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Lab # 3

Minerals and Earth's Layers

Instructions: Numerical answers require units and appropriate numbers of significant digits. **Remember to show your work!**

PRELAB

1 Introduction

As we saw in the lectures, the pressure inside the Earth increases with depth due to the increasing amount of rocks above (Fig. 1). From a thermodynamic perspective, as we will see later in the class, temperature also increases with depth. Various combinations of pressures and temperatures result in a variety of mineral structures in the Earth's interior.

In this lab, we will talk about minerals both as we know them on the Earth's surface and as they exist inside our planet. We will also talk about methods that are used in studying minerals and their structures at high pressures and temperatures.

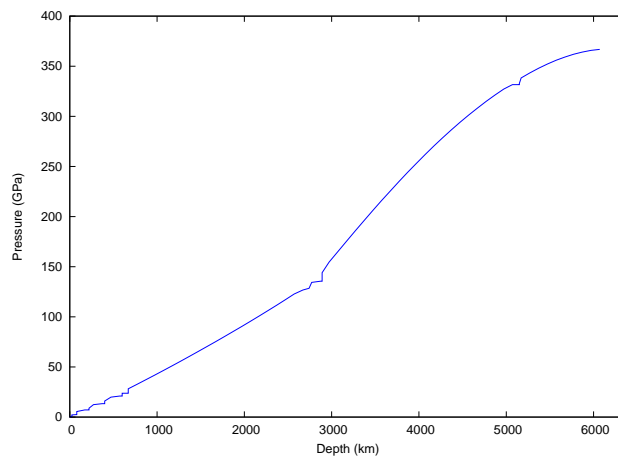


Figure 1: Calculated non-smoothed pressure curve for Earth's interior from the PREM model.

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2 Minerals and Rocks

Imagine that you were to pick up a stone on the beach. How could you tell if it was a mineral or a rock? In order for something to be classified as a *mineral*, it must:

- Be naturally occurring
- Be inorganic (not including living or once-living matter)
- Possess a definite crystalline structure
- Have a characteristic chemical composition
- Have characteristic physical properties (such as hardness, color and crystal form).

On the other hand, a *rock* is an aggregate of one or more minerals. For example, most people are probably familiar with the mineral quartz. Some sand can be 100% pure quartz crystals. These sands are made by natural processes, and have no organic material. The grains are clearly crystals, with a composition of SiO_2 , and a common hardness, specific gravity, and breaking strength. Otherwise, the grains of quartz-sand could be compacted together to form the rock sandstone.

There are many useful things that we can learn by identifying minerals and rocks. By looking at the minerals in a rock and how they are structured we can learn more about its history. We also can interpolate the conditions endured by the rock as it formed (e.g. magma type, source rock, pressure and temperature).

3 Identification of Minerals

There are thousands of different minerals, but most are very rare. Here we will discuss how to recognize some of the most common ones. Some of these methods are quite simple as they can be done simply by looking at a mineral or by using everyday objects and tools. Other methods, however, are complicated and expensive since they require special machines and controlled lab environments. In this section (3), we will discuss some of the methods to identify minerals.

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3.1 General Characteristics of Minerals

Using classifications based on composition and structure some of the most common properties used to identify minerals are:

Color- Color is a property which is surprisingly not always very useful. Many minerals can have similar colors – and some mineral may have many different colors! Colors vary because of minute amount of impurities in the mineral. Examples: Rose quartz, smoky quartz, amethyst, clear quartz.

Luster- Luster is the appearance of the mineral in reflected light. The two basic types of luster are: *metallic* (pyrite, galena) and *non-metallic*. Other types are: *vitreous* (quartz), *waxy* (chalcedony), *brilliant*, *greasy*, and *earthy* (hematite).

Streak- A mineral's streak is determined by rubbing it along an unglazed porcelain plate, where bits of the mineral can rub off and leave a mark on the plate. The color of the streak is closer to the true color of the mineral. Example: Hematite.

Crystal Form- Minerals possess an atomic structure that yields a definite crystal form if growth occurs under ideal conditions. In most cases, crystals may not be apparent, but are best observed with a hand lens. There are many different crystal forms, but the most important are *cubical* (pyrite), *hexagonal* or six-sided (quartz), and *rhomboidal* or slanted cube (calcite).

Cleavage and Fracture- Cleavage is demonstrated by a tendency for a mineral to break smoothly along a flat surface (which is determined by the strength of the bonds within the mineral crystal). Some minerals will cleave on only one or two planes, and some will not cleave at all. Examples of minerals with good cleavage: mica, calcite, gypsum, feldspar. Sometimes, the mineral breaks along an irregular surface called fracture. A common type is *conchoidal* fracture (e.g. quartz), which has the pattern of broken glass.

