles in solution. Red arrows indicate areas of maximum stress (= grain contacts). Right box shows the situation after compaction. In light coloured areas new mineral growth has reduced pore space. Image: Woudloper – Public Domain.

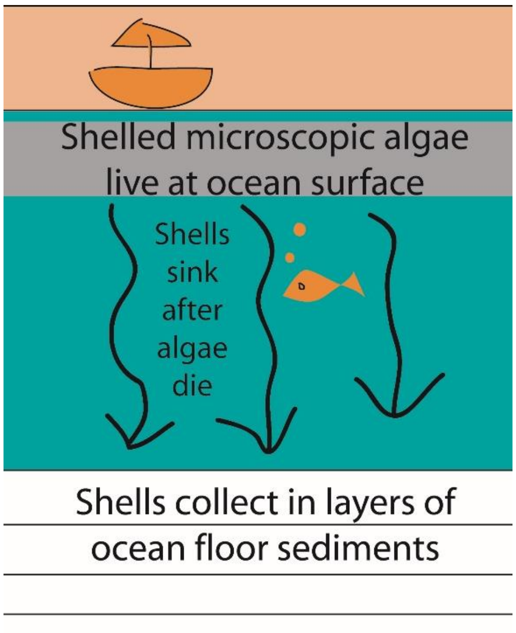


Figure 2. Chalk or diatomite formation

Grain size – Grains are largest near their **source** (exposed bedrock region, where first weathered off parent rock). As grains are moved away from their source by water or gravity, they continue to break down, becoming smaller. While small grains are easily transported, only high-energy water can transport large grains.

- **Gravel** – X > 2 mm – Probably close to source. Moved and deposited only by high-energy waters, like floods; typically found near exposed bedrock in mountainous areas or at the base of eroding cliffs and headlands.
- **Sand** – 1/16 < X < 2 mm – Probably far from source. Deposited by moderate-energy waters, like rivers or surf; typically found on beaches or river bars. Further divided into coarse, medium, and fine grained.
- **Mud** – 0.0002 < X < 1/16 mm – Probably very far from source. Deposited by low-energy waters, like lakes, lagoons, and the bottom of the seafloor.

Grain sorting (degree of similarity of grain sizes) **–** As grains are transported by water and deposited wherever the water slows, they sort themselves by size and weight. The longer they've been carried, the better the sorting. {Wind deposits are very well sorted, but only because wind can transport only a very narrow range of fine sands. Glaciers carry all grain sizes far from their source without significantly reducing size. They deposit their load by simply dropping it as the ice melts. Therefore, glacial deposits are very poorly sorted. Landslide deposits are also poorly sorted.}

- **Very poorly sorted** – Probably very close to source, with no transit by water.
- **Poorly sorted** – Probably close to source, with little if any transit by water.
- **Moderately sorted** – Probably far from source, with some transit by water.
- **Well sorted** – Probably far from source, with extensive transit by water.
- **Very well sorted** – Probably very far from source, with extensive transit by wind or water.

Grain shape – As grains are transported by wind or water or if they have water continually running across them (like waves moving across sand and pebbles at the beach), they knock against each other and round. When grains are first weathered from their parent rock, they are jagged. The degree of rounding is a good indicator of how much wind transport or water transport or wave motion has occurred or after initial grain formation. {Wind rounds and frosts only sand-sized grains. Glaciers trap sediment in ice, preventing rounding.}

- **Angular** – Probably very close to source. Little if any transit by water.
- **Subangular** – Probably close to source. Some transit by water.
- **Subrounded** – Moderate distance from source. Moderate transit by water.
- **Rounded** – Probably far from source. Significant transit by water.
- **Well rounded** – Probably very far from source. Major transit by water.

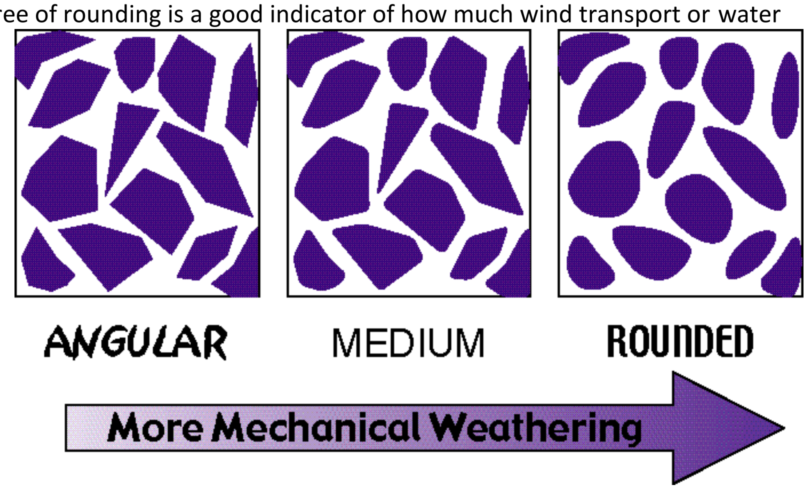


Figure 3. Grain shapes as weathering progresses.

Grain composition – As grains break off their parent rock, they are also undergoing chemical weathering. The longer a grain has been separated from its source, the more exposure it has had to the elements, and the more weathered it will be. We call the young grains immature, and the older ones mature. The range of grain composition found in sediment is a good indicator of maturity.

- **Quartz** – Mature; withstands chemical weathering. Grain could have traveled far.
- **Clay** – Mature; the main weathering product of silicates. Grain could have traveled far.
- **Magnetite and Feldspars** – Medium Maturity; withstands physical weathering long enough to be transported by rivers; will eventually weather. Grains could have traveled far.
- **Silicate minerals like olivine, pyroxene/amphibole, and micas**– Immature; weather quickly upon exposure. Grain could not have traveled far from source.
- **Rock fragments like basalt, serpentinite/chert, mudstone, and granite**– Immature; weather quickly upon exposure. Grain could not have traveled far from source.
- **Calcareous shells** – Immature; easily dissolved. Grain could not have traveled far from source.

Sedimentary structures and environments

We use sedimentary rock structure and composition to learn something about the environment in which the rock formed (deposited or precipitated). There are many things about an **environment of deposition** that sedimentary rocks preserve and which give us clues about its formation. For example:

Figure 4. Fossilized Ripple Marks – Glacier National Park

Ripple marks indicated sediment formed where water moved regularly over it – ripples can be symmetrical as like the ones that form in the surf zone of a beach where water moves back and forth or asymmetrical along the bottom of a river where water only flows in one direction.

Figure 5. Oyster Fossil – Fossil Ridge – Mt. Diablo State Park

Fossils of clams indicate the sediment formed in a near-shore marine environment (in climate conditions conducive to clams). Fossils of Oak tree leaves suggest sediment formed inland, near an Oak forest (again in climate conditions conducive to Oak trees).

Mud cracks indicate sediment formed in an area where muds were deposited and the surface dried out, like in the desert after floods (when lakes evaporate) or in the tidal flats in a marine environment.

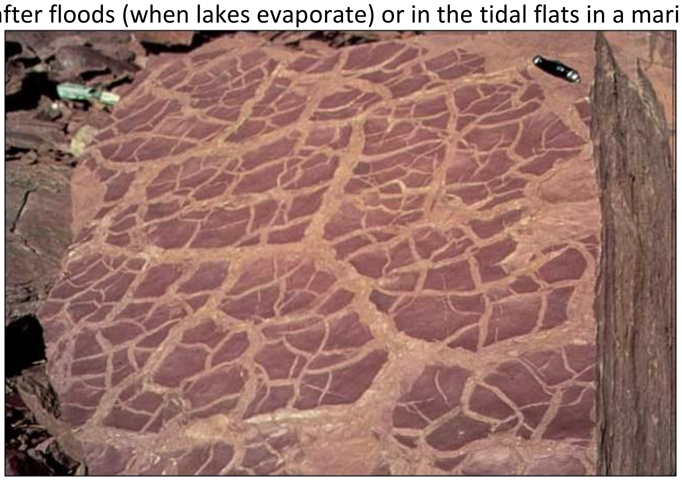


Figure 6. Fossilized Mud Cracks – Glacier National Park

Figure 7. Current Mud Cracks forming – Death Valley National Park – Marc Salomon

The most common sedimentary structure is layering or **stratification**. Sedimentary rocks form in horizontal layers or **beds**, because they come from accumulations of sediment or precipitation, both of which usually happen (thanks to gravity) along the horizontal. Contacts between different layers of sedimentary rock are called **bedding planes**. Sometimes sediment accumulates along an inclined surface, like sand along the slip-face of a sand dune. Such inclined deposits often change and shift as the wind changes. Sedimentary rocks that display this type of alternating inclined strata have **cross bedding**. Depositional environments that contain such deposits include sand dunes in the desert or those that exist behind a beach along the shoreline.

We can use sorting in a single bed to determine whether the sediment accumulated gradually or quickly, was sorted by water or not at all, etc. **Graded bedding** is a single layer of sediment where the bottom of the layer contains the largest grains, and as you move higher in the layer, the grain sizes decrease. Such a feature forms only when high-energy water that is strong enough to carry all grain sizes suddenly drops its energy (or velocity) and quickly dumps its sediment load. The larger, heavier particles settle first – the smaller finer ones are last. Depositional environments that contain such deposits include the base of a submarine canyon (turbidity current deposits) or in river deposits, where flood waters drop their sediment load.

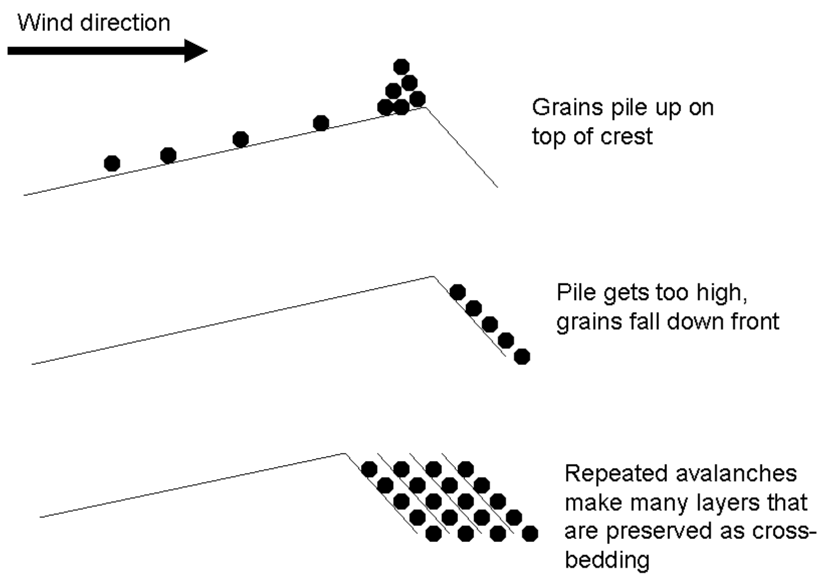


Figure 8. Cross-bedding formation in sand dunes. Diane M. Burns CC BY-NC-SA 3.0

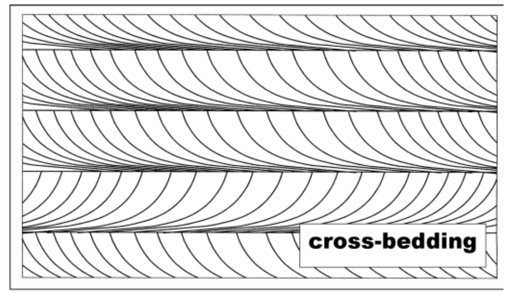


Figure 9. Cross-beding as it appears in layers of sand stone: Ralph Dawes and Cheryl Dawes – Creative Commons: CC BY 3.0 US

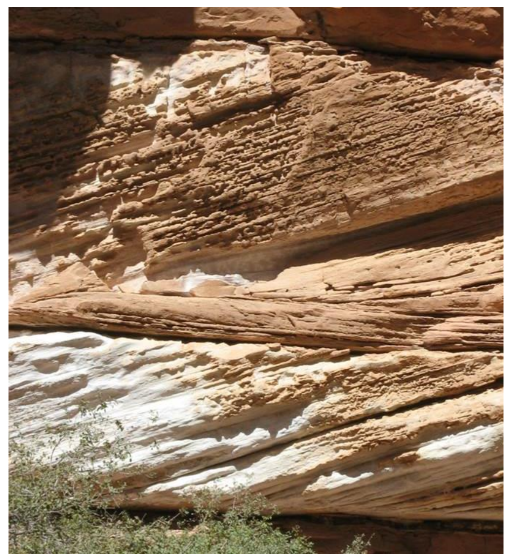


Figure 10. Fossilized Cross Beds Grand Canyon National Park

WEATHERING PROCESSES

During chemical weathering of a rock, the usual element distribution is:

- Fe – Oxidizes: combines with O to form insoluble iron oxides, giving red to yellow soil cover.
- Al, Si, O – Hydrolizes: combines with water to form clays (only if all three (Al, Si, O) are in mineral).
- Quartz – Stays in place; doesn't break down chemically.
- Na, Ca, K, Mg, other cations, AND excess silica (silica not in quartz or not combined with Al and O to form clays) – Dissolves and is removed by water.

Table 1. Chemical Weathering Processes

Types	Description of process and results
Dissolution	Water molecules gang up on ions on outside of mineral lattice (surface) and break the mineral bonds, releasing the ions into solution. Water carries ions away.
Hydrolysis	Water molecules enter mineral formula, replacing other components and changing mineral to a new one: a clay mineral. Example: $2KAlSi_3O_8 + 2H^+ + 9H_2O = Al_2Si_2O_5(OH)_4^+ 4H_4SiO_4 + 2K^+$ K-feldspar + water = Kaolinite clay + silicic acid and potassium ions
Oxidation	Oxygen bonds with Fe ions on outside of mineral lattice (surface) removing Fe from mineral and producing Hematite (rust). $O_2 + 2\ Fe^{2+}$ +/- $H_2O \rightarrow FeO$ or Fe_2O or Fe_2O_3 or $Fe(OH)_2$

Table 2. Sedimentary Rock Identification and Naming Table

Review and be able to distinguish diagnostic characteristics of each of the rocks listed in the following table (if these descriptions showed up in a multiple-choice exam, you could match them to the correct rock.)

Chemical sedimentary rock (precipitated minerals or recrystallized shells – interlocking microscopic crystalline texture)

Composition	Texture and physical properties	Name	Depositional environment
Calcium carbonate $CaCO_3$	Interlocking texture, crystals too fine to see. Light brown, grey, or white.	**Limestone***	Precipitation in the deep sea or recrystallization of shells accumulated on the deep sea floor (clastic texture gone).
	Layers of crystals – formed from evaporation of water.	**Limestone** (Evaporitic or crystalline)	Precipitation in salt lakes and inland seas.
Quartz SiO_2	Interlocking texture, crystals too fine to see. White, red, brown, black, or green.	**Chert**	Precipitation in the deep sea or hydrothermal zones or recrystallization of shells accumulated on the deep sea floor (clastic texture gone).
	Occurs as black nodules, usually surrounded by powdery white rind.	**Chert** (Flint)	Precipitation in hydrothermal zones.
Halite NaCl	Crystalline; salty taste	**Rock salt**	Precipitation in salt lakes and inland seas.
Gypsum $CaSO_4$ $2H_2O$	Very soft, crystalline	**Rock Gypsum**	Precipitation in salt lakes and inland seas.

***Remember: use mineral ID skills to help distinguish among these!**

Clastic sedimentary rock (cemented or compacted fragments)

Grain sizes: Gravel (>2mm); Sand (>1/16 mm; < 2 mm); Mud (<1/16) mm

Organic (biochemical) sedimentary rock (mostly shell fragments)

Composition and Texture	Grain size	Name	Depositional environment
Calcium carbonate $CaCO_3$ WHITE (usually); Macro/microscopic shell fragments; Loosely cemented; porous.	Gravel	Coquina (**Limestone**)	Beach with fringing reef
	Sand	Calcarenite (**Limestone**)	At outside edges of fringing reefs
	Mud	**Chalk** (Limestone)	Deep seafloor where zoo/phytoplankton with microscopic $CaCO_3$ shells rain down.
Silica SiO_2 WHITE (usually); Macro/microscopic shell fragments. Loosely cemented; porous.	Mud	**Diatomite** (Chert)	Deep seafloor where zoo/phytoplankton with microscopic SiO_2 shells rain down.

Detrital sedimentary rock (mostly rock and/or mineral fragments)

Grain size	Texture and composition	Name	Depositional environment
Gravel > 2 mm	Rounded fragments; poorly sorted	**Conglomerate**	Beach headlands, river banks, canyon fans.
	Angular fragments; poorly sorted	**Breccia**	Base of landslides, faults, and debris flows.
Sand < 2 mm > 1/16 mm	Mostly quartz grains; well sorted; well rounded	**Sandstone** (quartz sandstone)	Beach, sand dunes (desert or beach); river banks.
	>25% potassium feldspar grains, with quartz	**Sandstone** (arkose)	Beach sands; river deposits.
	Mixed mineral grains/rock fragments.	**Sandstone** (greywacke)	Beach sands; river deposits.
Mud < 1/16 mm	Microscopic quartz/clay grains; can be bedded. **Shale variety is compact; splits into thin layers.**	**Mudstone** or **Shale**	Shallow, quiet lagoon; tide flats; outer continental shelf; deep sea.

*Dolostone is similar to chemical limestone (same depositional environment, look, and texture), but has Mg in it.

Some more useful definitions:

Weathering	Breakdown of solid rock physically into smaller pieces and/or chemically (dissolution, rusting, or transformation to clay).
Erosion	Removal of weathered debris from one location and transported to another by agents such as rivers, wind, glaciers, gravity, waves, currents, and more.
Deposition	Dropping of weathered debris into a pile in a particular location (usually because the medium that previously transported it has slowed down or stopped).
High- vs. Low-Energy Water	Water energy translates to water velocity -- velocity of the current or the motion of the water. High-energy water has high velocity or high motion and can thus pick up and carry larger particles. The lowest-energy water is still.
Mature vs. Immature Sediment	Mature vs. immature sediment is a reference to how far sediment is from the original parent rock it broke off of. That's all. Sediment on a beach/shore can be immature OR mature. If it comes from the cliff behind the beach, it's immature. If it comes from the mountains via a river, it's mature! How to tell? A combination of composition (rock fragments are immature because over time they break down into quartz and clays) and grain size (the longer it's been in transit, the smaller the size becomes).
Sediment	Weathered rock or organic debris that collects in piles in low-lying areas on Earth’s surface.

Weathering and Sedimentary Rocks – Chapter Worksheet

1. CIRCLE which of the following is true for **weathering**. Breakdown in place | Transport away from area to a new area
2. CIRCLE which of the following is true for **erosion**. Breakdown in place | Transport away from area to a new area
3. How does chemical weathering add to the effectiveness of **physical weathering**?
4. How does physical weathering add to the effectiveness of **chemical weathering**?
5. What is the primary cause and effect of **frost wedging**? Where is it happening right now?
6. What is the primary cause and effect of **exfoliation**? Where is it happening right now?
7. What is the primary cause and effect of **spheroidal weathering**? Where is it happening right now?
8. What is the most common naturally formed acid? How does it form? (Give equation.)
9. Using the weathering processes table in the preceding pages, describe what happens to various elements present in minerals during chemical weathering:

Elements/minerals	**Results during chemical weathering**	**Elements/minerals**	**Results during chemical weathering**
Na, Ca, K, Mg, etc.		Al, Si, O (when all together in a mineral)	
Fe		Quartz	

10. Using the weathering processes table in the preceding pages, describe what happens to these minerals during chemical weathering. Map the elements in the mineral to their products as you did above.

Mineral undergoing chemical weathering:	**What happens to its components?**
Amphibole family: **Hornblende** [Silicate with Ca, Mg, Fe, Al, OH]	
Feldspar family: • **Plagiociase Feldspars**: Anorthite and Labradorite[$CaAl_2Si_2O_8$] to Oligoclase and Albite [$NaAlSi_3O_8$] • **Potassium Feldspars**: Orthoclase and Microcline [$KAlSi_3O_8$]	
Garnet Fe,Mg,Ca, Al Silicate	
Mica family: • Biotite [Silicate with K, Mg, Fe, Al, Ti, OH, F] • Muscovite [Silicate with K, Al, OH, F]	

Mineral undergoing chemical weathering:	What happens to its components?
Olivine $(Mg,Fe)_2SiO_4$	
Pyroxene family: Augite $Ca(Mg,Fe,Al)(Al,Si)O_6$	
Quartz SiO_2	
Serpentine $Mg_6Si_4O_{10}(OH)_8$	
Talc $Mg_3Si_4O_{10}(OH)_2$	

11. Which **silicate** minerals on Bowen's Reaction Series are most susceptible to chemical weathering? Give name of mineral(s) and explain why? *(For this question, refer to what you learned about these minerals in the Minerals chapter and their types of bonding.)*

12. CIRCLE which characteristics of a rock outcrop and its surroundings would make it weather fastest.

hot climate | cold climate | wet climate | dry climate | lots of vegetation | little vegetation (desert)

mafic rock composition | felsic rock composition | physically soft rock | physically hard rock

13. What two minerals are most common in detrital sedimentary rocks? Why are these minerals so abundant?

Mineral	Reason so abundant

14. What is a turbidity current? What sedimentary texture characterizes its deposits? (What do these deposits look like? Draw sketch.) What topographic feature do they produce?

15. What past sedimentary environment leads to **ripple marks** in a rock? (What does it look like and why? Provide sketch.)

16. What past sedimentary environment leads to **cross-bedding** in a rock? (What does it look like and why? Provide sketch.)

17. Distinguish between **clastic and chemical textures**. How does this differ from **detrital vs clastic**?

18. How is detrital sediment turned into sedimentary rock (lithified)? (Two main processes, not including precipitation.) For what kind of sediment does each apply?

19. Describe the three most common **cements** for sedimentary rocks and know how to identify each one.

20. What are **evaporites**? Provide some examples. How do they form?

21. What grain sizes and compositions are typical of mature sediments? Immature? Why?

22. Review the sedimentary rock identification table in the preceding pages. You should be able to use this table to identify all the sedimentary rocks listed by their description. (There is a photo album on the class website that shows you images of all these rocks as well, but you will have to identify them in lecture only by their description.) What is the difference between the three tables sedimentary rocks have been divided into and how are they sorted within?

Sedimentary Rock Activity: Identifying Sedimentary Rocks

Using the rock-naming table (Table 2) from the preliminary figures and tables for this chapter AND the photo album provided in the class materials, practice distinguishing between and naming the different sedimentary rocks:

Sedimentary rock name	Texture, including grain size, if appropriate	Composition	Possible depositional environments
Arkose sandstone			
Breccia			
Calcarenite Limestone			
Chalk			
Chert			
Coquina Limestone			
Conglomerate			
Diatomite			
Flint (Chert)			
Graywacke sandstone			
Limestone			
Mudstone			
Quartz sandstone			
Shale			

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Compare and contrast the different chemical and physical properties of sedimentary rocks and what they indicate about the formation process of each rock.	A | B | C | D | F	
Classify and name basic sedimentary rocks.	A | B | C | D | F	
Describe how chemical weathering occurs (processes and end products) for the basic rock-forming minerals.	A | B | C | D | F	
Compare and contrast different sedimentary structures (such as ripple marks and fossils) and what they indicate about the formation process of a rock.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

METAMORPHIC ROCKS

Metamorphic Rocks Review

Metamorphic rocks are igneous, sedimentary, or other metamorphic rocks that have undergone extreme change (without melting – remaining always solid). Such change results from pressure increase, temperature increase, and/or injection of hydrothermal, chemically active fluids. Metamorphism occurs generally between 200°C and 800°C. Lower temperatures are associated with sedimentary processes; higher temperatures would melt the rock, turning it into an igneous rock.

Table 1. Common metamorphic settings for metamorphism and their characteristics and symbol

Metamorphic setting		Presure (P)	Temperature (T)	Chemically active fluids
Contact metamorphism	**C**	Low	High: increasing toward magma	High – from magma and from heated surface waters.
Burial metamorphism	**B**	High: steadily increasing with depth	Low to High: steadily increasing with depth	Low – liberated from hydrous minerals
Converging continents (regional)	**R**	High: increasing with depth	Low to High: steadily increasing with depth	Low – liberated from hydrous minerals
Subduction zone metamorphism	**S**	High	Low to medium: slowly increasing with depth	High – from hydrous minerals in hydrothermally altered ocean sediments and basalts; and from water trapped in pores and cracks.
Hydrothermal circulation at spreading centers	**H**	Low	High because occurs at the mantle/crust boundary.	High – from magmas and from circulating seawater

We use mineralogy and texture in a metamorphic rock to determine the agents that caused the rock to form (the highest temperature and pressure and/or types of fluids to which a rock was exposed). We call the intensity of metamorphism to which a rock was exposed **metamorphic grade**.

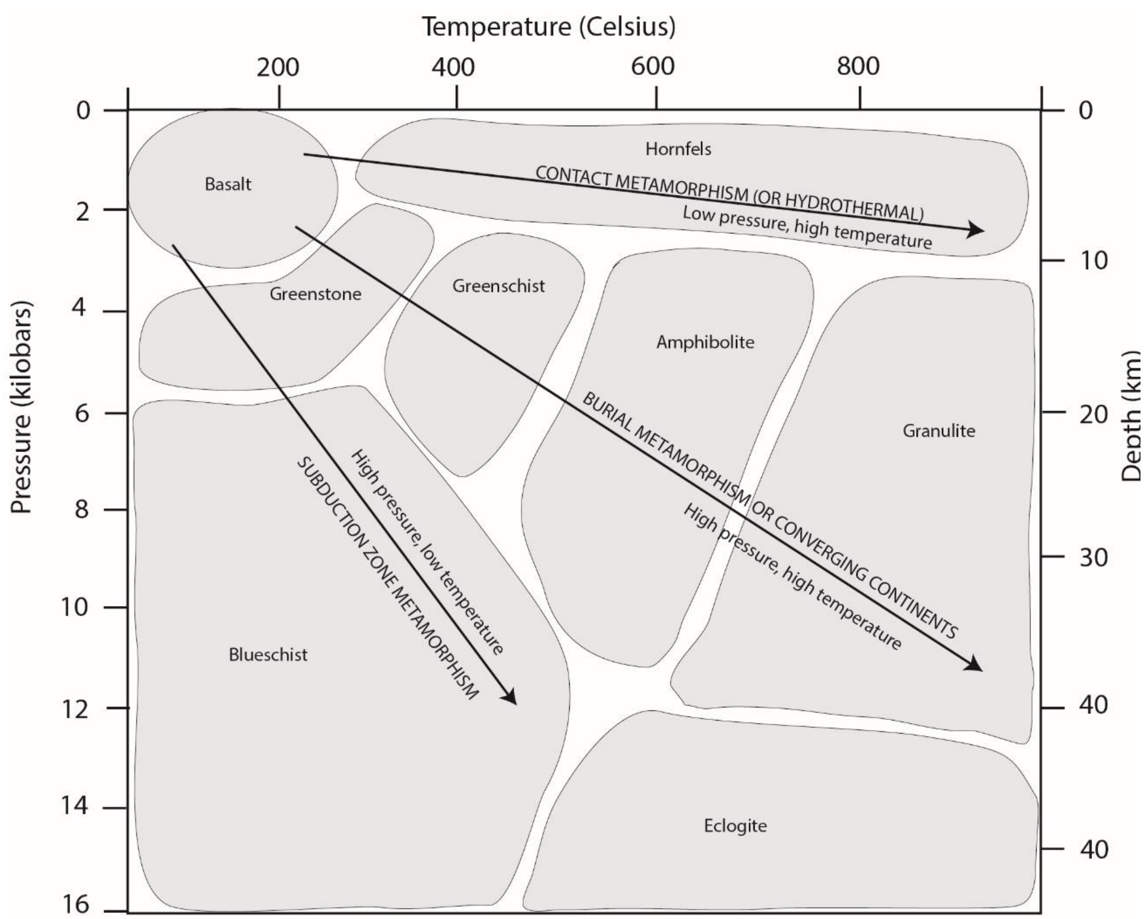


Figure 1. BASALT METAMORPHISM BY METAMORPHIC SETTING

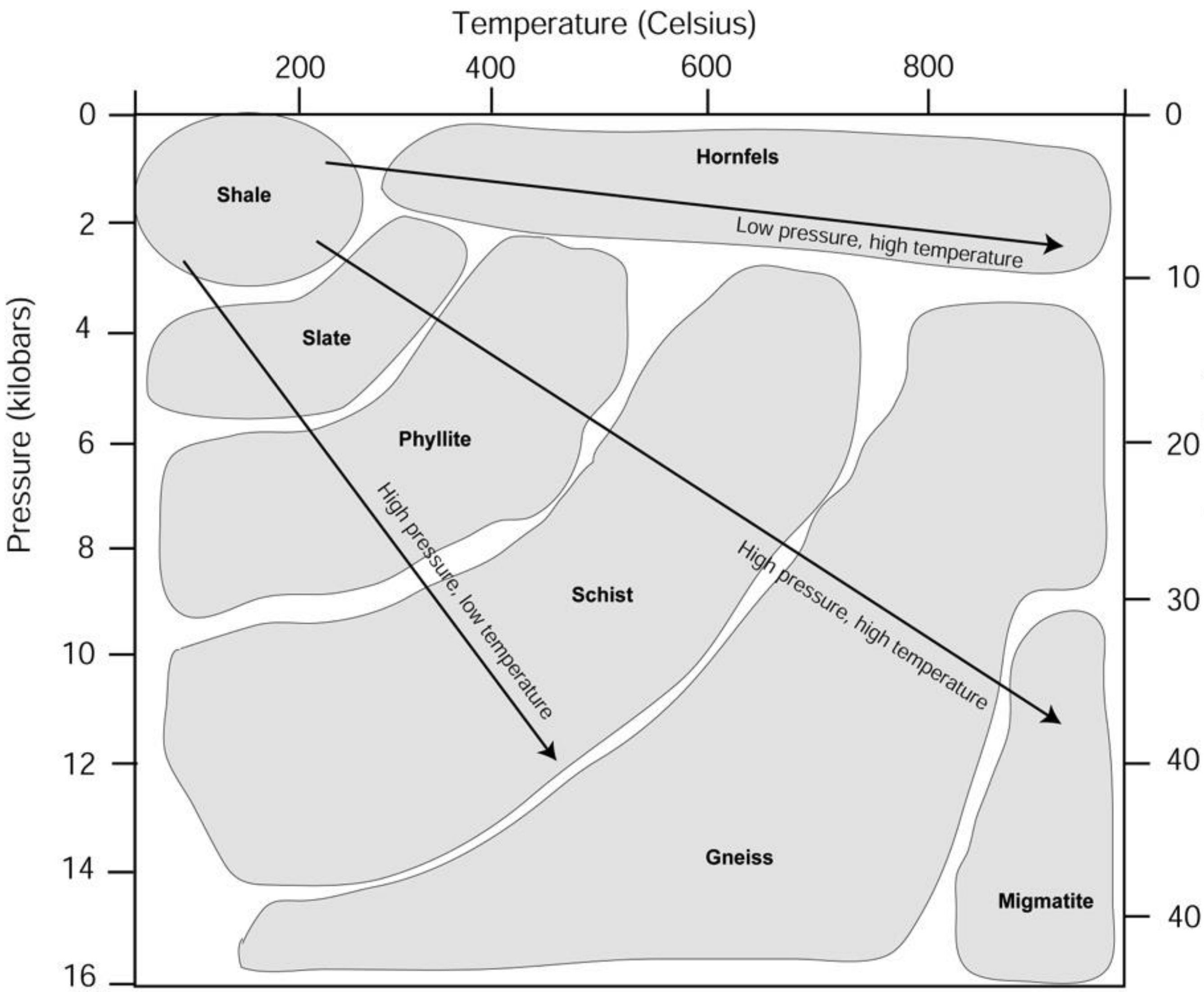


Figure 2. SHALE METAMORPHISM BY METAMORPHIC SETTING

Textural changes

Major textural changes occur as metamorphic grade increases, due to increased pressures and temperatures. If the pressures are uniform in all direction (**confining pressure**), the results are different than if the pressure is high in only one direction (**directed pressure**). In the latter case, pressure is released if minerals align themselves perpendicular to the direction of pressure.

- **Density increases (volume shrinks)** – Grains/crystals pack closer together under confining pressure.
- **Foliation increases** – Minerals align when under directed pressure.
- **Crystal size increases** – Grain boundaries migrate, enlarging crystal size as pressure (any kind) placed on crystal boundaries.

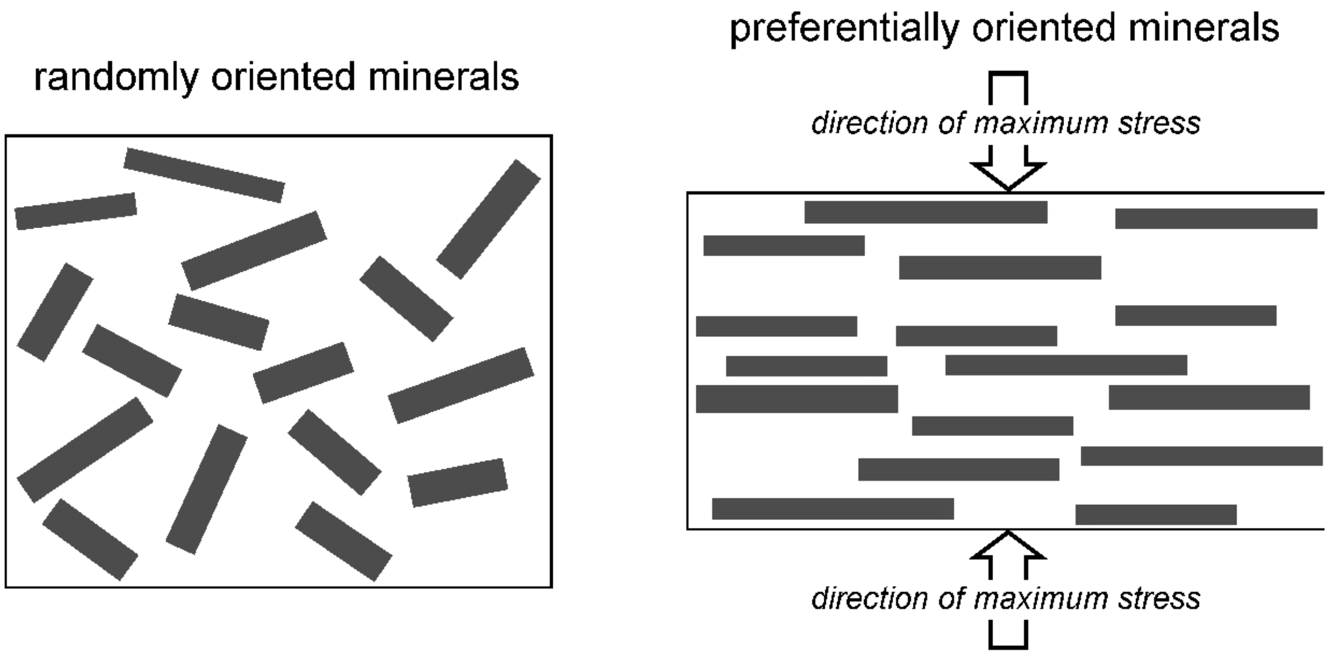
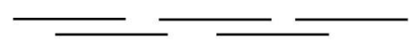
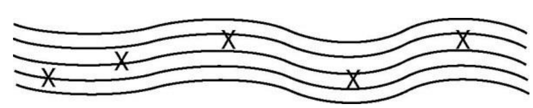
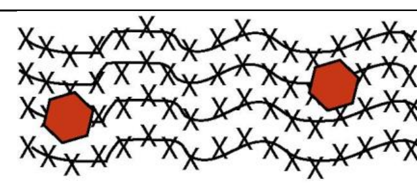


Figure 3. Foliation: Ralph Dawes and Cheryl Dawes – Creative Commons: CC BY 3.0 US

Other Textural Changes found in metamorphic rocks:

- **Veins** – Fractures filled by minerals that precipitated from hydrothermal fluids.
- **Porphyroblasts** – Unusually large crystals set in a finer-grained groundmass.
- **Folds, lineations, stretched or sheared grains** – Clasts or layers in the original rock are stretched out or folded under directed pressure.
- **Slickensides** – Smoothed, grooved surfaces – formed when two rocks move across one another, like along faults or cracks or rocks in glaciers moving across bedrock.

Table 2. Foliation Types

Grade	Foliation type	Description	Picture
Low	Rock or slaty cleavage	Microscopic, aligned mica minerals. Planar cleavage. No visible minerals. Dense.	
Low to med	Phyllitic texture	Mostly microscopic, aligned mica minerals. Only a few visible, isolated minerals peeking out of satiny background. Foliation is undulating.	
Med to high	Schistosity	Mostly visible biotite minerals – all aligned, giving rock a scaly look, like a fish. Foliation is undulating and fine. Some large porphyroblasts may peek out.	
High	Gneissic texture	All visible, interlocking crystals, separated into alternating dark- and light-colored layers.	
Very high	Migmatitic texture	Gneissic texture where ½ melted, and the high temperatures caused folding of the layers.	

Mineral changes

Minerals can change and grow in metamorphic rocks, without melting. The chemically active fluids and pressure at crystal grain boundaries can cause the ions in the solid rock to migrate as though they were in a fluid. For this reason, metamorphic minerals tend to show some of the most perfect crystal faces. In addition, as metamorphic grade increases, **minerals change to more stable ones** and **crystals get larger**. **Index mineral**s are minerals that are stable under narrow pressure and temperature conditions and therefore tell us something about the metamorphic environment to which a rock was subjected.

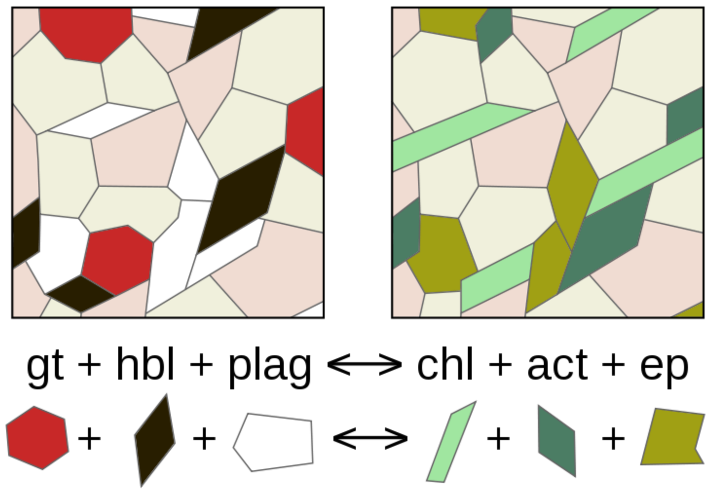


Figure 4. Simplified schematic representation of a metamorphic chemical reaction. Boxes represent the whole rock mineralogy. In this example the reaction is complete: no relict minerals remain. The reaction in question will in nature take place when a rock goes from amphibolite to greenschist facies or vice versa. Abbreviations of minerals: act = actinolite; chl = chlorite; ep = epidote; gt = garnet; hbl = hornblende; plag = plagioclase. Two non-participating minerals are present in the rocks: these could be (for example) K-feldspar and quartz. Woudloper – Creative Commons – CC BY-SA 3.0

Figure 5. Polymorph example: These three minerals have the same chemical formula (Al_2SiO_5), but are stable at different pressure and temperature conditions. During metamorphism, they can change from one form to another to reach stability at new temperatures and pressures.

