Journey to the Center of the Earth©

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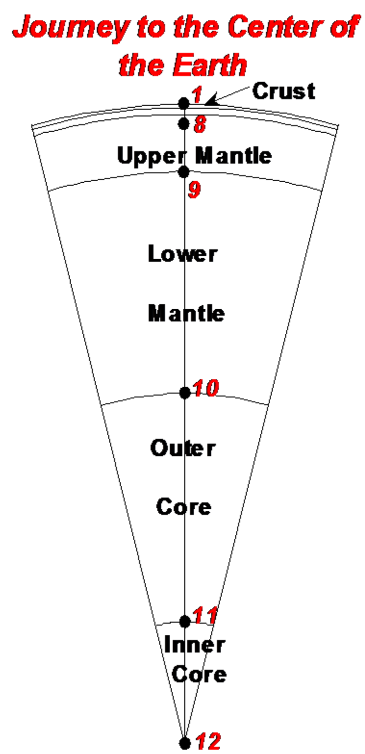
Explorations in Earth Science



"But in the cause of science men are expected to suffer." (p. 28, *A Journey to the Center of the Earth*, Jules Verne, 1864)

Objectives: This virtual journey to the center of the Earth introduces the traveler to the structure, material properties and conditions within the Earth's interior. The size and scale of the Earth and of the Earth's internal structure are also emphasized because the journey utilizes a scale model of the depths within the Earth. Opportunities for creative writing and connections to literature are also provided through Jules Verne's 1864 science fiction novel, *A Journey to the Center of the Earth*, and the 20th Century Fox 1959 movie adaptation (titled *Journey to the Center of the Earth*) starring James Mason, Pat Boone, Arlene Dahl, and Diane Baker.

Background: In the 1800's there was considerable scientific and popular interest in what was in the interior of the Earth. The details of the internal structure (crust, mantle, outer core, and inner core; and their composition and thicknesses; Figure 1) had not yet been discovered. And, although volcanic eruptions demonstrated that at least part of the interior of the Earth was hot enough to melt rocks, temperatures within the Earth and the existence of radioactivity were unknown. Jules Verne's book, *A Journey to the Center of the Earth* (1864, 272 pages; originally published in France as *Voyage au Centre de la Terre*), capitalized on this interest in the Earth and in adventure with an exciting science fiction story that is still popular today. Verne introduces us to a dedicated, and somewhat eccentric professor, and his nephew through whom the story is told (see selected quotations below), who eventually travel into the Earth's deep interior by entering into an opening in the crater of a volcano in Iceland.