Hardness- Hardness is a measure of how difficult it is to scratch a mineral. In 1872, Friedrich Mohs created a relative hardness scale that is still in use today. Since harder minerals (and other common objects) will scratch softer ones, he arranged his scale so that the hardest minerals have the highest number. His scale is listed in Table 1.

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Table 1: Mohs Scale of Hardness

Hardness	Mineral	Hardness	Common Object
10	diamond		
9	corundum		
8	topaz		
7	quartz		scratches window glass
6	orthoclase	steel knife	
		5.5	glass, steel knife, masonry nail
5	apatite		
		4.5	wire nail
4	flourite		
		3.5	copper penny
3	calcite		
		2.5	fingernail
2	gypsum		
1	talc		

Specific Gravity- This term dates back to the Middle Ages and it is used to measure the density of a particular substance. A good example of a mineral with high specific gravity is galena. Specific gravity is the ratio of the density of a particular substance compared to the density of an equal volume of water (and since it is a ratio; specific gravity is a dimensionless number). Since the two volumes, V are the same, the density of the substance, $\rho_{substance}$ is directly related to the mass of the substance, $M_{substance}$:

$$\rho_{water} = \frac{M_{water}}{V} \quad , \quad \rho_{substance} = \frac{M_{substance}}{V} \quad , \quad \frac{\rho_{substance}}{\rho_{water}} = \frac{M_{substance}}{M_{water}} \quad (1)$$

3.2 X-ray Diffraction (XRD)

X-rays were discovered by Wilhelm Roentgen. He was the first person to discover electromagnetic radiation with short wavelength commonly known as X-rays today. Although, many people had observed the effects of X-ray beams before, Roentgen was the first scientist to study them systematically. To highlight the unknown nature of his discovery, he called them X-rays though they are still known as Roentgen-rays as well.

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The first X-ray diffraction experiment on crystals was done in 1912 by Max von Laue. X-rays can be used to identify minerals (based on lattice parameters). X-ray diffraction is also being carried out on other planets like Mars. When intensity is measured, structures can be determined. The first crystal structure determinations were carried out by Sir William Bragg. Bragg first formulated the diffraction condition by noticing the layering in the crystal structure (Fig. 2).

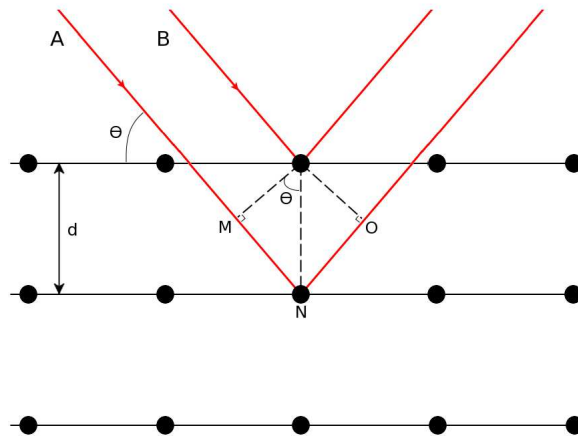


Figure 2: Interaction of X-rays with crystalline structure.

For diffraction to occur, the Bragg equation must be satisfied. Only certain specific angles of reflection are allowed.

$$2d \sin \theta = n\lambda \quad (2)$$

Questions:

1. In practice, X-ray diffraction experiments measure 2θ . Given that 2θ is 30° and the source of X-rays have a wavelength of 0.709 \AA , what is the the lattice spacing, d ?

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2. Given a d spacing of 5.6 \AA and a copper X-ray source with a wavelength of 0.154 nm what is the 2θ value?
3. In an EXCEL sheet, plot various values of lattice spacing against θ ranging from 0° to 90° for $n = 1$ and a wavelength of 0.709 \AA . Upload a copy of your spreadsheet onto Canvas AND turn in a hard copy with your lab.
4. Derive Eq. (2) for $n = 1$ (Hint: Use the extra path that ray A travels with respect to ray B in Fig. 2).

3.3 Spectroscopy

Spectroscopy is the study of the interaction between electromagnetic field/radiation and matter. There are two major spectroscopy methods:

1. Optical Spectroscopy
2. Mass Spectrometry

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3.3.1 Optical Spectroscopy

To understand optical spectroscopy, one must first understand electromagnetic waves. Electromagnetic waves are transverse wave with the electric and magnetic field perpendicular to each other and the direction of propagation (Fig. 3). Light is an electromagnetic wave.