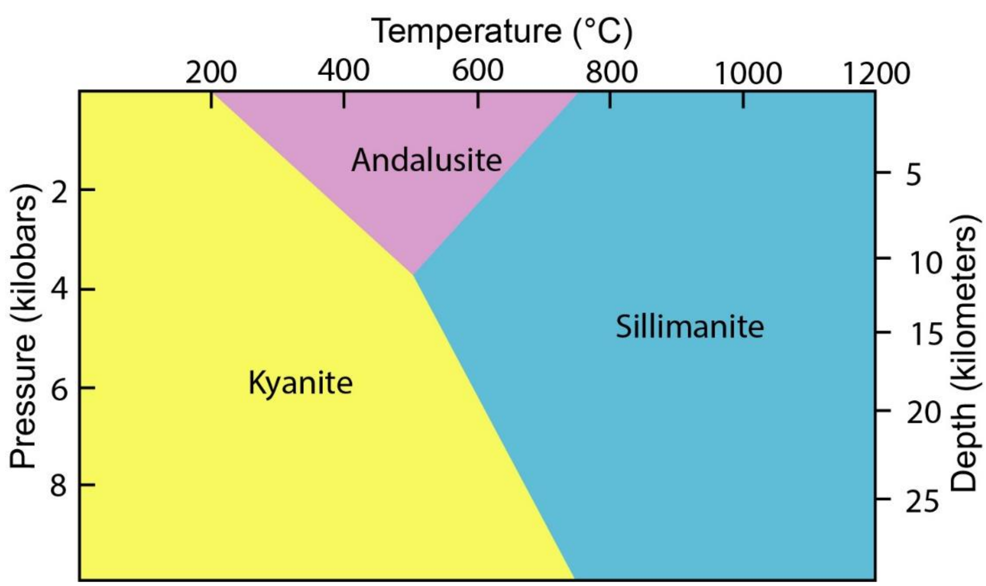


Table 3. Mineral Stability with increasing grade during regional or subduction zone metamorphism *(pressure and temperature both rise).*

Mudstone/Shale	Rocks: |---Slate----|---Phyllite-----|-----Schist-----------------|--------Gneiss------|----Migmatite----------| Minerals: |----CHLORITE--------------| |--MUSCOVITE--------------| |---BIOTITE---| |---------------GARNET---| |----STAUROLITE--| |-KYANITE-| |---------SILLIMANITE-----------| |--QUARTZ--| |---FELDSPAR---|

Table 4. Mineral Stability with increasing grade during all types of metamorphism

<table>
<tr><th>Parent Rock</th><th>Low Grade</th><th>Medium Grade</th><th>High Grade</th></tr>
<tr><td>Sandy limestone</td><td colspan="3">Rocks:
|--Quartzite---|
|--Marble--|
Minerals:
|--QUARTZ--|
|--CALCITE--|</td></tr>
</table>

Table 5. Metamorphic rock names based on parent rock, geologic setting, and metamorphic grade.

Metamorphic settings	**B, R, S**	**B, R, S**	**S**	**S**	**BR**	**B, R, S**	**B, R, S**
Parent rock	Shale	Granite	Serpent-inite	Basalt	Basalt	Chert (SiO_2)	Limestone ($CaCO_3$)
GRADE: Low Low - Med Med - High High Very High	 *Slate* *Phyllite* *Schist* *Gneiss* *Migmatite*	 *Gneiss* *Migmatite*	 *Soapstone*	 *Greenstone* *Blueschist* *Eclogite*	 *Greenstone* *Greenschist* *Amphibolite* *Granulite*	*Quartzite* (crystals grow larger)*	*Marble* (crystals grow larger)*

Metamorphic settings	**C**	**C**	**C**	**C**	**C**	**H**
Parent rock	Chert (SiO_2)	Limestone ($CaCO_3$)	Mixture of minerals	Shale	Basalt	Mantle rock (Peridotite)
GRADE: Low Low - Med Med - High High Very High	*Quartzite* (crystals grow larger)*	*Marble* (crystals grow larger)*	*Skarn* (crystals grow larger; form new minerals)*	*Hornfels* (crystals grow larger)*	 *Hornfels*	 *Serpentinite*

Quartzite, Marble, Skarn, and shale-metamorphosed Hornfels exist through all grades. The only way to tell grade of these rocks is through crystal size and in the case of skarn, mineral composition.

Table 6. Metamorphic Rock Identification and Naming Chart

Review and be able to distinguish diagnostic characteristics of each of the rocks listed in the following table (if these descriptions showed up in a multiple-choice exam, you could match them to the correct rock.)

Texture	Name	Parent rock	Geologic settings	Grade	Description
Foliated	**Slate**	Shale/Mudstone	B, R, S	Low	Dull; similar to shale, but more dense and breaks into hard flat sheets.
	Phyllite	Shale/Mudstone	B, R, S	Low-med	Similar to slate, but sheets are undulating (wrinkled). Luster is more silky or satiny than slate. Some isolated crystals might be visible.
	Schist	Shale/Mudstone, Basalt/Gabbro	B, R, S	Med-high	Crystals easily visible throughout rock – usually all micas, giving it a scaly look. Foliation greater than phyllite. Minerals can be garnet + biotite + chlorite + muscovite + quartz + plagioclase + epidote + kyanite. Chlorite disappears and kyanite appears as grade increases.
	Gneiss	Granite/Rhyolite, Shale/Mudstone	B, R, S	High	Grains medium to coarse; light and dark minerals segregated into bands. Gneissic texture.
	Migmatite	Granite/Rhyolite, Shale/Mudstone (+ Gneiss)	B, R, S	Very high	Contorted layers: gneissic texture that has been folded: some of the layers/bands have melted and crystallized as granite.
Weakly foliated	**Greenstone**	Basalt/gabbro	B, R, S	Low	Very fine grained (too small to see crystals); light to yellow green (from chlorite, epidote, and/or actinolite).
	Eclogite	Basalt/gabbro	S	High	Red garnets scattered uniformly throughout a finer-grained green groundmass (bright-green pyroxene: omphacite). May have quartz, biotite, or kyanite.
	Serpentinite	Peridotite	H	Med-high	Mostly serpentine. Green, mottled, massive. Smooth, rounded slippery surfaces. Can be black or reddish. Usually displays slickensides
Non foliated	**Hornfels**	Basalt/gabbro, mudstone	C	All	Smooth (glassy) or sugary microcrystalline, usually dark-colored.
	Marble ($CaCO_3$)	Pure limestone (only $CaCO_3$)	B, R, S, C	All	Sugary, sandy, or crystalline; calcite or dolomite (form of calcite with Mg) crystals fused together. White to pink. Might have dark streaks.
	Quartzite (SiO_2)	Chert (only SiO_2) Quartz Sandstone	B, R, S, C	All	Sugary, sandy, or crystalline; can sometimes see quartz sand grains fused together; grains won't rub off like sandstone.
	Skarn	Impure limestone or chert, arkose, greywacke…	C	All	Crystalline; usually with large crystals, including calcite, quartz, garnet, epidote, pyroxene and other rare minerals.

***Remember: use mineral ID skills to help distinguish among some of these!**

Epidote – Green, striated prisms, similar in shape to hornblende. **Kyanite** – Blue or grey thin, long blade. **Chlorite** – Green sheet silicate, like a green biotite.
Actinolite – Green chain silicate, like a green, needle-like hornblende.

Metamorphism and Metamorphic Rocks – Chapter Worksheet

1. When metamorphic rocks form, what main factors/agents dictate the rock that will form?

2. Describe the boundary between sedimentary rocks and metamorphic rocks. In other words, a little pressure compacts a rock, a lot metamorphoses it – what determines the point at which a rock stops being classified as a sedimentary rock and starts being classified as metamorphic? Where does metamorphism due to pressure and weathering/sediment lithification due to pressure meet or overlap and how can we distinguish between them?

3. Describe the boundary between metamorphic rocks and igneous rocks. What determines the point at which a rock stops being classified as a metamorphic rock and starts being classified as igneous?

4. Define **metamorphic grade**.

5. What are at least three major textural changes that signal increasing metamorphic grade? (Give details!)

6. List the **levels of foliation** in order from lowest grade on left to highest on right (see table 2 in workbook!):

7. Which types of metamorphic rocks will likely display the levels of foliation described above? Names?

8. How and why do mineral compositions change as metamorphic grade increases?

9. What is an index mineral? (Definition)

10. CIRCLE: Which of the following minerals are **good index minerals**? Biotite | Calcite | Garnet | Feldspar | Quartz

11. CIRCLE: which of the following metamorphic settings are associated with **high pressure**?
Contact metamorphism | Burial metamorphism | Converging continents (regional)
Subduction zone metamorphism | Hydrothermal circulation at spreading centers

12. CIRCLE: which of the following metamorphic settings are associated with **high temperature**?
Contact metamorphism | Burial metamorphism | Converging continents (regional)
Subduction zone metamorphism | Hydrothermal circulation at spreading centers

13. CIRCLE: which of the following metamorphic settings are associated with **high water/fluid content**?
Contact metamorphism | Burial metamorphism | Converging continents (regional)
Subduction zone metamorphism | Hydrothermal circulation at spreading centers

14. For the settings above that you indicated had high water/fluid content, where does that water/fluid come from? Provide specific water sources for each setting.

15. Complete this table for **slate, phyllite, schist, gneiss,** and **migmatite.** Similarities? Differences?

Parent rock:	Setting:	Grade:
Slate		
Phyllite		
Schist		
Gneiss		
Migmatite		

Similarities:

Differences:

16. Complete the same table for **marble, quartzite, hornfels,** and **skarn.**

Parent rock:	Setting:	Grade:
Marble		
Quartzite		
Hornfels		
Skarn		

Similarities:

Differences:

17. How are **greenstone** and **eclogite** formed? (Parent rock, setting, and grade) What are their similarities? Differences?		
Parent rock:	Setting:	Grade:
Greenstone		
Eclogite		
Similarities:		
Differences:		
18. How is **serpentinite** formed? (Parent rock, setting, and grade)		

Metamorphic Rock Activity: Identifying Metamorphic Rocks

Using the rock-naming table (Table 6) from the preliminary figures and tables for this chapter AND the photo album provided in the class materials, practice distinguishing between and naming the different metamorphic rocks:

Metamorphic rock name	Foliation	Distinguishing characteristics (textural and compositional as appropriate)	Parent Rock	Metamorphic Setting (BRSC okay)	Metamorphic Grade
Eclogite					
Gneiss					
Greenstone					
Hornfels					
Marble					
Migmatite					
Phyllite					
Quartzite					
Schist					
Serpentinite					
Skarn					
Slate					

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Compare and contrast metamorphic settings, where they're found, and the pressure, temperature, and fluid conditions of each.	A | B | C | D | F	
Compare and contrast the different chemical and physical properties of metamorphic rocks and what they indicate about the formation process of each rock.	A | B | C | D | F	
Classify and name basic metamorphic rocks.	A | B | C | D | F	
Identify the parent rock and metamorphic grade and setting of basic metamorphic rocks.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

MASS MOVEMENT AND RIVERS

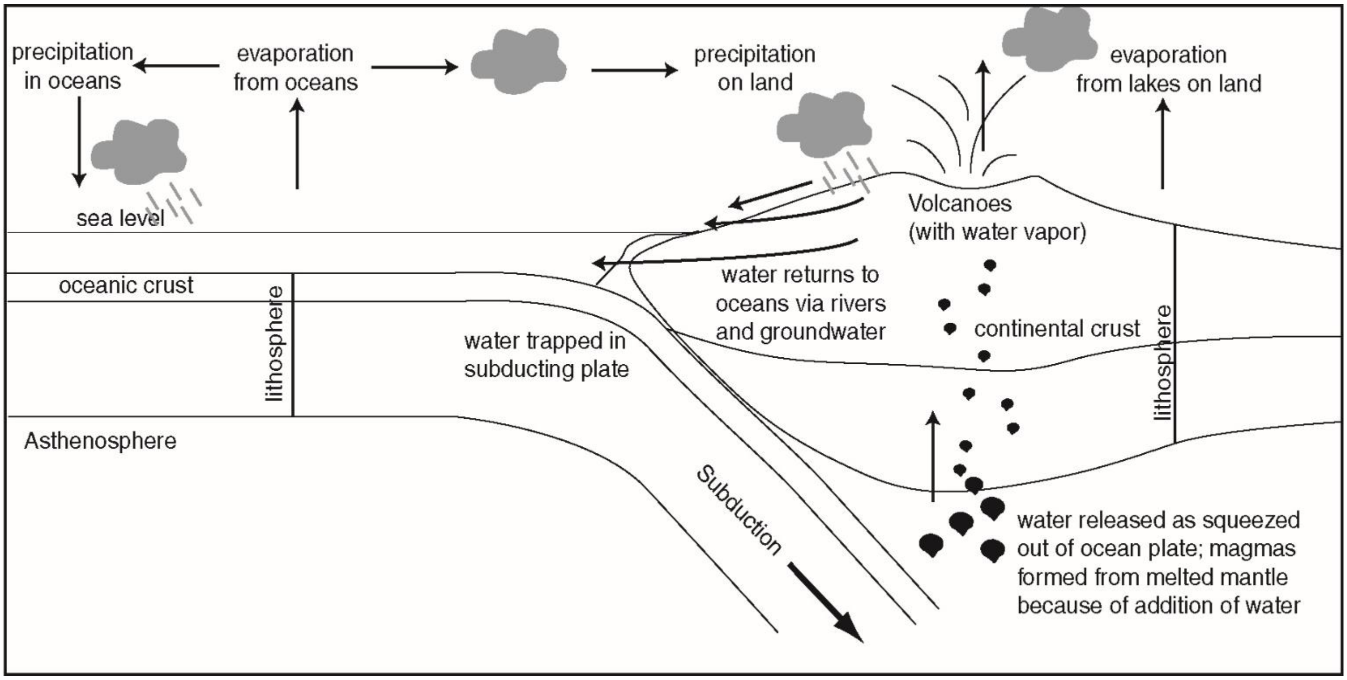


Figure 1. Water Cycle

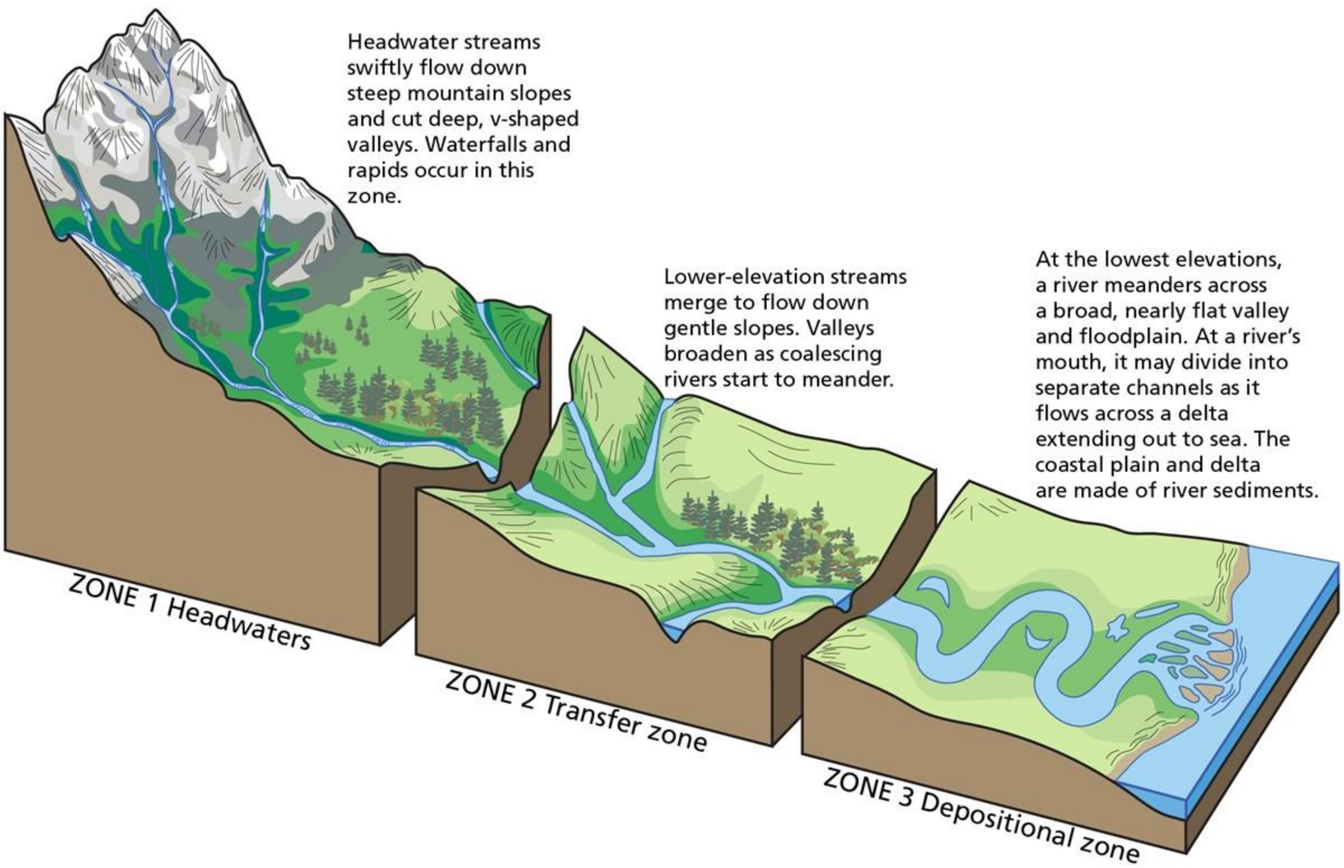


Figure 2. Drainage basin – from Headwaters to Mouth of a river – the edges of this basin are lines called DIVIDES that run between two drainage basins. Water that falls on a drainage basin divide will move into one drainage basin or the other.

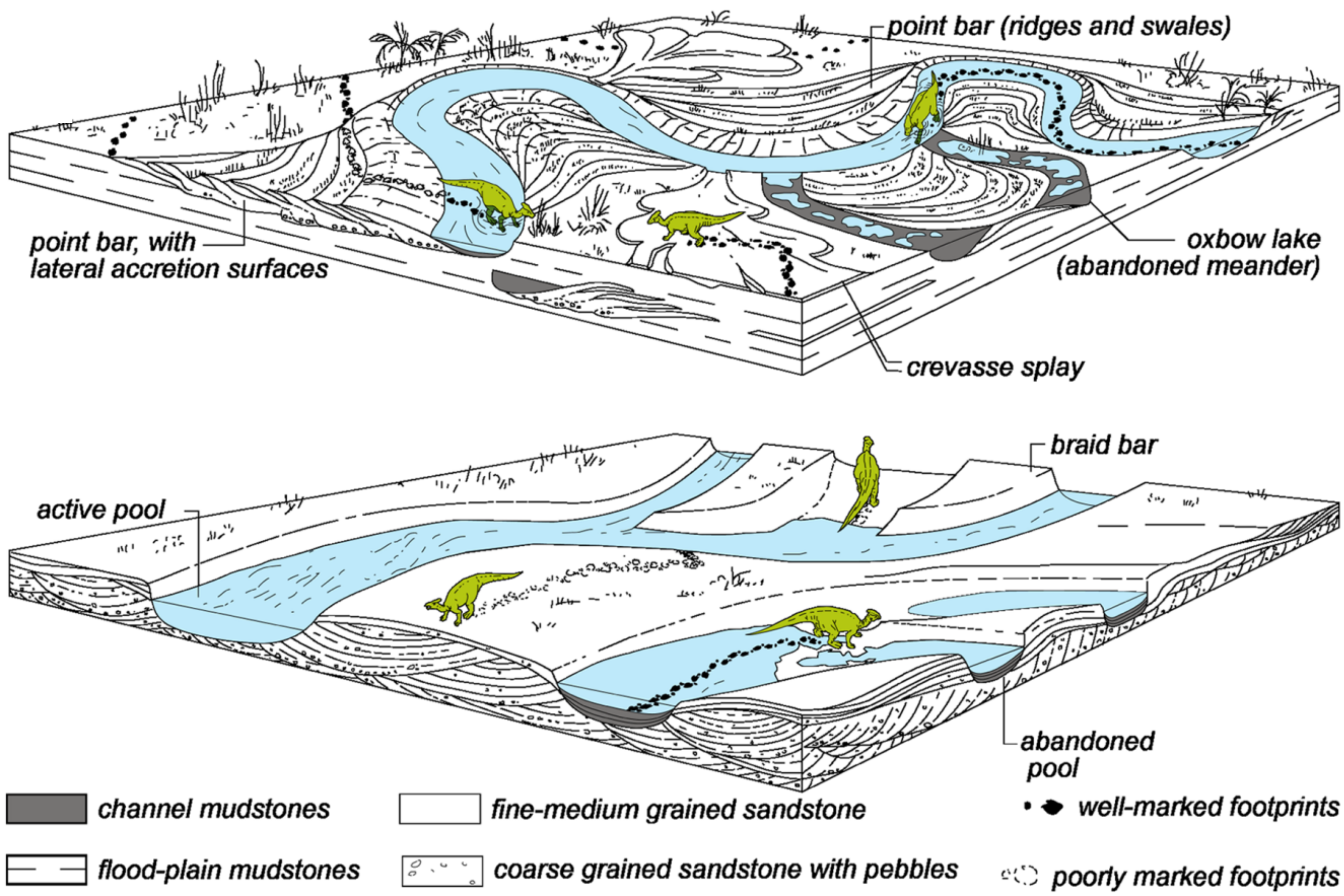


Figure 3. River sediments – variations as a river changes course. Note the buried sediments representing different parts of the river channel/floodplains as the river changed course throughout its history.
Image from: The Latest Succession of Dinosaur Tracksites in Europe: Hadrosaur Ichnology, Track Production and Palaeoenvironments. 2013 Vila et al.. Copyright: CC BY-SA 3.0

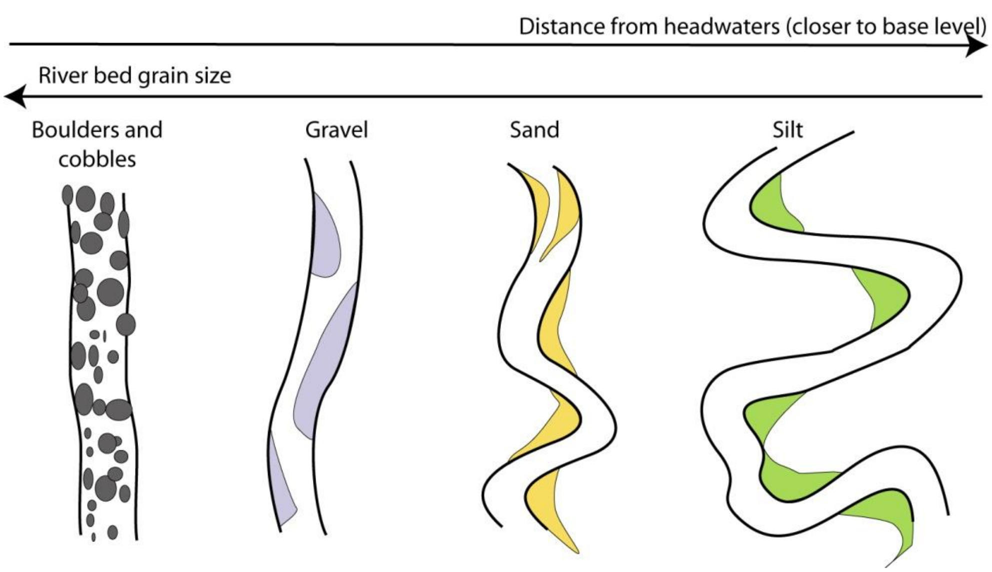


Figure 4. River bed grain sizes – changes as the rivers evolve from steep and straight (headwaters) to flat and meandering (mouth).

Table 1. River Channel Patterns

	Description or picture	Conditions in which found
Meandering	Stream that take circuitous, bending, looping path to base level.	Mature streams, which have eroded the backcountry mostly flat. Slope very gentle.
Braided	Stream that separates into multiple strands, all crossing an area of high sediment.	At the base of a steep slope, where there is an alluvial fan (much sediment dumped by stream, then stream makes its way across pile).
Straight	No bends. V-shaped in cross-section.	Steep slopes, usually up in the mountains.

Table 2. River characteristics and how they change along the path of a river.

	Definition	Factors that increase it	Headwaters	Mouth
Gradient	elevation difference / horizontal length	Base level drops Headwaters uplift	High	Low
Discharge	Volume of water passing a point in the river every second *= channel width X channel depth X velocity =* m^3/s	High precipitation (rain) Large drainage basin High river velocity	Low	High
Drag or friction	slowing down of the river as a result of its shape and materials	• Channel shape is narrow and deep or shallow and wide. • Channel bed is rough, like boulders, gravel, and sand.	High	Low: shape is deep and wide, and bed is mud.
Speed	distance traveled / time for travel	High gradient Low drag or friction High discharge Narrow channel	Low *(in general) – varies considerably along channel!*	High *(in general) – varies considerably along channel!*
Amount of erosion	Material picked up by the running water of the river and removed.	Velocity increases Discharge increases Load of river decreases	High	Low
Amount of deposition	Material dropped by the river and left in a pile (deposit).	Velocity decreases Discharge decreases Load of river increases	Low	High
Capacity	Maximum load that a portion of a river can transport at any given time.	Discharge increases.	Low	High
Competence	Largest grain size that a portion of a river can transport.	Velocity increases		

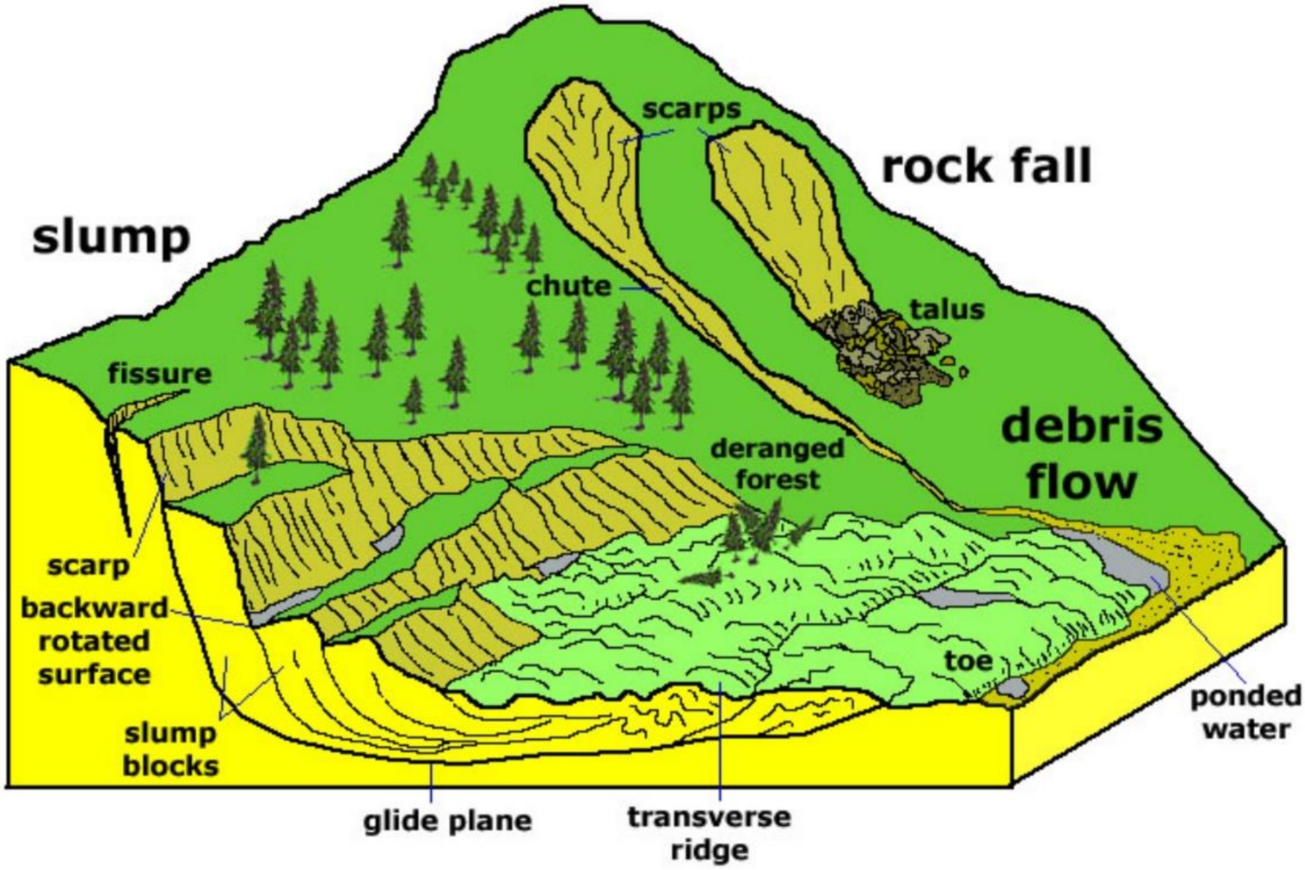


Figure 3. Types of Mass Movement – USGS.gov

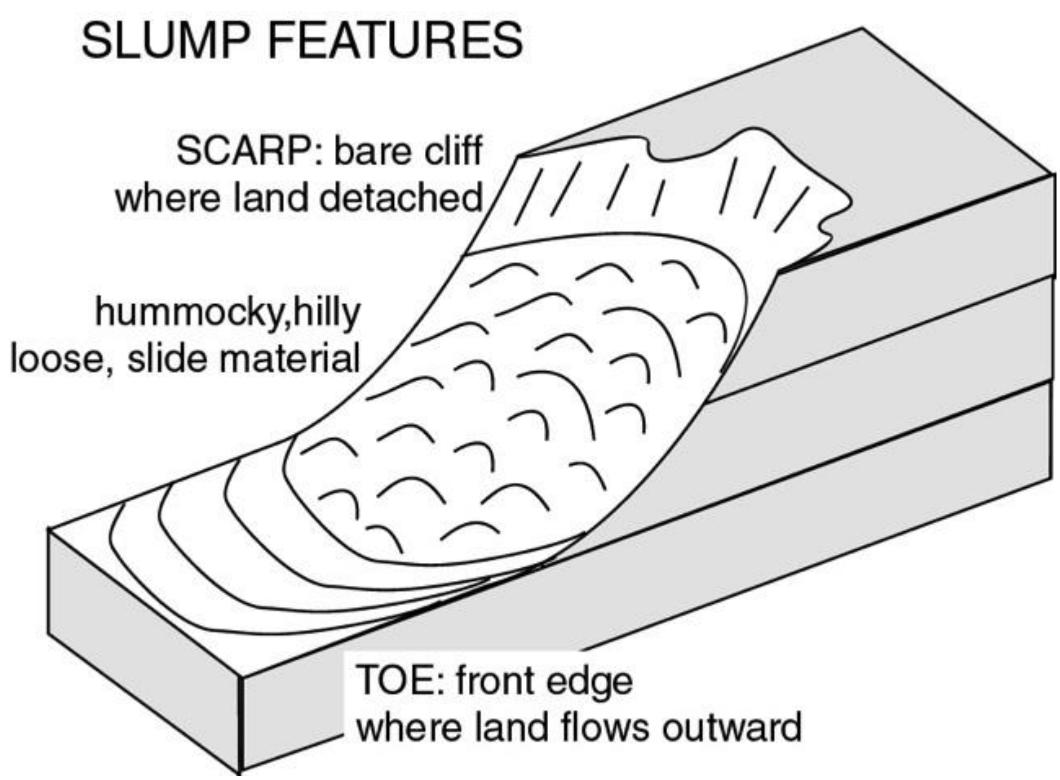


Figure 4. Slump features.

Some more useful definitions:

Slump	movement of unconsolidated rock, soil, or sediment along a curved downhill.
Slide	movement of rock, soil, or sediment along a planar surface downhill.
Rock fall	fall of a single rock or group of rocks down a steep hill
Rock avalanche	rock fall that is big enough to trap and ride atop a layer of air that reduces its friction and allows it to reach speeds >100 mph (and move up and over ridges)
Creep	slowest of all mass movement -- result of individual surface grains of sediment or soil alternately heating and cooling with day/night cycles and in process migrating in small increments downhill
Scarp	bare cliff at top of a slump or landslide where the land detached/broke
Toe	front edge of a slump, slide, or flow
Talus slope	pile of rocks that accumulate at the base of cliffs experiencing rock fall
Gravity	attractive force that exists between two objects of mass. Increases with the mass of the objects and their closeness to each other.
Friction	stickiness force that keeps two unattached objects stuck together
Angle of repose	maximum angle a pile of unconsolidated sediment can maintain before gravity overcomes friction and the rocks slip and move downhill.

Evaporation	The change of phase of water from liquid to gas/vapor. Caused by the addition of large amounts of heat which give the molecules enough energy to break their liquid bonds and escape as a gas.
Precipitation/Rain	The change of phase of water from gas/vapor to liquid. Caused by the removal of large amounts of heat which take away enough of the molecules enough to allow them to get close enough together to stick to each other (bond as a liquid).

Discharge	Volume of water that moves past a given point in river channel per second (cubic meters per second)
Drainage basin or watershed	The area of land within which any rain that falls will migrate downhill and end up in the main river system within the basin.
Drainage divide	the ridges that mark the edges of a drainage basin (any water that falls on these edges will split and fall into separate drainage basins.
Tributaries	all the smaller streams, creeks, and rivers in a drainage basin that feed into the main river.
Headwaters	the water at the top of the highest elevation tributaries in a drainage basin.
Mouth	the location where a river enters a lake or the ocean
Delta	sediment dropped at the mouth of a river
Alluvial fan	sediment dropped along the path of a river where its slope decreases (like at the base of the mountains)
Alluvium	sediment dropped by a river when its velocity or discharge decreases -- usually rounded well-sorted grains (all the same size).
Dissolved load	sediment carried dissolved in a river (not solid particles, but ions broken up and surrounded by water molecules)
Suspended load	sediment carried in suspension in a river due to the velocity of the water (drops out when the river's velocity gets to zero.
Bed load	sediment pushed along the bottom of a river by the weight and force of the water moveing downhill.
Base level	level to which a stream will erode (after which it has eroded the country behind it flat).

Mass Movement & Rivers Chapter Worksheet

1. What principle force causes downslope movement?	2. What principle force provides resistance against downslope movement?
3. In what two ways does water increase the likelihood of mass movement on a slope?	
4. Describe a slope that would be most prone to downslope movement.	5. Describe a slope that would be least prone to downslope movement.
6. What are some triggers for mass movement events?	

7. Define and distinguish among these different types of mass movement:

Fall	Slide	Flow	Slump	Creep

8. What % of Earth's water is fresh?		
9. Of that, what % is in glaciers?	What % is In groundwater?	What % is in lakes and streams?

10. What is the term used to describe the process whereby liquid water from the oceans, rivers, or lakes turns into vapor that is transported into the atmosphere?

11. What is the term used to describe the process whereby water vapor from the atmosphere turns back into liquid water that drops into the ocean or on land?

12. What major energy source drives the above transport?

13. Where does water go when it leaves the oceans (SINKS)? CIRCLE: atmosphere | subduction zones | rivers | glaciers | sea ice | groundwater | ocean crust cracks/sediment | volcanoes

14. Where does the water in the oceans come from (SOURCES)? CIRCLE: atmosphere | subduction zones | rivers | glaciers | sea ice | groundwater | ocean crust cracks/sediment | volcanoes

15. Which type of river channel pattern happens when the slope is steep, the river youthful, and the location in the mountains? CIRCLE: Braided | Meandering | Straight

16. Which type of river channel pattern happens when the slope becomes gentler, sediment drops in large amounts, and the river has to migrate across the sediment like in alluvial fans? CIRCLE: Braided | Meandering | Straight

17. Which type of river channel pattern happens when the slope is flat and river mature? CIRCLE: Braided | Meandering | Straight

18. A stream starts 2000 m above sea level and travels 250 km to the ocean. What is its average gradient in m/km? This stream develops extensive meanders lengthening its course to 500 km. Calculate its new gradient. Which steepness represents the more youthful stream? Why?

19. Through what methods do streams physically weather rock?

20. Under what conditions do streams erode?

21. Where along a river does this most occur? CIRCLE:
Where slopes change from steep to gentle | Where slopes change from gentle to steep (like a waterfall)
Inside of meander | Outside of meander | Narrowing channel | Widening channel | Steep slopes | Gentle slopes
High-friction bed | Low-friction bed | Where tributaries join | At mouth

22. Define and distinguish among these different sediment loads in a river: what and how carried.

Dissolved Load	**Suspended Load**	**Bed Load**

23. If you collect a jar of stream water from the side of a boat and bring it home to sit on your table, what part slowly settles to the bottom? CIRCLE: Bed load | Dissolved load | Suspended load

24. What part remains in the water? CIRCLE: Bed load | Dissolved load | Suspended load

25. What part is missing from the jar? CIRCLE: Bed load | Dissolved load | Suspended load

26. Under what conditions do streams deposit sediment?

27. Where along a river does this most occur? CIRCLE:
Where slopes change from steep to gentle | Where slopes change from gentle to steep (like a waterfall)
Inside of meander | Outside of meander | Narrowing channel | Widening channel | Steep slopes | Gentle slopes
High-friction bed | Low-friction bed | Where tributaries join | At mouth

28. What is unique about alluvium (river-deposited sediment)? Why?

29. Compare an alluvial fan and a delta.

30. What is base level?

31. Give some examples of local versus ultimate base level.

32. Which factors below are higher at the headwaters than the mouth of a river (IN GENERAL)?
Gradient | Discharge | Drag or friction | Speed | Amount of erosion | Amount of deposition | Capacity | Competence

33. Which factors below increase as speed increases?
Gradient | Discharge | Drag or friction | Amount of erosion | Amount of deposition | Capacity | Competence

34. Which factors below increase as discharge increases?
Gradient | Drag or friction | Speed | Amount of erosion | Amount of deposition | Capacity | Competence

35. Which factors below increase as a river narrows?
Gradient | Discharge | Drag or friction | Speed | Amount of erosion | Amount of deposition | Capacity | Competence

36. Which factors below increase as a river slope decreases?
Discharge | Drag or friction | Speed | Amount of erosion | Amount of deposition | Capacity | Competence

37. Explain what happens during flood stage of a river. Include a description of levees and floodplains.

Landslides & Floods Activity: Case Study & Concept Sketch

Go online and find a landslide or flood that happened (anywhere in the world) in the last two years. What circumstances led to the event? What about this particular event was most interesting to you (why did you choose it)? Use your research to draw a concept sketch of that particular event below (with scale!). Describe and label its key characteristics. Add your name and a bibliography of any sources you used.

