WAVE EFFECTS AND THE INTERNAL STRUCTURE OF THE EARTH

In the other two modules in this series wave characteristics or properties and wave motions have been examined. In this module, the effects of waves will be examined. Two effects of waves, diffraction and polarization, are more commonly associated with light waves and will not be examined. Two other effects of waves, however, are very important in understanding how scientists have deduced that the interior of the Earth, which has never been directly observed, is layered into a crust, mantle and core. The focus of this module will be these two wave effects:

Reflection, and Refraction.

Both reflection and refraction occur when wave energy strikes a boundary between materials that transmit the wave at different velocities. Waves are transmitted at different speeds, depending on the type of wave and properties (e.g., densities) of the material through which the wave is propagating. In the case of seismic waves, both P waves and S waves travel faster in more dense materials and slower in less dense materials.

Figure III.1 is typical of the way reflection and refraction are illustrated in science textbooks. In this picture, an **incident ray** of light strikes a piece of glass at an oblique (not perpendicular) angle. The light ray is then reflected and refracted. The **angle of incidence** is labeled θ_1. This is the angle of the incoming ray as measured from the **normal**. The **angle of reflection** θ_1 will equal the angle of incidence if the boundary is smooth. If the boundary has an irregular shape the reflected wave energy scatters in all directions (see Figure III.2)

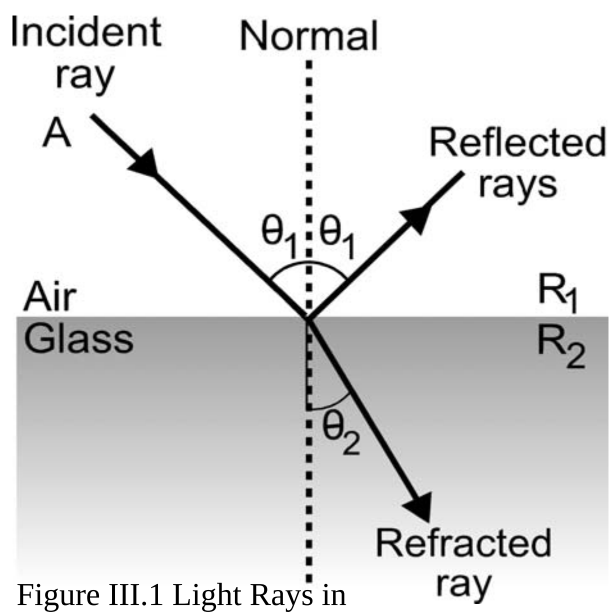

Figure III.1 Light Rays in Air and Glass

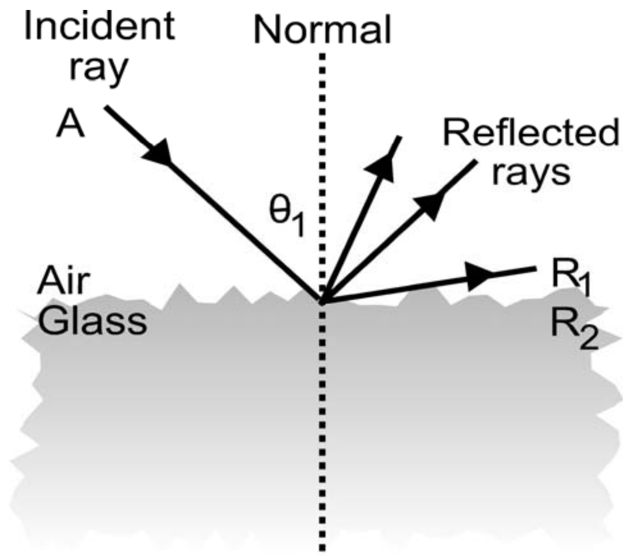

Figure III.2 Energy Hitting Irregular Surface

However, the **angle of refraction** θ_2, also measured from the normal, will depend on the difference in wave speed between the two mediums. When a wave travels through a medium with one density and suddenly encounters another medium with a different density, the wave speed must change as it enters the new medium. If the wave travels faster in the first medium than it does in the second medium, the angle of refraction (in the second medium) is less than the angle of incidence. If, however, the wave travels slower in the first medium than it does in the second medium, the angle of refraction is greater than the angle of incidence. In Figure III.1, because glass transmits light at slightly lower speeds than air, the ray bends toward the normal. In this case, θ_2 is less than θ_1.