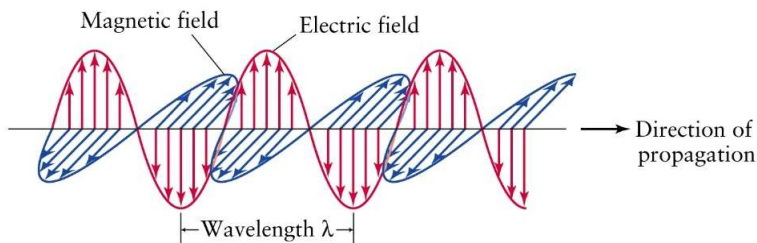


Figure 3: Electromagnetic waves are made of oscillating electric and magnetic fields. Image modified from OurEdu.Blog.

Electromagnetic waves travel at the speed of light (c) and while their frequencies (ν) are constant (depends on their source), their wavelengths (λ) change in different media (why?). These quantities are related by

$$c = \nu\lambda \quad (3)$$

In optical spectroscopy, we often do not use wavelengths, but spectrums are reported in *wavenumbers*. Wavenumber is the inverse of wavelength and has units of cm^{-1} :

$$\bar{\nu} = \frac{1}{\lambda} \quad (4)$$

Under some experimental conditions, light does not behave like an electromagnetic wave; rather it behaves like a stream of photons¹. The energy of the photons is related to the frequency of the electromagnetic wave:

$$E = h\nu \quad (5)$$

where h is the Planck's constant and its value is 6.63×10^{-34} Js.

¹Photons are uncharged particles with zero rest mass.

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Different spectroscopic methods utilize different sources of the electromagnetic spectrum. See Fig. 4.

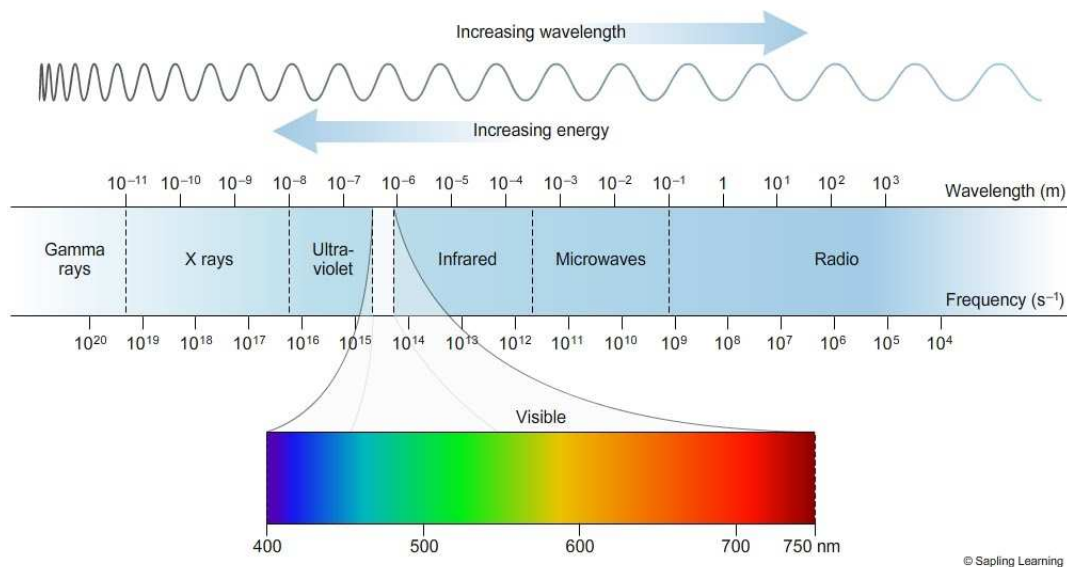


Figure 4: The electromagnetic spectrum.

Raman Spectroscopy

An important form of optical spectroscopy is called *Raman scattering* which uses inherent vibrations of material. Imagine that the bonds between two atoms are a spring and thus they vibrate at a certain common frequency. This vibration can, in principle, interact with electromagnetic waves of the right frequency and affect the reflections off the material's surface. Raman "scattering" is due to such interactions of the incident electromagnetic wave (commonly laser) with vibrations in the sample. A spectrum obtained from Raman spectroscopy is unique to every given material and can be used much like a fingerprint. For example, the mineral quartz (SiO_2) has a characteristic spectrum shown in Fig. 5.