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Compare and contrast gravity and running water as erosional processes including their associated landforms.	A | B | C | D | F	
Evaluate the conditions under which rivers deposit and the landforms that result.	A | B | C | D | F	
Evaluate the conditions under which rivers erode and the landforms that results.	A | B | C | D | F	
Evaluate the triggers and characteristics that increase the risk of mass movement.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

GROUNDWATER & WINDS

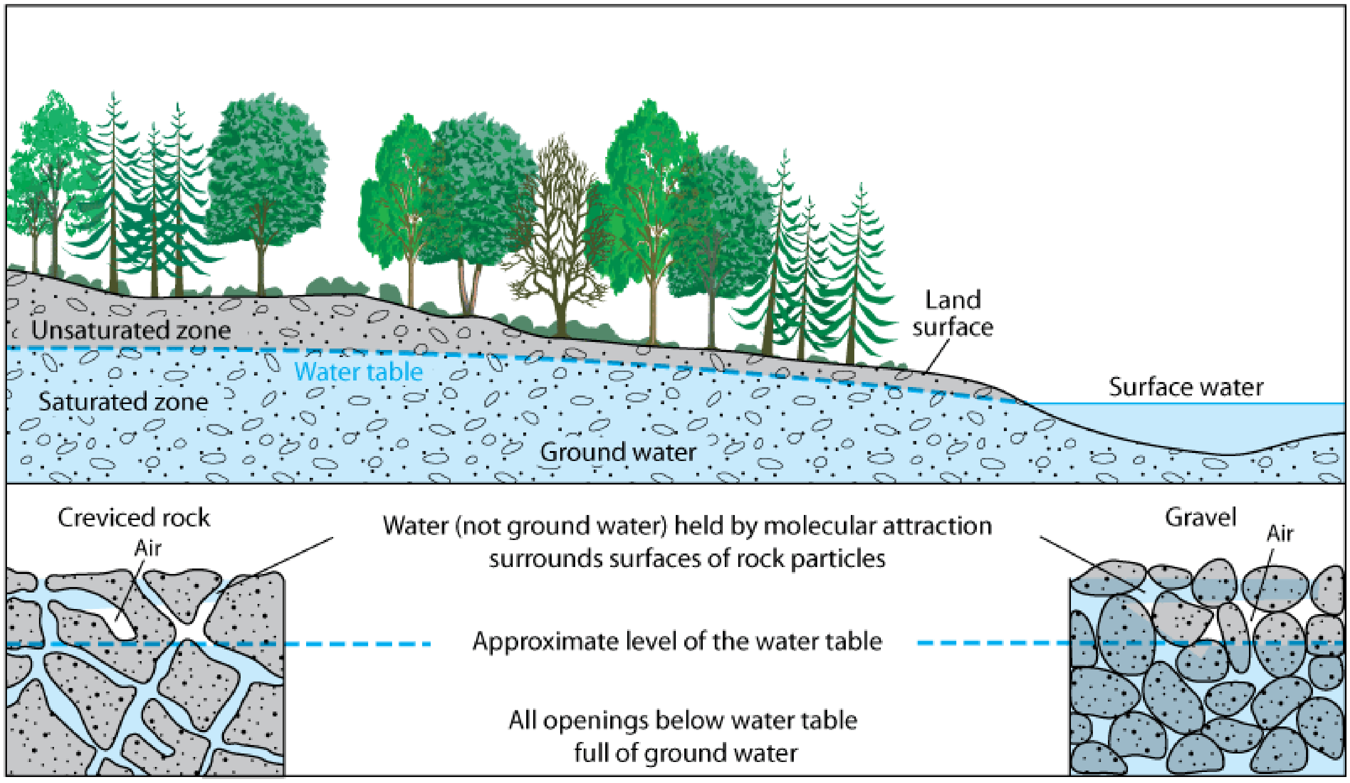


Figure 1. Water Table – USGS

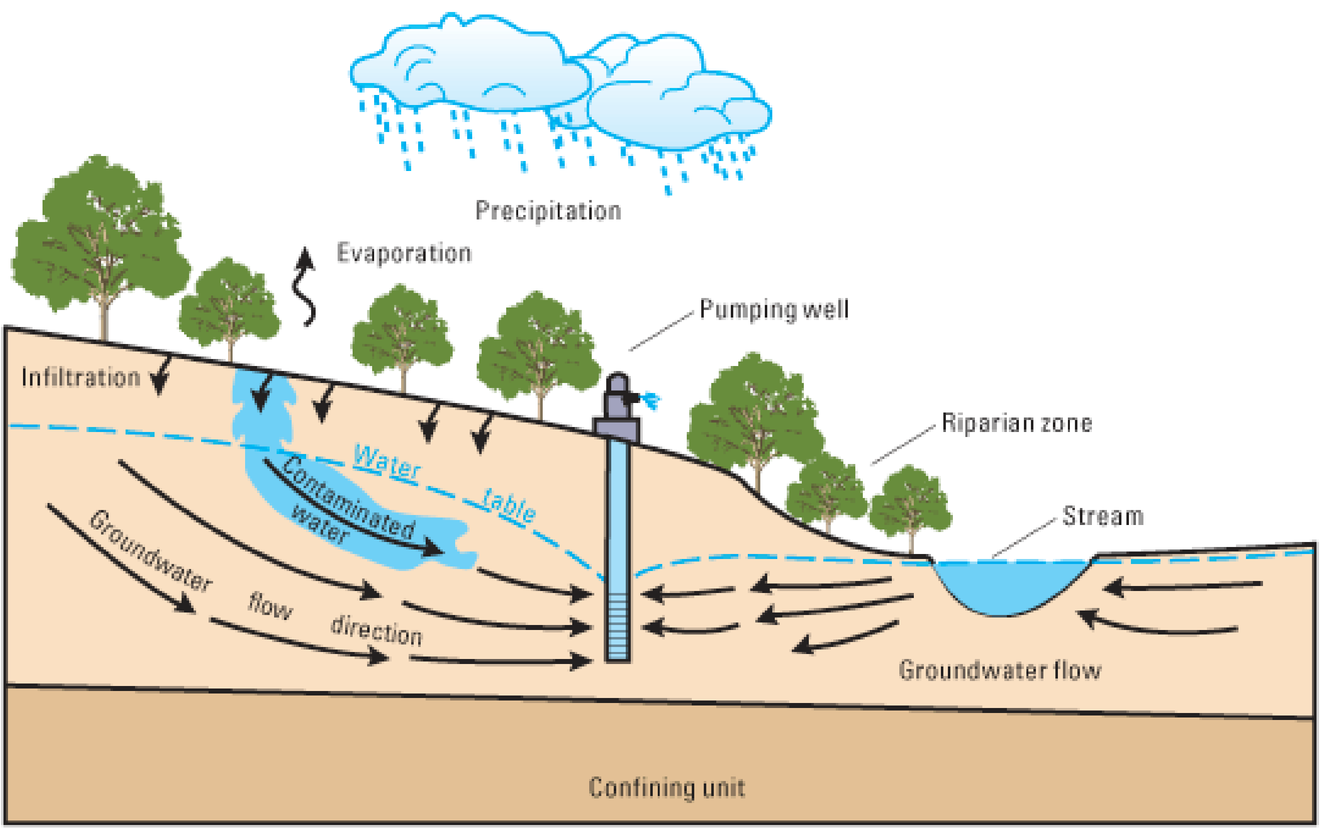
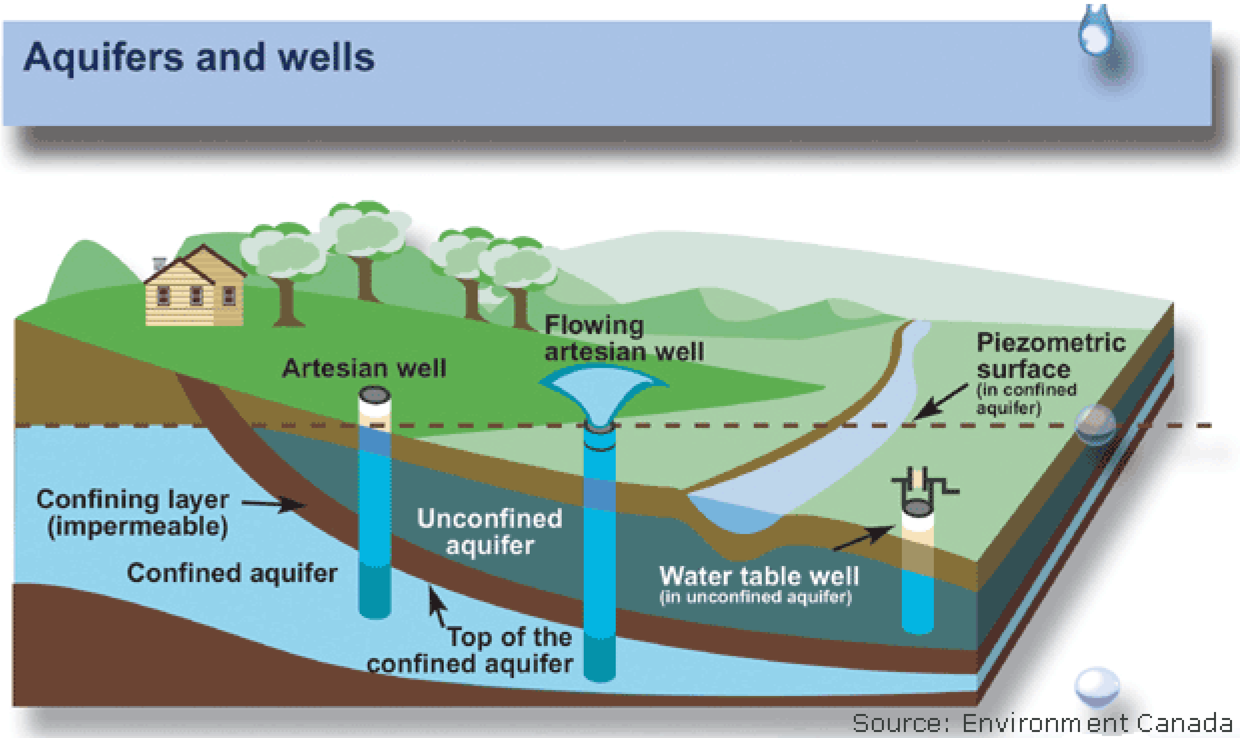


Figure 2. Schematic of a groundwater-flow system in an agricultural setting. In this example, infiltration of water from either precipitation or irrigation can transport phosphorus or other chemicals to the unsaturated zone and aquifer. USGS.



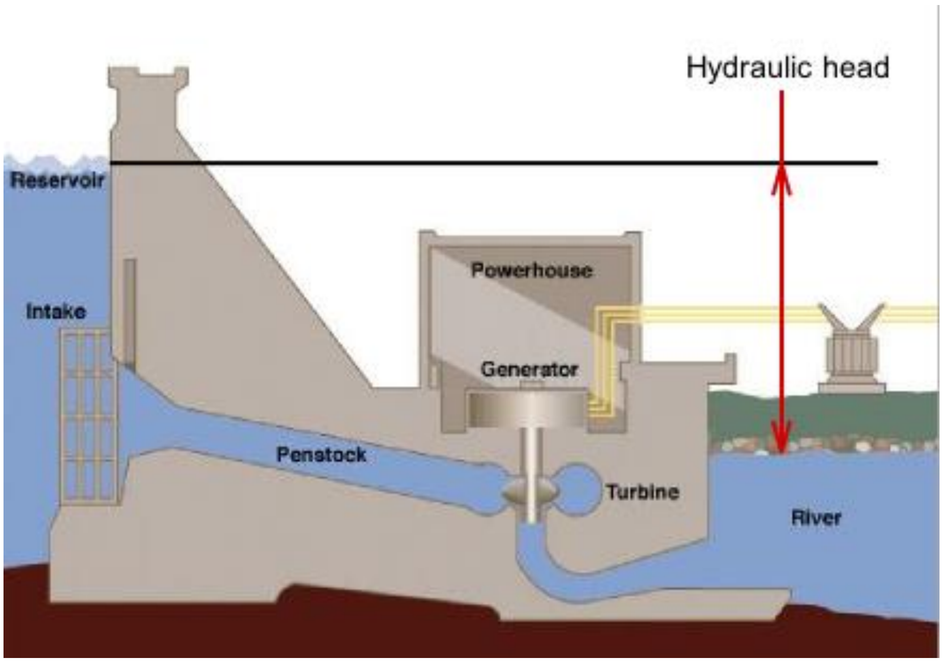


Figure 3. Hydraulic head is an indicator of the total energy available to move ground water through an aquifer. Hydraulic head is measured by the height to which a column of water will stand above sea level or a lake level. Ground water flows from locations of higher hydraulic head to locations of lower hydraulic head. Image: Tennessee Valley Authority

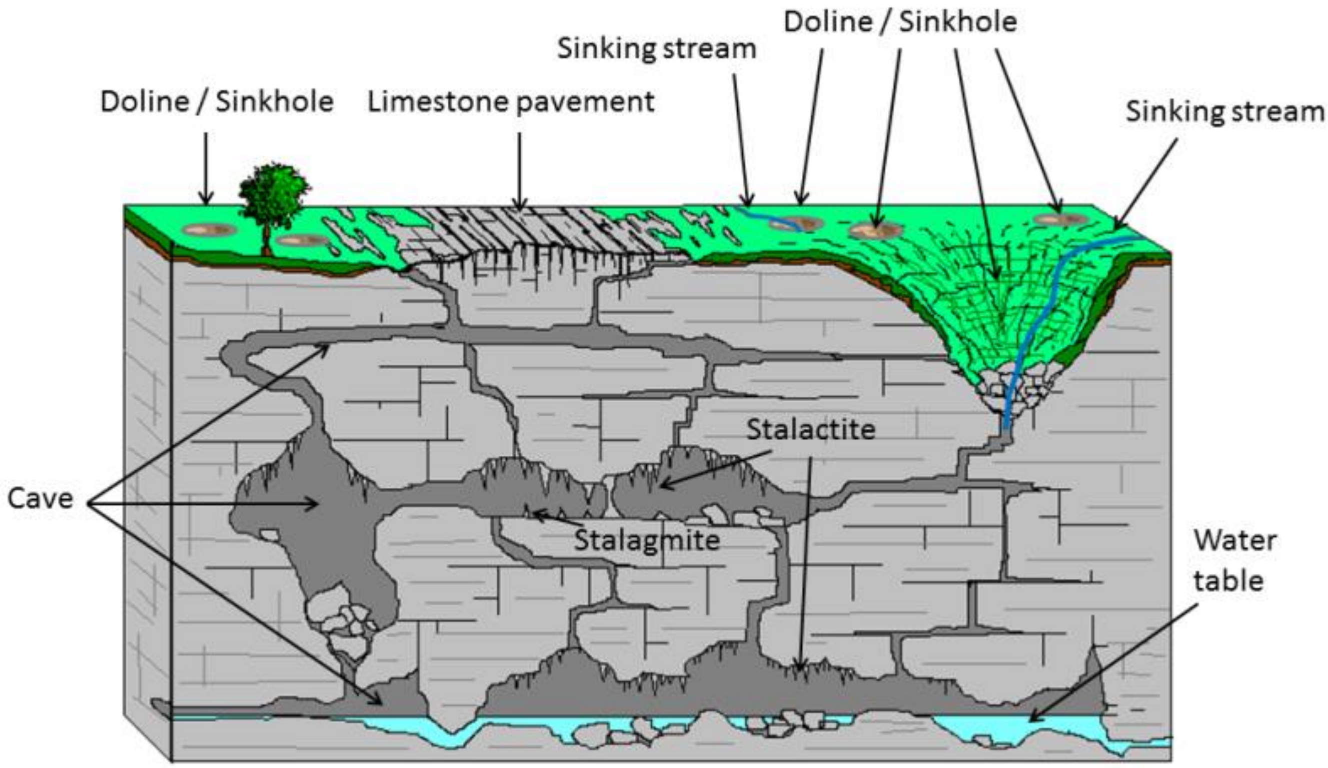


Figure 4. Landforms and features of Karst. Geological Survey Ireland © 2020

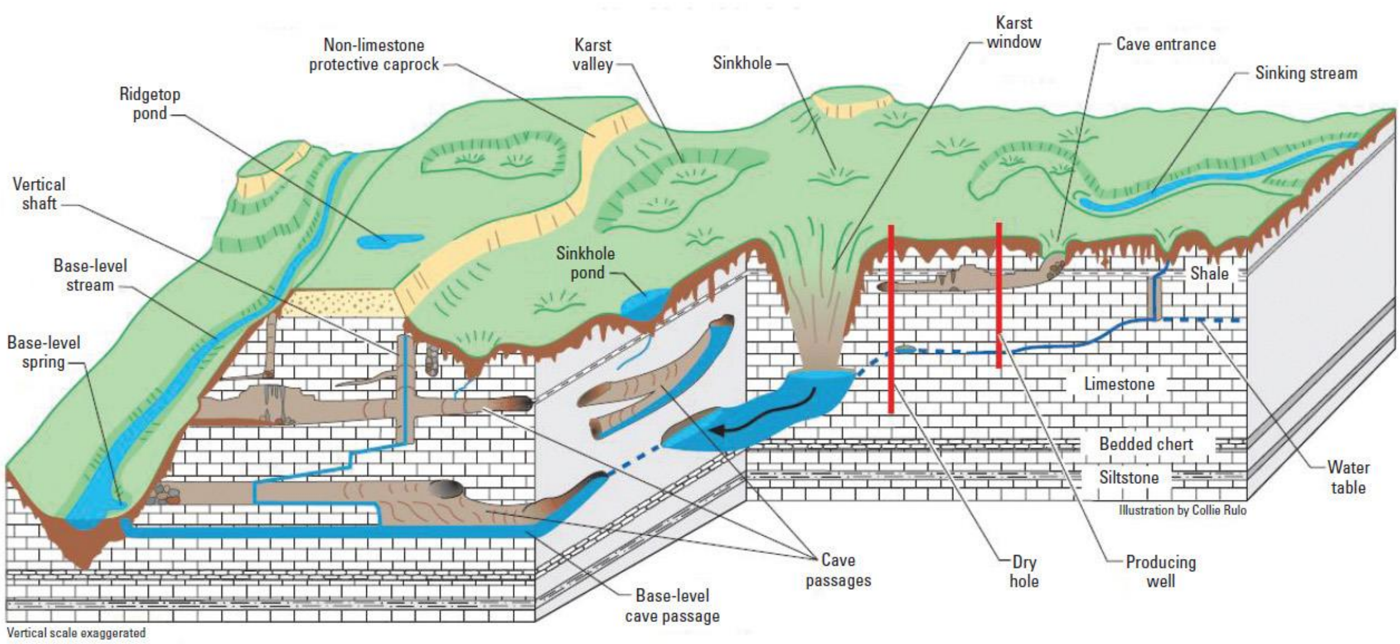


Figure 5. Landforms and features of Karst. USGS

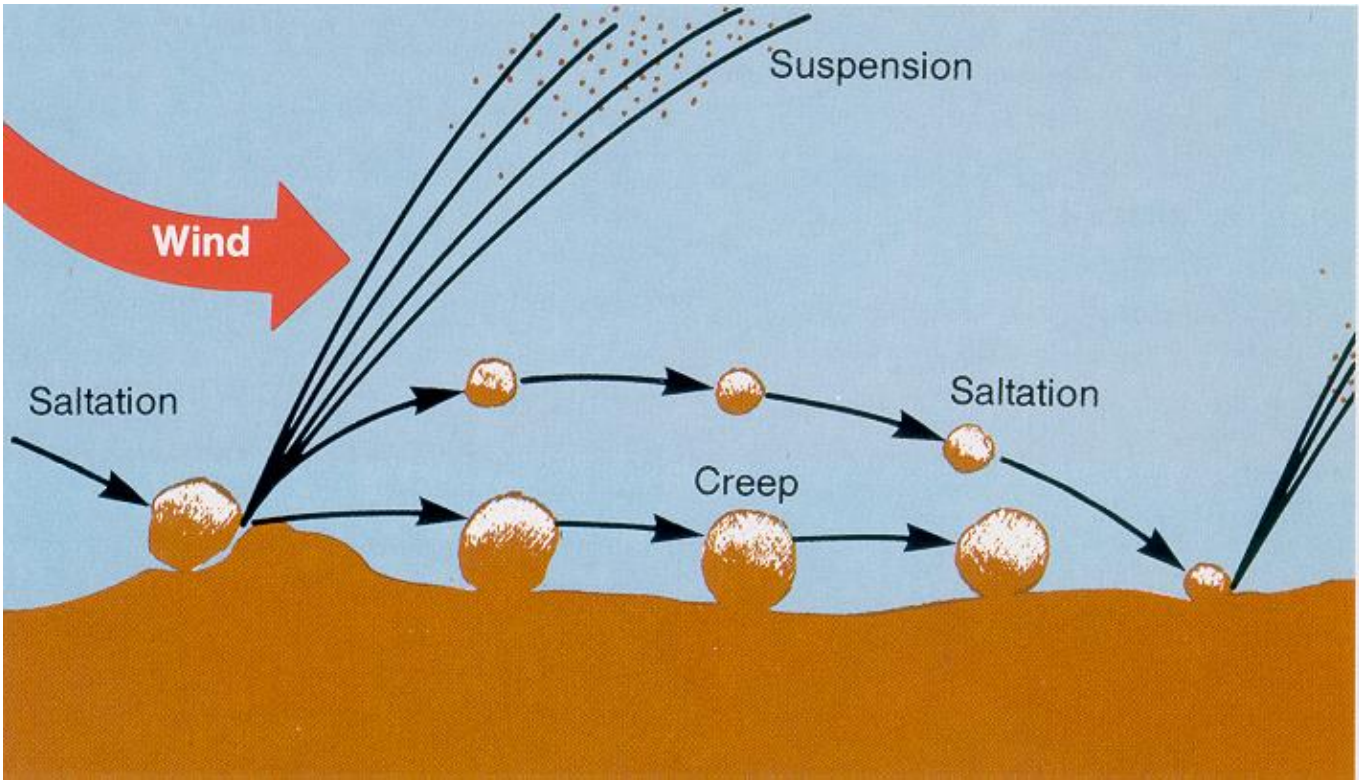


Figure 6. Wind transporting sediment grains through creep, saltation, and suspension.. From USDA.gov.

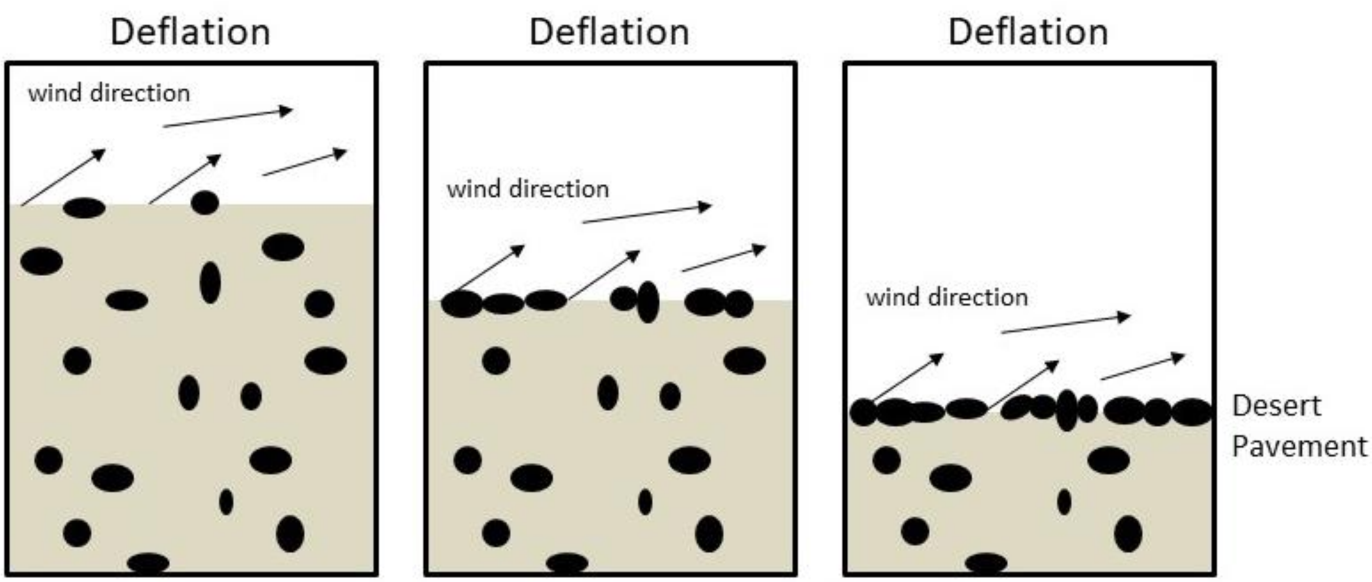


Figure 7. Winds moving over ground sediments pull away the finest material, leaving the larger grains gradually deflating the surface and leading to a cap of gravel rocks – called desert pavement.

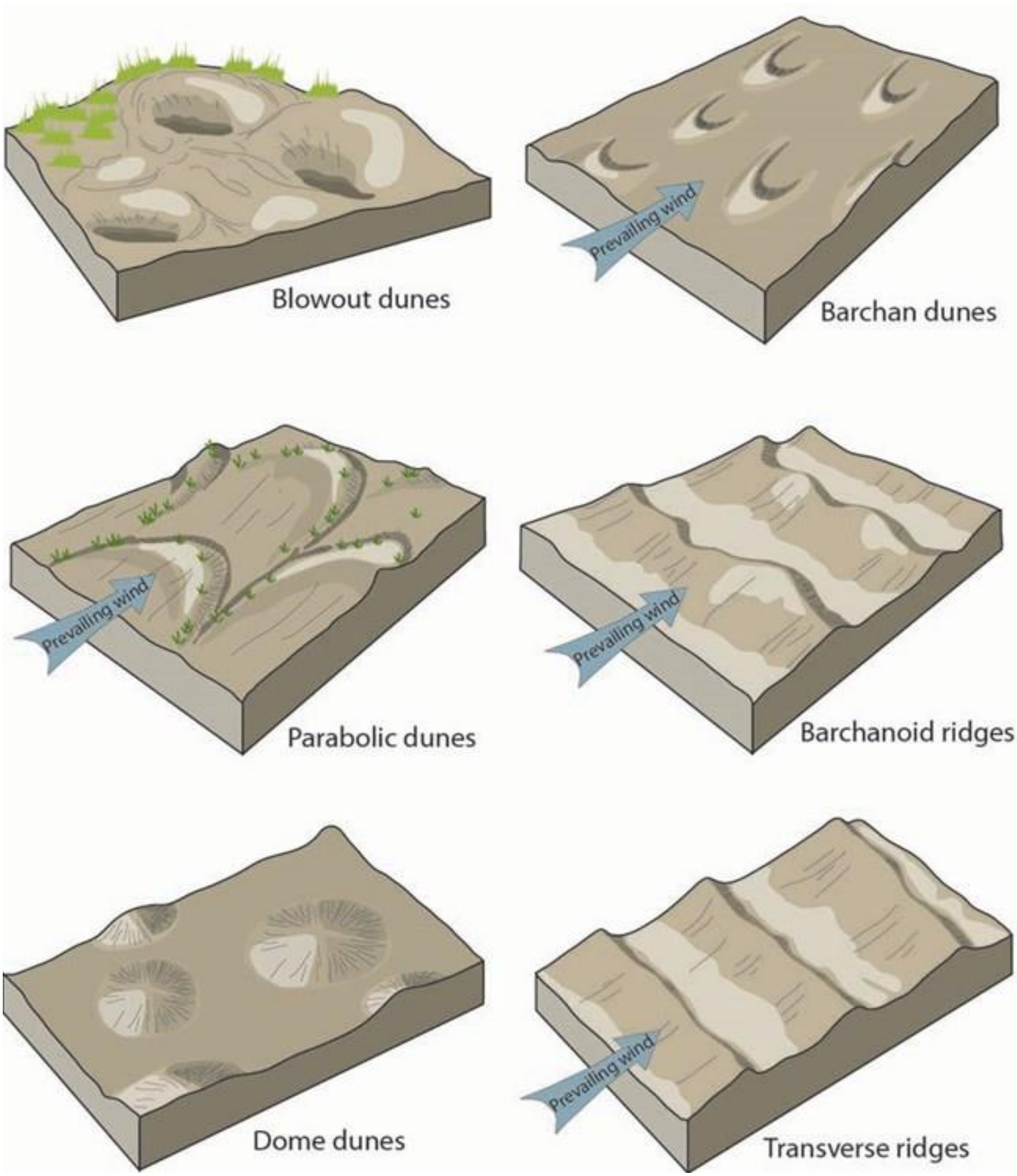


Figure 8. Illustration of dune types, White Sands National Monument, New Mexico from NPS.gov, based on images from Trista L. Thornberry-Ehrlich, Colorado State University after Fryberger, S.G., L.F. Krystinik, and C.J. Schenk. 1990; and McKee, E.D. 1966.

Some more useful definitions:

Gaining stream	Stream that gains water from the water table (net direction of water between ground and surface is out onto the surface and into the stream).
Losing stream	Stream that loses water to the water table (net direction of water between ground and surface is down into the ground).
Porosity	Measurement of total empty space available between grains or in cracks or pits in the rock layer that can be used to hold fluids.
Permeability	Measurement of ability of fluids to migrate through a rock layer (generally requires connected pores or vesicles or cracks in the rocks).
Aquifer	Rock units with pore space into which surface waters sink and are stored as groundwater.
Aquitard	Rock units with little to no permeability that prevent water from moving downward.
Hydraulic head	From usgs.gov: "Hydraulic head (often simply referred to as "head") is an indicator of the total energy available to move ground water through an aquifer. Hydraulic head is measured by the height to which a column of water will stand above a reference elevation (or "datum"), such as mean sea level. Because hydraulic head represents the energy of water, ground water flows from locations of higher hydraulic head to locations of lower hydraulic head. The change in hydraulic head over a specified distance in a given direction is called the "hydraulic gradient.""
Stalactite	"Icicle" of hundreds to thousands of years of calcite deposits that hangs from the ceiling of a cave.
Stalagmite	Upside-down "Icicle" of hundreds to thousands of years of calcite deposits that projects upwards from the floor of a cave.

Desert pavement	Hard ground with packed large gravels that makes a lid on top of sediment below diminishing the erosion rates of the ground material. Forms when winds remove the smaller grains in a pile of sediment, leaving the larger ones behind in a deflated ground level.
Ventifact	Physically carved out shapes on a rock face formed through wind abrasion.
Loess	Deposits of wind-blown dust and silt that blanket the land or collect behind objects that act as wind breaks. Sediment can come originally from fine glacially carved flour or stream deposits.
Dune	From National Geographic: "A dune is a mound of sand formed by the wind, usually along the beach or in a desert. Dunes form when wind blows sand into a sheltered area behind an obstacle. Dunes grow as grains of sand accumulate. Every dune has a windward side and a slipface. A dunes windward side is the side where the wind is blowing and pushing material up. A dunes slip face is simply the side without wind. A slipface is usually smoother than a dunes windward side.

Groundwater & Winds Chapter Worksheet

1.	REVIEW: What % of Earth's freshwater supply is groundwater?
2.	What is most groundwater used for? *(Give list of uses and % of each.)*
3.	What is the difference between porosity and permeability?
4.	How do porosity and permeability of soils or surface sediments and rocks impact the amount of water that soaks into the ground?
5.	Arrange the following types of rock in order of their likely permeability (highest permeability first): mudstone, fractured granite, limestone in a karst region, sandstone, and unfractured gneiss.
6.	Compare and contrast gaining streams and losing streams.
7.	Compare and contrast aquifer and aquitard.
8.	What are the two dominant causes of groundwater movement (flow direction)?

9. What are some of the consequences of overpumping out groundwater?

10. How does groundwater create caverns?

11. How do stalactites and stalagmites form?

12. List a number of different world locations where you can find karst topography.

13. Describe the process by which desert pavement forms and the consequences.

14. What are the different ways in which winds transport material?

15. Describe the formation of wind deposits – specifically sand dunes and loess.

16. In what ways does wind help to physically weather a rock? What is the product called?

Groundwater and Oil Exploration Activity

This first part of this activity is based on an activity developed by Jennifer Sliko, Penn State.
Note: before completing this activity, you'll want to read the web page link on the class website: **Hydraulic Fracturing and its Impact on Water Resources.

Welcome to Happyville

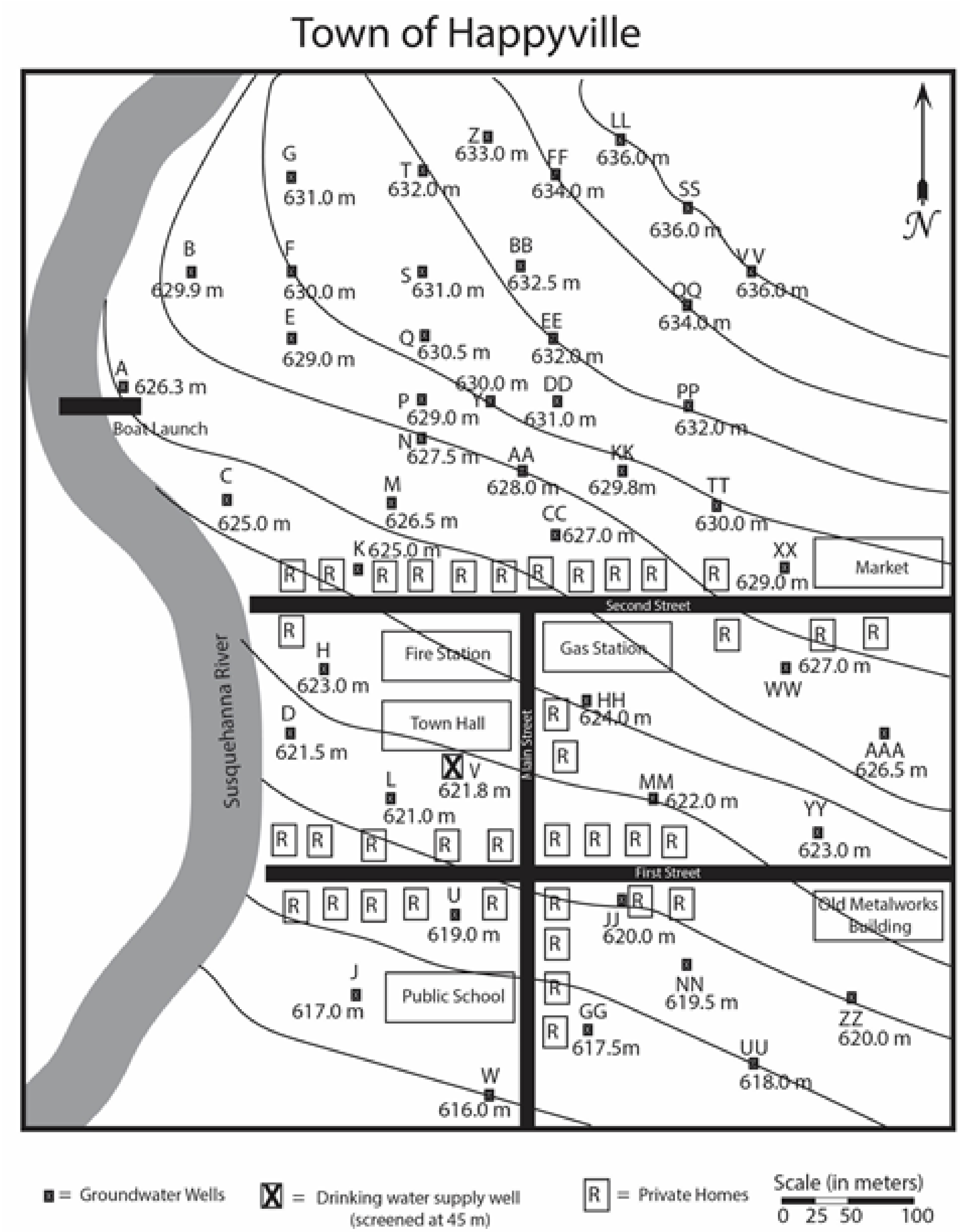
Recent geologic surveys have revealed a large Marcellus Shale natural gas deposit in north central Pennsylvania near the Susquehanna River. "Bob's Gas Company" wants to drill several wells to start the process of hydraulic fracturing just north of Happyville. Hydraulic fracturing uses water injected into the ground to fracture the rock to release any trapped oil, which would float up atop the water. One of the possible consequences of this process is to contaminate groundwater. To be an "informed citizen" one needs to evaluate groundwater movement in Happyville.