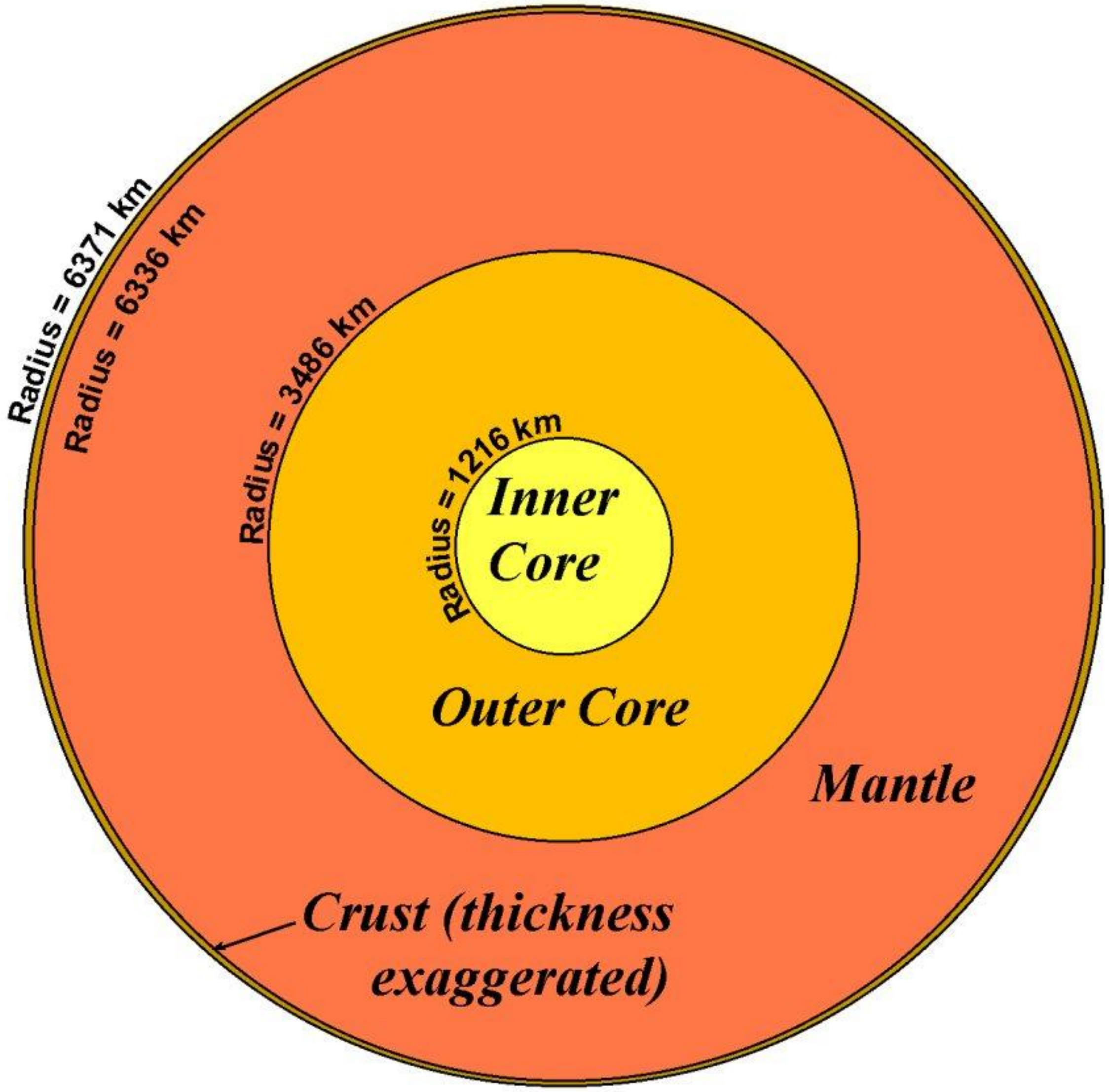


Figure 1. Earth's interior structure. The Earth's crust is made up primarily of silicic (high percentage of Silicon and Oxygen) crystalline (distinct crystals of individual minerals are visible) rocks. The mantle makes up about 82% of the Earth by volume and consists of Iron- and magnesium-rich silicate rocks. The core is mostly iron, with a small percentage of nickel. The outer core is molten and the inner core is solid.

"…and my uncle a professor of philosophy, chemistry, geology, mineralogy, and many other ologies." (p.1, Jules Verne, 1864)

"I loved mineralogy, I loved geology. To me there was nothing like pebbles—and if my uncle had been in a little less of a fury, we should have been the happiest of families." (p.3, Jules Verne, 1864)

"His imagination is a perfect volcano, and to make discoveries in the interest of geology he would sacrifice his life." (p. 14, Jules Verne, 1864)

Verne's novel is science fiction. We know today that such a journey would be impossible. The temperature and pressure conditions within the Earth are so extreme that humans could not survive below a few kilometers depth within the 6371 km radius Earth. Furthermore, we know of no significant openings that would provide access to the deep interior of the planet, and caves or cavities at great depth are nearly impossible based on our knowledge of temperature and pressure within the Earth and the properties of Earth materials. However, Verne's story is an interesting one and it is the inspiration (along with the desire to provide materials for learning about the Earth's interior) for this Earth science educational activity.

By the late 1800's, observations of temperature in mines and drill holes had demonstrated that temperature within the Earth increased with depth, and thus it is possible that the Earth's interior is very hot. Seismographic recordings in the early 1900's were used to identify the Earth's thin (about 5 – 75 km thick) crust (in 1909) and the existence of the core (in 1906). In 1936, Danish seismologist Inge Lehman presented evidence for the existence of a solid inner core. Since then, seismology and other geological and geophysical studies have provided considerably more detailed information about the structure, composition and conditions of the interior of the Earth. These features will be highlighted during our virtual "Journey to the Center of the Earth".