The Raman effect was discovered by C. V. Raman in 1928. He went on to win the Nobel prize for this discovery.

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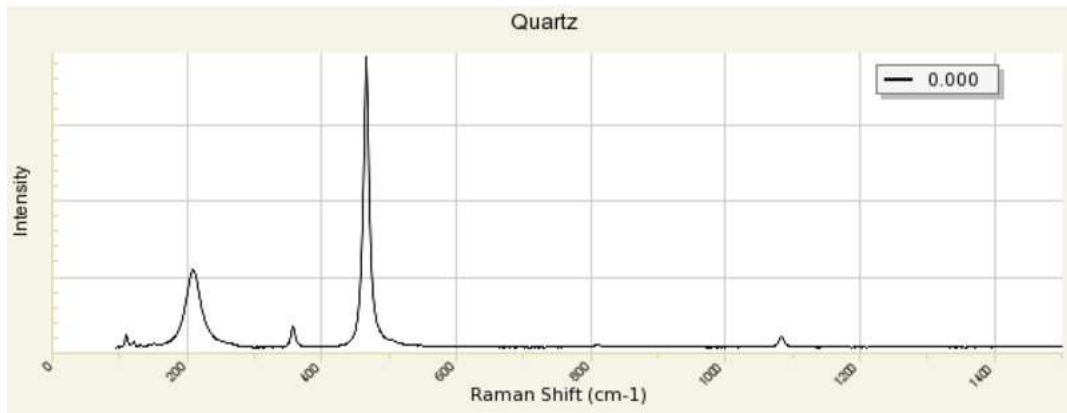


Figure 5: Raman spectrum of quartz. The positioning of the observed peaks is unique to quartz.

The peak around 464 cm^{-1} in Fig. 5 corresponds to the Si-O vibration. There are Raman databases that are used to identify minerals. This can be useful for identifying unknown minerals and can be used in studying the composition of other planets.

3.3.2 Mass Spectrometry

Mass spectrometers are used to measure the amount/ratio of various isotopes of an element. This is done through measuring the different paths traveled by each isotope.

The schematics for a *general* mass spectrometer is shown in Fig. 6. In this set-up, a sample as the object of measurement is ionized (1), and a variety of resultant ions are guided through an accelerating voltage (2). Then these ions are passed through a capacitor where an electric and magnetic fields are applied simultaneously (3). Upon exiting the capacitor, another magnetic field is applied to the ions and they will move in circular paths as a result of the resulted force (4). The radius/curvature of the ions' path will be proportional to their mass-to-charge ratio. As a result, a mass spectrum (5) is obtained, which consists of peaks of the measured ion intensity (ion peak) for each mass-to-charge ratio value.

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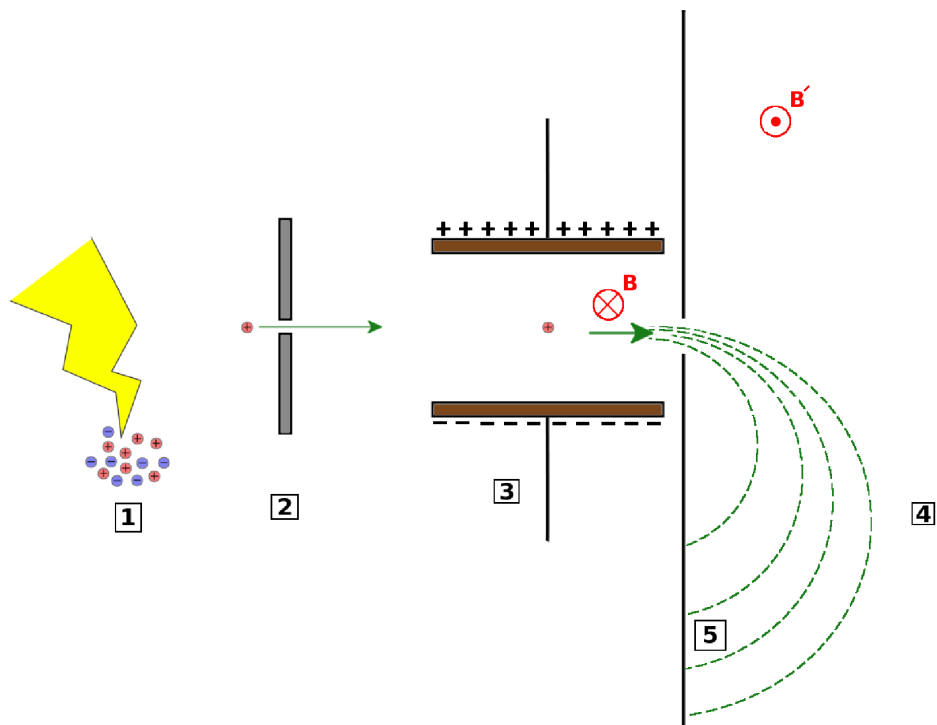


Figure 6: General schematics of a mass spectrometer.