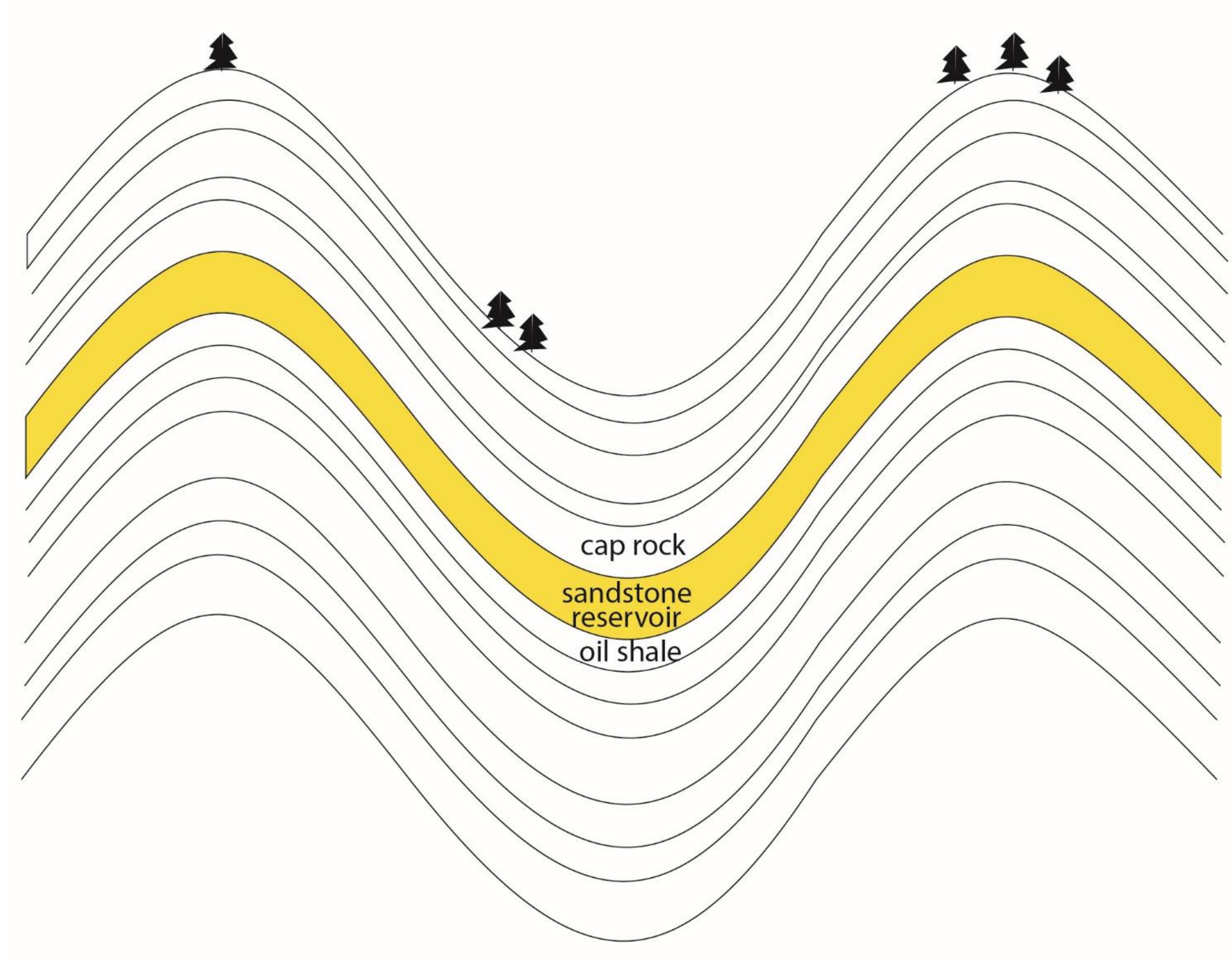
Happyville is underlain by ~150 m of Manhantango sandstone, which is on top of the Marcellus Shale. First, you need to determine where Happyville gets its groundwater. Then, you need to determine the direction of groundwater flow in the region. To help you determine this information, the Pennsylvania Department of Environmental Protection (PaDEP) has drilled several wells in Happyville to determine the direction of groundwater flow. Wells are drilled down about 10-20 m deep. They are completely cased within so they get water only from the bottom of the well. In these wells, the water levels vary from 0.5 to 2 m below the ground surface. Those water levels are indicated with well locations on the following map.

1. Which has a higher natural permeability - sandstone or shale? Why?
2. What geologic rock unit supplies the drinking water to the town of Happyville? How do you know? (everything you need to know is in the text above.)
3. The drinking water well is labeled X. On the map on the following page, circle the drinking water well.
4. What is the direction of groundwater flow in Happyville? Draw arrows on map of the following page to indicate that direction.
5. Look at the industry and land use around town. Put square boxes around the areas that could produce pollution that might make its way into the groundwater.
6. Following your arrows, indicate with stars the houses and buildings that might be already getting those pollutants (from answer to 5) in their ground water.
7. If the energy company decides to drill holes for fracking into the Marcellus shale under the northeast section of this map, would there be an impact on the drinking water supply in town? If so, what kind and why?

Water Table Contour Map of Happyville

The contour lines drawn on this map represent lines of equal water table elevation (Imagine the land itself is basically flat). The highest contour line should be 636 m above sea level, the lowest contour interval should be 616 m above sea level, and the contour interval is 2 m. Again, these contour lines are not land elevations, but elevation of the top of the water table. How is it measured? First we measure the elevation of the land above sea level and then we measure how far down from that surface we have to go in our well before we hit water. Then we subtract. For example, if a well was drilled into land at 620 m above sea level and the well water rises to 0.5 m below that surface, then the water table is 620-0.5 = 619.5 m.





Oil Exploration

In the picture above, you are seeing the cross-section view of perfectly vertical and symmetrical anticlines and synclines.

- Assume that the shaded layer is a sandstone, rich in pore space, like an aquifer, but for oil and gas, we call this type of rock a **reservoir rock**.
- The layer directly above the shaded rock layer is impermeable (acts as a **cap rock** preventing liquids from moving through it – similar in principle though opposite in direction to an aquitard.
- The layer directly below the reservoir rock is an organic-rich shale (material degrades under pressure to produce oil and gas).
- Remember, fluids and gases are less dense than the rocks around them and will migrate towards the surface, unless prevented somehow! *(**Although liquids and gases can't naturally migrate through impermeable rock, oil wells CAN be drilled through that rock.**)*

8. Indicate with a drill well where you would drill if you were an oil company looking for trapped oil. Explain below your reasoning:

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Describe the processes of groundwater and other ground fluid migration, including the principles of porosity and permeability.	A | B | C | D | F	
Evaluate the value of groundwater as a public resource and the consequences of overpumping.	A | B | C | D | F	
Evaluate the conditions under which Karst topography forms.	A | B | C | D | F	
Evaluate the conditions under which geysers form.	A | B | C | D | F	
Compare and contrast the depositional and erosional landforms and features produced through winds.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

GLACIERS & SHORELINES

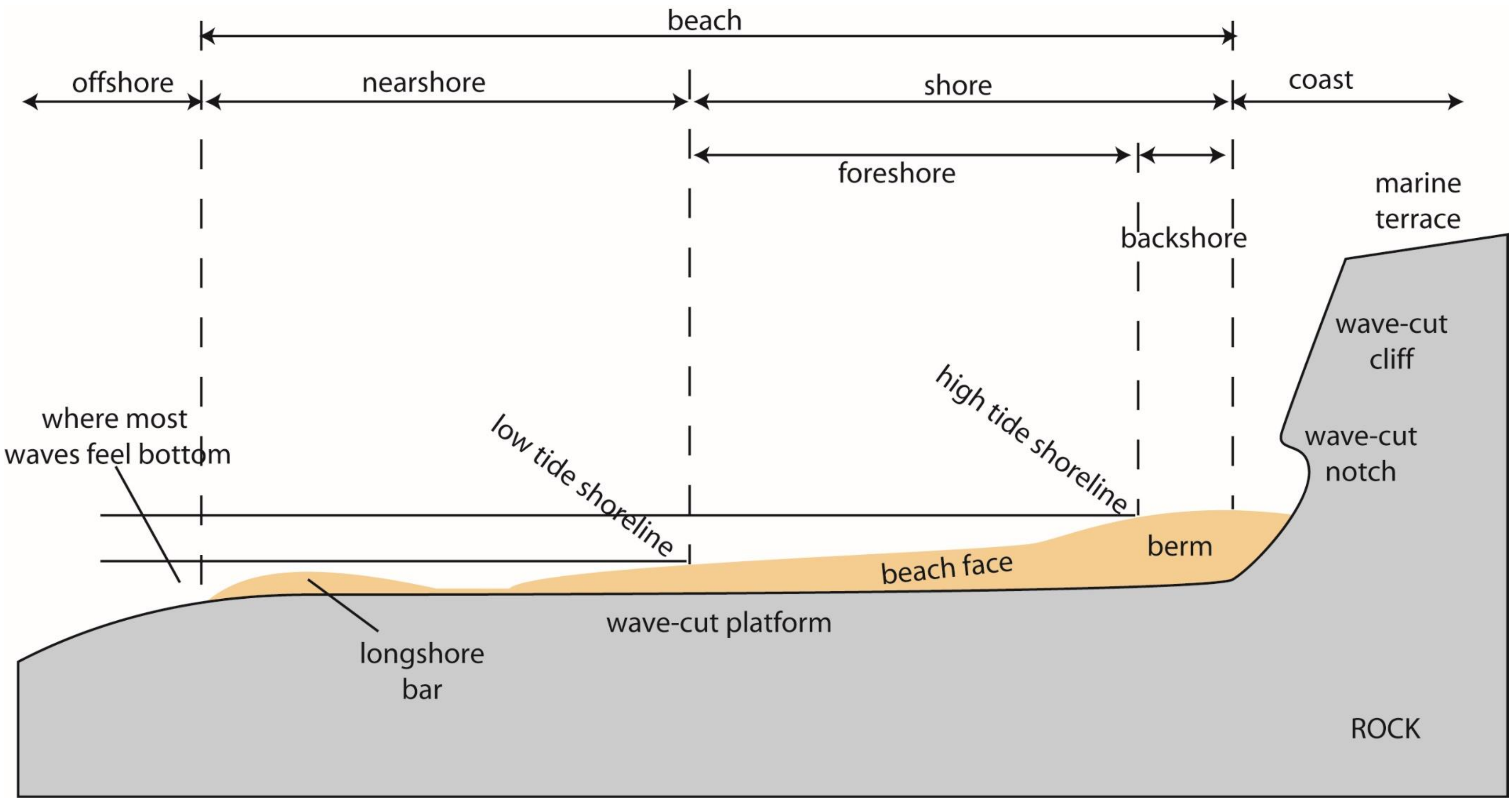


Figure 1. Generalized beach profile along coast with a resistant, eroding cliff at the back of the beach. Yellow represents sand.

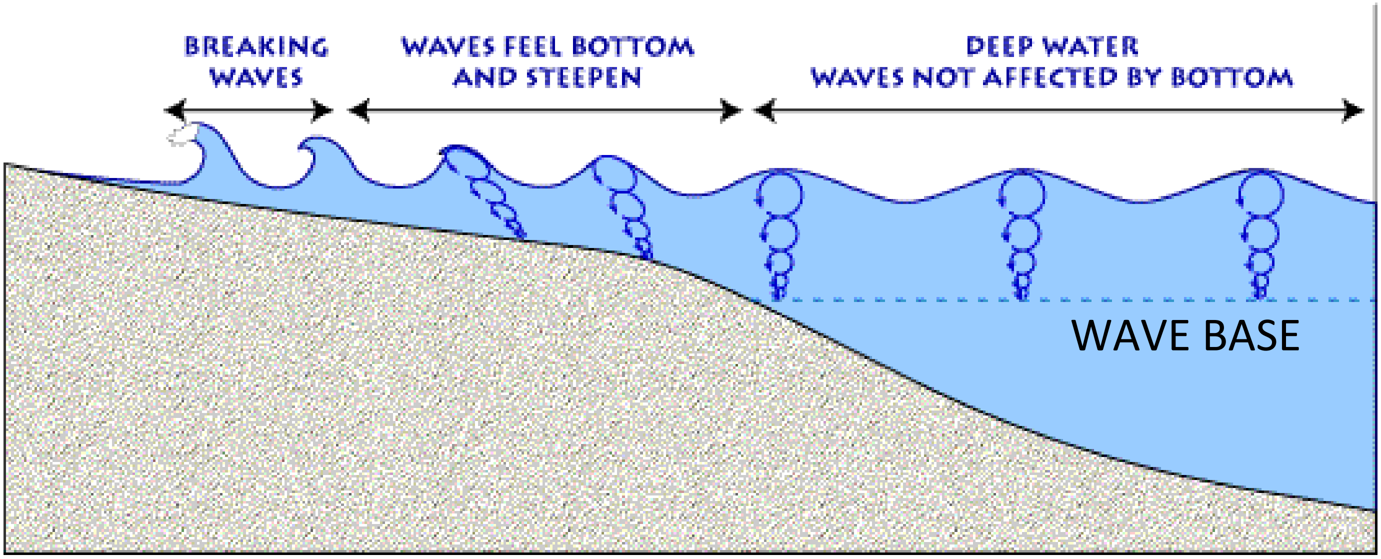


Figure 2. Changes to wave height, length, and motion when waves approach the shore and wave base hits seafloor. (Wave base = ½ wavelength measured below stillwater point.) Image from USGS

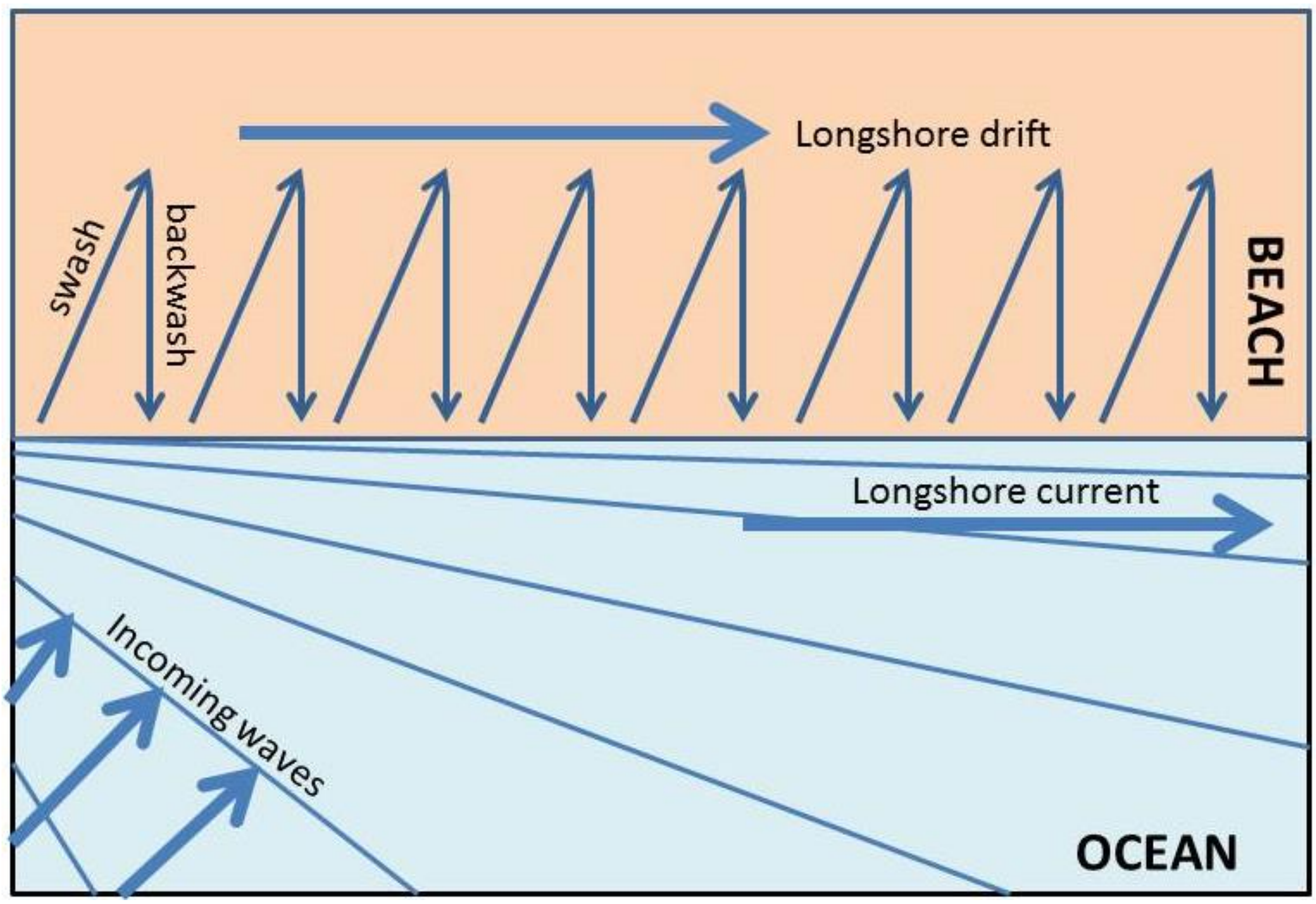


Figure 3. Generalized schematic of how waves approaching the shore at an angle produce a zig-zag migration of sand and water along the beach. The incoming waves push the sand up at an angle. Gravity returns it straight down. The result = beach and longshore drift (sand migration) and longshore current (water migration).

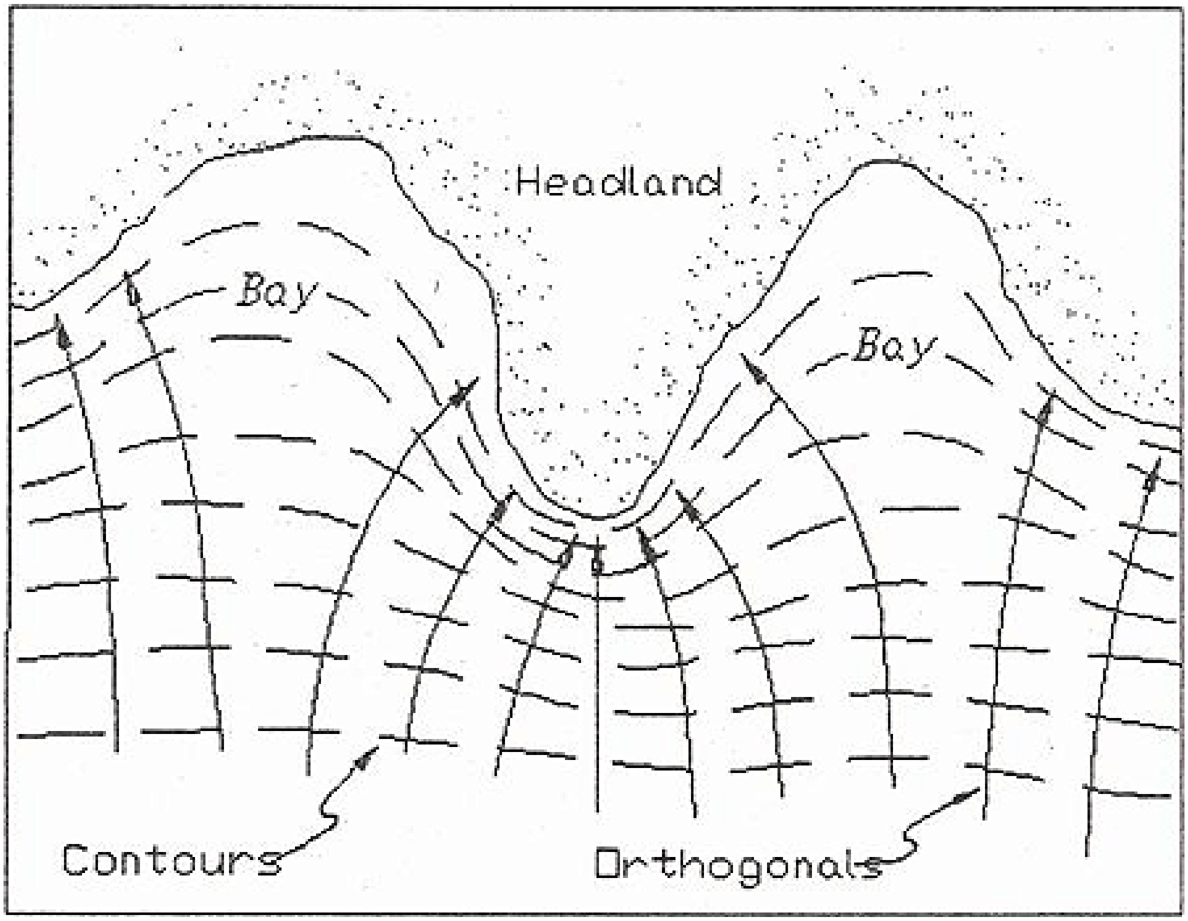


Figure 4. Wave refraction and dispersion as waves approach a shoreline. Orthogonals are rays (or arrows) indicating the direction that the wave is travelling. Contours are lines of equal depth in the ocean. These waves are approaching an irregular shoreline an bending or REFRACTING as one part of the crest feels bottom first, slows down, and the faster-moving crest bends toward the slower part. Anything that sticks out from the shoreline (such as headlands) will act as a focal point for waves, which bend toward it. And waves will bend toward the shore coming in nearly parallel (but never perfectly parallel.) US Department of Transportation, Federal Highway Administration.

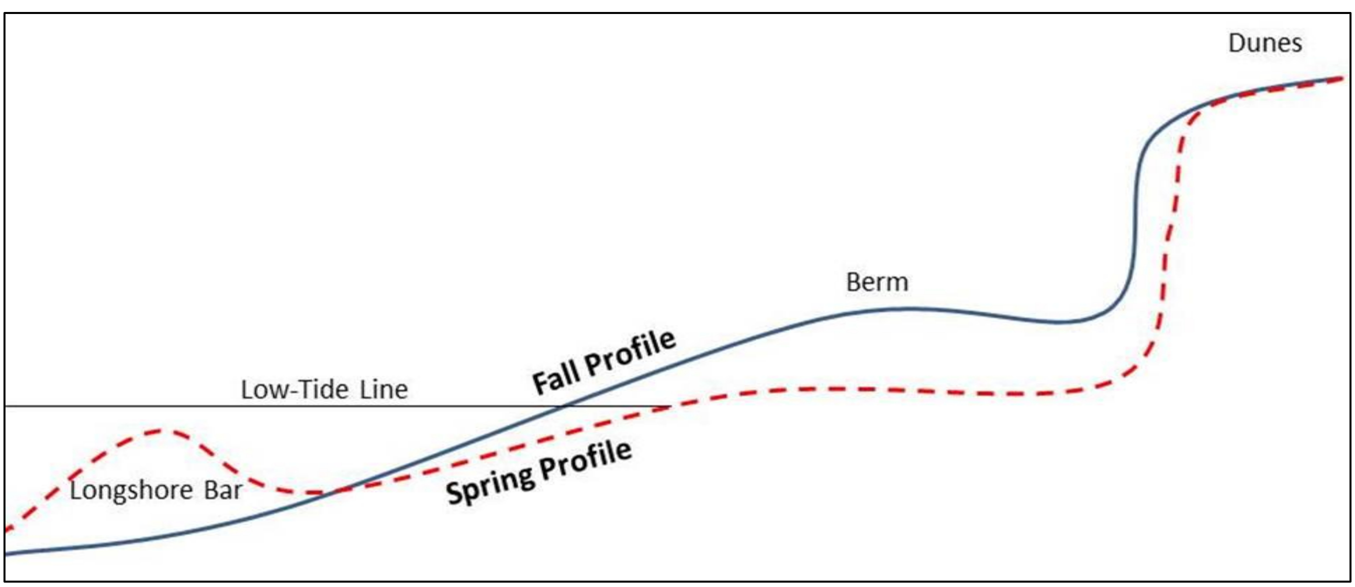


Figure 5. Beach profiles – from dunes/cliff to offshore bar – based on seasons.

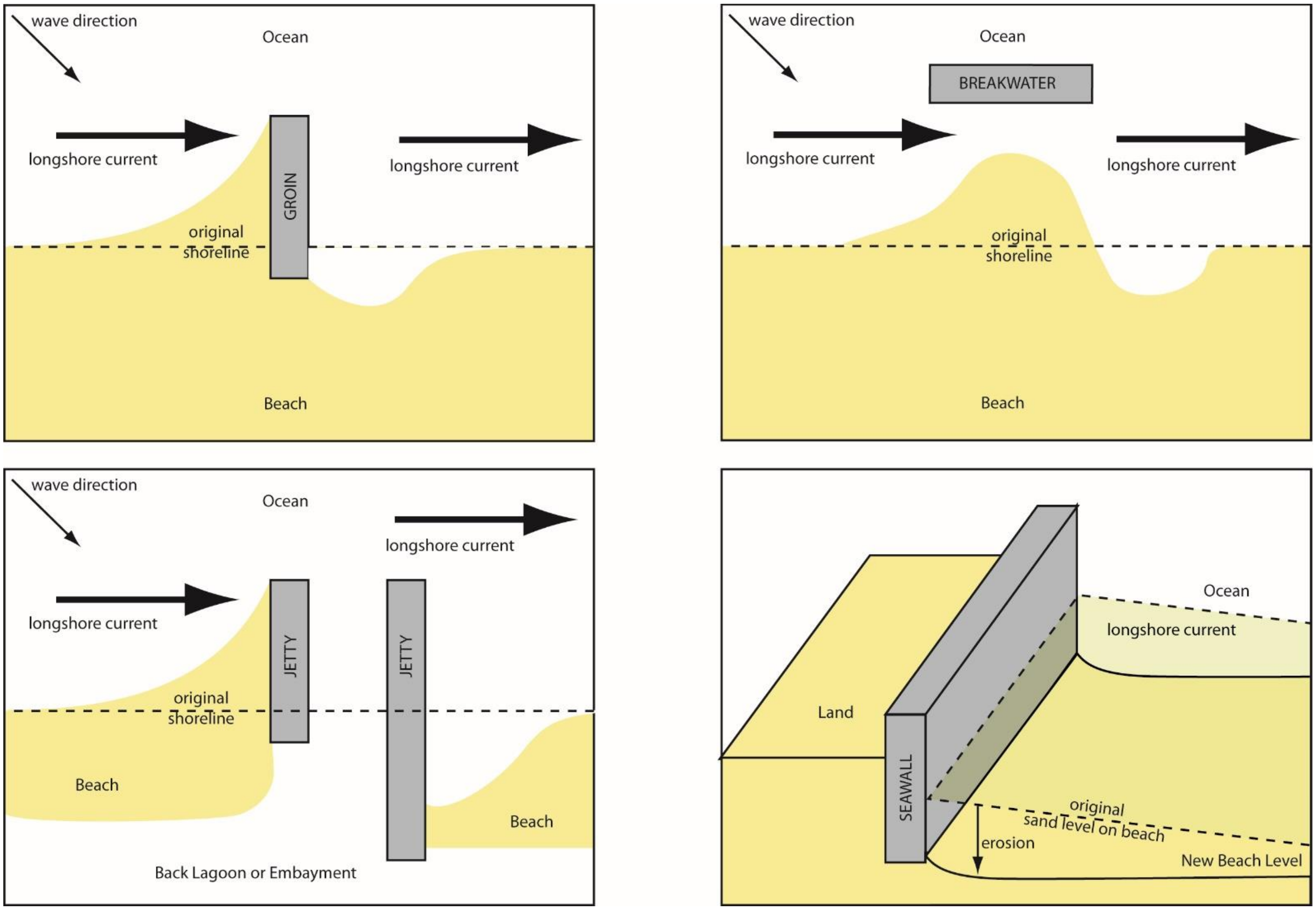


Figure 6. Groin. Breakwater. Jetties. Seawall. Images show how deposition and erosion are impacted by these structures.

Table 1. Results of installation of various structures on a shoreline.

Structure	**Groin**	**Jetty**	**Seawall**	**Breakwater**
Picture or description	Wall running perpendicular to beach, extending off beach	Two parallel walls running alongside harbor mouth, perpendicular to beach	Wall running parallel to beach, on the beach	Wall running parallel to beach, but offshore
Why used?	Create a beach	Prevent mouth closing	Prevent homes, roads, etc. from erosion	Create a gentle water region for boats to anchor
Results?	Another beach is eroded to compensate; wall must be maintained.	Sand builds up in harbor mouth eventually and must be dredged. Beach forms in one location at expense of another. Jetty must be maintained.	Sand on local beach diminishes; erosion increases elsewhere; rip rap must be added.	Sand on local beach grows, eventually requiring dredging; erosion increases downcurrent; wall must be maintained.

All beach sand **ultimately** comes from two sources: rivers (90%) and local beach erosion (minor amounts come from local reef erosion, if a reef exists). All beach sand **ultimately** ends up in two sinks: sucked down submarine canyons (sometimes by turbidity currents, sometimes through rip currents (water that's piling up along a headland or jetty pushes offshore) and just gradual raining down the canyon walls) where it lies in a pile at the base of the canyon or blown on land as a sand dune where it is later buried and turned to sandstone. In between source and sink, the longshore current distributes sand along the beaches.

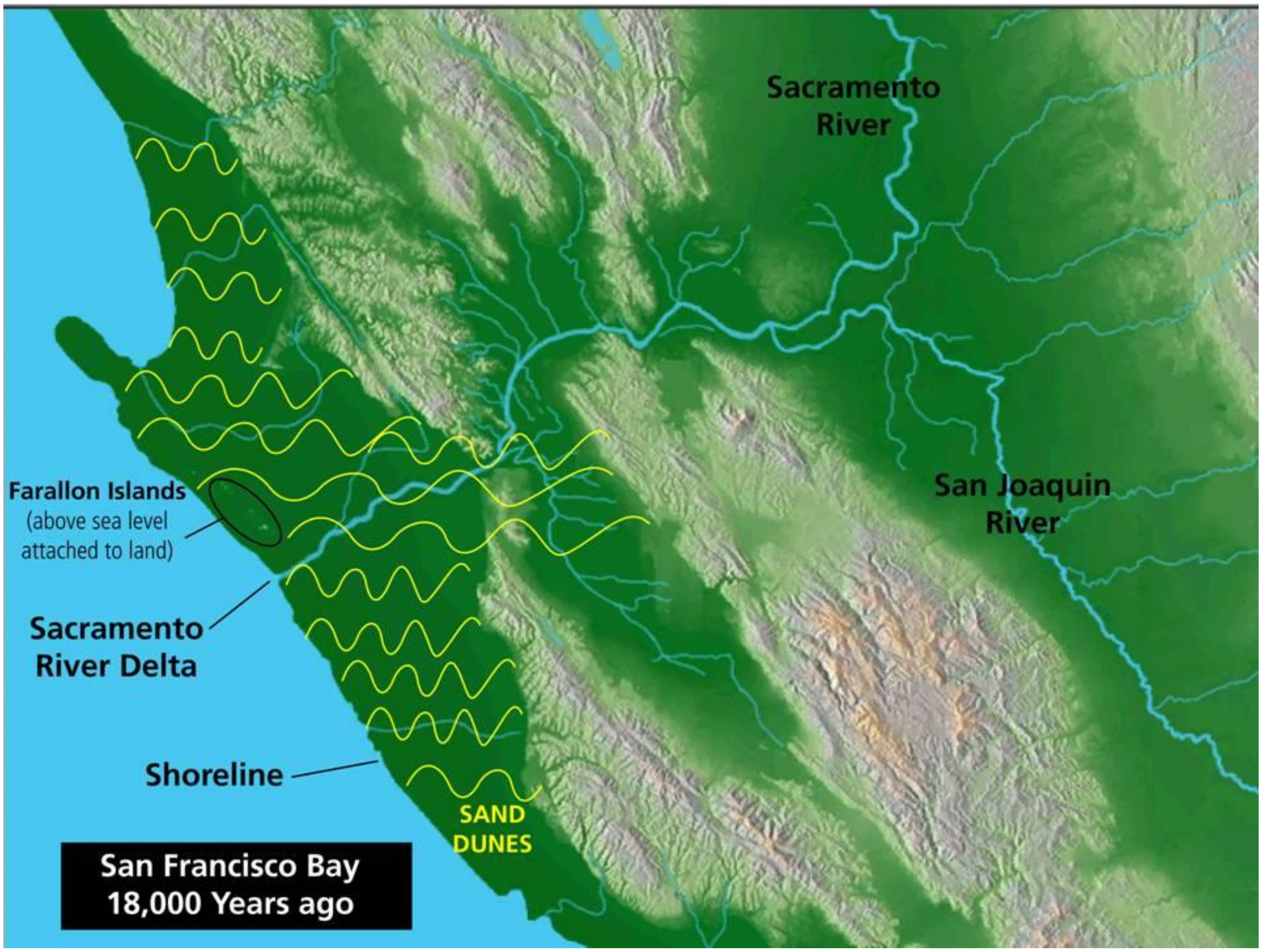


Figure 7. San Francisco Bay Area coastline (and sea level) at the height of the last ice age, 18,000 years ago. Yellow curved lines represent extent of sand dunes covering continental shelf. Modified from work by Tanya Atwater – UC Santa Barbara

Ocean Beach has no local rock to erode and has no upcurrent river to distribute sand to it. Longshore current cannot cross over the Golden Gate entrance, because of deep channels carved by tidal currents. Where does Ocean Beach sand come from? It comes from offshore sand deposits, left during the last ice age, when the Sacramento River flowed all the way to the beach (15 miles west of its current location). The Sacramento River, during an ice age, would have contained large quantities of water and sand, making for a large sand delta at the Pacific Ocean. Winds blew this sand onshore, where it covered large expanses of continental shelf, including most of the San Francisco Peninsula. These sands formed a massive sand dune province. Since the ice age, sea level has risen. The current Sacramento River dumps its load in a delta far inland, in Sacramento. Only muds stay suspended in this water as it mingles with the seawater entering San Francisco Bay. Ocean Beach's only source of sand are these offshore dunes that are now underwater and are picked up daily by incoming waves and pushed onto Ocean Beach.

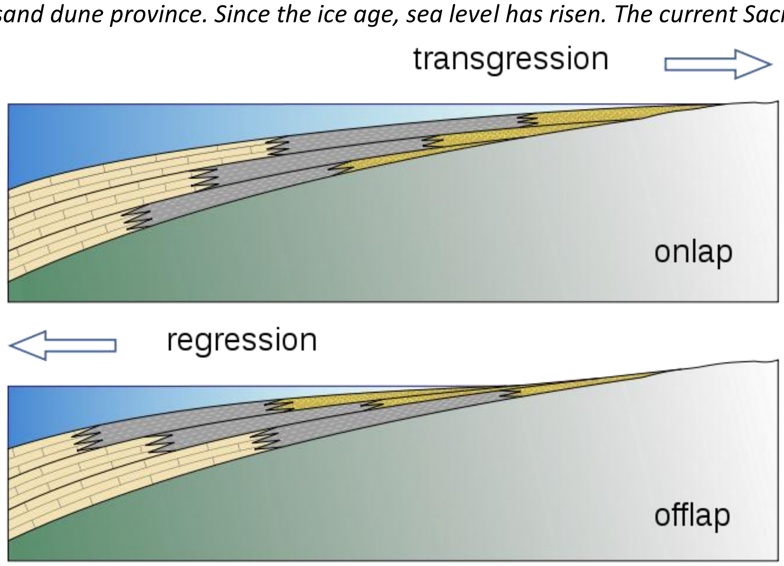


Figure 8. The shift of sedimentary facies during sea-level transgression (creating "onlap" structures) and during sea-level regression (creating "offlap" structures). Brick pattern offshore represents mud-sized calcareous shells. Grey pattern in middle represents muds. Yellow pattern near shore represents sands. Woudloper –Copyright: CC BY-SA 1.0

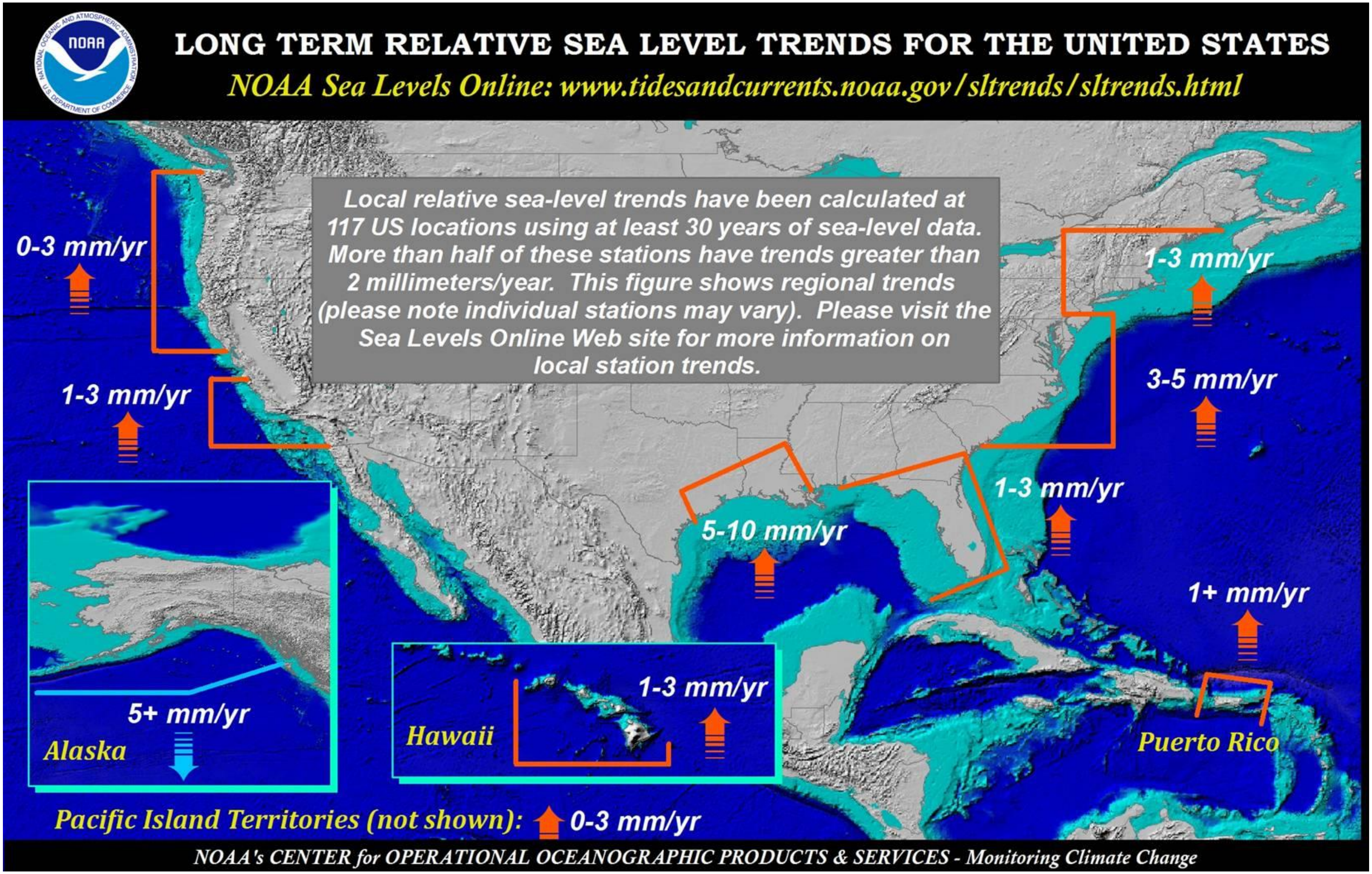


Figure 9. Sea level change along various coastlines in the U.S. Changes are caused by a combination of global sea level rise combined with local land subsidence or uplift.