As it is commonly done, we have represented (Figure 1 and Table 1) the Earth as a layered sphere of 6371 km radius. The Earth is actually not quite spherical. Because of the rotation on its axis, the Earth is approximately an ellipsoid with the equatorial radius being about 21 km larger than the polar radius. Also, in detail, the Earth is not exactly spherically symmetric. Lateral as well as vertical variations in composition and rock properties have been recognized from seismological and other geophysical observations. Finally, because of plate tectonics, there are significant differences in shallow Earth structure in continental versus oceanic areas, near plate boundaries, and at different locations on the surface. For these reasons, the depths to the boundaries that we will encounter in our journey would be slightly different if we chose a different location for the start of our journey. The depths, properties and other descriptions listed in the scale model for our journey are reasonable average values for a continental region.

Once one realizes that the interior of the Earth is hot, it is natural to ask, why is it hot? Because the Earth is 4.5 billion years old, it would seem logical that the planet would have cooled by now. The heat within the Earth results primarily from two sources – original heat from the Earth's formation and radiogenic heat (Poirier, 2000). The largest of these sources, radiogenic heat, is mostly produced by three, naturally occurring, radioactive elements, Uranium, Thorium and Potassium. These elements are present in the mantle at concentrations of about 0.015 ppm (parts per million; meaning that only about 15 of every billion atoms in the mantle are Uranium) for

Uranium, 0.080 ppm for Thorium and 0.1% for Potassium (Brown and Mussett, 1981). Spontaneous radioactive decay of these elements releases heat. Although the major radioactive elements are more concentrated (10 to 100 times as abundant) in the Earth's crust, most of the radiogenic heat production comes from the mantle because of the much greater volume. The original heat from formation of the Earth dates from the accretion of the Earth from planetesimals that bombarded the early planet converting gravitational energy into heat.

Modern scientific information about the interior of the Earth comes from a variety of studies including: seismology in which seismic waves from earthquakes and other sources are used to generate images of the interior structure and determine the physical properties of Earth materials; analysis of the Earth's gravity field indicates density variations; high-pressure mineral experiments that are used to infer the composition of deep layers; thermal modeling of temperature measurements in drill holes; modeling of the Earth's magnetic field that is produced by convection currents in the electrically-conductive outer core; and chemical analysis of rock samples (called xenoliths) from deep within the Earth that are brought to the surface in volcanic eruptions. More information about the deep Earth and the methods of study of the Earth's interior can be found in the references listed below. A good starting point is the book by Bolt (1993), the American Scientist article by Wysession (1995) or a chapter on the Earth's interior by Wysession from an introductory geology textbook (see reference list). More advanced readers may wish to refer to Brown and Mussett (1981), Jeanloz (1993), Ahrens (1995), Wysession (1996), Poirier (2000) and Gurnis (2001). For younger readers, examine the children's book by Harris (1999). Much of the information about deep Earth properties and conditions given in Table 1 comes from Ahrens (1995). Information about microbes in the Earth's crust (mentioned in the Narrative, Stop number 3) is from Fredrickson and Onstott (1996).

Procedure and Teaching Strategies: A scale model (either a "classroom" scale or a "playground or hallway" scale; Figures 1 and 2 and Table 1) is used to provide the depths and locations of stops for a virtual journey to the center of the Earth.

Using a meter stick or meter wheel, mark out the locations of the 12 stops in the classroom (1:1,000,000 scale model; 6.37 m long) or playground or hallway (1:100,000 scale model; 63.7 m long). Masking tape placed on the floor or pavement is a convenient method for marking the stops. A felt pen can be used to label the stop number on the strip of masking tape. Folded index cards, labeled with the stop number, can also be used and have the advantage that the numbers can be seen from a distance (looking forward or backward to stops along the journey. Depths and the names of the locations can also be labeled using the masking tape, if desired. Provide each student in the class with a copy of the "Tour Guide" that can be produced as described near the end of this document. Folding the page in "thirds" creates a small brochure that each student can use on the tour and take home to help them remember the information that they learned and their experiences on the Journey to the Center of the Earth.

1. With the class, start at stop number 1 (the Earth's surface) and read the first part of the "Journey to the Center of the Earth Narrative" (below). Proceed to the other stops and read the appropriate section of the narrative at each stop. Be sure to point out the

distance that you've traveled in each move (by looking forward and backward along the model and using the scaled and actual distances from Table 1) and the distance that is remaining to travel to the Earth's center. Answer student (traveler) questions at each stop. The information in Table 1 may be useful for answering questions. Other questions may form the basis of class or individual student research ("let's find out") using the references listed below or library or Internet searches.