Using the information above, answer the following questions:

- Assuming that the direction of an electric field is from positive to negative charges, draw a vector on the figure above showing the direction of this field inside the capacitor.
- The electric force is given by $\vec{F}_E = q\vec{E}$ where q is the electric charge of a particle and \vec{E} is the electric field. On the figure, draw a vector representing this force exerted on the ion in the capacitor from the electric field.
- The magnetic force is given by $\vec{F}_B = q\vec{v} \times \vec{B}$. The direction of the magnetic *field*, as shown, is perpendicular to the page, pointing inward. Draw a vector representing the force exerted on the ion from the magnetic field.

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- d. What is the condition for the ion to move in a “straight line”?
- e. For an ion moving in a straight line *inside* the capacitor (as shown), derive an expression for its velocity in terms of magnitude of the fields (you answer will show that we can “select” the velocity at which the ion will move in a straight line).
- f. As the ion exits the capacitor, \vec{E} and \vec{B} will no longer be applied it and the only driving force will come from a new magnetic field, \vec{B}' . Draw a vector showing the direction of $\vec{F}_{B'}$.
- g. Write the condition for force equilibrium, resulting in the ion moving in circular path. with velocity v , and radius r until it hits the screen at “5”.
- h. Derive an equation for the mass-to-charge ratio of the ion in terms of the magnetic field (\vec{B}'), velocity v , and radius r until it hits the screen at “5”.

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- i. Plug in your solution for (e) to replace velocity.

- j. From your final answer to (i), what determines the radius of curvature?

- k. If we apply this method to a single element from the periodic table, what – in your answer to (i) – will be the same for all of the ions?

- l. If so, what will control the “sorting order” for the ions on the screen at “5”?

- m. Explain why this method (mass spectroscopy) is useful in studying the earth.

3.4 Synchrotron Radiation

Another important method in studying the minerals at high pressures and temperatures is the evidence from synchrotron radiation. A synchrotron is an evacuated ring in which particles (usually electrons) are injected and accelerated into the ring as shown in Fig. 7). They then are accelerated in a circular orbit by external magnets.

Synchrotron radiation is important because it is extremely intense with a continuous spectrum. A continuous spectrum means that it extends from the far infrared to the gamma ray region (see Fig. 4). The high intensity is a million times stronger than what a normal X-ray tube can reach in a typical lab. This kind of radiation is important in high pressure mineral studies as often sample sizes are small (order of microns).

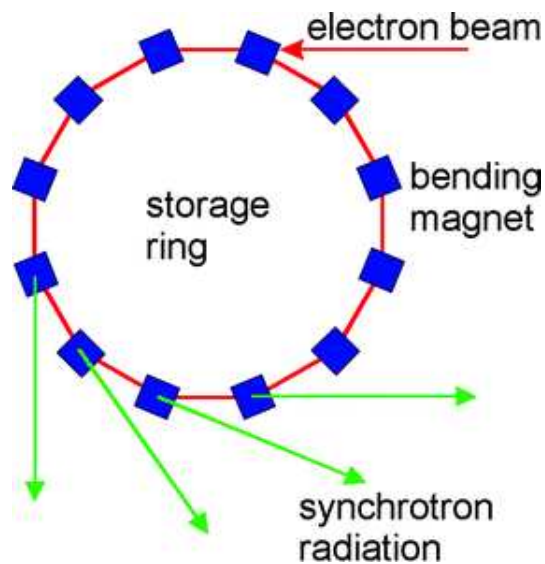


Figure 7: Schematics of a synchrotron (Clegg, 2000).

There are only a few synchrotrons in the world and the synchrotron radiation is used to study a multitude of materials not just minerals. Besides earth science chemistry and biology also make use of synchrotron radiation. A lot of other fields also make use of synchrotron radiation. Time at these facilities is granted on a proposal system. One must write a proposal for their experiment and have it approved by the board.

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4 High Pressure Lab at Northwestern

As a part of this lab, we will visit the high pressure lab at Northwestern University located at the Hogan building. In this visit, we will take a look at some of the equipment we discussed here.