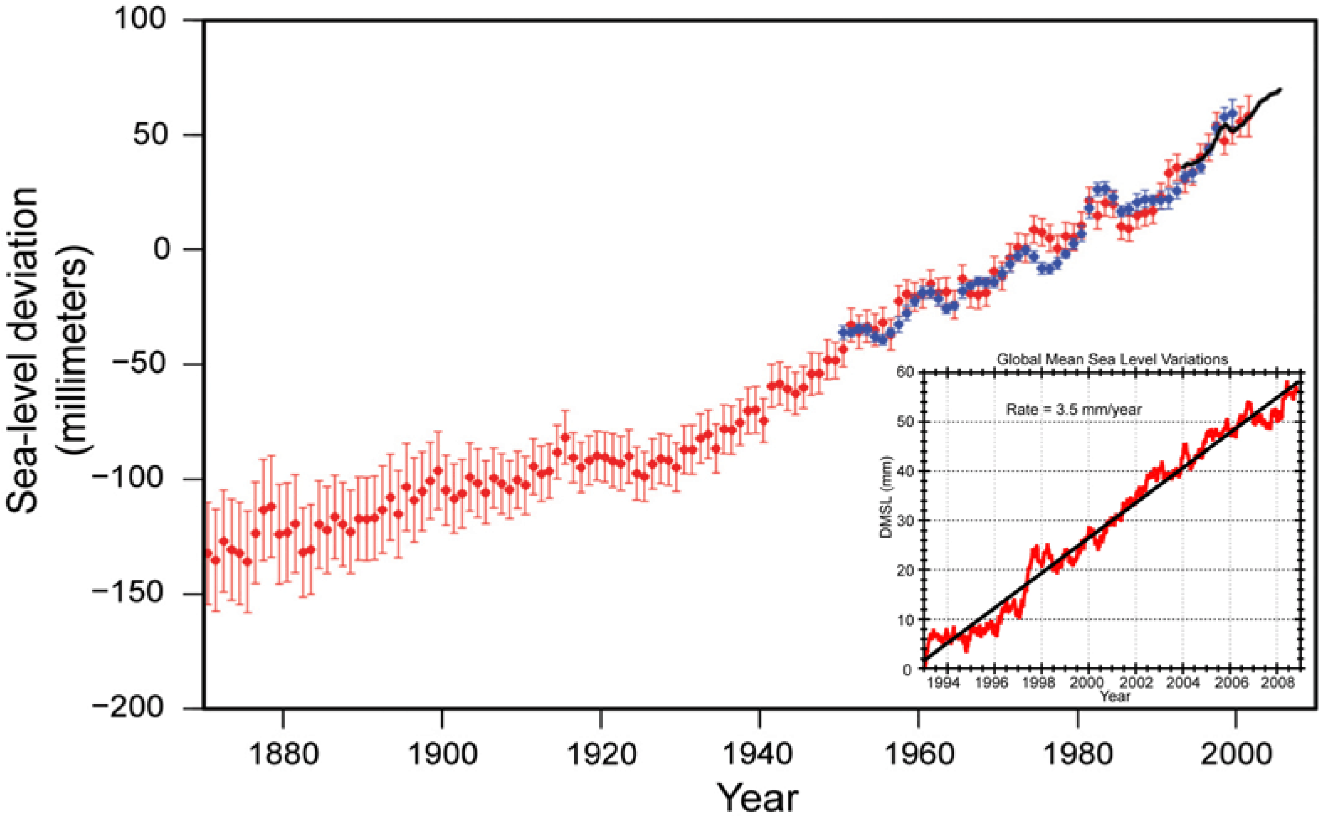


Figure 10. Average global sea level changes over the past 100 years. Image from NOAA

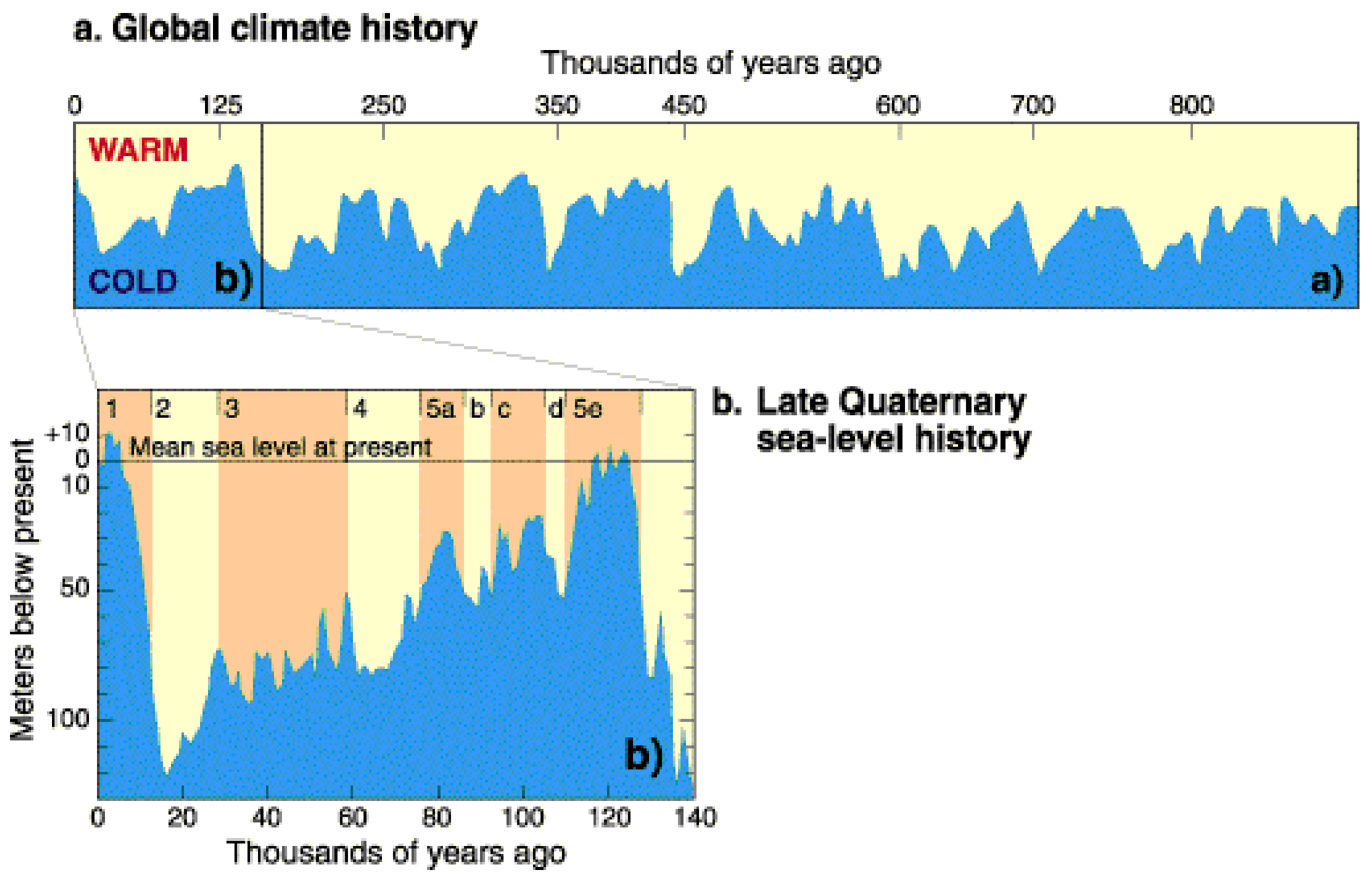


Figure 11. Sea level changes over the past 1 million years. Image from NOAA

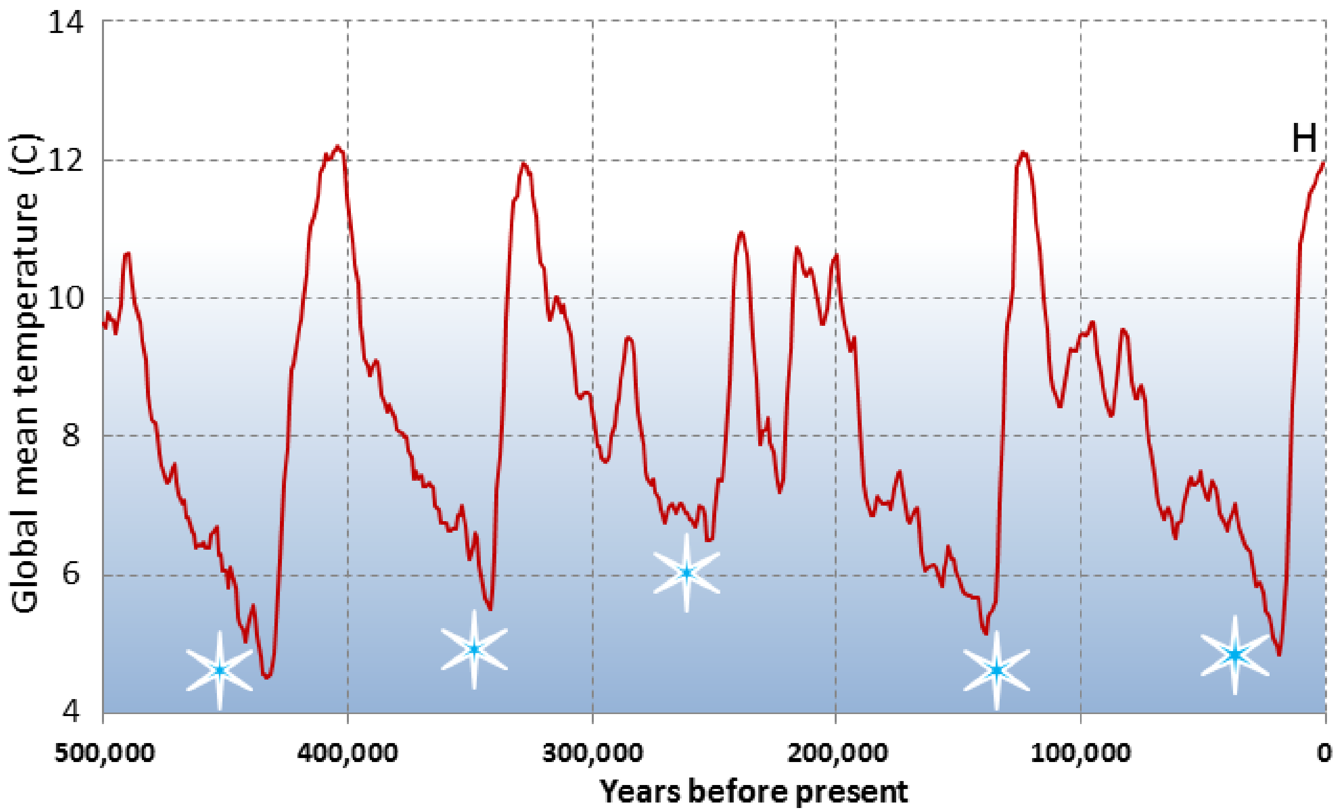


Figure 12. Glaciations over the past year. Steve Earle, Physical Geology, CC-Attribution 4.0 International.

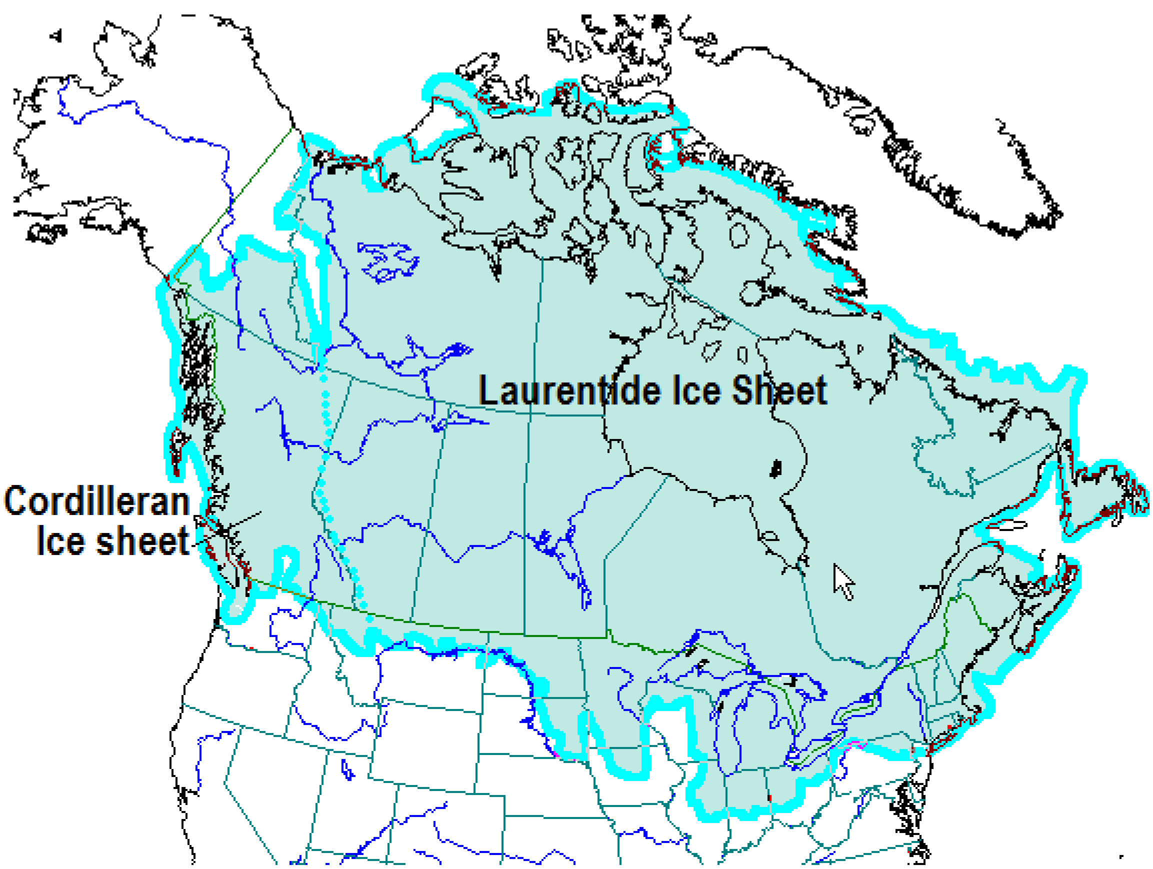


Figure 13. The extent of the Cordilleran and Laurentide Ice Sheets near the peak of the Wisconsin Glaciation, around 15 ka. [redrawn based on a map at: https://www.ncdc.noaa.gov/paleo/glaciation.html] Steve Earle, Physical Geology, CC-4.0 Intl.).

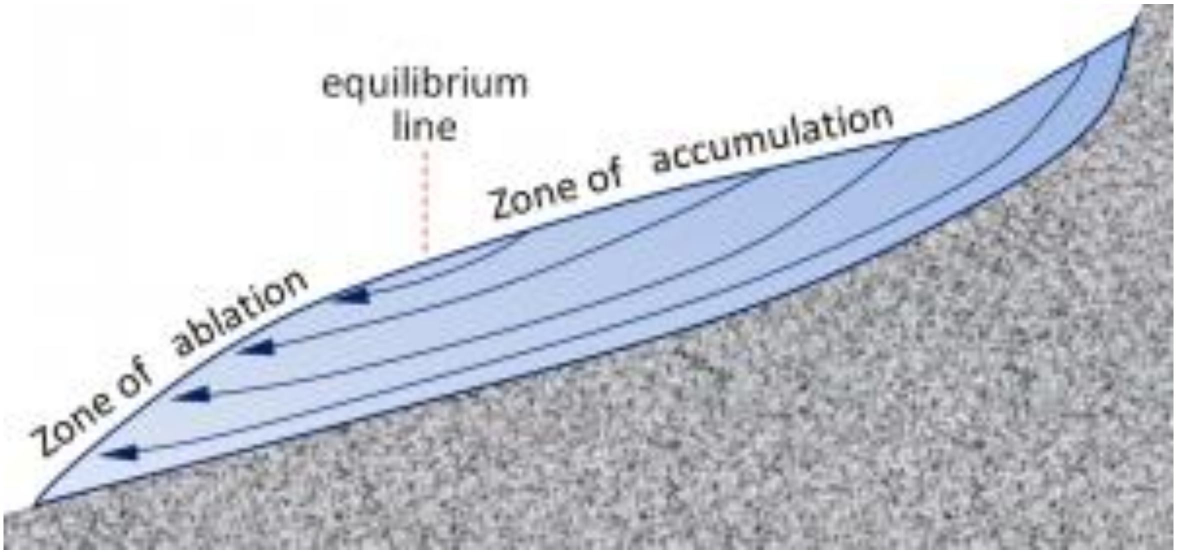


Figure 14. Alpine glacier budget – snow added in zone of accumulation and removed in zone of ablation. When ablation zone > accumulation zone, glacier toe retreats. When ablation zone < accumulation zone, glacier toe advances.

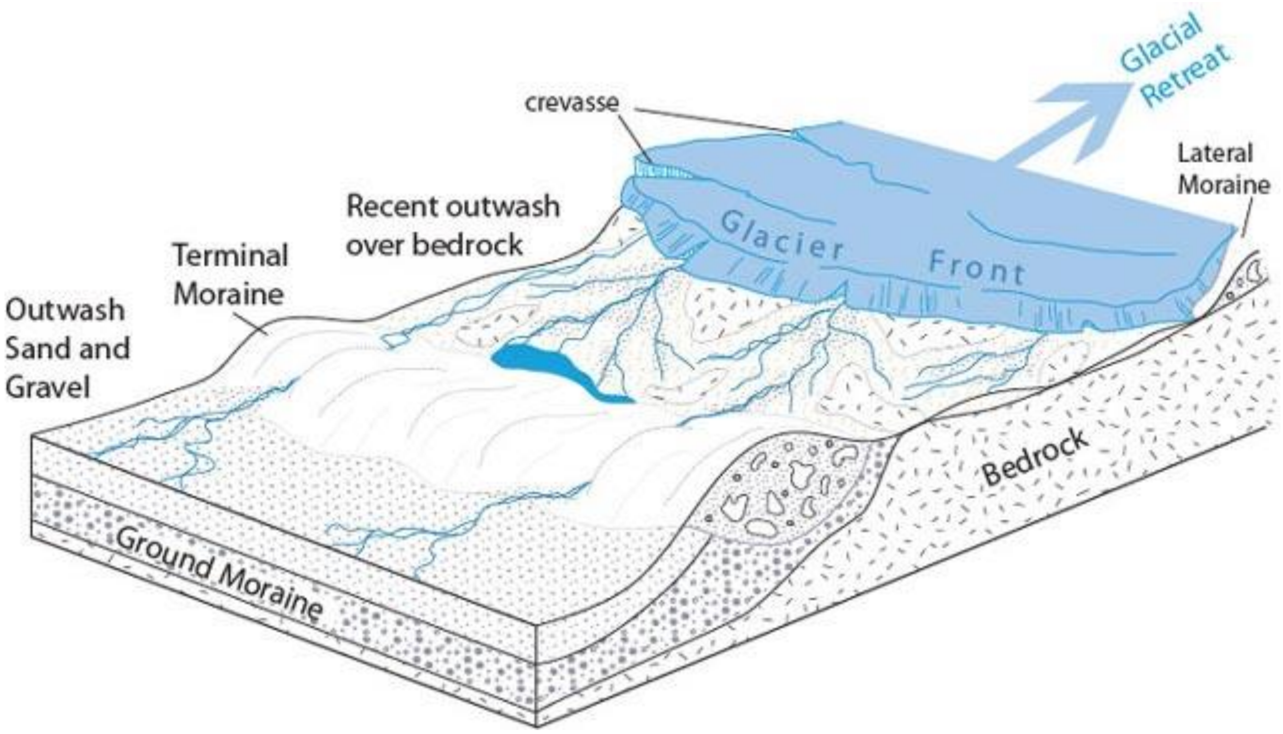


Figure 15. Sediments deposited by glaciers. ***Outwash*** *comes from the meltwater coming out the base and front of the glacier.* ***Moraine*** *dropped in place as glacier melts. Image: National Park Service.*

Figure 16. Sólheimajökull Valley Alpine Glacier. Katla Geopark Iceland. Photo source unknown. Note the ice cap in the background covering the top of the mountain.

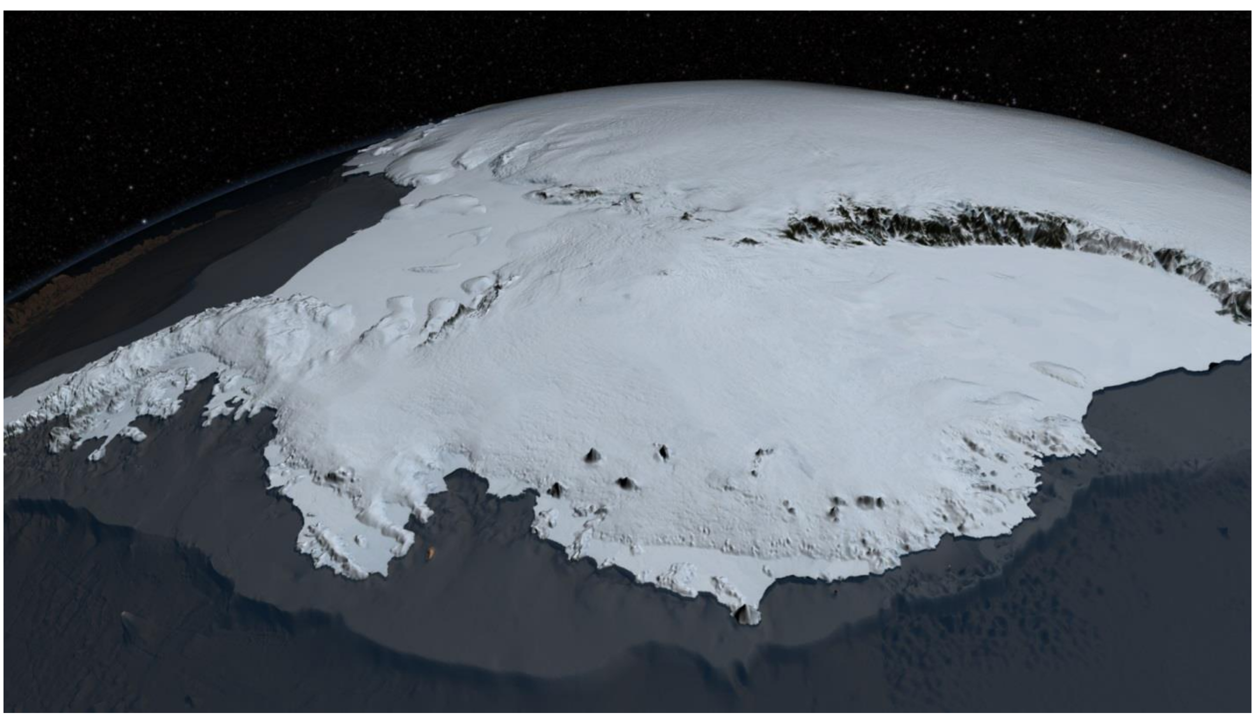


Figure 17. Antarctica Ice Sheet. NASA.

Some more useful definitions:

Glacier	A mass of compressed ice that has accumulated on land over many years of snowfall and that moves under its own weight.
Alpine glacier	Glaciers that are found in the mountains
Continental ice sheet	Glaciers that are found atop continents at high latitudes (Greenland and Antarctica)
Valley glacier	Alpine glacier in a valley between two ridges
Arete	ridges carved between two parallel valley glaciers
Cirque	bowl carved by the top of a valley glacier
Horn	Sharp single peak formed when multiple cirques erode backwards and upwards toward each other.
Hanging valley	U-shaped valley carved by a tributary glacier that merged with a large deeper-eroding glacier -- after glaciers retreat, the tributary valley hangs above the larger deeper main valley.
Outwash plain	Sediment that deposits from meltwaters flowing out of the toe of a glacier -- usually spread out in a plain
Till	any sediment dropped by a glacier at its toe or along its sides or at its base when it melts (not carried by moving water -- only dropped in place by the ice)
Moraine	a pile of till
Lateral moraine	a moraine bulldozed along the edges of a glacier
Terminal moraine	a moraine found at the terminus/toe/front of a glacier (bulldozed forward by an advancing glacier)
Medial moraine	two lateral moraines that combine when two valley glaciers merge
Ground moraine	a moraine that is flat and covers the ground where a glacier is retreating
Esker	sediment that deposited on the bottom of a meltwater stream coming out the toe of a glacier (channel and sediment were originally above the surface of the surrounding land because the meltwater could more easily erode ice than the ground)

Crest	Highest point in a wave form
Trough	Lowest point in a wave form
Wave Height (H)	The vertical distance beween a wave's crest and its trough.
Wavelength (L)	The horizontal distance between crests or between troughs.
Wave period	the amount of time it takes for one wavelength to pass a given point (time for one wave)
Equilibrium surface of a wave	Horizontal line that cuts exaclty through the center of the wave form, connecting nodes, halfway between crests and troughs.
Wave base	The lower limit of motion experienced by water when an ocean wave passes through. Water moves in an orbital (circular) motion as waves pass by, and that orbit gets smaller and smaller the deeper below the surface one goes. At one point, the motion is no longer detectable. This it he wave base. Anything under that won't "feel" the wave. Anything above it does "feel" the wave and is moved in an orbit. Wave base is calculated as 1/2 the wavelength!
berm	The dry, gentle sloping region at the foot of the coastal cliffs or dunes. Composed of sand, making it a favorite place of beachgoers. Sand is pushed up in summer (bigger berm) and eroded away in winter (smaller berm).
shoreline	the edge of the water, as it migrates back and forth with the tide.
Longshore Drift and Current	Water and sand that moves along the shore. Waves from distant storms approaching the beach at an angle move the sand and water along beaches, moving it in the opposite direction from which the wave originate. Typically in North America this direction is south (because most storms and thus storm waves originate north of us).
Rip current	Rip currents form whenever water piles up on the shore and needs to move offshore. Rip currents move through the incoming waves.
Ebb Current	water that moves offshore after a high tide (retreat of the tides).
Flood Current	water that moves onto shore as high tide approaches (tides advance onto and flood the land)
Slackwater	high tide or low tide, when there is no tidal current.

Glaciers and Shorelines Chapter Worksheet

1. What are the causes and consequences of longshore currents?	
2. What general (most probable) direction does beach sand move on North American beaches? Why?	
3. List landforms (features) caused by coastal **deposition**?	
4. List landforms caused by coastal **erosion**?	
5. Shorelines that have marine terraces are likely experiencing what process(es)?	CIRCLE: deposition | erosion CIRCLE: subsidence | uplift | sea level rise | sea level drop
6. Which process dominates the **East Coast** of the United States? Why?	CIRCLE: deposition | erosion
7. Which process dominates the **West Coast** of the United States? Why?	CIRCLE: deposition | erosion
8. During what **month of the year** would you expect the **berm** on the beach to be smallest? Why?	
9. During what **month of the year** would you expect the **berm** on the beach to be largest? Why?	
10. What are the main sources of beach sand globally (in decreasing abundance order)?	
11. What are the two primary sinks for all beach sand globally?	
12. What factors besides sea level rise would cause a beach to shrink?	
13. What are the main consequences of building a seawall, jetty, groin, or breakwater on the coast?	
14. **REVIEW:** How deep does sea level drop during an ice age?	15. **REVIEW:** What is the name of the feature that marks this depth?
16. What are the main natural ways that sea level **drops** globally? *(Be specific!)*	
17. What do ice ages have to do with the source of sand today at Ocean Beach? ((Figure 7.)	

18. What is a glacier?

19. What are the two main types of glaciers? Where do you find each?

Glacier types	Where found?	Shape and direction of motion?

20. Under what circumstances do alpine glaciers move downhill?

21. Under what circumstances does the front of a glacier retreat?

22. At what rates do glaciers move? What is the fastest and slowest?

23. List landforms caused by glacial **deposition**?

24. List landforms caused by glacial **erosion**?

25. What percentage of Earth's land area do glaciers cover today?

26. What percentage of Earth's land area did glaciers cover 20,000 years ago?

27. **REVIEW:** Where is the world's freshwater held on our planet (give locations and percentages):

28. How was California affected during the last ice age?

- Describe the effects of glaciers on sea level.
- Describe the effects of glaciers on flora and fauna.
- Describe other indirect effects of glaciers on the landscape (to land not covered by glaciers).

29. How does a glaciated mountain valley differ from a river-eroded mountain valley? Why?

Glaciers Activity: Case Study & Concept Sketch

Case Study: pick a glacier, anywhere in the world, and research it in class materials and online. If alpine, what is the geologic setting of that mountain? If part of a continental ice sheet, what is the geologic setting of the area over which the ice sheet is moving? it shrinking or growing? At what rates? What kind of landforms are associated with it? Why did this particular glacier interest you enough to choose it? Use the answers to these questions, and your research to draw a concept sketch of the glacier below (with scale!). Describe and label its key characteristics. Add your name and a bibliography of any sources you used.

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Compare and contrast glaciers and waves as erosional processes including their associated landforms.	A | B | C | D | F	
Evaluate the causes of sea-level change and its impact on coastal erosion and deposition.	A | B | C | D | F	
Evaluate the extent and impacts of ice ages on Earth History and local climates.	A | B | C | D | F	
Analyze the impacts of tides, waves, and currents on coastal processes and landforms.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

GEOLOGIC TIME

Geologic Time Review

Geologists piece together Earth history from the geologic record of past events. Events include intrusions and extrusions of igneous rock, crustal metamorphism and deformation accompanying mountain building, and the erosion and deposition of sediments. Information about Earth's geologic history comes largely from exposures of rocks and sediment at the surface called **outcrops**. To understand crustal history, we need to view it in **cross section**, like viewing a slice of through crust edge on. Outcrops at highway excavations, railroad cuts, stream valleys, and cliffs all provide a cross section of Earth's crust.

Cross sections of sedimentary rocks reveal layers called **strata**. The study of strata is **stratigraphy**. Building the geologic time scale has required modern science to develop techniques to determine the age of rocks, minerals, and sediments. **Relative dating** involves interpreting the sequential relations between different rocks and the events they record. **Radiometric dating** involves calculating the numerical age of certain Earth materials and makes use of the natural phenomenon of radioactivity.

Relative dating is a technique of dating a rock unit relative to other nearby strata. The relative ages of two strata can be fixed in terms of which came first and which second. Those two strata then can be dated relative to a third stratum, and so on. This process continues until all the layers in a cross section are ordered within a relative time scale that reflects a sequence of events.

Each rock in a cross section represents a geologic event in Earth history. Sedimentary rocks, for example, represent events of deposition. A sandstone records an event of sand deposition, either on a shallow continental shelf, beach, or as sand dunes in the desert. Granite records the event of an igneous intrusion in the crust, indicating volcanic activity and magma migration. Schist records an event of high temperature and pressures in the crust, either from deep burial or collision of plates. A geologic event can be any natural occurrence involving geologic materials, including deposition, erosion, deformation (tilting or folding), faulting, intrusion, and others.

The relative ages of many strata in a complex portion of crust can be established through the use of various principles:

The Principle of Original Horizontality describes the general tendency for sediments to be deposited in horizontal beds. If left undisturbed, particles of sediment accumulate in beds that are parallel to this surface. Tilted or folded sedimentary strata record tectonic events that have deformed Earth's crust.

Principle of Original Lateral Continuity describes the tendency for lava flows and sedimentary beds to extend laterally in all directions until they thin to nothing (pinch out) or reach the edge of the deposition basin.

The Principle of Superposition states that the lowest sedimentary rocks in an undisturbed sequence were deposited first and therefore are oldest. Vertical sequences of different rock types are often exposed in cliff faces. If such a sequence is undeformed, the lowest layer of rock is the oldest, and the highest is the youngest. The intervening strata represent a sequence of successive ages between the two extremes.

The Principle of Cross-Cutting Relations describes how certain geologic events (such as folding, faulting, intrusion, and erosion) are younger than the rock bodies they alter. For example, igneous intrusions are younger than the surrounding crustal rock they intrude, and faults are younger than the strata they fracture. It is often possible to determine the relative ages of several mutually cross-cutting intrusions and faults.

Inclusions are pieces of one rock that you find in another rock. Included rocks must be older than the rocks in which they are found. For example, a cliff face of granite will weather. Pieces of the granite will make their way into beach sand deposits. The sandstone that forms from such deposits must be younger than the granite.
Principles of **unconformities** – Most contacts between adjacent rocks are conformities – meaning that rocks on both sides of the contact formed at about the same time. An unconformity is a rock surface that represents a gap or hiatus in the rock record – like pages missing from a book. Unconformities can occur when there is a pause in sedimentation in an area or when an area has been uplifted and eroded.

Erosion-caused unconformities are often identified by a layer of coarse sediment that remains after the erosional event. This horizon results from the removal of finer, easily eroded material and the formation of a lag deposit, often composed of gravel. Later lithification can turn the layer into a conglomerate bed. In certain strata, the erosional surface stands out because of its unique texture and weathered appearance. In other strata, it might be indiscernible, sometimes leading to erroneous interpretations of the geologic history.

Intervals of nondeposition or erosion can also be identified by a sudden change in rock type. For instance, a sandstone might overlie a shale, with no gradation between the two. Such a drastic change in sedimentary conditions rarely occurs in nature without some intermediate unit, such as a sandy shale or shaly sandstone, recording the change. Thus, a sharp boundary separating two such distinct units can signify an interval of nondeposition, erosion, or both.

Types of unconformities:

Figure 1. Disconformity – Unconformity between parallel strata or lava flows – usually the contact is irregular and pieces of underlying rock are included in the strata above them.

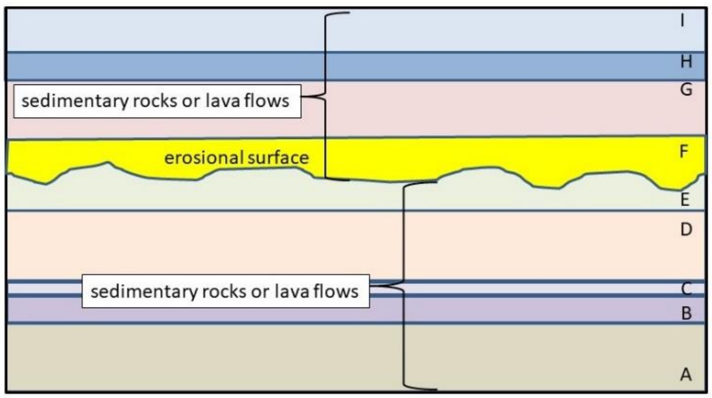


Figure 2. Nonconformity – Unconformity between intrusive igneous rock or metamorphic rock below and flat, parallel sedimentary rock layers (or lava flows) above – due to sediments deposited on top of uplifted and eroded igneous or metamorphic rock.

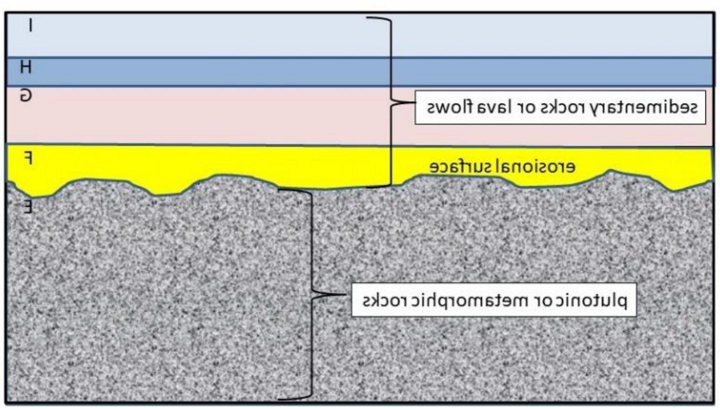
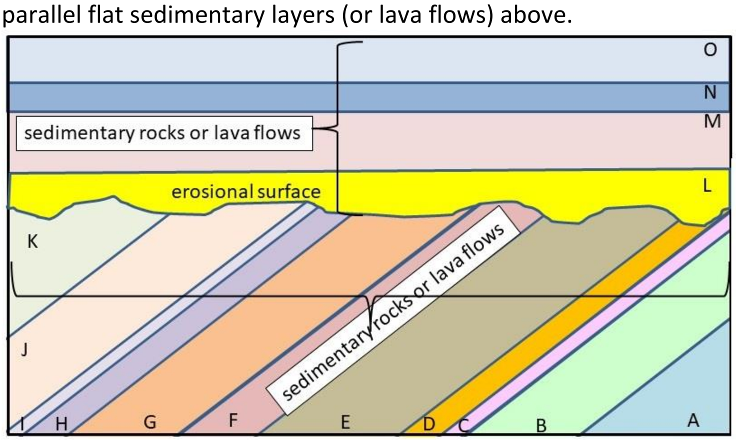


Figure 3. Angular unconformity – Unconformity between tilted or folded sedimentary layers (or lava flows) below and parallel flat sedimentary layers (or lava flows) above.