2. When back in the classroom, use transparencies (or copies) of Table 1 and Figures 1, 2 and 3 to review with the students the main features of the Earth's interior and the properties and conditions at various depths within the Earth. Note the increases in density, temperature and pressure with depth within the Earth and the abrupt changes in density at the major boundaries between layers. Additional questions can be answered or used to prompt additional study (such as other activities related to the Earth's interior structure or plate tectonics) or research or to provide an assessment of student learning from the activity.

3. As an extension, or to connect to reading, writing and literature study, have the class read Jules Verne's *A Journey to the Center to the Earth* (or selected chapters) or watch the movie (it is about 2 hours long, although one could skip the first approximately 30 minutes; starting as the explorers begin to climb the volcano). Relevant writing assignments for the students could be to write their own brief version of *A Journey to the Center of the Earth* based on the more accurate information about the nature of the Earth's interior; write a review of the book or movie, or write about the inaccuracies and misconceptions that are evident in the book and movie. The accuracies and misconceptions also can provide material for an effective class discussion and assessment of student learning after reading Verne's book or viewing the movie.

4. For younger students, reading *Journey to the Center of the Earth* (Harris, 1999) or *The Magic School Bus Inside the Earth* (Cole, 1987) before or after completing the journey is a useful extension and connection to literature.

5. Related Earth structure activities include Earth's Interior Structure (Braile, 2000) and Three-D Earth Structure Model (Braile and Braile, 2000). A useful and attractive color poster (Earth Anatomy poster) illustrating Earth's interior structure is available from the Wright Center for Science Education, Tufts University. A page size version of the poster can be downloaded from http://www.tufts.edu/as/wright_center/svl/posters/erth.html.

6. Additional extensions are also possible. An interesting assignment is to have each student or pair of students select one stop (depth) along the journey. Have the student or student team learn about the materials and conditions at that depth (some additional reading from the references provided below or from online sources would be necessary) and then draw an illustration that can be used to help describe each stop on the journey. Rock samples, if available (even photographs of rock or mineral samples from a book or from the Internet*), could also be placed at each stop to help illustrate the materials that

make up the Earth's interior. A piece of iron or steel can be used for the Earth's core remembering that it will be liquid iron in the outer core. The student experts from one class, stationed at each stop, could also be the tour guides that would provide information, show their illustration and rock sample, and read the appropriate section of the journey narrative for another class or group of students. The experience of students learning in-depth information about one area of the tour and serving as "experts" can be an excellent "students teaching students" approach to learning. To emphasize the long journey or tour experience in the "Journey to the Center of the Earth" activity, a glass of water, a piece of candy or other refreshments could be served at one of the stops, probably the core/mantle boundary (stop 10) which is a little less than half way along the journey in terms of depth.

7. Connections of this activity to the National Science Education Standards (National Research Council, 1996) are listed in Table 3 below.

* Photographs of appropriate rocks and minerals can be found at several online sources, including: http://www.soes.soton.ac.uk/resources/collection/minerals/ (these photos can be enlarged by clicking on the photo until the photograph is almost full screen size); examples of sedimentary rocks are appropriate for the surface stop, number 1, click on "Sedimentary Rocks" at top of web page; for example, see sample #8, a sandstone; Granite samples from the "Igneous Rocks" link can be used for stops 2, 3, 4, and 5, alternatively, Gneiss samples could be used to represent crustal rocks, particularly for stops 4 and 5 that are deeper in the upper continental crust; Gabbro or Basalt samples, also from the "Igneous Rocks" link can be used to represent lower crustal rocks; a photograph of Olivine, an iron-magnesium silicate that is a common mineral in the Earth's mantle – stops 6 – 10 – can be found in the "Minerals" section of the above web site or at: http://www.musee.ensmp.fr/gm/836.html; for the Earth's core, a photo of an iron-nickel meteorite (http://www-curator.jsc.nasa.gov/outreach1/expmetmys/slideset/IronMet.JPG) is a good representation of the material that forms the core. A selection of photos that are useful for representing typical rocks from the Earth's interior is provided in Table 2 below.