When a seismic wave strikes a boundary between two materials of different properties, which cause the wave speed to be changed, the same type of effect can be observed. In general, seismic wave speed increase in materials with higher densities. However, density increases alone do not increase seismic wave speed. The strength of the material is actually the primary control on seismic wave speed. In fact, in theory, an increase in density alone would result in a decrease in seismic wave speeds! But, since stronger materials are usually also more dense, we observe in nature that more dense materials do indeed have higher seismic wave speeds. We use this terminology, that density increases lead to wave speed increases, here since it is more familiar to the reader.

Figure III.3 illustrates a P-wave moving through successive layers of the Earth. The reflected wave was removed in order to keep the drawing uncluttered. Notice how the wave energy bends both toward and away from the normal as different layers have different densities. Each layer in this stack has a different thickness (h) and P-wave speed (V).

The density of layer 1 is less than the density of layer 2. As a result, the angle of refraction at the boundary between layers 1 and 2 is greater than the angle of incidence. The opposite effect takes place at the boundary between layers 2 and 3. Because layer 2 has a wave speed that is greater than that of layer 3, the angle of refraction is less than the angle of incidence. This example is simplified, but similar to the path a seismic wave takes through the Earth. In the Earth, with a few exceptions, the density and wave speeds increase continuously with depth. There are few sharp boundaries and therefore seismic waves follow paths that are continuously curving as the density changes.

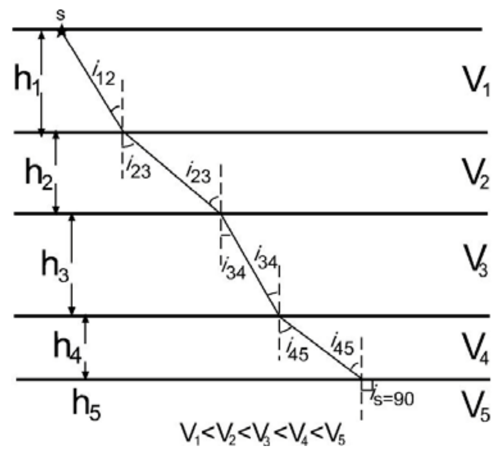

Figure III.3 Energy traveling through a layered substance

Finally, a wave will eventually strike a layer at such an angle so that the wave travels along the boundary. That particular angle of incidence is known as the **critical angle.** The end result is shown in the Figure III.4. When the distribution of wave speeds in the layers is such that a critical angle exists, the seismic wave begins to travel horizontally in the deeper layer just below the boundary between the layers (layer four in this case). Some energy from this wave is transmitted back to the surface. Because it is travelling horizontally in the fastest layer, a critically refracted wave can arrive before energy traveling in more shallow layers.

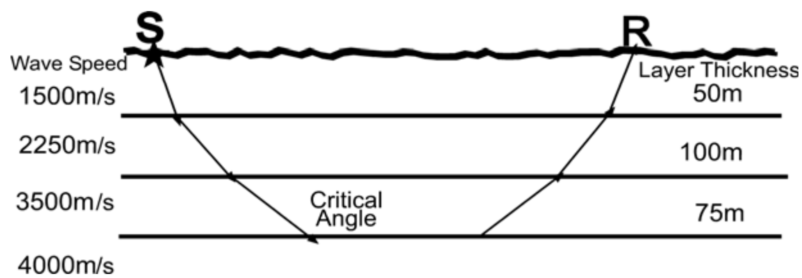

Figure III.4 Critical angle of seismic waves

USING SEISMIC WAVES TO DETERMINE THE INTERNAL STRUCTURE OF THE EARTH

Earthquakes are fundamental in determining the internal structure of the earth! Many rocks that were formed at depths of a few kilometers to tens of kilometers do exist at the Earth's surface. Far fewer rocks (like those in diamond pipes) that were formed at depths of hundreds of kilometers are available for scientists to study. Thus, to determine what the interior of the Earth is like, scientists use knowledge from seismic P and S waves that travel through the interior of the Earth.

WHAT HAPPENS TO P AND S WAVES IN THE EARTH'S INTERIOR?

As we discussed in the section entitled "**What are Waves?",** P and S waves propagate outward from the focus of an earthquake and get farther apart because they travel at different speeds. The farther the earthquake is from a recording station, the greater the difference in time between the arrival of the first P wave and the arrival of the first S wave. If you know the speeds at which P and S waves travel and the route along which they travel, then you can calculate how far away the earthquake focus is. The tricky part, however, is determining the speeds of P and S waves in the deep interior of the Earth.