During this visit, Michelle Wenz – from the Department of Earth and Planetary Sciences – who is in charge of several projects at the high pressure lab will show us some aspects of the research performed at the lab.

More details will follow through the week. **STAY TUNED!**

5 Olivine

As we saw in the lectures, olivine $[(\text{Mg,Fe})_2\text{SiO}_4]$ is an important mineral when it comes to the composition of Earth. The Earth's mantle makes up 84% of the planet's volume. Olivine makes up the majority of the mantle. However, with increasing pressure and temperature olivine transforms to wadsleyite which is a high-pressure polymorph of olivine – a high-pressure polymorph means that it has the same chemical composition but has a different structure.

As a result, there will be a structural change as we go deeper in the Earth's mantle. This change is responsible for the so-called 410 km discontinuity. This *physical* boundary is observed in the velocity profile of Earth and has also been confirmed in lab experiments.

Upon a further increase in temperature and pressure, wadsleyite transforms to ringwoodite, another high-pressure polymorph of olivine responsible for the 660 km discontinuity. Wadsleyite and ringwoodite make up what is known as the *transition zone* in the Earth's mantle from 410 to 660 km. We will see more of this in the next problem set.

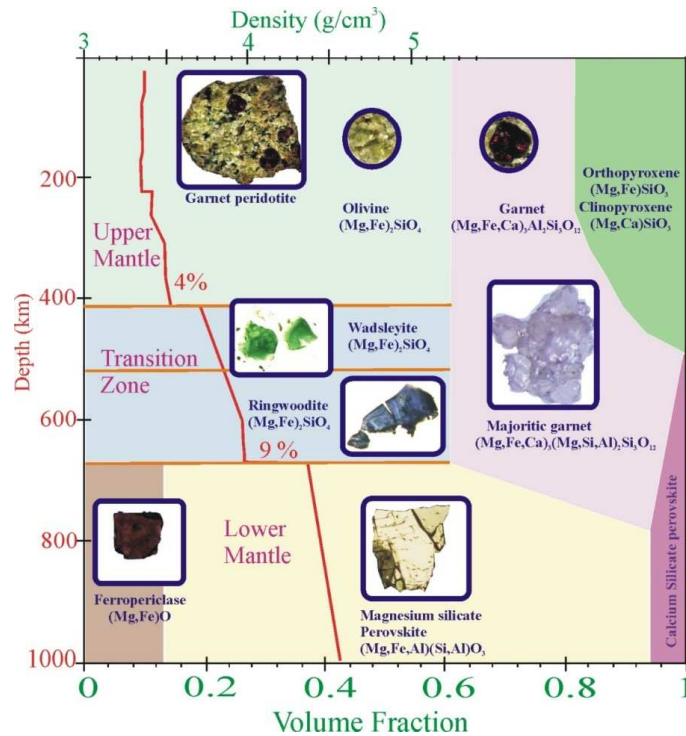


Figure 8: Abundance of minerals in the mantle (Frost, 2008).

The volume fractions shown in Fig. 8 depend on pressure and temperature which can be best shown using *ternary diagrams*.

6 Ternary Phase Diagrams

Ternary diagrams are often used in geoscience. These diagrams (as shown in Fig. 9) are triangles that represent *relative* compositions of the entire (100%) mixture. Various points in a ternary diagram with A, B and C at the three corners show how much of A, B and C exist in a sample, given the physical state (e.g. pressure, temperature, etc) of the system.

For instance, in Fig. 9, at the top where olivine is written, the composition is 100% olivine $[(\text{Mg,Fe})_2\text{SiO}_4]$. If you are at the label orthopyroxene, then you have 100% orthopyroxene. But like with most things in life, there are a lot of intermediate compositions. Ternary diagrams easily allow for intermediate compositions to be plotted. If they fall in a certain region, they have a specific name. For example, lherzolite is a rock that contains 40-90 percent olivine along with amounts of orthopyroxene and clinopyroxene.