Table 1. ***Journey to the Center of the Earth***

Stop Num.	Depth (km)	Scaled Depth (m) 1:1 million	Scaled Depth (m) 1:100,000	Name or Location	Rock/ Material	Density (g/cm^3)	Pres-sure (MPa)	Temp. (Deg C)
1	0	0	0	Earth's Surface	Atmosphere Sediments	0.001 1.5	0.1	~10
2	1	0.001 (1 mm)	0.01 (1 cm)	Top of "Basement"	Sed. Rocks Granitic Rk.	2.0 2.6	20	~16
3	3.6	0.0036 (3.6 mm)	0.036 (3.6 cm)	Deepest Mine	Granitic Rock	2.7	100	~50
4	10	0.01 (1 cm)	0.1 (10 cm)	Upper Crust	Granitic Rock	2.7	300	~180
5	12	0.012 (1.2 cm)	0.12 (12 cm)	Deepest Drill Hole	Granitic Rock	2.7	360	~200
6	35	0.035 (3.5 cm)	0.35 (35 cm)	Base of Crust ("Moho")	Mafic Rock Olivine-rich Rk.	3.0 3.3	1100	~600
7	100	0.1 (10 cm)	1	Base of Lithosphere	Olivine-rich Rock	3.4	3200	~1200
8	150	0.15 (15 cm)	1.5	Astheno-sphere	Olivine-rich Rock	3.35	4800	~1300
9	670	0.67 (67 cm)	6.7	Upper Mantle Transition	Fe-Mg Silicate	4.1	23800	~1700
10	2885	2.885	28.85	Core/Mantle Boundary	Fe-Mg Silicate Liquid Iron	5.6 9.9	135800	~3500
11	5155	5.155	51.55	Inner Core/Outer Core Bound.	Liquid Iron Solid Iron	12.2 12.8	329000	~5200
12	6371	6.37	63.7	Center of Earth	Solid Iron	13.1	364000	~5500

Table 1. (cont.) *Journey to the Center of the Earth*	
Stop Num.	**Description/Comments**
1	The Earth's surface is a marked boundary, between the solid or liquid Earth below and the Atmosphere above, with distinct changes in properties. Surface materials on land are usually soil, sediments, sedimentary rocks or weathered crystalline rocks.
2	Beneath surface sedimentary rocks, lies a crystalline "basement" made up of igneous or metamorphic rocks, usually of granitic composition. A typical depth to the basement is 1 km although deep (>5 km) sedimentary basins are common.
3	The deepest depth that humans have explored on land is in a gold mine in South Africa -- almost 3.6 km deep. In the oceans, a special submarine carried explorers to the bottom of the Mariana trench at over 11 km below the Pacific Ocean's surface.
4	Upper layer of continental crust consists of granitic (high % of Silicon and Oxygen) rocks. Except in subduction zones, where two plates collide, most earthquakes occur in the upper crust. Lower crust is more mafic (higher % of Mg and Fe).
5	The deepest drill holes in the Earth are about 12 km deep. Rock samples have been recovered from these depths. The holes have been drilled for scientific study of the crust and to explore for petroleum in deep sedimentary basins.
6	The crust-mantle boundary, or "Moho", separates mafic rocks of the lower crust from Olivine-rich rocks that make up the Earth's mantle. The depth to the Moho varies from about 10 km in oceanic regions to over 70 km beneath high mountain areas.
7	The depth of this boundary is controlled by temperature. It is a gradual rather than an abupt boundary. The lithosphere (tectonic plates) above is relatively cool, rigid and brittle. Lower lithosphere is mantle. Beneath is the "soft" asthenosphere.
8	Partial melting of mantle rocks in this layer produces magma for volcanic eruptions and intrusions. Although a solid, asthenosphere is hot enough to flow in convection currents. Lithosphere/asthenosphere boundary is shallower in hot regions.
9	As pressure increases with depth in mantle, Fe and Mg silicate minerals compress into more dense crystalline forms in the transition zone and below. Mantle is relatively homogeneous chemically and forms ~82% of Earth by volume. Deep earthquakes in subduction zones are found to a depth of about 670 km.
10	Boundary separates liquid iron core from the silicate rock mantle. A transition zone (~200 km thick) exists just above the core-mantle boundary that may represent areas of partially melted mantle (the bottom of mantle plumes) from heat flowing from the outer core, or old lithospheric slabs that have descended to the bottom of the mantle. The core is ~16.5% of the Earth by volume but about 33% of the Earth by mass. No seismic shear waves travel in outer core. Convection currents in the electrically conductive outer core produce Earth's magnetic field.
11	This boundary separates the solid inner core from the liquid iron (and ~10% nickel, sulfur, silicon and oxygen) outer core. Although the radius of the inner core is about 1216 km, the inner core includes only about 0.7% of the volume of the Earth.
12	Earth's center is within the dense, iron inner core. Although the temperature is very high, the pressure is so great (~3.6 million times the pressure at the surface), that the inner core is solid.