Each type of seismic wave travels at speeds and in directions that are dependent on the type of rock and the density of rock through which they pass. Thus what seismographs record on the opposite side of the Earth from an earthquake are various types of P and S waves that have traveled at different speeds as they move through the Earth's interior.

Recall that P waves travel at greater speed than S waves. But, the speed of neither P waves nor S waves is constant. The speed of a wave (P or S) is a function of the density of the rock through which it travels. The denser the rock, the higher the speed. From other, non-seismic, evidence, we know that density increases toward the center of the Earth. That would be obvious, even if the interior of the Earth was composed of the same material throughout, because of the weight of the overlying rock. Therefore, any wave traveling through the deep interior of the Earth accelerates as it travels toward the Earth's center and decelerates as it travels back toward the Earth's surface.

But, the picture of the interior is more complicated than that. Part of how we know the Earth's layers are different is because of the behavior of P and S waves as they travel through the

Earth's interior. In particular, abrupt changes in speeds occur at various depths within the Earth's interior. Dramatic increases in speeds correspond to sharp increases in densities. If the Earth were composed of the same material throughout, we would not expect sharp increases in density. Therefore, there must be another explanation.

We know from laboratory studies that when seismic waves strike a boundary that separates rocks of distinctly different densities, refraction of the wave will occur. The amount of refraction will depend on the difference in the speeds at which the wave will propagate in the two layers. Since differences in speeds are directly related to differences in density, we can say that the amount of refraction will depend on the difference in densities of the two layers through which the wave is propagating. Therefore, sharp increases in the speeds as a wave travels from near the surface toward the center of the Earth can best be explained by assuming that the interior of the Earth has distinctly different, progressively denser, layers.

A seismic wave that strikes a boundary between rock layers with distinctly different densities can also be **reflected**, just like a mirror reflects light. In that case, the angle of incidence (the acute angle between the wave and the boundary) equals the angle of reflection. If a wave is reflected, it simply moves back toward the Earth's surface. For the purpose of this module, however, we do not consider reflection.

LAYERS WITHIN THE EARTH

From a variety of studies, but especially those of earthquakes, scientists have determined that the Earth is made of a series of concentric enveloping spheres. From the Earth's surface to its center, the major spheres are the Crust, Mantle, and Outer Core and Inner Core (see Figure III.5). In general, the rock of each of these spheres is progressively denser than that in the sphere above it. Thus, the mantle is more dense than the crust, and the core is more dense than the mantle. Moreover, density within each sphere generally increases

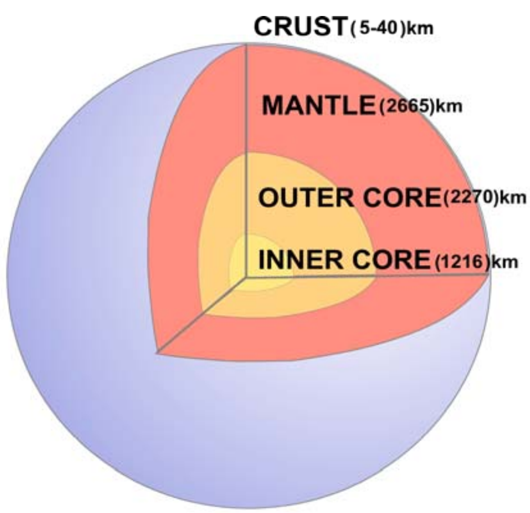

Figure III.5 Layers of Earth's Interior

inward from the outer part of that sphere downward toward the center of the Earth. This increase in density is due to the increase in pressure created by all the rock sitting above each point. Imagine how squished you would be a few hundred kilometers deep in the mantle. Then, imagine how much more squished you would be beneath thousands of kilometers of dense rock in the core! All that rock is being pulled toward the center of the Earth by gravity, and its weight compresses rocks downward into more dense forms.

CRUST

The crust is the thin, solid, outer rind of the Earth, about like an eggshell surrounding the material inside. The crust is composed of continents and ocean basins. Both crustal continental rocks and crustal ocean basin rocks are predominantly made up of silicate minerals. Silicate minerals contain silicon and oxygen, with lesser amounts of other chemical elements, including, but not limited to, sodium, calcium, aluminum, iron, magnesium, etc. In general, crustal rocks of continents, while highly varied are less dense than crustal rocks of the ocean basins.