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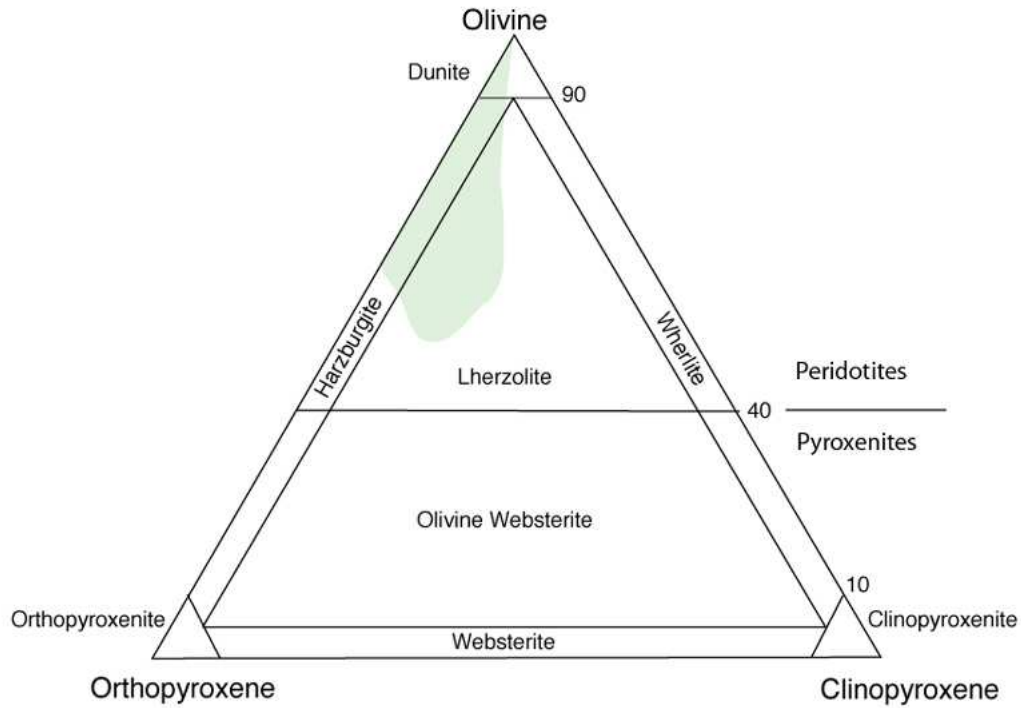


Figure 9: An example of ternary diagrams for the Earth's mantle.

Questions:

1. Based on how a lherzolite is defined. What would you expect websterite to be composed of?

2. What would harzburgite be composed of?

7 Rock Types & Layers of the Earth

As we have seen in the lectures so far, in terms of gross structure, Earth is a layered planet. Each of these layers can be defined by a certain composition, making up Earth's core, mantle and crust (Earth is also layered according to the way rocks display different physical characteristics, which we will soon discuss in lecture. These layers are the *lithosphere*, a rigid outer layer, containing the crust and upper-most mantle; the *asthenosphere*, a weaker layer in the mantle; and the *mesosphere*, a stronger layer in the lower mantle.

Earth's crust is the most accessible to study, but also is more complex with many more variations in composition. The crust of Earth is divided into two types: *oceanic* and *continental*. *Basalt* is a type of rock which is a good representative of most oceanic crust. This rock is mafic (the name mafic refers to its high magnesium and iron content) primarily composed of plagioclase feldspar (calcium-rich), olivine, amphibole and pyroxene. Continental crust has more of a range of compositions, but for our purposes we will assume that its average composition is *granite*, having many similar properties to the felsic rock *granite* (the name felsic refers to its high feldspar and silica content). Granite is composed of quartz, potassium-rich feldspar, and micas. Since mafic rocks contain heavier minerals, oceanic crust is denser than continental crust (with densities 3.0 and 2.7 g/cm³, respectively). On average, continental crust is much thicker and older than oceanic crust.

We assume upper mantle rocks have a composition similar to the rock *peridotite*, which is largely made up of olivine and pyroxene, and is more dense than crustal rocks (3.2–3.4 g/cm³). Laboratory experiments indicate that peridotite has similar physical properties to account for the mantle's density and observed rates of seismic wave transmissions. Also, samples from the field show peridotites below crustal rocks in areas of deformation where rocks have been uplifted and exposed at the surface. Peridotite inclusions are also found in *kimberlite pipes*, cone-shaped bodies of rock where magma has been volcanically emplaced into pre-existing rocks. Kimberlite deposits contain certain minerals (one of which is diamond) which can only form under the high temperature and pressure conditions found between 100–300 km depth. The inclusions of peridotite in the kimberlites are thought to represent pieces of the mantle brought up to the surface during eruptions. A final piece of evidence used to determine the mantle's composition comes from *stony meteorites*, since they are thought to be remnants of material left over from the formation of the solar system, and they have peridotite composition. In earth's lower mantle, below the transition zone, greater pressures cause rock of the same composition as peridotite to undergo phase changes to form higher density material.