Table 1. (cont.) ***Journey to the Center of the Earth*** **Description of Column Headings:**
1. Stop Number -- The stop number for our virtual "Journey to the Center of the Earth", in which we will travel from the Earth's surface to the Earth's center (using a scale model).
2. Depth -- The depth (in the Earth) in kilometers corresponding to each stop in our journey. Many of the depths are approximate and will vary by location.
3. Scaled Depth -- The depth (in meters) for each stop in the 1:1 million scale model. Total depth (surface to center) in the scale model is 6.37 m. "Classroom scale" model.
4. Scaled Depth -- The depth (in meters) for each stop in the 1:100,000 scale model. Total depth (surface to center) in the scale model is 63.7 m. "Playground or hallway scale" model.
5. Name or Location -- Description or name of the location of each stop.
5. Rock/Material -- Rock type, description or composition of the material at each stop. Two entries separated by a line give the rock type or material both above and below a boundary at the corresponding depth.
6. Density -- The approximate density (in grams per cubic centimeter; for comparison, the density of water is 1 g/cm^3) of the material at each stop. Two entries separated by a line give the density of the rock or material above and below the boundary.
7. Pressure -- The approximate pressure (in Mega-Pascals) at each stop (depth in the Earth). One atmosphere of pressure (the pressure at the Earth's surface due to the weight of the atmosphere above us) is about 0.1 MPa (1 Kg/cm^2 or ~14 lbs/in^2). The pressure in the tires of a car (and at about 10 meters depth under water) is about 2 atmospheres or about 0.2 MPa.
8. Temperature -- The approximate temperature in degrees Celsius at each stop (depth in the Earth).
9. Description/Comments -- Description and comments about the material and conditions at each stop in the journey.