Much of what we know concerning the details of the structure of the crust has been determined by geological studies. But one particular feature, namely recognition of the base of the crust, was the direct result of earthquake studies nearly a century ago. That boundary separates the crust and the underlying mantle. It has been named the Moho, **or Mohorovicic discontinuity** after its discoverer. It is a boundary at which wave speeds abruptly increase, indicating that the upper part of the mantle is composed of denser, chemically different material than the crust. The depth to the Moho is partially dependent upon what kind of material makes up the crust above it. The continental crust, composed of less dense rocks, is much thicker than the oceanic crust, which is composed of more dense rocks (see Figure III.6). Thus the Moho is shallower (10-15 km) beneath the more dense oceanic crust and is deeper (15-60 km) beneath less dense continental crust.

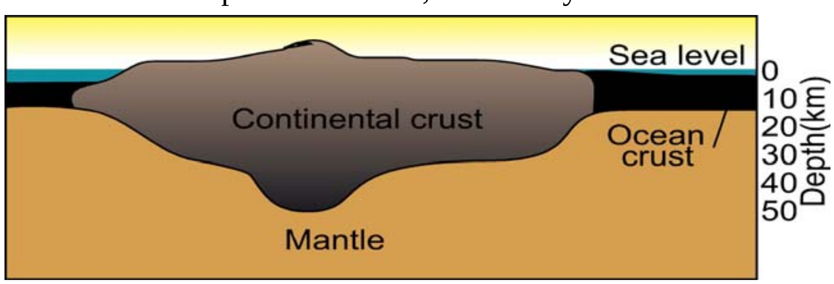

Figure III.6 The Earth's Crust & Mantle

MANTLE

The mantle forms nearly 70% of the Earth and extends from the variable base of the crust (10-15 km beneath the floor of the oceans and 15-60 km under continents) to its base at a depth of about 2890 km. The boundary between the mantle and overlying crust is well defined by dramatic changes in seismic wave speeds. Similarly, the boundary between the mantle and underlying core is well defined by dramatic changes in seismic wave speeds. Other boundaries also occur within the mantle. These internal contacts are generally more transitional in nature and probably represent changes in the crystal structure, but not chemical, properties of mantle rocks due to progressively increasing temperature and pressure. These internal boundaries within the upper mantle are detected by reflection of seismic waves. Like the crust, the mantle consists of rocks composed of silicates, but these mantle rocks are denser than crustal rocks because they are composed of denser minerals than those that make up crustal rocks. While Earth scientists have never drilled deep enough to obtain a piece of rock from the mantle, they have theorized that the composition of the mantle is similar to a common type of meteorite known as a stony meteorite. Even though meteorites have an extra-terrestrial origin, Earth scientists believe that they represent material similar to what is found in the Earth. Earth scientists have also collected other rocks that they think have been ripped away from the mantle and incorporated into the crust. These rocks have a similar composition to that of the stony meteorites.

One complicating feature of the mantle is the Gutenberg Low Velocity Zone. This zone, found in the upper part of the mantle was recognized only forty years ago. This low velocity zone is at a variable depth from as shallow as 60 km beneath oceans to 200-330 km beneath continents. It is believed to be a layer of relatively low density rocks that behave like plastic solids, e.g., “Silly Putty”, and flow as solids, much like a liquid would flow. The mantle rocks above the low velocity zone behave like rigid solids, similar to the physical properties of crustal rocks. Together, the crustal rocks and the uppermost, rigid rocks of the mantle are known as the **lithosphere** (see Figure III.7). Rocks of the lithosphere, both crustal and mantle form the tectonic plates that move relatively independently

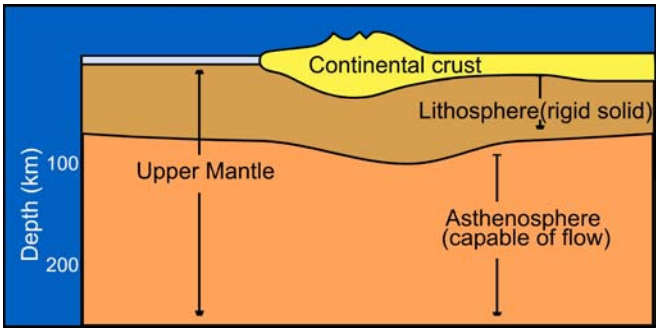

Figure III.7 The Earth’s Lithosphere & Atmosphere above the lower part of the upper mantle. Seismic studies tell us that the mantle below the low velocity layer has some variations in rock type or density. However, below a depth of about 1050 km, the mantle appears to be relatively uniform.