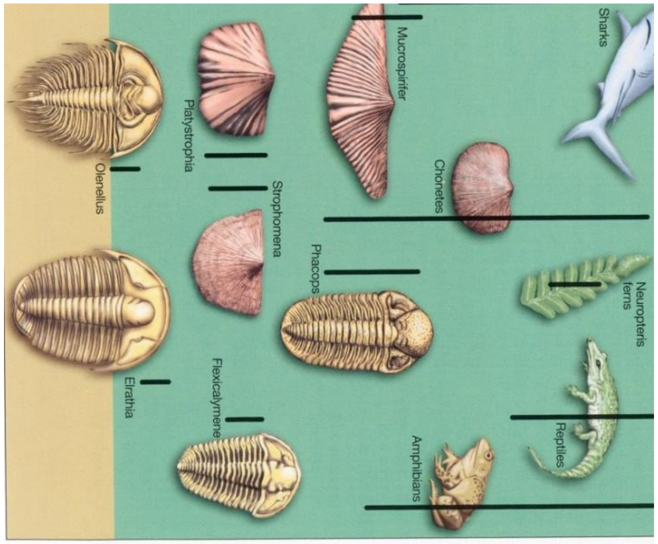


Figure 4. (image modified from Laboratory Manual in Physical Geology, Busch Ed., Prentice Hall Pub., 1997)

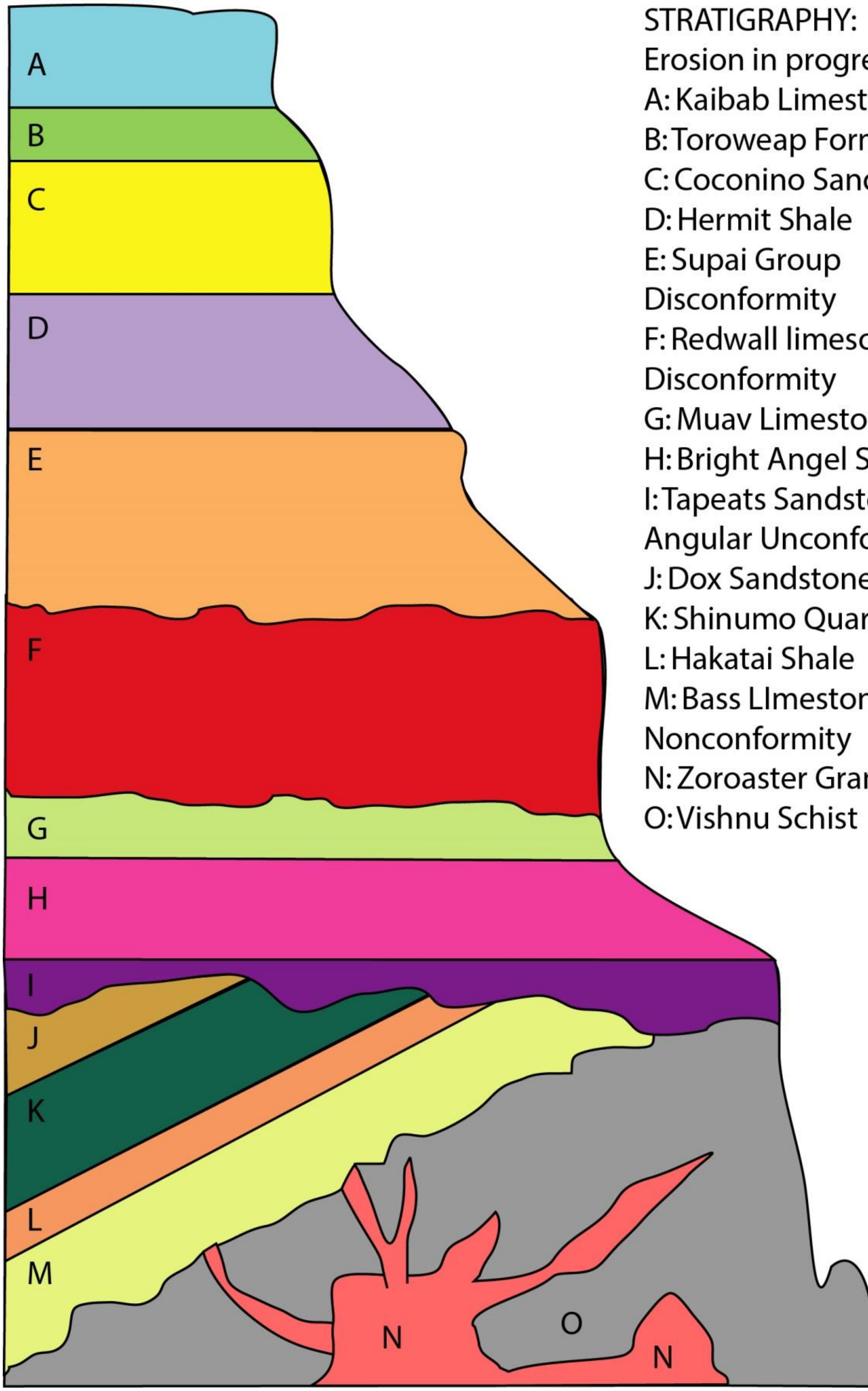
The **principle of faunal succession**

Fossils found in sedimentary rock layers can be used to relatively date these layers, when compared with the evolutionary record. Flora and fauna fossils succeed each other in a reliable order. For example, a fossilized ammonite will never be found in the same rocks as dinosaurs, as ammonites lived and went extinct many millions of years before dinosaurs lived. Note: not all fossils are good indicators of age. For example, stromatolites have existed on planet Earth since 3.5 billion years ago (still exist today), so they cannot uniquely place or order rocks younger then 3.5 billion years old. However, other fossils, known as **index fossils**, are of flora or fauna that lived for very short periods of time. These index fossils are most useful for relatively dating rocks.

Figure 5. Fossil assemblages (not to scale)

	Precam	**Paleozoic**							**Mesozoic**			**Cenozoic**	
		Cambr	**Ordovi**	**Siluria**	**Devoni**	**Mississ**	**Pennsy**	**Permi**	**Triassic**	**Jurassi**	**Cretac**	**Tertiar**	**Quater**
(period starts)	**4.6 Ga**	**570 Ma**	**505 Ma**	**438 Ma**	**408 Ma**	**360 Ma**	**320 Ma**	**286 Ma**	**245 Ma**	**208 Ma**	**144 Ma**	**66.4 Ma**	**1.6 Ma**
Humans													xx
Fagopsis trees												xxx	
Mammals									xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx				
Dinosaurs									xxxxxxxxxxxxxxxxxxxxxxxxxx				
Neurop.ferns							xxxxxx						
Reptiles							xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx						
Sharks					xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx								
Amphibians					xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx								
Mucrospirifer (b)					xxxxxxxxxx								
Chonetes (b)				xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx									
Phacops (t)				xxxxxxxxxxxxxxx									
Flexicalymene (t)			xxxxxx										
Platystrophia (b)			xxxxxxxxx										
Elrathia (t)		xxxx											
Olenellus (t)		xxxx											

(b) = brachiopod species; (t) = trilobite species



STRATIGRAPHY:
Erosion in progress
A: Kaibab Limestone
B: Toroweap Formation
C: Coconino Sandstone
D: Hermit Shale
E: Supai Group
Disconformity
F: Redwall limesone
Disconformity
G: Muav Limestone
H: Bright Angel Shale
I: Tapeats Sandstone
Angular Unconformity
J: Dox Sandstone
K: Shinumo Quartzite
L: Hakatai Shale
M: Bass LImestone
Nonconformity
N: Zoroaster Granite
O: Vishnu Schist

*Figure 6. Simplified Geologic Cross-Section Through Grand Canyon and corresponding **stratigraphic column** (modified from images of Peter Coney, USGS.)*

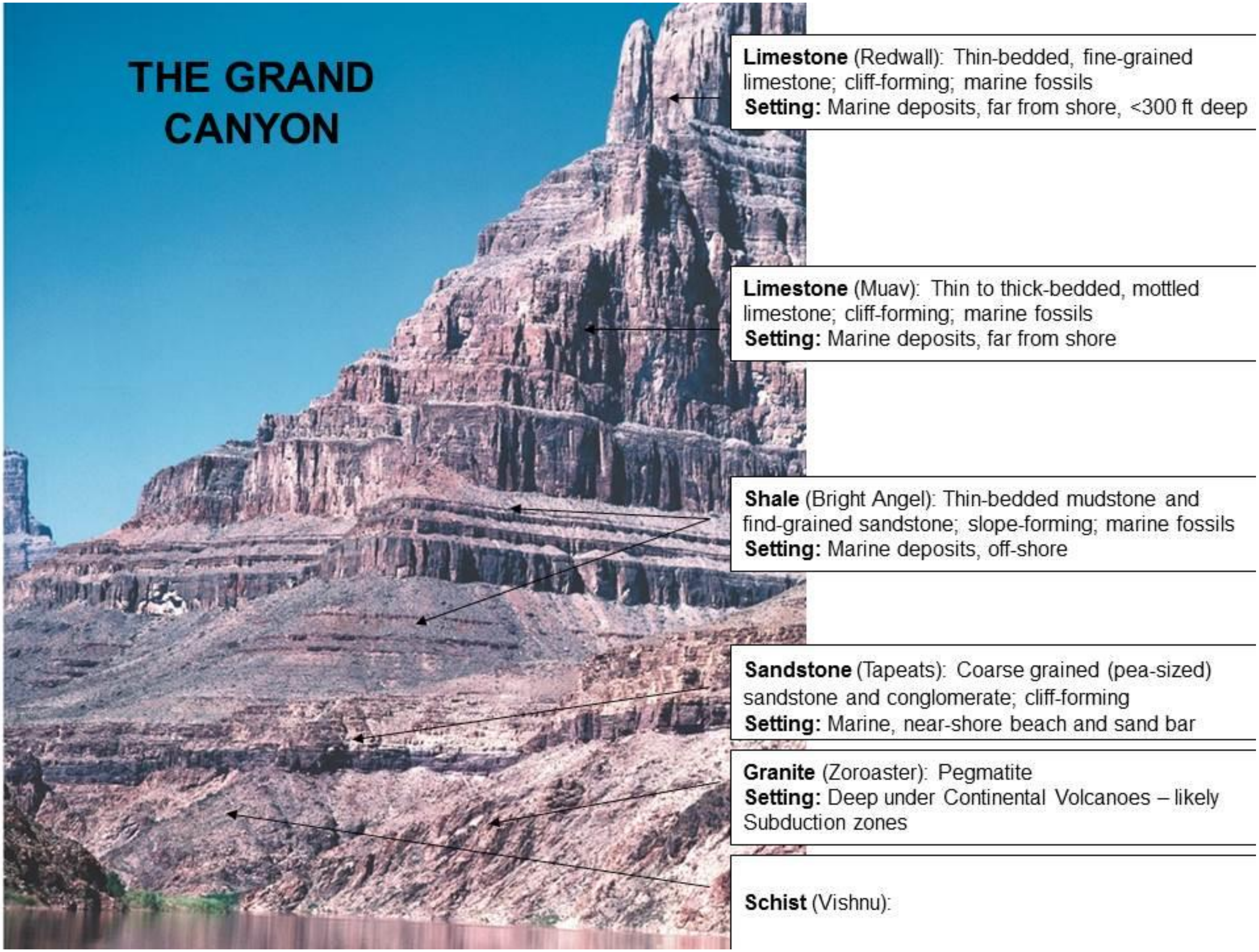


Figure 7. The Grand Canyon stratigraphy correlated to a field photo

Radioactive decay

Radioactive parent materials will decay into daughter materials through one of the following mechanisms:

- **Alpha decay**: nucleus spontaneously emits an alpha particle (symbol: a particle), which is 2 p+ and 2 n (or also the same as a Helium (He) atom).
  - Result: atomic number decreases by 2 (lost 2 p+)
  - Result: atomic mass decreases by 4 (lost 2 p+ and 2n = 4 amu)
- **Beta decay**: neutron in nucleus spontaneously emits a beta particle (symbol: b particle), which is essentially an electron trapped in a neutron. The neutron, therefore, turns itself into a proton.
  - Result: atomic number increases by 1 (gained 1 p+)
  - Result: atomic mass stays same (no mass lost or gained: b particle or electrons have no mass)
- **Beta or electron capture**: proton in nucleus captures a beta particle (symbol: b particle), which is essentially an electron that can become part of a neutron. The proton, therefore, turns itself into a neutron.
  - Result: atomic number decreases by 1 (lost 1 p+)
  - Result: atomic mass stays same (no mass lost or gained: b particle or electrons have no mass)
- **Gamma decay:** no change in protons or neutrons, just the release of energy from an activated state of a nucleus to a more stable state through the emission of a gamma ray (a photon, or light wave). Gamma radiation doesn't change the atomic mass or number.

Radiometric dating

We can use radiometric dating only on specific rocks – ones that contain radioactive isotopes (like those listed in the table below) – and ones that can maintain a closed system – no atoms lost or gained. Not all rocks can be dated. Not all rocks contain useful isotopes for dating.

When radioactive parent isotopes (P) decay, they produce daughter products (D) at a constant rate, called the **half-life (T)**. Example: if we start with 84 atoms of a particular parent, after one half-life (say 10 years), there will be 42 parent atoms remaining and 42 daughter atoms newly made. After another half-life (another 10 years, for a total of 20 years), there will be 21 parent atoms remaining and now 63 daughter atoms. Each parent-daughter isotope pair has its own half-life. To achieve the above example with U-238 takes 9 billion years. To achieve the above example with C-14 takes 11400 years.

In the geologic environment, we use a mass spectrometer to count the number of Parent and Daughter atoms in a closed-system substance (like minerals crystallizing from magmas) and use the relative proportions to calculate the age of the closed-system. For example: If the ratio of P:D is 1:1, that means there are equal amounts of each: 50% P and 50% D (or ½ P and ½ D). One half life has passed. If the ratio is 1:3, there is 75% D, 25% P (or ¼ P, ¾ D): two half-lives have passed.

Table 1. Useful isotopes for dating

Parent (P)	Daughter (D)	Half-lives ($T_{1/2}$)	Materials dated
U-238	Pb-206	4.5×10^9 yr	Zircon (felsic igneous rocks – source; sedimentary rocks as grains)
U-235	Pb-207	0.7×10^9 yr	
K-40	Ar-40	1.4×10^9 yr	Micas, volcanic rock (igneous rocks)
C-14	N-14	5700 yr	Shells, limestone, organic materials

***Not all rocks can be dated radiometrically. Some because they cannot maintain closed systems (like metamorphic rocks); others because they do not contain radioactive isotopes (like quartz sandstones); and finally some because the radioactive isotopes that they do contain have half-lives that are either too long or too short to be measured for a rock of a certain age (like trying to date a 1 m.y.-old rock by using C-14 decay – which would have been completely decayed after about 150,000 years).*

Calculating radioactive age

If you want to date the age of a shell in an archeological dig, which isotope pair would you measure? You'd use C14-N14 because the age range fits. Ancient man isn't more than 100,000 years old. Using any other isotope pair would be prone to error.

If such a measurement was made, and the P:D ratio was found to be 1:7, how old is the sample? Out of 8 parts, 1 is P and 7 are daughter. That means that 1/8 or 12.5% of the parent is remaining. Such occurs after 3 half lives. C14-N14 half-life is 5700 years, so the shell is 5700 x 3 = 17100 years old.

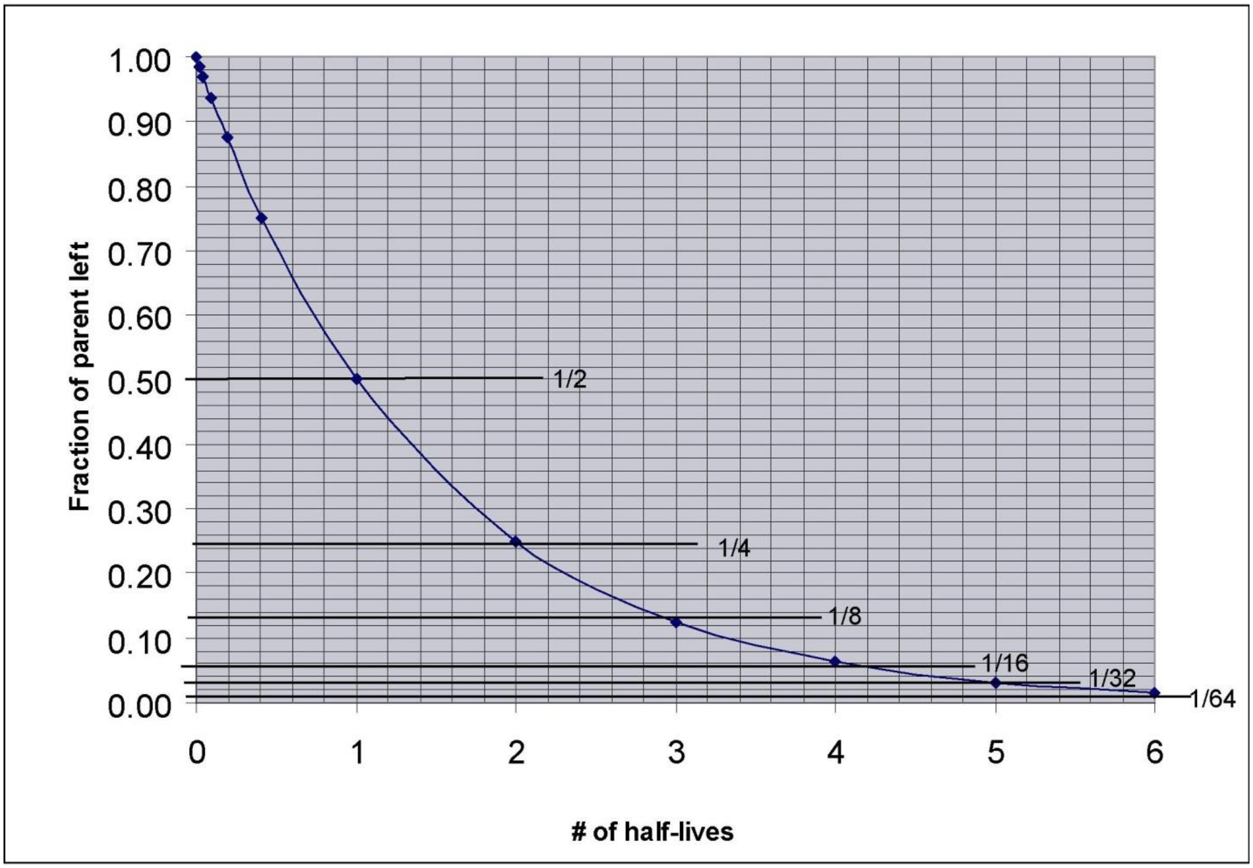


Figure 8. Graph showing the fraction of parent that remains as the number of half lives increases.

Table 2: Parent to daughter ratios (P:D) as half lives pass.

T	1	2	3	4	5	6
P:D	½:½	¼:¾	1/8:7/8	1/16:15/16	1/32:31/32	1/64:63:64
P:D	1:1	1:3	1:7	1:15	1:31	1:63

Table 3: More parent:daughter ratios including increments less than 1 half life.

T (# of)	**Fraction**			
Half lives	**Parent**	**Daughter**	**Ratio**	
0	1	0	infinity	:1
0.0227	63/64	1/64	63	:1
0.0458	31/32	1/32	31	:1
0.0931	15/16	1/16	15	:1
0.1927	7/8	1/8	7	:1
0.4151	3/4	1/4	3	:1
1.0000	1/2	1/2	1:	1
2.0000	1/4	3/4	1:	3
3.0000	1/8	7/8	1:	7
4.0000	1/16	15/16	1:	15
5.0000	1/32	31/32	1:	31
6.0000	1/64	63/64	1:	63

CURVE EQUATION: T = -1.443ln(f)
f = fraction of parent left;
T = # of half lives that have passed
Reads: # half lives passed equals minus 1.433 times the natural logarithm of the fraction of parent left.
Example: If the fraction of parent remaining is ½ or 0.5, then take the natural logarithm of 0.5, and that equals -0.693… or -1/1.443 (same number), so when you multipley -1.433 and -1/1.433, you get 1 – 1 half life has passed!

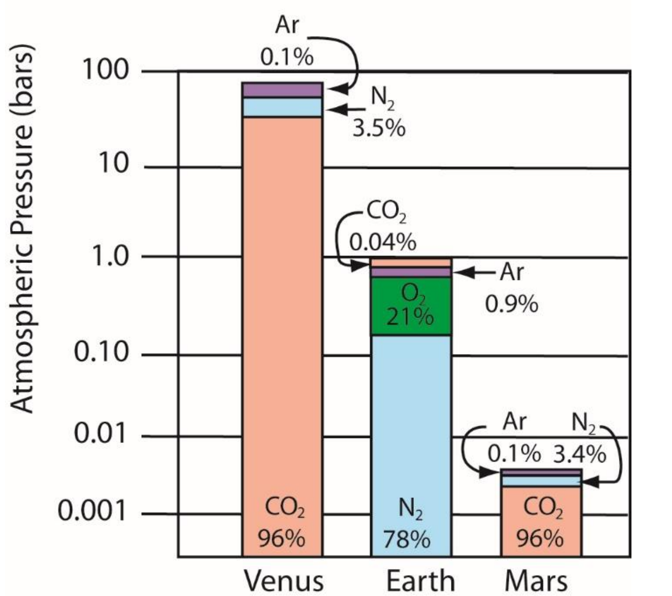


Figure 9. Major gas components of the atmospheres of Earth and its neighboring planets, showing CO_2 as the dominant gas on Mars and Venus, while only a minor component on Earth.

Table 4.

Composition of Earth's early atmosphere:	**Composition of Earth's current atmosphere:**
In decreasing abundance	MAJOR
CO_2 (carbon dioxide)	78% N_2 (nitrogen)
N_2 (nitrogen)	21% O_2 (oxygen)
H_2O (water vapor)	MINOR
CH_4 (methane)	0-4% H_2O (water)
NH_3 (ammonia)	0.9% Ar (Argon)
CO (carbon monoxide)	0.04% CO_2 (carbon dioxide)
SO_2 (sulfur dioxide)	
H_2S (hydrogen sulfide)	
HCN (hydrogen cyanide)	

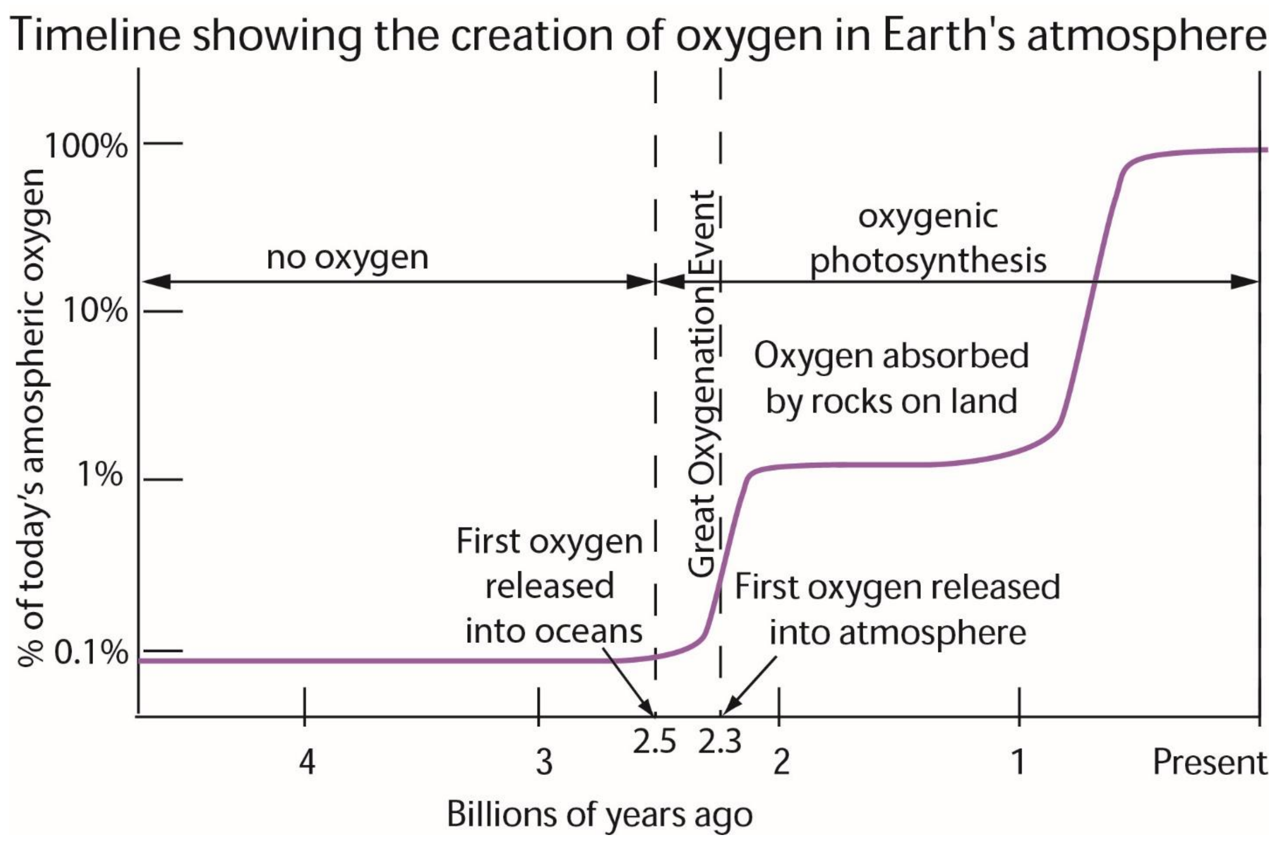


Figure 10. Oxygen in Earth's atmosphere since Earth' formation. Oxygen likely first began being produced through photosynthesis, about 2.5 Ga. It either combined with dissolved iron to produce iron oxide minerals (rust) that settled to the seafloor and were buried OR it bubbled out into the atmosphere and was immediately used up in oxidizing the atmospheric gases. By 2.3 Ga, most of the dissolved iron in the oceans had been removed, and oxygen was starting to accumulate at levels of 1% of today's Oxygen levels in the atmosphere. We call this the Great Oxygenation Event. Oxygen in the atmosphere allowed for the first iron oxide minerals to form in surface rocks (above sea level). By about 700 Ma, the atmospheric gases were sufficiently oxidized, and oxygen began to accumulate in larger amounts in the atmosphere, bringing it to current day levels and allowing an ozone layer to form in the stratosphere.

Table 5. Geologic Time Scale (not to scale)

Eons		Era	Period	Epoch	Age	Events
Phanerozoic		**Cenozoic**	Quaternary	Holocene	10 Ka	
				Pleistocene	1.6 Ma	Wisconsin ice age (10-25 Ka) Fort Funston marine terrace formed (100 Ka) (CALIF) Illinoisian ice age (130-270 Ka) Homo Sapiens first appear (100-300 Ka) Eruption of Mt. Lassen spews ash across state (400 Ka) (CALIF) Kansan ice age (350-600 Ka) San Francisco Bay forms (400 Ka) (CALIF) Nebraskan ice age (1-2 Ma) Merced formation begins accumulating (1 Ma) (CALIF)
			Tertiary	Pliocene	5.3 Ma	Ancient hominids first appear (3.4-3.8 Ma) Purisima Formation deposited (Moss Beach) (3-5 Ma) (CALIF) Uplift of Coast Ranges and Mt. Diablo begins (5 Ma) (CALIF)
				Miocene	23.7 Ma	
				Oligocene	36.6 Ma	San Andreas fault formed (25 Ma) (CALIF)
				Eocene	57.8 Ma	
				Paleocene	66.4 Ma	
		Mesozoic	Cretaceous	Upper	97.5 Ma	Last dinosaur (66.4 Ma) Montara Mountain granite forms in Sierras (88 Ma) (CALIF) First modern mammal (90 Ma)
				Lower	144 Ma	Marin Headlands Terrane accretes in Franciscan Subduction Zone (100 Ma) (CALIF)
			Jurassic		208 Ma	Pangaea break up (Atlantic Ocean) (175 Ma) Franciscan subduction zone (65-175 Ma) (CALIF) Marin Headlands Chert and Shale accumulate on seafloor (100-200 Ma) (CALIF) Marin Headlands Pillow Basalt forms at spreading center (200 Ma) (CALIF)
			Triassic		245 Ma	Pangaea formation is complete (225 Ma) Smartville subduction zone (175-225 Ma) (CALIF) First dinosaur (228 Ma)
		Paleozoic	Permian		286 Ma	Mass extinction event (245 Ma)
			Carboniferous	Pennsylvanian	320 Ma	First reptiles
				Mississippian	360 Ma	First bony fish (360 Ma)
			Devonian		408 Ma	First amphibians Sonomia subduction zone (225- 375 Ma) (CALIF) First forests and insects (400 Ma)
			Silurian		438 Ma	First land plants
			Ordovician		505 Ma	First primitive fishes
			Cambrian		570 Ma	First trilobite (540 Ma) First organisms with shells (570 Ma)
Precambrian supereon	Proterozoic	Late			900 Ma	First multicelled organisms (670 Ma) North American western margin is passive (900-400 Ma) (CALIF)
		Middle			1.6 Ga	
		Early			2.5 Ga	First one-celled organisms with nucleus (2.2 Ga)
	Archean	Late			3.0 Ga	
		Middle			3.4 Ga	
		Early			3.8 Ga	First evidence of photosynthesis (stromatolites) (3.5 Ga) First evidence of life (bacteria – single celled with no nucleus) (3.8 Ga)
	Hadean				4.6 Ga	Formation of oceans and oldest known rocks (4.4 Ga) Formation of Earth and its immediate differentiation into layers (4.6 Ga)

*Age is when division begins: Ka = thousands of years old; Ma = millions of years old; Ga = billions of years old.

Some more useful definitions:

Absolute Dating	Determining the numeric age of a rock with associated error. Absolute dating can happen through measuring of tree rings or lichen build up (for very young materials) or radiometric dating through measuring ratios of radioactively decaying parent to daughter isotopes.
Stratigraphic column or stratigraphy	A stratigraphic column is a vertical sequence/stacking of events (youngest at top, oldest at bottom) that describe the geologic history of an area as evidenced by the rock layers (units), faults, and unconformities viewed in a cross-section (cliff face). To see an example of stratigraphic column being built, look to the Relative Dating video on the website. To see one completed, see Figure 6: a simplified geologic cross-section through the Grand Canyon.
Correlation	A process by which geologists match the rock units across a wide area as being part of the same event. Example: a mudstone in Grand Canyon might correlate to the same mudstone in Bryce Canyon and other nearby canyons; the event that produced that mudstone covered the entire area at some time in the past. Correlation is useful for relative dating of events because if a geologist can correlate at least one rock layer, they can use the information in multiple exposed cliff faces from different regions to fill in a more complete story of the geologist history of an area, especially where past erosional events (unconformities) might have removed them from one area, while leaving them preserved in another.
Fossil	A preserved record in a rock of a prehistoric organism -- either all or a piece of the organism or evidence that it was there (footprints, for example).
Stromatolites	Structures left behind by a species of photosynthetic cyanobacteria. These cyanobacteria were the first known photosynthesizers on planet Earth (evolved 3.5 Ga) and still exist today. The particular species of cyanobacteria that produces stromatolite mounds are often referred to themselves as stromatolites. I'm not fussy about which term you use. Either works.
Molds vs Casts	Molds and casts are preservations of a dead organism that are three dimensional and show the outer surface of the organism, but from different sides. A **mold** shows from the outside in -- a **cast** from the inside out. Imagine a clam buried in mud. The mud surrounding the shell will take on the shape of the shell from the outside producing a **mold**. If that mold is preserved, and the shell dissolves, any new mud that fills that hole (or fluids that precipitate inside) will take on the shape of the mold producing a **cast**.

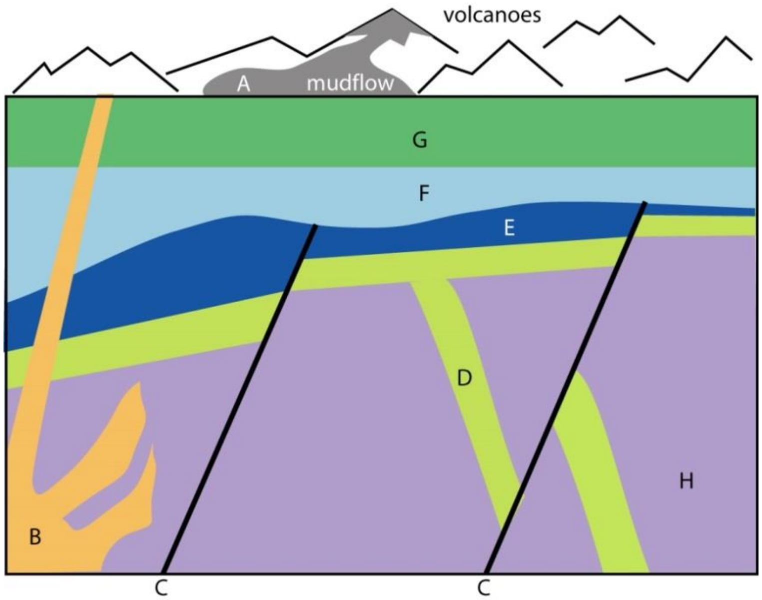
Geologic Time Chapter Worksheet

1. Distinguish between **numeric (absolute) dating** and **relative dating**. Why do we use both?

2. Build a stratigraphic column for the sample cross-section below. *****For example of a stratigraphic column, LOOK to Grand Canyon sample in workbook – Figure 6.*****

Label, name, and order all **rocks units (layers), faults, and unconformities** from oldest (bottom of stratigraphic column) to youngest (top of stratigraphic column). *(Note: D is a dike and sill combination. B is an igneous intrusion: cooled magma chamber and dike that erupted. H is metamorphic. E, F, G, and A are sedimentary.)*

VERTICAL STRATIGRAPHIC COLUMN



3. Distinguish among these types of unconformity: angular unconformity, disconformity, and nonconformity.

Disconformity definition	**Angular unconformity definition**	**Nonconformity definition**
Disconformity sketch	**Angular unconformity sketch**	**Nonconformity sketch**
Disconformity history (what does it mean?)	**Angular unconformity history (what does it mean?)**	**Nonconformity history (what does it mean?)**

4. What is meant by the term **correlation** as used by geologists? *(Please look for answer in glossary or video scripts, not internet.)* How is it used by geologists to improve stratigraphies?

5. What is required to create a **fossil**?

6. What about an organism gives it the best chance of being preserved as a fossil?

7. Describe several **types** of fossils (a fossil is any type of evidence – direct or indirect – of past life).

Fossil type	**Definition**
Mold or Cast	
Carbonization	
Trapped in amber or tar	
Mineral replacement	
Trace fossils like footprints, burrows, tooth marks, nests, coproplites, gastroliths	

8. What is an index fossil? What characteristics make for a strong index fossil?

9. In addition to providing some age constraints, how else are fossils helpful in geologic investigations?

10. What are the four major divisions of the Geologic Time Scale and what age ranges do they represent?

Division name	**Start date**	**End date**
Youngest era of the Phanerozoic Eon:		
Middle era of the Phanerozoic Eon:		
Oldest era of the Phanerozoic Eon:		
Oldest Supereon:		

11. Explain why the first 4 b.y. of Earth history is more difficult to decipher than more recent geologic history.

12. Order these events in Earth's history from oldest (1) to youngest (16)!

Action/Environment	Order	Action/Environment	Order
Dinosaurs first appear		Earliest evidence of photosynthesis	
Trilobites first appear		Earth formed	
Earliest evidence of life with hard parts		Opening of Atlantic ocean (Pangea breaks up)	
Earliest evidence of multicellular life		Dinosaurs go extinct	
Earliest evidence of life moving onto land		Earliest evidence of life (prokaryotes)	
Pangea came into existence.		Earliest evidence of rocks (hard crust)	
Oceans first appear (water)		Eukaryotes first appear (nucleus in cells)	
Mammals first appear		Fishes first appear	

13. If a radioactive isotope of Thorium (atomic number 90, mass number 232) emits 6 alpha particles and 4 beta particles during radioactive decay, what is the atomic and mass number of the stable daughter product? Show work. (See weekly activity, two pages ahead, for review of definitions and terms.)

14. A hypothetical radioactive isotope has a half-life of 10,000 years. If the ratio of radioactive parent to stable daughter product is 1:3, how old is the rock containing the radioactive material? Show work.

15. To provide a reliable radiometric date, a mineral must remain a closed system from the time of its formation until the present. What is a closed system?

16. What two main geologic processes would open a closed system? Why?

17. Which rock types are the best closed systems? Why?

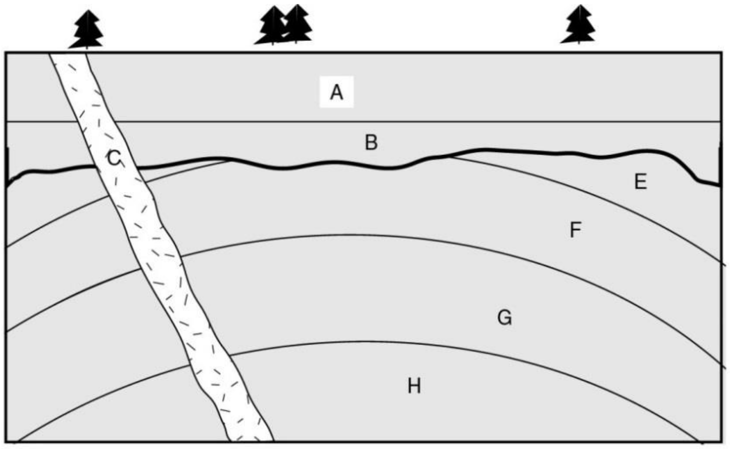
18. Review the table that shows decay rates for various isotope pairs. What is the benefit of having more than one pair?

19. Review table 4: planetary atmospheres. Compare Earth's early and current atmospheric compositions. Where did the oxygen come from in Earth's atmosphere? What evidence do we have of it?

Geologic Time Activity: Part I—Relative Dating

Create a stratigraphy for each cross-section (list each feature in order from youngest on top to oldest on bottom). Include all beds, faults, and unconformities (appear as irregular, wavy lines). IDENTIFY faults (normal or reverse) and unconformities (disconformity, nonconformity, or angular unconformity). Look at surface to see if youngest event is erosion or deposition.

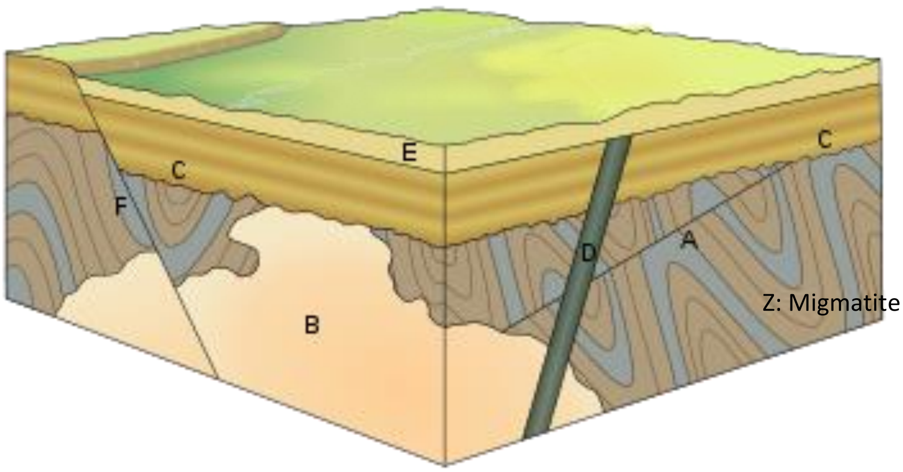
All rocks are sedimentary except C, which is a basalt dike.



YOUNGEST

OLDEST

All rocks are sedimentary except D, which is a pegmatite dike; B, which is a granite; and Z, which is a Migmatite.