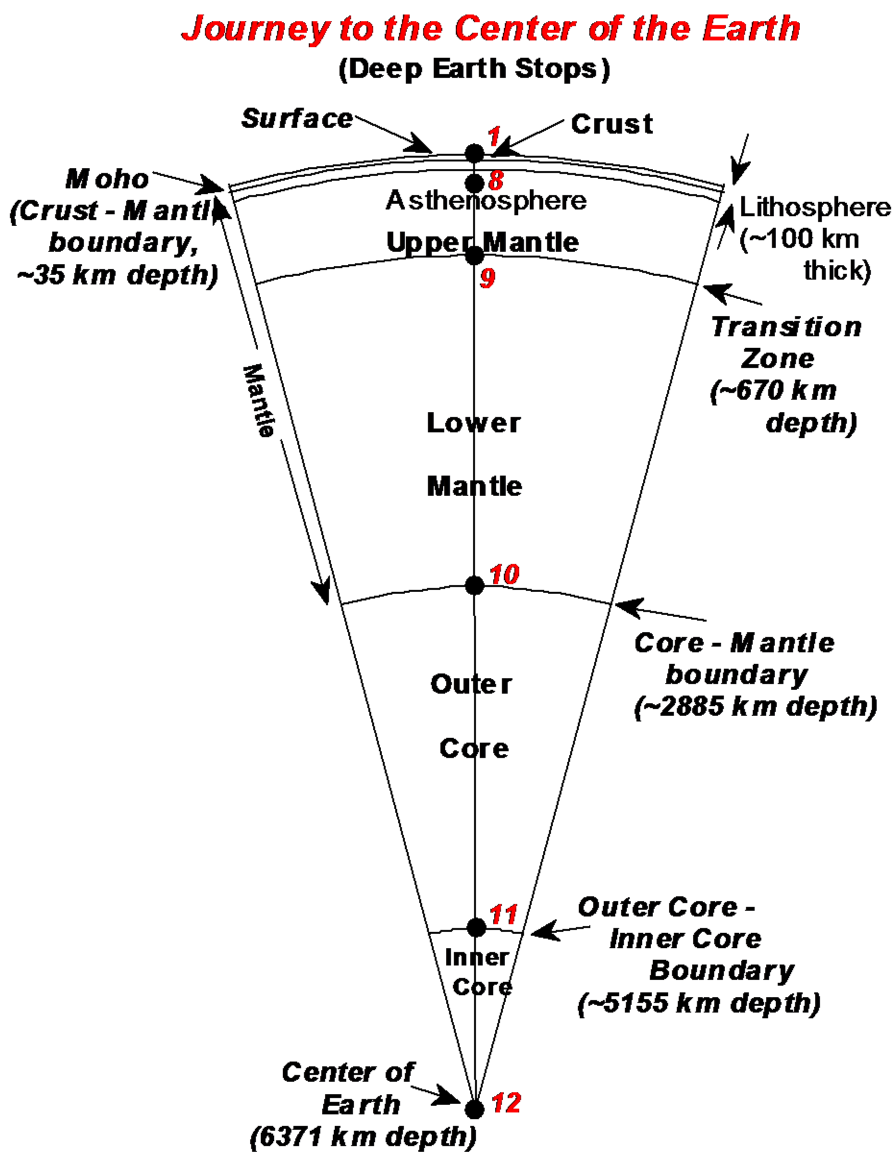


Figure 2. Earth's interior (to scale) showing the depths to the major boundaries between the Earth's layers (spherical shells). The numbered dots indicate the locations of the stops (Table 1) in our virtual journey. A close-up view (Figure 3) of the upper 150 km of the Earth's interior shows the locations of the first eight stops.

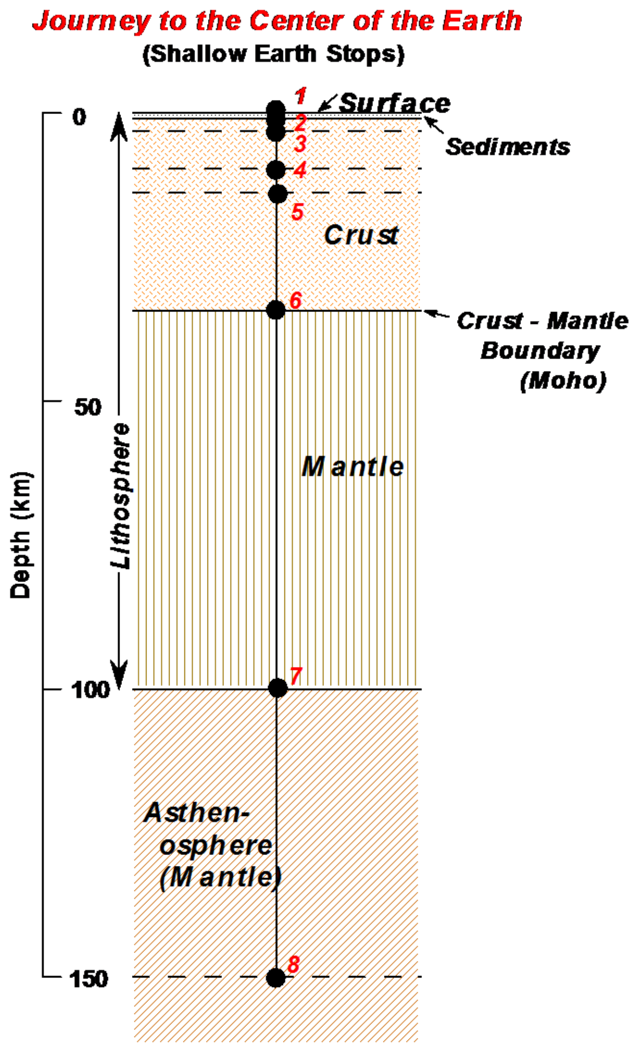


Figure 3. Shallow Earth structure showing the depths to boundaries in the upper 150 km of the Earth. The numbered dots indicate the locations of the first 8 stops (Table 1) in our virtual journey.