To gain ideas about the composition of Earth's core, we are faced with a tougher chal-

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lence. We can estimate the inner core to have a density in the range of 12.6–13.0 g/cm³ using evidence from seismology. But our best evidence of core composition comes from *iron meteorites*, which are composed of alloys of iron and nickel. Seismic evidence and characteristics of Earth's magnetic field are consistent with a liquid outer core (density = 9.9–12.2 g/cm³), composed of a mixture of iron and an element of lower density.

IN LAB

8 PART I: Mineral Identification

In this part of the lab, we will use general characteristics of minerals (see 3.1) to identify them from a set of samples. These samples are mostly composed of the same mineral crystals, even though there are some times *impurities* in a samples structure. When doing this part, please disregard such impurities and focus mainly on the mineral as a whole.

You can use a variety of tools such as coins, hand lenses, ceramic plates (used for scratching minerals), pieces of glass, nails, etc., as well as their visual characteristics. Please consult Table 1 for details on mineral hardness test.

Using the characteristics given in the Table 2, match each sample number with its respective *mineral* name. Use the label number next to each mineral.

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Table 2: Examples of Earth's Most Common Minerals

#	mineral name	hardness	streak	luster	Distinctive Properties
	plagioclase feldspar	H = 6	white	non-metallic	white or gray, cleavage good or excellent, 2 cleavages at nearly 90°, with striations
	potassium feldspar	H = 6	white	non-metallic	orange, brown, white, gray, green or pink, cleavage good or excellent, cleavages at nearly 90°, sub-parallel ex-solution lamellae
	quartz	H = 7	white	vitreous or greasy	colorless, white, gray, or other colors, massive or hexagonal prisms and pyramids, conchoidal fracture, no cleavage
	garnet	H = 7	white	non-metallic	red, black or brown, forms dodecahedrons (12-sided crystals), cleavage absent, translucent to opaque
	olivine	H = 7	white	non-metallic	pale olive green to yellow, conchoidal fracture, cleavage absent, forms short stout prisms
	muscovite mica	H = 2 - 2.5	white	non-metallic	colorless, yellow, brown, or red-brown splits along 1 excellent cleavage into thin transparent sheets
	hornblende (amphibole)	H = 5.5	grey, green, white	non-metallic	cleavage excellent or good, opaque, dark green-black color, 2 cleavages at about 60° and 120°
	augite (pyroxene)	H = 5.5 - 6	white-pale gray	non-metallic	cleavage excellent or good, 2 cleavages at nearly 90° green-black color
	biotite mica	H = 2.5 - 3	gray-brown	non-metallic	black-green-brown color, splits easily along 1 excellent cleavage plane into thin sheets

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9 PART II: Relating Different Rock Types to the Layers of the Earth

As we discussed in section 7, as various layer of Earth are made up of different material, the mantle is made of certain types of rock. In this part of the lab, we will take a look at some of these rocks and will think about their origins in our planet.

9.1 Experiment

In the labroom are rock samples which are representative of earth's layers: granite, basalt, peridotite or dunite (an olivine-rich peridotite), and iron-nickel meteorite. For this exercise, you will use Archimedes' principle to find the density of each rock sample.

Follow through these steps:

1. The density of an object is defined as mass per unit volume.
 - measure the mass of each sample, using the digital scale.
 - To find the volume of each sample, fill a graduate cylinder halfway with water and record the volume (V_a).
2. Carefully place the rock sample in the graduated cylinder. Record the new level of water (V_b).
3. The difference between the original level of water (V_a) and the new level of the water (V_b) is the volume of the sample (V). Notice the units of the graduated cylinder are millimeters (mL).
4. Calculate the density. Convert to units g/cm^3 ($1 \text{ mL} = 1 \text{ cm}^3$).

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Rock	Mass (g)	V_a (mL)	V_b (mL)	V (mL)	density (g/cm ³)
basalt					
granite					
peridotite-dunite					
iron meteorite					

9.2 Interpretation

i. How do these densities compare with the values presented in the discussion? with the average density of Earth? What does this imply about Earth's moment of inertia?

ii. A theory of planetary formation is that in the early history of a planet, a certain process called *differentiation* occurs where denser matter sinks under its own weight toward the center of the planet, and lighter matter floats to the surface. How do the observations from this lab relate to this theory?

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- iii. Earth's Moon has an average density of 3.3 g/cm^3 and a moment of inertia ratio of 0.394. The prevailing theory of its formation is that a very impactor (the size of Mars) collided with Earth, and the material that was thrown out into space coalesced to form the moon. Based upon our observations and this theory, would you think that the Moon formed before or after Earth's differentiation? Please explain your answer.