OUTER AND INNER CORE

The spherical core extends from a depth of about 2890 km to the center of the Earth at a depth of 6371 km. It is 3481 km thick and makes up 30% of the Earth's mass! The boundary between the inner and outer core is at a depth of about 5155 km. We know a lot about the core of the Earth from studies of gravity and meteorites. Calculations, which are based upon the gravitational attraction of the Earth relative to other solar bodies, indicate that the total mass of the Earth is greater than it would be if it were only composed of rocks that we see at the surface. This means that the average density (mass per unit volume) of the Earth is greater than the density of surface rocks and therefore the density of the material near the center of the Earth must be much greater than that of surface rocks.

Obviously, scientists have never directly sampled the outer or inner core. But, they still have a good idea about what must make up the core. The density of the core is so great that it must consist primarily of heavier elements than the main elements that make up surface rocks. In order to narrow down the choices of heavy elements that might comprise the core, we look again at meteorites that have been recovered from numerous places on the Earth's surface. Another type of meteorites consists almost exclusively of metallic iron and nickel. These iron-nickel meteorites have a density that is consistent with that needed for the Earth's core when the overall gravity of the Earth is determined. For those reasons, both the inner and outer core are believed to consist mostly of iron and nickel.

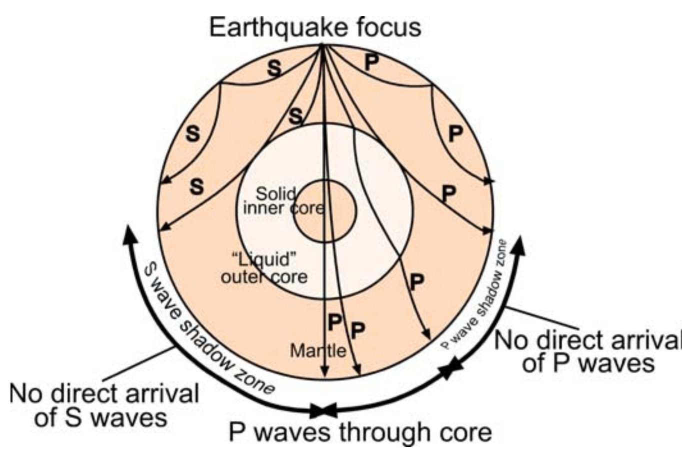

Figure III.8 The Shadow Zone

Earth scientists now believe that the outer core consists of iron and nickel in the liquid state. The reasons for this belief are complex. One reason for this belief is that nearly a century ago early seismologists detected a zone on the opposite side of the Earth from big earthquakes where P waves were not recorded by seismographs, even though the slower moving surface waves were recorded. This "Shadow Zone" occurs between 103^o and 144^o from the focus of an earthquake regardless of where the earthquake occurs in the world (see Figure III.8). Hence the absence of P waves in the Shadow Zone must be a reflection of something that happens during their passage through the Earth's interior.

P-waves traveling from the lower mantle to the outer core go from higher density rock (higher speed) to lower density liquid (lower speed) and the P waves are refracted more toward the center of the Earth. By the time the refracted P waves reach the opposite side of the Earth from the earthquake, they emerge within an inner cone at 144^o from the focus. The P-wave shadow zone thus lies between 103^o, where P waves just graze the core, and 144^o, where the first P waves refract into the core.

It has been found that S waves cannot be propagated through at least the outer part of the core. From that fact one could infer that the outer core must be liquid. A molten, metallic iron-nickel core is also thought to be able to explain the origin of the Earth's magnetic field. All of these observations support the theory that the outer core is composed of molten, metallic iron and nickel.

Earth scientists also believe that the inner core consists of iron and nickel, but in the solid state. This idea is based on studies that showed that P-wave speeds smoothly increase through the outer core and abruptly increase in speed at a boundary within the core. Second, P-waves can be refracted into the inner core and produce both P- and S-waves there. The detection of S-waves indicates that the inner part of the core is solid. The inner core boundary lies at about 5155 km.