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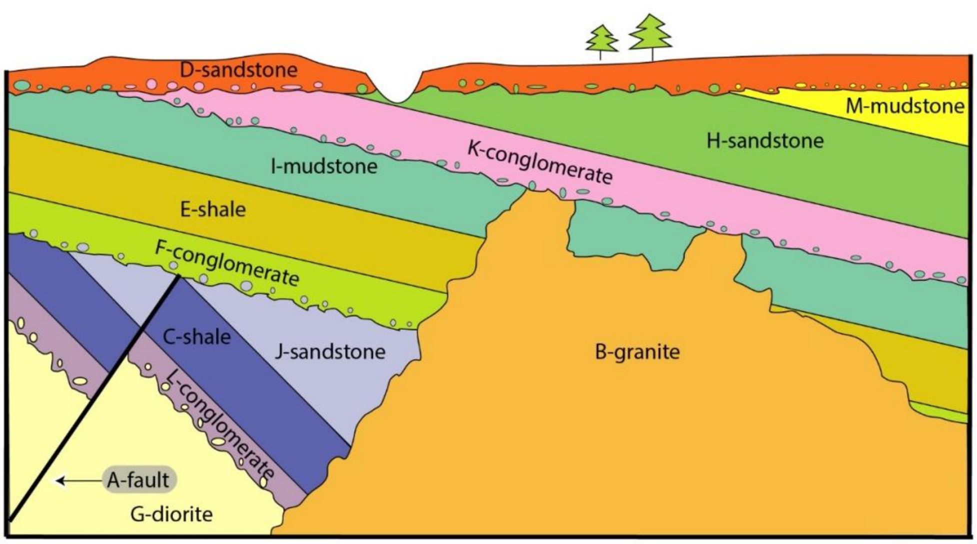

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OLDEST

Geologic Time Activity: Part 2—Radioactive Decay and Radiometric Dating

(**See Atom Review information in Minerals Chapter for more information on atomic structures.**)

Atomic mass = total mass of atom = # of protons + # of neutrons
Atomic number = # of protons = designation for element

Alpha decay: nucleus spontaneously emits an alpha particle (symbol: a particle), which is 2 p+ and 2 n (or also the same as a Helium (He) atom).

Result: atomic number decreases by 2 (lost 2 p+)
Result: atomic mass decreases by 4 (lost 2 p+ and 2n = 4 amu)

Beta decay: neutron in nucleus spontaneously emits a beta particle (symbol: b particle), which is essentially an electron trapped in a neutron. The neutron, therefore, turns itself into a proton.

Result: atomic number increases by 1 (gained 1 p+)
Result: atomic mass stays same (no mass lost or gained: b particle or electrons have no mass)

Beta or electron capture: proton in nucleus captures a beta particle (symbol: b particle), which is essentially an electron that can become part of a neutron. The proton, therefore, turns itself into a neutron.

Result: atomic number decreases by 1 (lost 1 p+)
Result: atomic mass stays same (no mass lost or gained: b particle or electrons have no mass)

Example

Original	alpha decay	beta decay	alpha decay	beta capture	beta decay	alpha decay
85	83	84	82	81	82	80
At	Bi	Po	Pb	Tl	Pb	Hg
Astatine	Bismuth	Polonium	Lead	Thallium	Lead	Mercury
210	206	206	202	202	202	198

Complete this table

Original	beta decay	alpha decay	beta capture	alpha decay	alpha decay	beta decay
90						
Th						
Thorium						
232						

Complete this table

Original	beta capture	alpha decay	alpha decay	beta capture	alpha decay	beta decay
92						
U						
Uranium						
238						

When radioactive isotopes (parent – P) decay, they produce daughter products (D) at a constant rate, called the half-life (**T**). Example: if we start with 100 atoms of the parent, after one half-life, there will be 50 parent atoms remaining and 50 daughter atoms newly made. After another half-life (two half-lives), there will be 25 parent atoms remaining and now 75 daughter atoms. Each parent-daughter isotope pair has its own half-life. To achieve the above example with U-238 takes 9 billion years (two half-lives). To achieve the above example with C-14 takes 11400 years (two half-lives). In the geologic environment, we use a mass spectrometer to count the number of Parent and Daughter atoms in a closed-system (like minerals crystallizing from magmas), and use the relative proportions to find out how old the closed-system is.

1. Assuming we start with only parent isotopes (no daughter), after one half-life has passed, there should be ½ parent remaining and ½ daughter newly formed. The ratio of P:D is ½ : ½ or 1:1. Complete the rest of this table, as in the first example:

# Half lives	**Fraction of original Parent remaining**	**Fraction of original parent turned into daughter**	**Parent:Daughter ratio**
1	½	½	1:1
2			
3			
4			
5			
6			

2. If you want to date lava flows on an old lava flow on Kauai (probably about 8 m.y.), which isotope pair would you measure? Why?

3. If you want to date zircon crystals in ancient sandstones in Australia, which isotope pair would you measure? Why?

4. If the C-14:N-14 ratio in a shell in a sandstone was found to be 1:3, how old is the shell?

5. If the U-235:Pb-207 ratio in a zircon in a sandstone was found to be 1:3, how old is the zircon?

6. If the K-40:Ar-40 ratio in a zircon in a granite was found to be 1:1, how old is the sample?

7. If the U-238:Pb-206 ratio in a zircon in a lava flow was found to be 3:1, how old is the flow?

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Compare and contrast relative and radiometric dating	A | B | C | D | F	
Apply the correct procedures to calculate the radiometric date of rocks of various ages.	A | B | C | D | F	
Create stratigraphic columns of geologic cross-sections.	A | B | C | D | F	
Compare and contrast unconformities and what they say about the geologic history of a region.	A | B | C | D | F	
Evaluate the definition of a closed system and how it relates to radiometric dating.	A | B | C | D | F	
Evaluate the major divisions of the geologic time scale, in particular the events that mark the beginning and end of each.	A | B | C | D | F	
Compare and contrast different types of fossils and what they tell us about past environments.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

GLOBAL CLIMATE CHANGE AND ENERGY RESOURCES

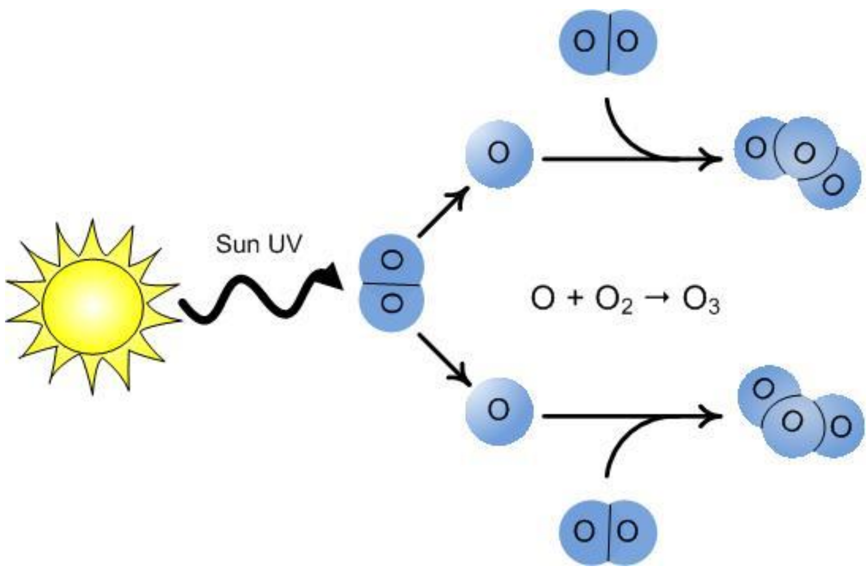

Figure 1. Ozone formation in the stratosphere. Image from Environment Canada. http://www.ec.gc.ca/

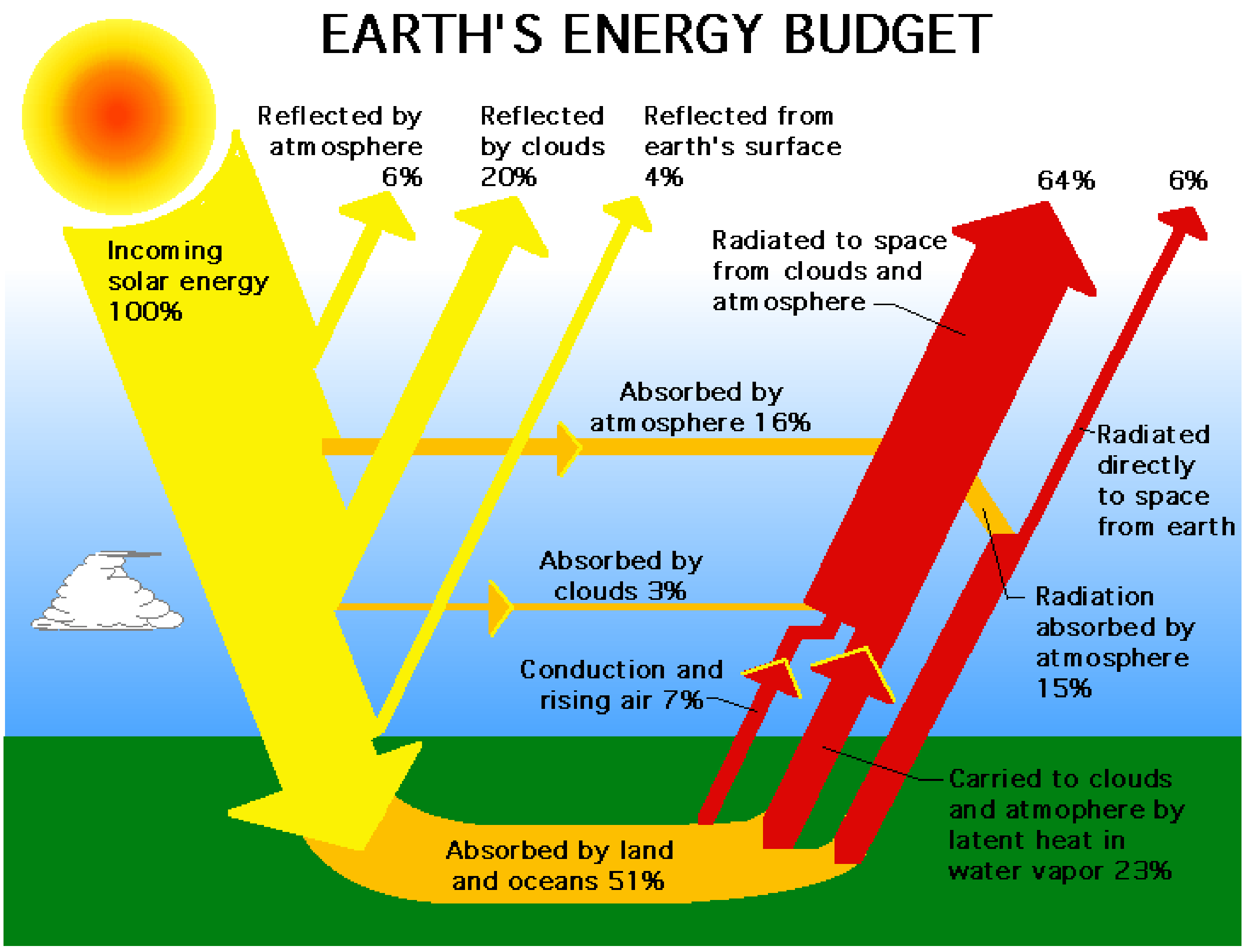

Figure 2. Generalized heat budget of Earth's atmosphere assuming the only source is incoming solar radiation. NASA. % values are all relative to a 100% original input of solar energy (UV, visible, IR radiation). 30% of this energy is reflected by atmosphere, clouds, and earth's surface. 19% is absorbed by the atmosphere, leaving 51% to be absorbed by Earth's surface. Assuming an unchanging global surface temperature, all of this heat absorbed by Earth's surface is released back upwards into the atmosphere and escapes to space. (If it didn't Earth's surface temperatures would increase.) 7% transfers through conduction and rising air. 23% transfers through the latent heat of water vapor. 21% through direct IR radiation (15% is absorbed by the atmosphere en route). The 33% total that is absorbed by the atmosphere (both during incoming path and outgoing path) is also a steady amount that is balanced by equal loss outward through radiation, so with an unchanging Earth temperature, the net energy gain by Earth is 0.

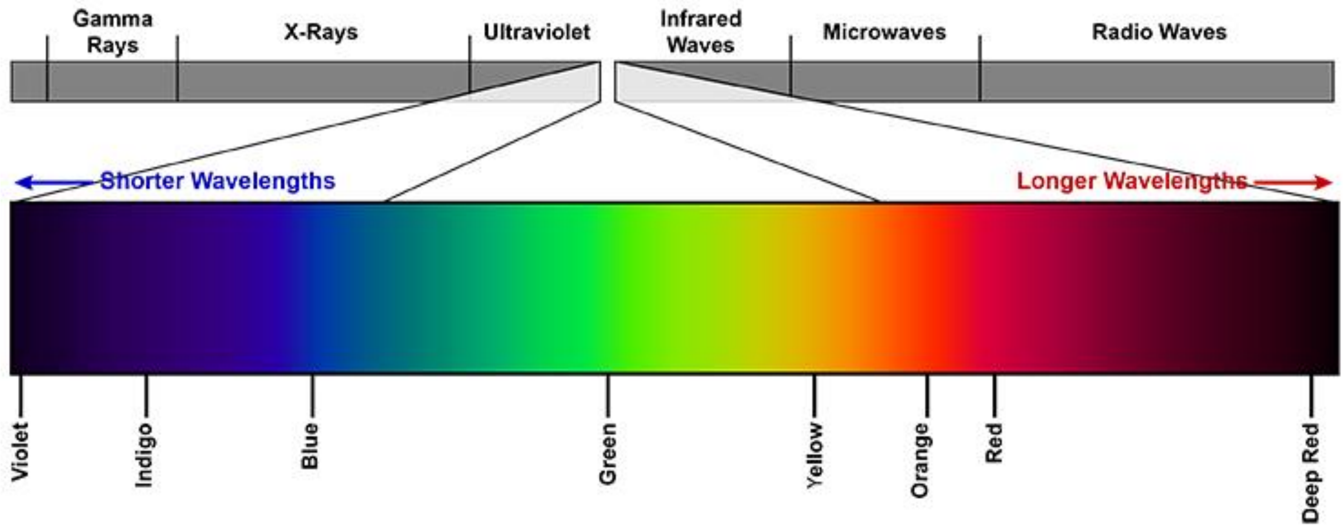

Figure 3. Colors of Visible light, and their place within the electromagnetic spectrum – NOAA
Gamma rays have a wavelength of 10^{-12} m; Ultraviolet (UV) rays: 10^{-8} to 10^{-9} m (nanometers); Visible light: 10^{-6} to 10^{-7} m; Infrared (IR): 10^{-4} to 10^{-5} m; Microwaves: centimeters and millimeters; Radio waves: 1-100 m.

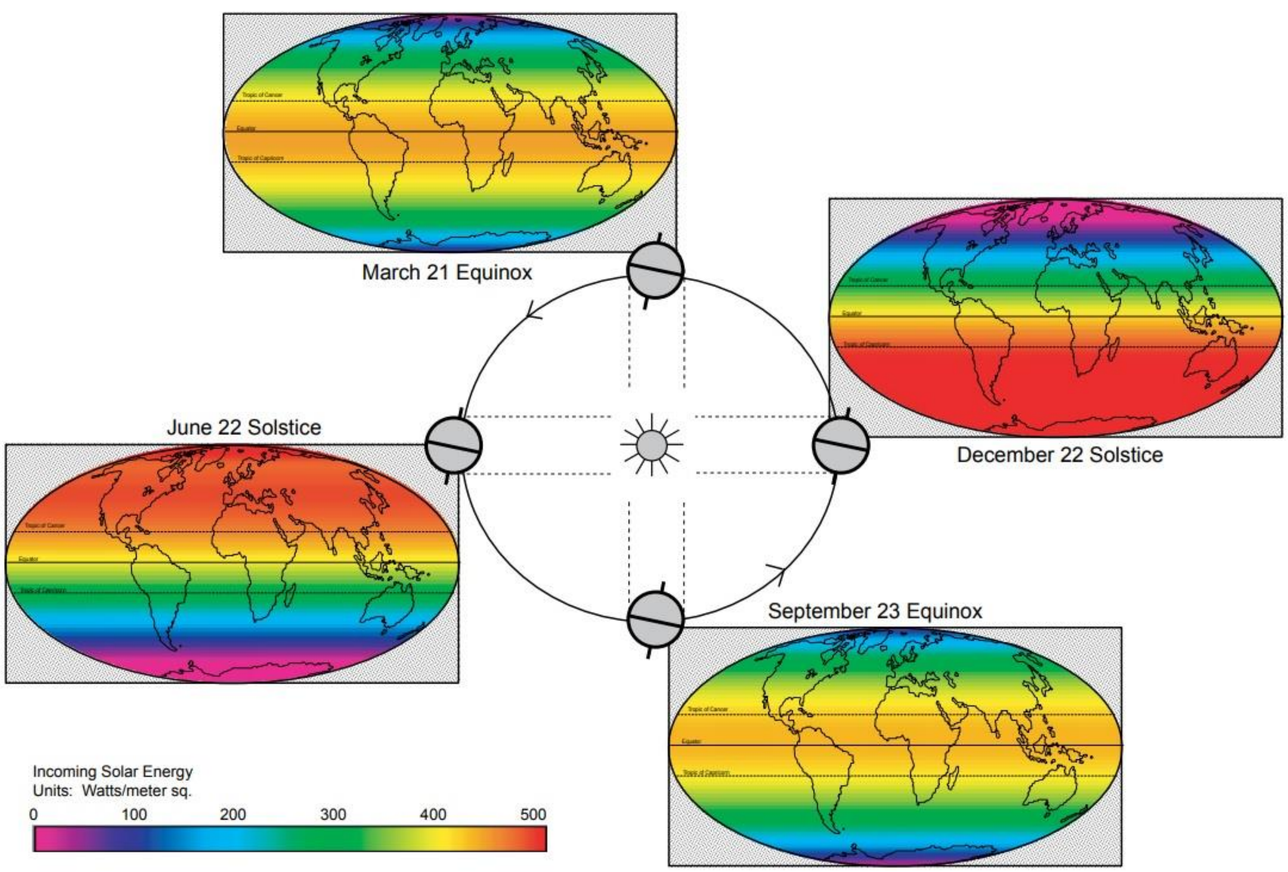

Figure 4. Incoming solar energy throughout the seasons. From Globe.gov

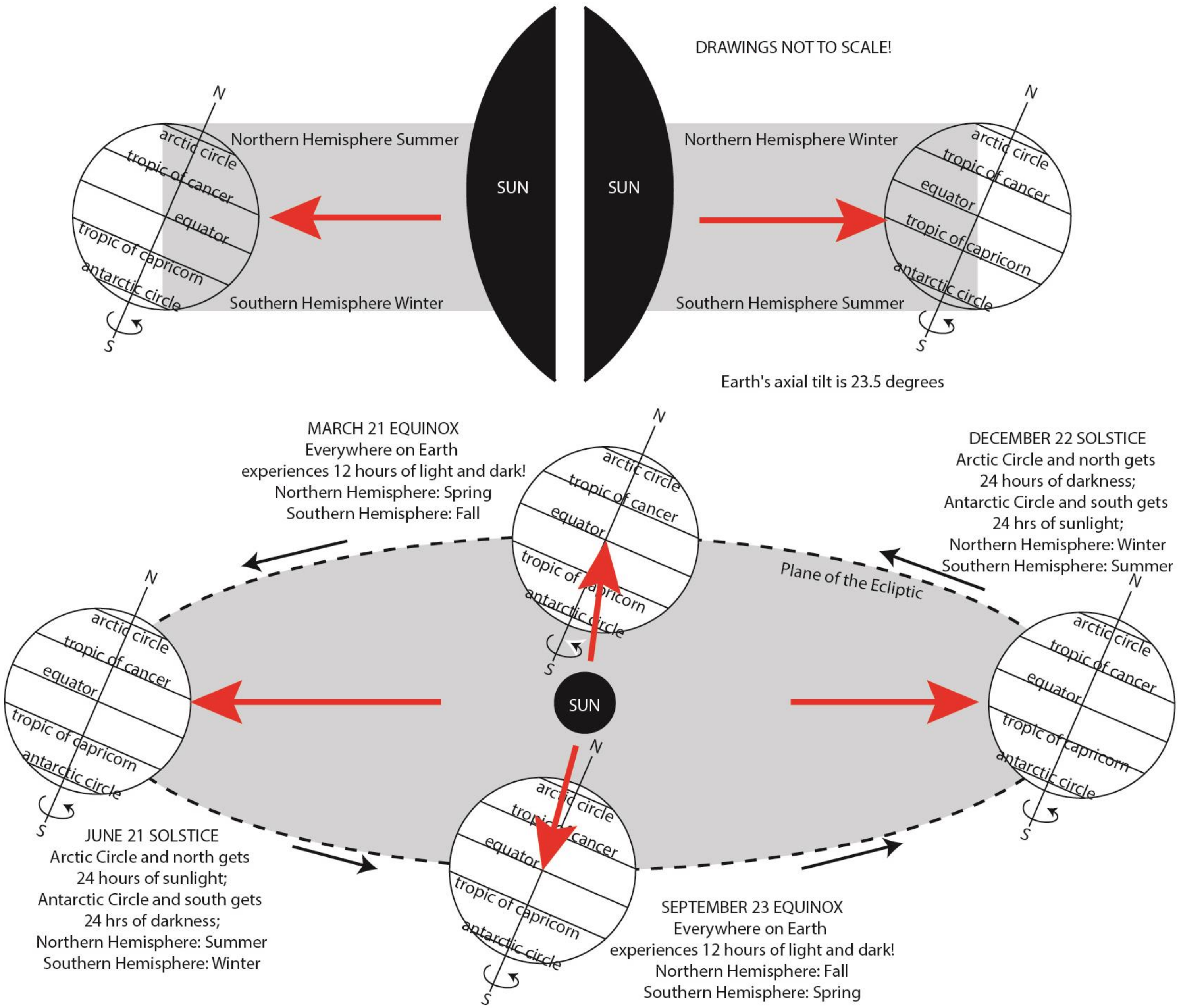

Figure 5. Earth's orbit around the sun and the relationship between its tilted rotational axis and the seasons.

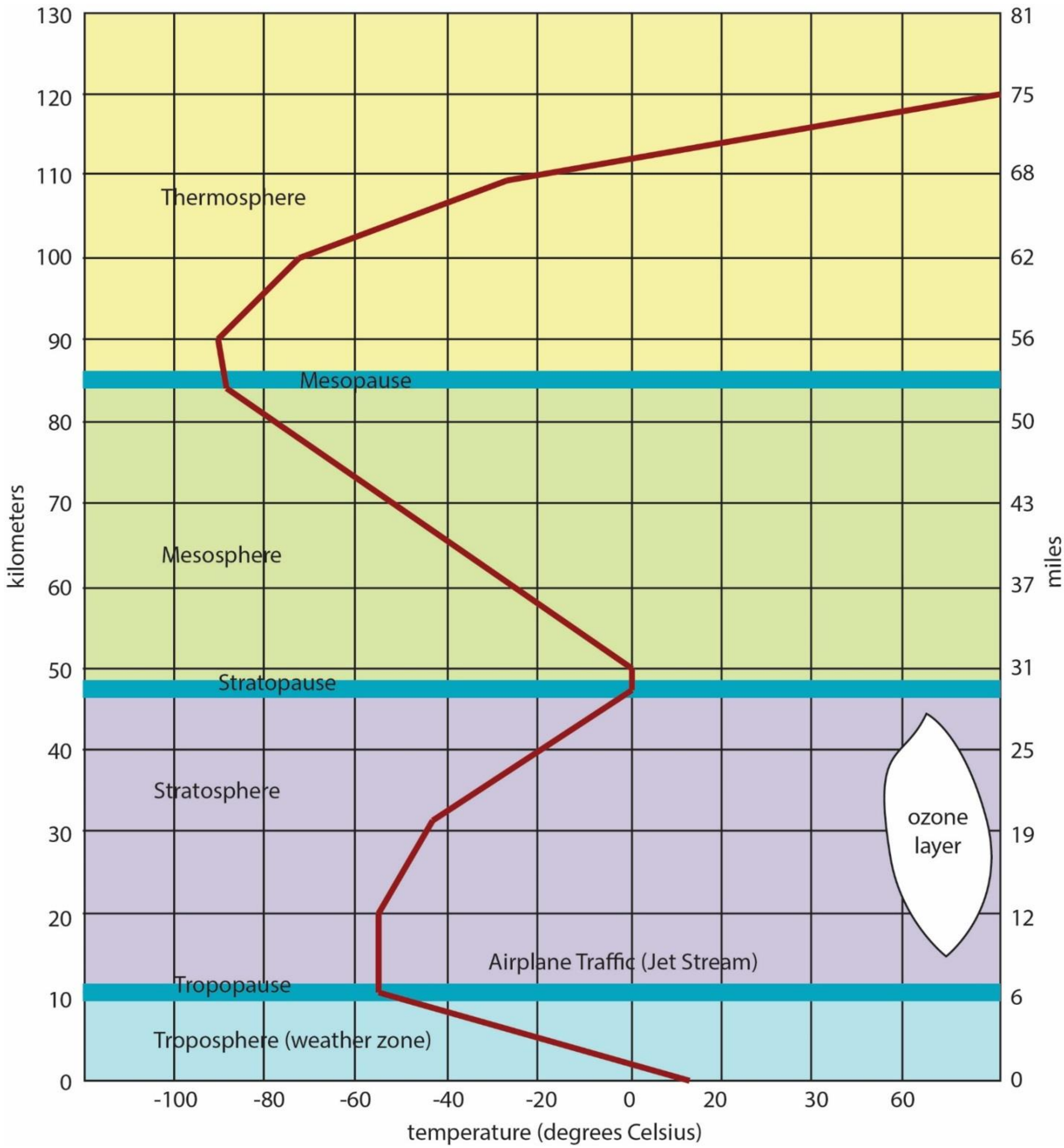

Figure 6. Layers of Earth's atmosphere. Based on image from NOAA.

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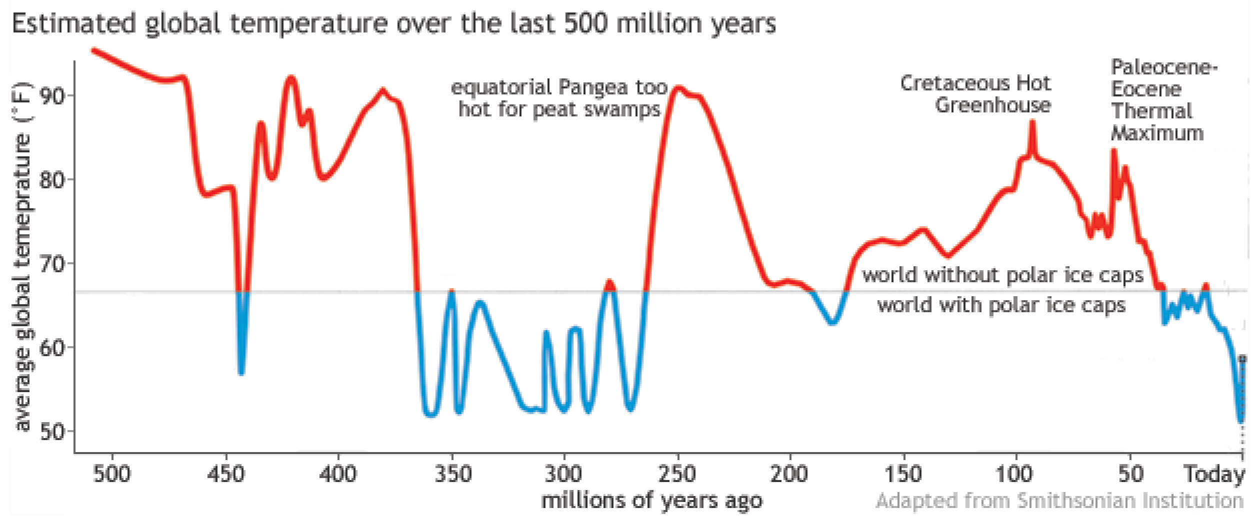


Figure 7. Earth's average surface temperature over the past 500 million years. For most of the time, global temperatures appear to have been too warm (red portions of line) for persistent polar ice caps. The most recent 50 million years are an exception. Image adapted from Smithsonian National Museum of Natural History. NOAA.

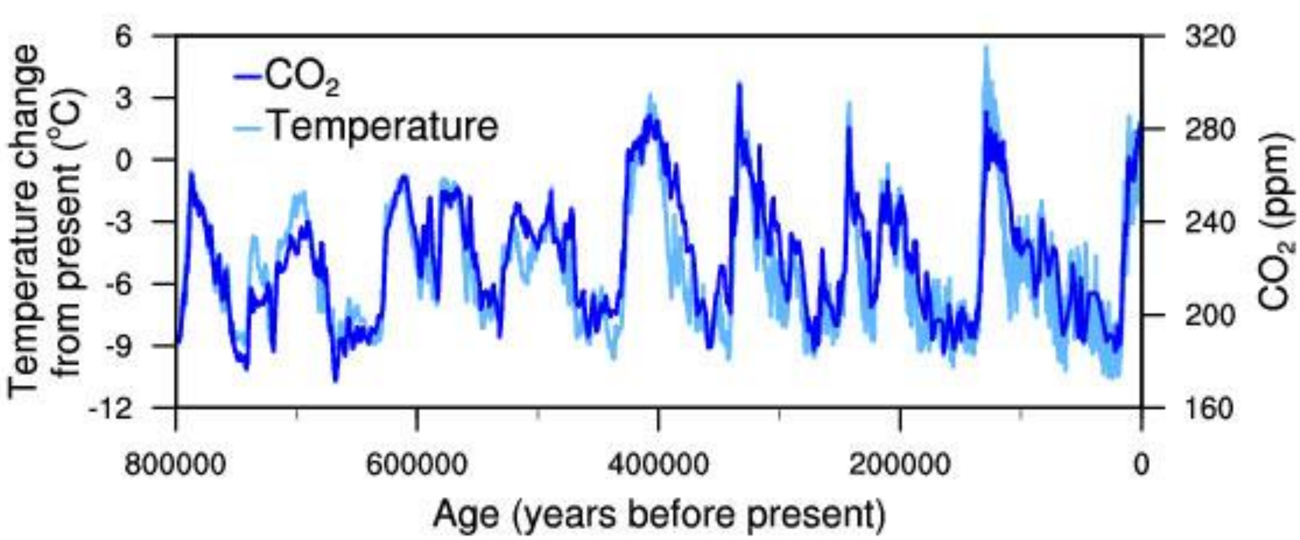


Figure 8. Temperature change (light blue) and carbon dioxide change (dark blue) measured from the EPICA Dome C ice core in Antarctica (Jouzel et al. 2007; Lüthi et al. 2008).

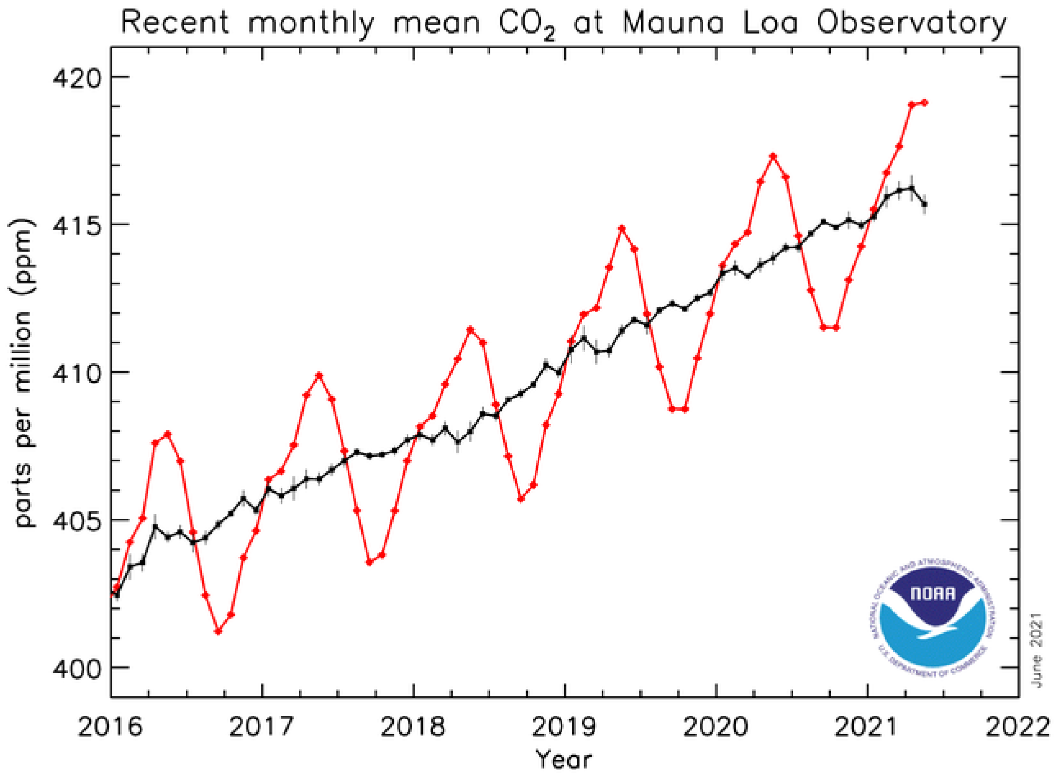


Figure 9. Carbon dioxide in our atmosphere measured in parts per million atop Mauna Loa. Data from 2016 to today shows seasonal variations. NOAA.

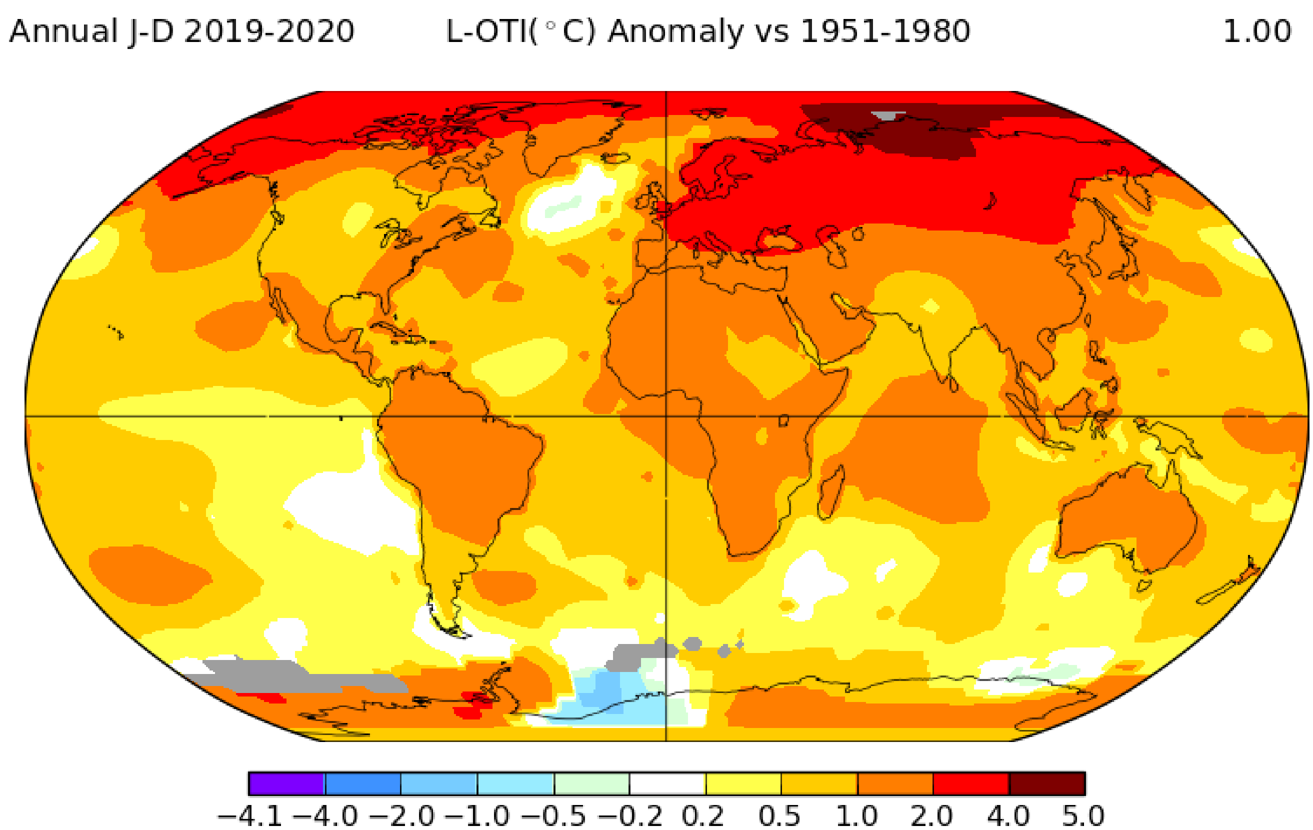


Figure 10. Global temperature anomalies for 2019 + 2020 in degrees Celsius: how much temperatures in 2019/20 varied from the average between 1951-1980. Credit: NASA https://data.giss.nasa.gov/gistemp/maps/

Some more useful definitions:

Ozone layer	Region of the stratosphere where ozone levels are high and much of the Sun's incoming UV radiation is absorbed.
Ultraviolet light	is the beyond the violet in the spectrum, corresponding to light to having the wavelengths that is shorter than 4000 angstorm unit.
Climate	From NOAA: "describes what the weather is like over a long period of time in a specific area. Different regions can have different climates. To describe the climate of a place, we might say what the temperatures are like during different seasons, how windy it usually is, or how much rain or snow typically falls. When scientists talk about climate, they're often looking at averages of precipitation, temperature, humidity, sunshine, wind, and other measures of weather that occur over a long period in a particular place. In some instances, they might look at these averages over 30 years. And, we refer to these three-decade averages of weather observations as Climate Normals. While descriptions of an area's climate provide a sense of what to expect, they don't provide any specific details about what the weather will be on any given day.
Weather	From NOAA: "mix of events that happen each day in our atmosphere. Even though there's only one atmosphere on Earth, the weather isn't the same all around the world. Weather is different in different parts of the world and changes over minutes, hours, days, and weeks. Most weather happens in the part of Earth's atmosphere that is closest to the ground—called the troposphere. And, there are many different factors that can change the atmosphere in a certain area like air pressure, temperature, humidity, wind speed and direction, and lots of other things. Together, they determine what the weather is like at a given time and location."
Equinox	Day when the Earth's orbit places its tilted axis alongside the Sun so that both poles are always getting sunlight. Happens around March 22 and September 2. On this day there are 12 hours day and 12 hours night everywhere around the planet.
Solstice	Day when the Earth's orbit places its tilted axis pointing directly towards or away from the Sun. Happens around December 22 (northern hemisphere tilted away) and June 21 (southern hemisphere tilted away). On these days, the region that is tilted away receives 24 hours of darkness and the region tilted towards the sun receives 24 hours of light.
Coriolis Effect	Causes moving objects on Earth to follow curved path. This effect is a result of Earth's rotation toward the east.
Absolute Humidity	Amount of water vapor present in a unit volume of air expressed in millibars of pressure.
Relative Humidity	Percentage of maximum water vapor possible in a unit volume of air is actually in the air. Example: 50% relative humidity means water vapor in the air is at only 50% of the maximum that can be there. Lots more water can be absorbed by the air and thus evaporation rates will be high.
Atmosphere	Earth envelope/layers that is composed almost entirely of gases (can also contains liquid water droplets -- clouds -- and particulates in suspension).
Biosphere	All the biologic materials that reside on the Earth's surface and in its oceans.
Cryosphere	All the ice on planet Earth: sea ice and glaciers.
Geosphere	All the rocks on planet Earth -- sometimes referring to just those found at the surface or in contact with the others spheres mentioned here.
Hydrosphere	All the liquid water on planet Earth: oceans, rivers, lakes, and ground water.
Climate proxy	From USGS Website: "Paleoclimate proxies are physical, chemical and biological materials preserved within the geologic record (in paleoclimate archives) that can be analyzed and correlated with climate or environmental parameters in the modern world. "

Global Climate Change Chapter Worksheet

1. What is the average composition of the atmosphere (with no water) -- give percentages?

2. What is the range in % that water can contribute to atmospheric gases?

3. List all known greenhouse gases in decreasing order of importance (most important first):

4. At what time of the year are the Earth and the Sun closest together?	5. What is the angle of axial tilt?

6. What causes the seasons?

7. What percentage of Solar radiation is reflected back to space?	8. What percentage of Solar radiation is absorbed by Earth's surface?

9. What are the primary mechanisms for redistributing heat on Earth's surface? (Between the equator and poles)

10. Which type of radiation comes from the Sun?	CIRCLE: infrared | visible | ultraviolet
11. Which type of radiation comes from Earth?	CIRCLE: infrared | visible | ultraviolet
12. Which type of radiation is absorbed by the ozone layer?	CIRCLE: infrared | visible | ultraviolet
13. Which type of radiation is absorbed by greenhouse gases?	CIRCLE: infrared | visible | ultraviolet
14. Which type of radiation is the longest wavelength?	CIRCLE: infrared | visible | ultraviolet
15. Which type of radiation is the shortest wavelength?	CIRCLE: infrared | visible | ultraviolet

16. What is the chemical reaction that occurs to produce the majority of ozone found in Earth's ozone layer?

17. Prepare a sketch with labels that explains the greenhouse effect.

18. What has been happening to CO_2 levels in the atmosphere over the past 200 years? Give detail.

19. What are the primary effects of a warming planet? (Be sure you include a discussion of how it impacts sea level.)

20. Distinguish between weather and climate.
Temperatures and moisture levels on a particular day. CIRCLE: WEATHER | CLIMATE
Seasonal changes throughout a given year. CIRCLE: WEATHER | CLIMATE
Average temperatures and moisture levels over many years. CIRCLE: WEATHER | CLIMATE
Changeable. CIRCLE: WEATHER | CLIMATE

21. Which of these are major parts of the climate system?
CIRCLE: atmosphere | biosphere | cryosphere | geosphere | hydrosphere

22. List the various kinds of proxy data gathered from the geologic record by paleoclimatologists on past climate. For each, indicate how far back in time they provide evidence?

23. What are some natural and human processes that **contribute to increased greenhouse gases** and thus global climate change? *(Be sure you list includes enough information that we can see the connection between the process and which gas it contributes.)*

24. Looking at the NOAA image of sea level changes along various US coastlines *(see figure 9 in Shorelines chapter of workbook)* where is sea level rising fastest? Is sea level dropping anywhere? Why the differences?

25. Looking at the NASA image of global temperature anomalies *(figure 10 in your workbook images for this chapter),* where is global warming least? Are there places where there's global cooling?

Energy Resources Activity

Renewable Energy	Nonrenewable Energy
Definition: "Energy from sources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time." EIA (US Energy Information Administration)	**Definition:** "Energy that does not form or replenish in a short period of time." EIA

Examples:
Biomass—includes:
    Wood and wood waste
    Municipal solid waste
    Landfill gas and biogas
    Ethanol
    Biodiesel
Hydropower
Geothermal
Wind
Solar
	Examples:
	Crude oil (petroleum)
	Natural gas
	Coal
	Uranium (nuclear energy)
	"Nonrenewable energy sources come out of the ground as liquids, gases, and solids. We use crude oil to make liquid petroleum products such as gasoline, diesel fuel, and heating oil. Propane and other hydrocarbon gas liquids, such as butane and ethane, are found in natural gas and crude oil. Fossil Fuels (oil, gas, and coal): formed from the buried remains of plants and animals that lived millions of years ago. Uranium ore, a solid, is mined and converted to a fuel used at nuclear power plants. Uranium is not a fossil fuel." EIA

Petroleum	Natural Gas	Coal
Formation process: *"Crude oil was formed from the remains of organisms that lived millions of years ago in a marine environment. Over millions of years, the remains of these organisms were covered by layers of sand, silt, and rock. Heat and pressure from these layers turned the remains into what we now call crude oil. The word **petroleum** means rock oil or oil from the earth." EIA* *Note: Most oil is removed from the Earth through natural seeps or through wells drilled into the ground through which the oil is pumped out. Oil sands are mixtures of clay and sand combined with water and thick oil (bitumen). In oils sands, the oil is SOOOOOO viscous, it can't be pumped out, so these rocks are mined. 80% of these are in Alberta.* Top petroleum-consuming countries in 2015 and their share of total world petroleum consumption: United States—20.5% China—12.6% Japan—4.3% India—4.3% Russia—3.7% -- EIA	**Formation process:** *Like crude oil, natural gas (methane) is a breakdown product of buried organisms. "Pressure and heat changed some of this organic material into coal, some into oil (petroleum), and some into natural gas. In some places, the natural gas moved into large cracks and spaces between layers of overlying rock. In other places, natural gas occurs in the tiny pores (spaces) within some formations of shale, sandstone, and other types of sedimentary rock, where it is referred to as shale gas or tight gas. Natural gas also occurs in coal deposits, where it is called coalbed methane." EIA* *Note: Water under high pressure can be pumped into the ground where oil exists but rocks have low permeability (connected pore spaces through which fluids can migrate). This pressure can fracture the rock, thereby creating cracks along which the gases can migrate to the surface. This is called "fracking."*	**Formation process:** *"Coal is a combustible black or brownish-black sedimentary rock with a high amount of carbon and hydrocarbons. Coal contains the energy stored by plants that lived hundreds of millions of years ago in swampy forests. The plants were covered by layers of dirt and rock over millions of years. The resulting pressure and heat turned the plants into the substance we call coal." EIA* *"Coal was the source of about 30% of U.S. total electricity generation in 2017." EIA* ***Types of coal*** • ***Anthracite*** *86%–97% carbon and generally highest heating value* • ***Bituminous coal*** *45%–86% carbon.* • ***Subbituminous*** *coal 35%–45% carbon and lower heating value than bituminous coal.* • ***Lignite*** *25%–35% carbon and lowest energy content of all coal.*

Some additional useful terms

Oil sand	"'Oil sands' or 'tar sands' are a mixture of sand, clay, and water that contain an extra heavy crude oil variant known as bitumen. Bitumen is highly viscous, meaning it does not flow unless it is heated or mixed with lighter hydrocarbons. It is often compared to cold molasses." https://www.studentenergy.org/topics/oil-sands
Hydraulic fracturing	"Hydraulic fracturing or, as it is commonly called, fracking, is a technique used for accessing natural gas and oil in tight geologic formations. The process involves the horizontal directional drilling of wells in addition to the use of water, sand and chemicals at high pressures to fracture rock and release hydrocarbons. The hydraulic fracturing process can be categorized into the follow four steps: • A well is drilled vertically to the desired depth, then is turned at an angle and continues horizontally for several thousand feet into the formation believed to contain the trapped natural gas or oil. A mixture of water, sand, and chemicals is pumped into the well at high pressure in order to create fissures in the shale rock, which increases permeability and allows the hydrocarbons to escape. • Natural gas or oil is released through the fissures and is drawn back up the well to the surface. • Wastewater (also called "flowback water" or "produced water") returns to the surface after the fracking process is completed.1 • The natural gas or oil is collected at the surface and is processed, refined, and shipped to the market." https://www.studentenergy.org/topics/hydraulic-fracturing

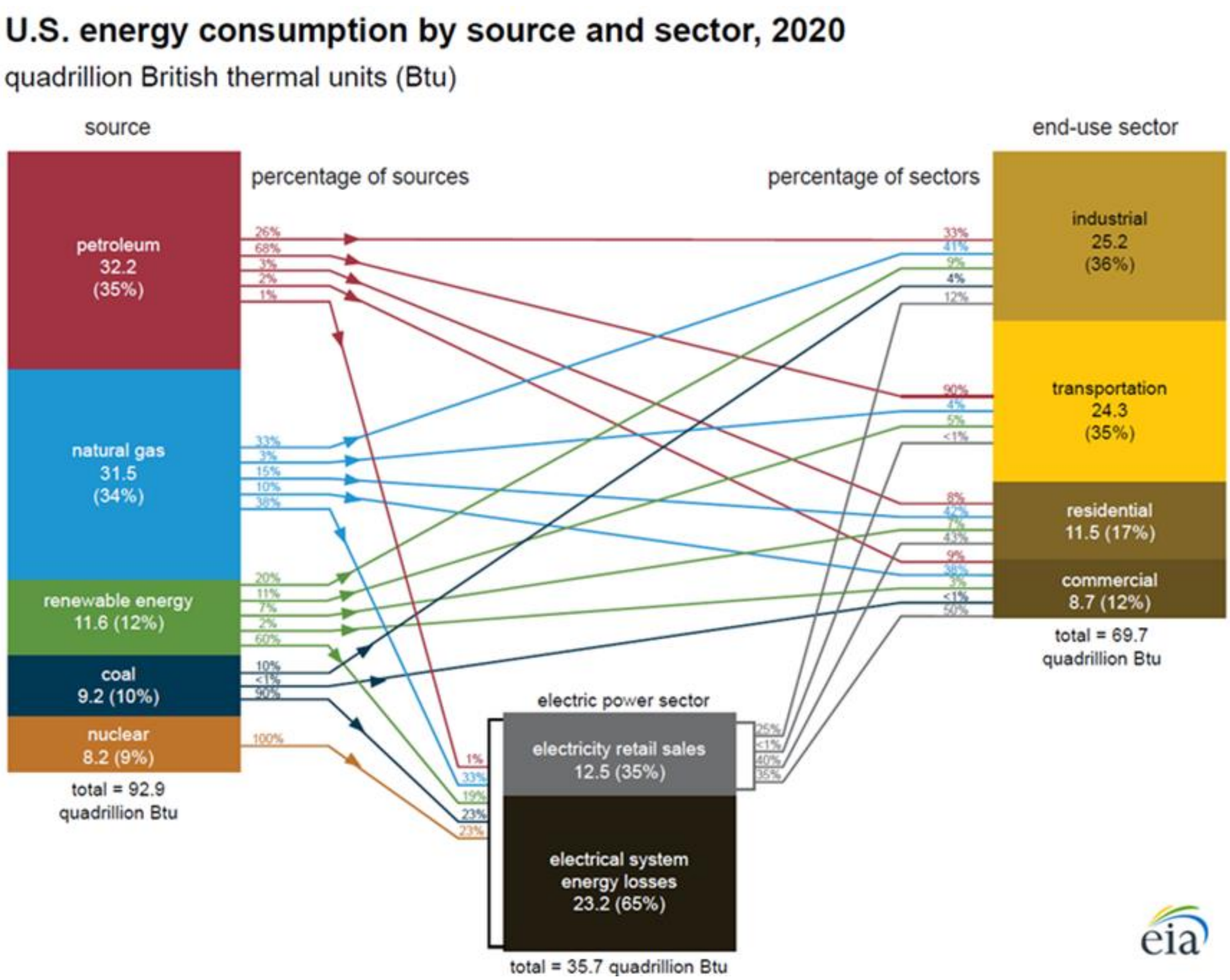


Figure 1. US energy consumption by source and sector, 2020.
US Energy Information administration, June 4, 2021 report.

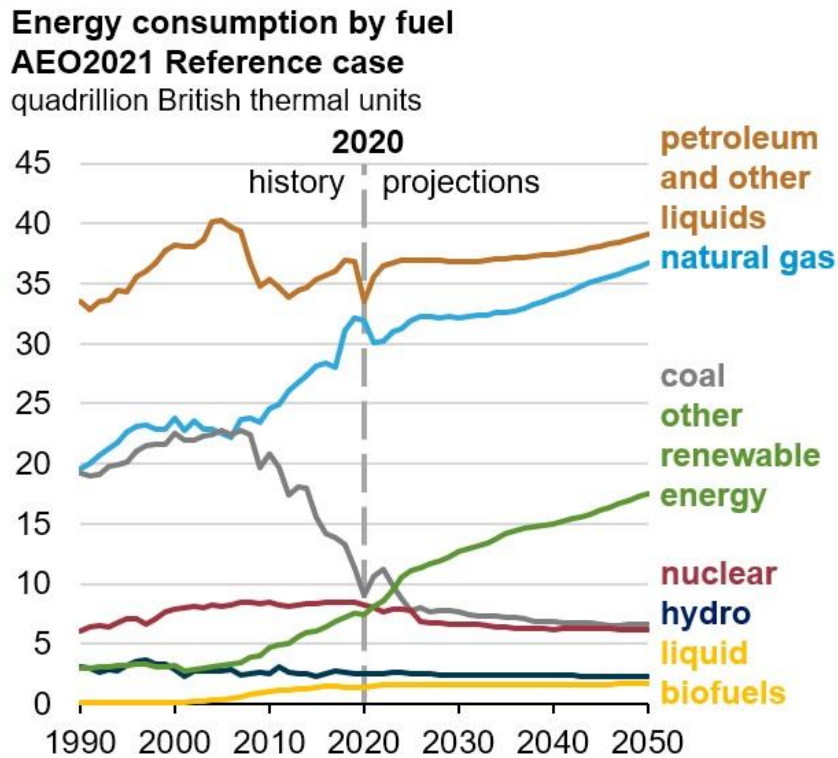


Figure 2. US Energy consumption by fuel source.
US Energy Information administration, Annual Energy Outlook 2021

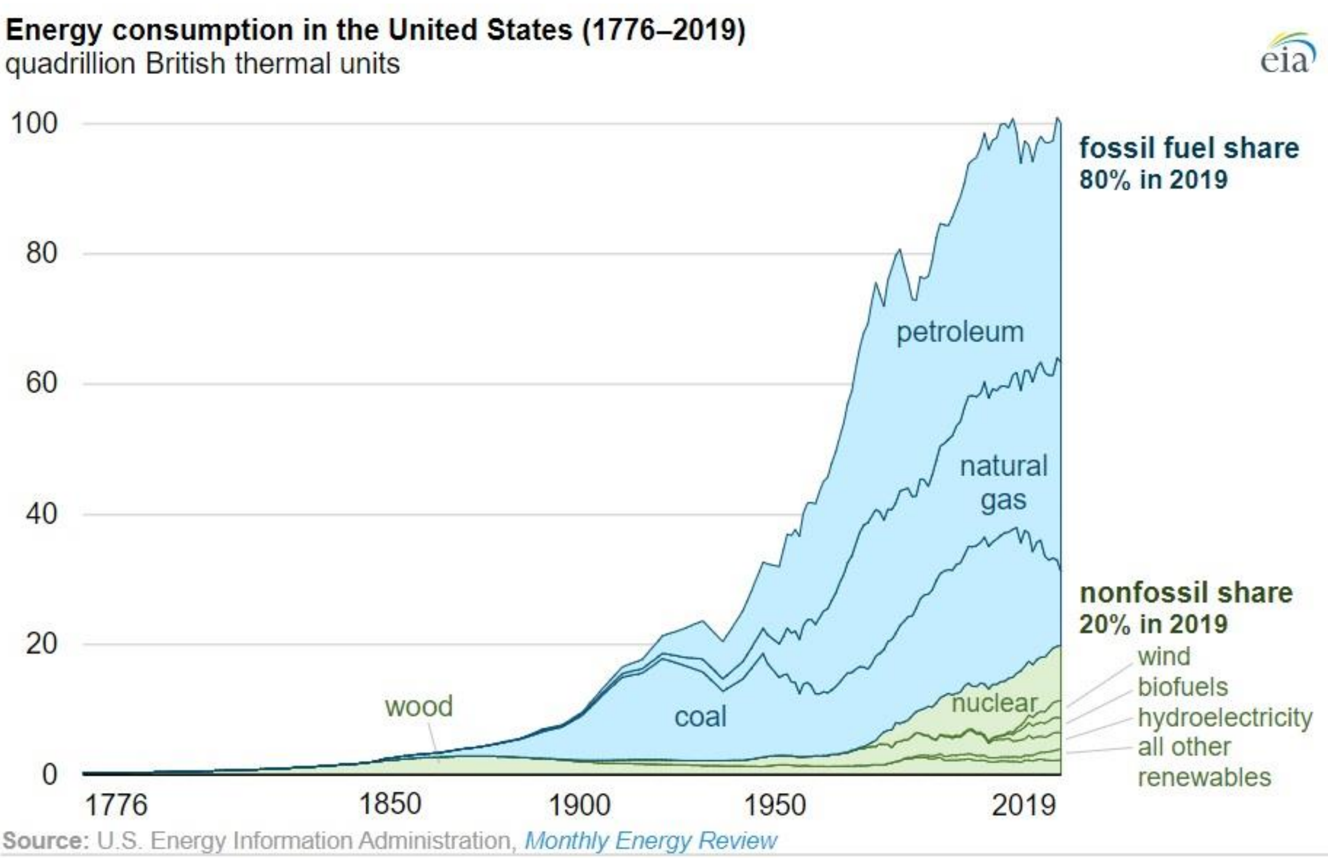
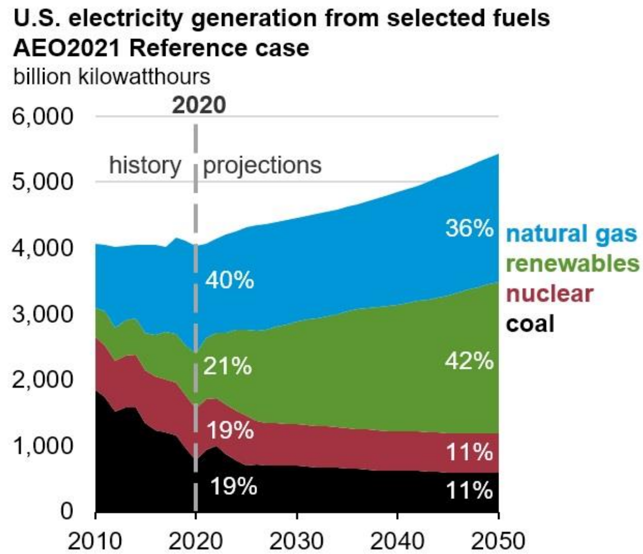
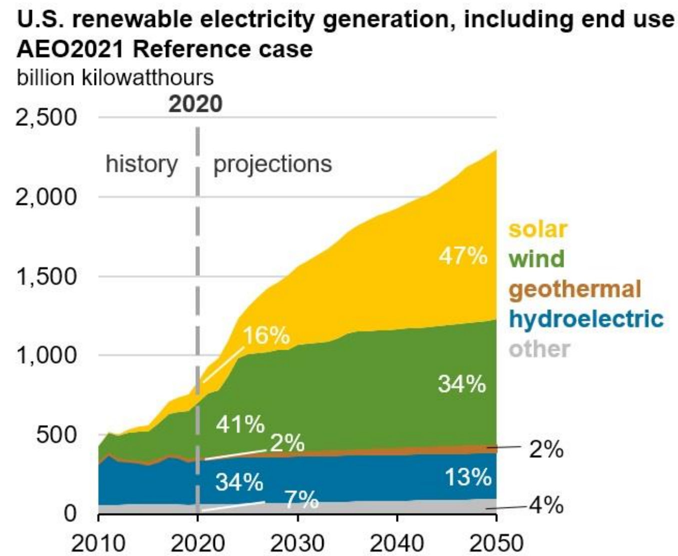


Figure 3. Historical energy consumption in the US. 1776-2019, by source.
US Energy Information Administration.





Figures 4 and 5. Charts showing the % of various fuels used for electricity generation.
US Energy Information administration, Annual Energy Outlook 2021.

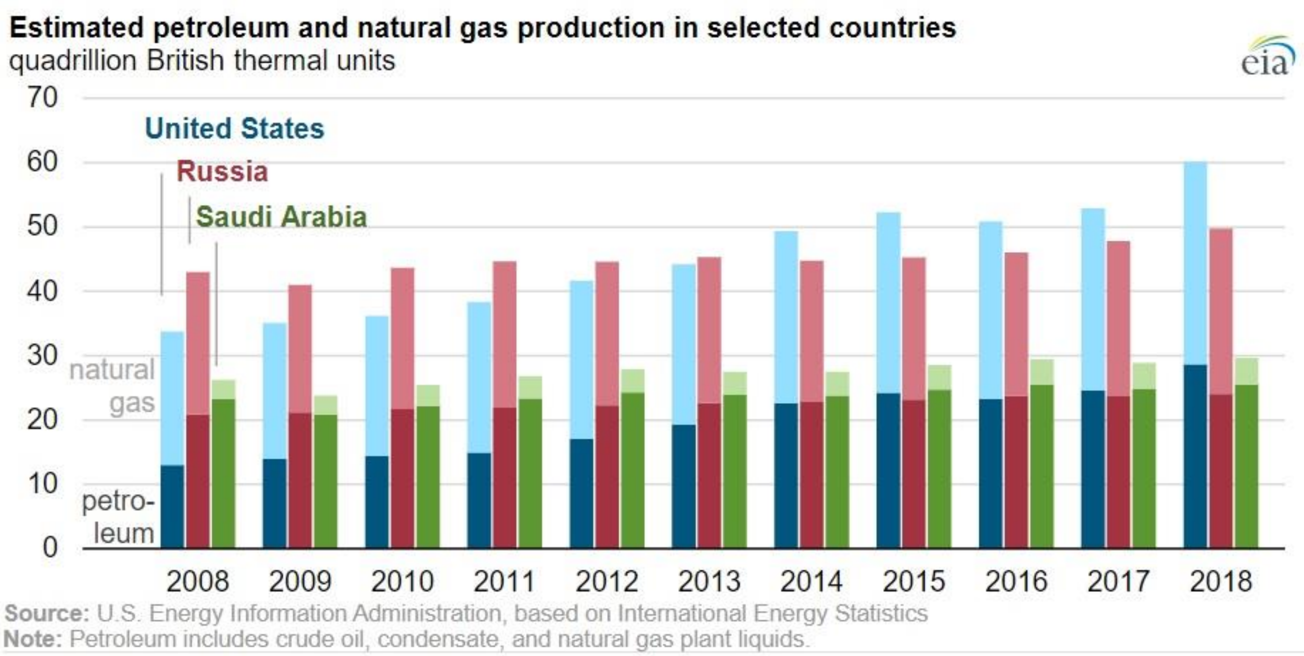


Figure 6. Estimated petroleum and natural gas production by the three largest producing countries.
US Energy Information Administration.

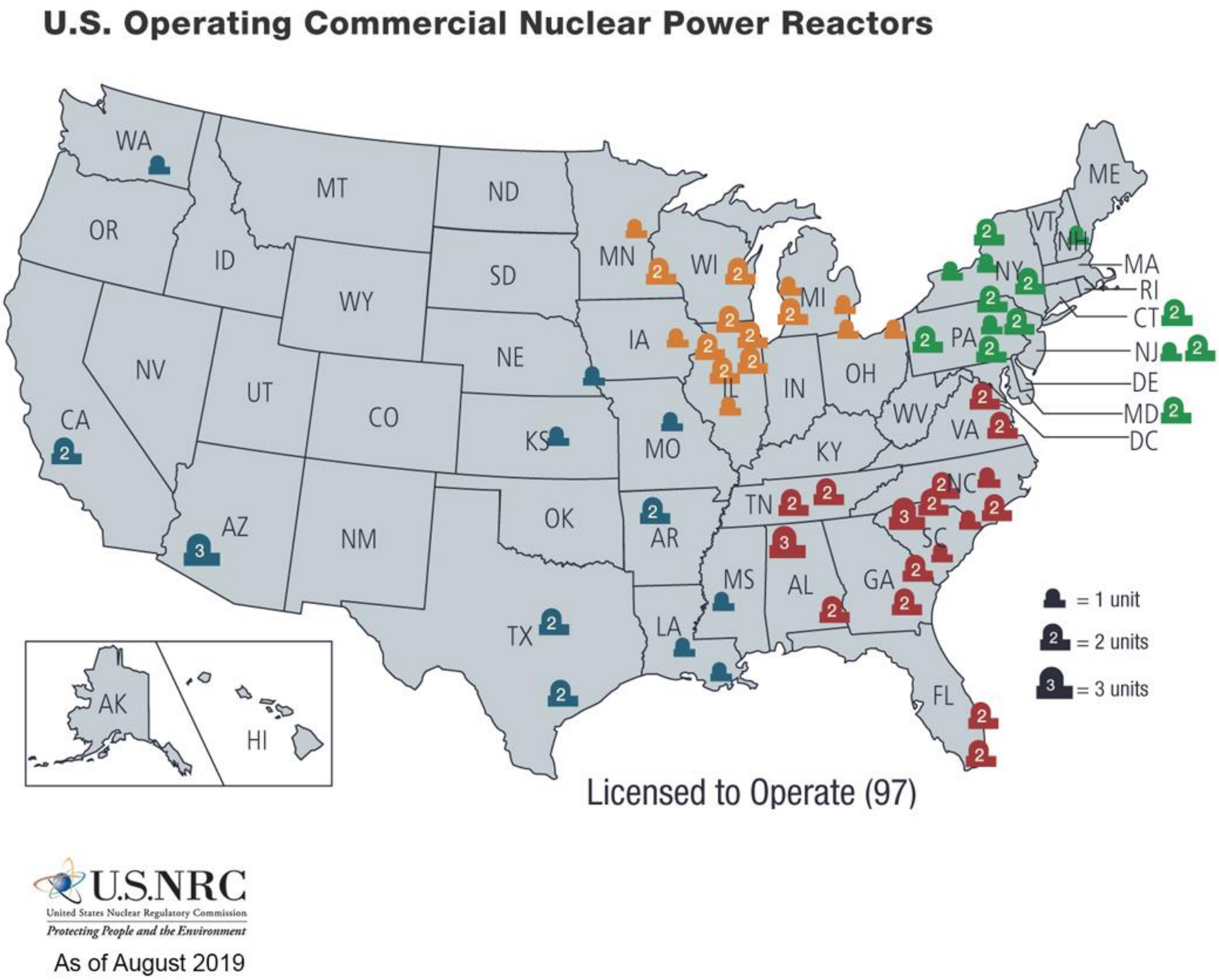


Figure 7. Nuclear power plants operating in the U.S. by state. (US NRC)

“Nuclear power plants heat water to produce steam. The steam is used to spin large turbines that generate electricity. Nuclear power plants use heat produced during nuclear fission to heat water. In nuclear fission, atoms are split apart to form smaller atoms, releasing energy. The heat produced during nuclear fission in the reactor core is used to boil water into steam, which turns the blades of a steam turbine. As the turbine blades turn, they drive generators that make electricity. Nuclear plants cool the steam back into water in a separate structure at the power plant called a cooling tower or they use water from ponds, rivers, or the ocean. The cooled water is then reused to produce steam. Nuclear power plants are the source of about 20% of annual U.S. electricity generation. Uranium is the fuel most widely used by nuclear plants for nuclear fission. Nuclear power plants use a certain kind of uranium, referred to as U-235, for fuel because its atoms are easily split apart. Although uranium is about 100 times more common than silver, U-235 is relatively rare. Most U.S. uranium ore is mined in the western United States. Once uranium is mined, the U-235 must be extracted and processed before it can be used as a fuel.” EIA

“Of the 31 countries in the world with commercial nuclear power plants in 2015, the United States had the most nuclear electricity generation capacity and generated more electricity from nuclear energy than any other country. France had the second-highest nuclear electricity generation capacity and electricity generation and obtained about 78% of its total electricity generation from nuclear energy, the largest share of any other country. Fourteen other countries generated at least 20% of their electricity from nuclear power.” EIA

Nuclear energy produces no direct carbon dioxide or air pollution, however it does have the following environmental impacts/concerns:

- The processes for mining and refining uranium ore and making reactor fuel all require large amounts of energy. Nuclear power plants also have large amounts of metal and concrete, which require large amounts of energy to manufacture. If fossil fuels are used for mining and refining uranium ore, or if fossil fuels are used when constructing the nuclear power plant, then the emissions from burning those fuels could be associated with the electricity that nuclear power plants generate.

- An uncontrolled nuclear reaction in a nuclear reactor could result in widespread contamination of air and water. The risk of this happening at nuclear power plants in the United States is considerably small because of the diverse and redundant barriers and numerous safety systems in place at nuclear power plants; the training and skills of the reactor operators; testing and maintenance activities; and the regulatory requirements and oversight of the U.S. Nuclear Regulatory Commission. U.S. reactors also have containment vessels that are designed to withstand extreme weather events and earthquakes.
- Produces radioactive waste that can remain dangerous for thousands to millions of years.
- Spent reactor fuel assemblies are highly radioactive, and initially, must be stored in specially designed pools of water. The water cools the fuel and acts as a radiation shield. Spent reactor fuel assemblies can also be stored in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling. The United States does not currently have a permanent disposal facility for high-level nuclear waste.
- When a nuclear reactor stops operating, it must be decommissioned. Decommissioning involves safely removing from service the reactor and all equipment that has become radioactive and reducing radioactivity to a level that permits other uses of the property.

Energy Resources QUESTIONS

1. Compare and contrast renewable vs. nonrenewable resources. Give definitions and examples of each.
2. What are the top 5 sources of energy used in the US? *(List them in order from highest to lowest.)*
3. What sectors are the primary users of that energy? *(List them in order from highest to lowest.)*
4. Why are petroleum, natural gas, and coal called “fossil fuels”?
5. Why are petroleum, natural gas, and coal deposits NOT evenly distributed in use across the US? What primarily governs their distribution?

6. How does oil concentrate underground? Draw some examples, including reservoir and cap rock (label each).

7. What is oil sand? Where are oil sands found?

8. What is hydraulic fracturing (or “fracking”) and why is it used?

9. What portion of US energy consumption is provided by nuclear power?	10. What is the primary fuel used in nuclear power plants?

11. What are the primary environmental impacts/concerns associated with the use of nuclear power?

12. What renewable energy resources are limited in geographic use? Why?

13. What renewable energy resources can be best stored for later use? How?

14. Do electric vehicles contribute greenhouse gases to the environment? If so, how?

Weekly Reflection

You will not be turning in this page. Take a moment to reflect on your comfort level and mastery of the week's objectives and describe an action plan for how you will practice or improve on anything that challenged you.

Weekly objective	**Self-assessment of mastery level**	**Action plan for improvement**
Evaluate the variations in **solar input latitudinally and seasonally** and the natural mechanisms for **redistributing this heat**.	A | B | C | D | F	
Evaluate the different methods used to gather data on past climates.	A | B | C | D | F	
Analyze the causes of **Earth's greenhouse effect and its impact on global warming**.	A | B | C | D | F	
Analyze and evaluate how society is impacted by global warming and climate change.	A | B | C | D | F	
Evaluate the societal and environmental costs of various energy sources.	A | B | C | D | F	

AHA! Moments

What content from this week really resonated with you, helped you understand something you've always wondered about, or made you think about the world with new eyes? (Consider sharing this information in the weekly Discussion board, as I'd like to hear it, and it might inspire other students.)

FINAL EXAM WORKSHEET

Distances (in kilometers or meters only!)	
1. What is the **average thickness of continental crust**?	2. What is the **average thickness of ocean crust**?
3. What is the **depth sea level would fall during an ice age**?	4. What do we call the feature that represents that depth?
5. What is the **radius of the planet**?	6. What is the **depth of the deepest hole drilled by humans**?

Time	
7. What is the **age of the Earth**?	8. When did the **oceans first form**?
9. When did **life first evolve**?	10. When did **life move onto land**?
11. When did **Pangaea** form?	12. What is the **age of the oldest ocean crust** currently in the oceans?

Other numbers	
13. What is the **density of freshwater at 4°C**?	14. What is the **density of quartz**?
15. What **% of the world's freshwater** is in glaciers?	16. What **% of the world's freshwater** is in rivers, streams?
17. What **% of the Earth's land surface** is covered by glaciers (maximum) during ice ages?	18. What **% of the Earth's land surface** is covered by glaciers today?

Drawings and more	
19. Draw a scaled cross-section through **Earth's layers (show and label all layers):**	
20. From what main source did the **water** in today's atmosphere and oceans originate?	21. From what main source did the **oxygen** in today's atmosphere originate?
22. Where is Earth's magnetic field created? How has its poles behaved throughout Earth's history?	

23. Which Earth layer is liquid? How do we know?

24. Give all the ways that continental crust differs from oceanic crust (be SPECIFIC!).

25. What are the three types of plate boundaries and the stresses, faults, and mountain systems associated with each? Where you can find samples of each on Earth's surface?

Plate Boundary	Stress	Faults	Mountain systems	World Examples

26. In which geologic settings are **earthquakes** found globally?

27. In general, where in the oceans is the **newest** ocean crust found?

28. In general, where in the oceans is the **oldest** ocean crust found?

29. What kind of plate boundary do we live on here in San Francisco?

30. Which characteristics of magmas make a volcano more dangerous?

31. What is the chemical formula of **quartz**?

32. What is the chemical formula of **calcite**?

33. Which **igneous rock** is formed when primitive lavas cool?

34. Which **igneous rock** is formed when evolved magmas cool underground?

35. What **sedimentary rock** is composed of calcium carbonate mud-sized shells of dead organisms?

36. What **sedimentary rock** is composed of rounded gravel-sized rock and mineral fragments?

37. What is the sequence of rocks formed when basalt **metamorphoses** in a subduction zone?

38. What is the sequence of rocks formed when mudstone **metamorphoses** during burial or continental convergence?

39. Compare the **grain size** and **composition** of immature (locally derived) versus mature (long traveled) **beach sediment**? (Be specific!)

	IMMATURE:	**MATURE:**
grain size		
composition		

40. How does physical weathering add to the effectiveness of **chemical weathering**?

41. What is the most common naturally formed acid? How does it form? (Give equation.)

42. How are limestone and chert similar? Different?

43. What are at least three major textural changes that signal increasing metamorphic grade?

44. What chemical changes occur as metamorphic grade increases?

45. CIRCLE: which of the following metamorphic settings is associated with **high temperature**?

Contact metamorphism | Burial metamorphism | Converging continents (regional)
Subduction zone metamorphism | Hydrothermal circulation at spreading centers

46. CIRCLE: which of the following metamorphic settings is associated with **high water/fluid content**?

Contact metamorphism | Burial metamorphism | Converging continents (regional)
Subduction zone metamorphism | Hydrothermal circulation at spreading centers

47. How is **serpentinite** formed? (Parent rock, setting, and grade)

48. Build a stratigraphy for the sample cross-section below – label and order all rocks, faults, and unconformities from oldest to youngest. Rock layer with all the folds is a Migmatite (call it M). B is a granite. D is a dike. E and C are sedimentary layers.

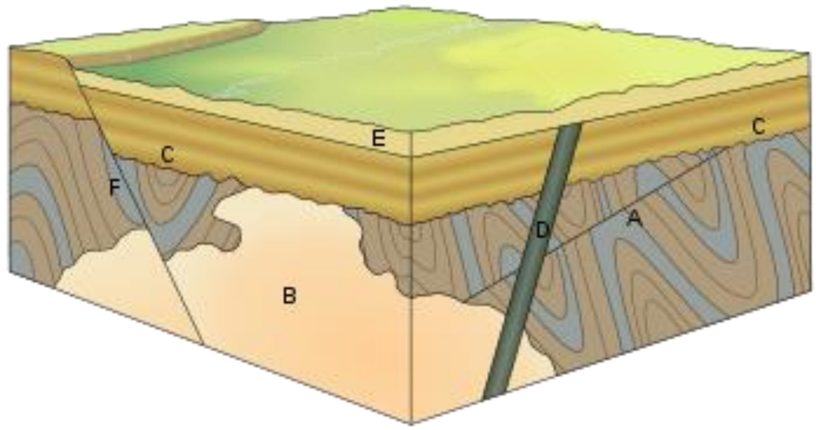


Image: Woudloper Copyright: CC BY-SA 1.0

49. What are the four major divisions of the Geologic Time Scale and what age ranges do they represent?

Eon or Era	Start date	End date

50. A hypothetical radioactive isotope has a half-life of 100,000 years. If the ratio of radioactive parent to stable daughter product is 1:7, how old is the rock containing the radioactive material?

51. CIRCLE which of the following will INCREASE the risk of slope failure for a given slope.

Rock layers perpendicular to slope | Rock layers parallel to slope | River or Waves at base | Lake at top
Arid Climate | Wet Climate | Lots of animal/human foot traffic | Little to no foot traffic
Covered in vegetation | Barren (no vegetation) | Buildings on top | Buildings at base

52. In which of the following locations within a river will erosion > deposition? CIRCLE:

Headwaters | Mouth | Entering a narrow channel | Where the river widens
Where gradient increases | Where gradient decreases | During rains | After rains

53. What is unique about alluvium (river-deposited sediment)? Why? How does it differ from glacial sediment?

54. Using the terms **porosity** and **permeability**, describe the formation of an aquitard and aquifer or oil reservoir and cap rock??

55. What is **karst** topography?

56. Which process dominates the **East Coast** of the United States? Why? CIRCLE: deposition | erosion

57. During what month of the year would you expect the **berm** on the beach to be smallest? Why?

58. What are the main sources of beach sand globally (in decreasing abundance order)?

59. What are the two primary sinks for all beach sand globally?

60. What are the main ways to get sea level to drop globally?

61. How was California affected during the last ice age?

62. How does a glaciated mountain valley differ from a river-eroded mountain valley?

63. What is the average composition of the atmosphere (with no water) -- give percentages?

64. When did the Pleistocene period of alternating ice ages begin? And what was the average global temperature before the Pleistocene began?

65. Through what primary methods (proxies) do we learn about past climate on our planet?