Narrative for "Journey to the Center of the Earth":

Attention! Attention! We are ready to start our journey to the center of the Earth. My name is Mrs. Braile[1] and I will be your tour guide today. We are going to learn many fascinating things about the interior of the Earth. Please feel free to ask questions along the way and I will try to answer them. Our journey is long, so I hope that you've had a big breakfast. Also, there are no rest rooms along the way. So, prepare yourself for an exciting journey!

We will begin at the Earth's surface – our familiar home. Except for natural caves, tunnels, mine shafts, and drill holes that extend from the surface to depths of a few kilometers, we know of no large openings that could provide access to the Earth's deep interior. Furthermore, the very high temperature and pressure and the lack of air in the deep Earth create conditions that we could not survive. In addition, it is a long journey – it is 6371 kilometers to the Earth's center. If we were able to walk directly to the Earth's center, it would take about 53 days (at 5 km/hr, 24 hours per day) of walking. And then, we'd have to walk back! Even if there were a very fast elevator that would take us to the Earth's center, the time that our journey would take would only be reduced to about 4 ½ days. If there was a highway to the Earth's center, it would take about 64 hours to drive there at 100 km/hr. Because of these facts, we will be taking a *virtual* journey to the center of the Earth using a scale model. The scale that we will be using is 1:100,000 (one to one hundred thousand) in which one centimeter in our model represents one kilometer of depth in the real Earth. Using this scale, our model of the distance from the Earth's surface to its center is 63.7 meters long.[2] Another way to understand the concept of scale is to realize that we would have to multiply the depths in our scale model by *100,000* in order to produce the actual depths in the Earth! We will begin at the surface and make 12 stops along our journey to the center of the Earth. At each stop, we'll observe the relative distance that we've traveled in our scale model, and learn about the materials and conditions that exist at these locations within the Earth.

Stop Number 1 – Earth's Surface: We're already at our first stop – the Earth's surface. If we began our journey at a different location we would probably find different geological materials at the surface. For example, if we started in a desert region, we might find sand deposits or sandstones at the surface, or if we started in Hawaii, we would most likely begin on volcanic rock. If we began our journey in the middle of the ocean, we would find a layer of ocean water at the surface. Here in Indiana, the near-surface deposits are mostly glacial sediments deposited during the period of 15,000 to about a million years ago.[1] Beneath the glacial sediments are layers of Paleozoic sandstones, shales and limestones that were deposited in a shallow ocean over 300 million years ago. Of course, above us is the Earth's atmosphere, consisting of about 21% oxygen, which we breathe in order to live. Deep in the Earth, we would not have sufficient air to breath. However, that won't be a problem in our virtual journey.

Let's go to our next stop – it isn't far.

Stop Number 2 – Top of the Crystalline Basement: Here we are about 1 km beneath the surface. In continental regions, this is a typical depth to the bottom of the near-surface sediments and sedimentary rocks. The crystalline basement is immediately beneath us. In areas where there are deep sedimentary basins, or in ocean basins, the depth to the basement is significantly greater – up to 10 km or more. In continental areas, the crystalline basement usually consists of igneous and metamorphic rocks of granitic composition. These rocks have interlocking crystals made of minerals that are easily visible and have a composition that includes about 70% Silicon and Oxygen. You may be familiar with the common igneous rock of this type, called granite. The crystalline basement is the top of a layer that makes up most of the Earth's crust.

Our next stop is even deeper in the crust.

Stop Number 3 – Depth of Deepest Mine: This stop is at a depth of 3.6 km (3600 meters) below the surface and is the depth of the deepest mine in the world. It is a gold mine in South Africa, and it's the greatest depth that humans have gone beneath the continents. However, it is not the greatest depth where life exists. Subsurface bacteria (microbes) have been found in drill holes about 3 km beneath the surface and have been shown to be able to survive temperatures as high as 110 degrees Celsius. At this temperature, it is likely that microbes exist in the Earth's crust as deep as about 7 km beneath oceans and about 4-5 km beneath continents.

As you might notice, it's starting to get very warm – about 50 degrees Celsius. You can touch the rocks but don't leave your hand on the rocks for very long or you will burn your hand!

Let's move on.

Stop Number 4 – Upper Crust: We're now deep within the crust at a depth of 10 km. Because these granitic rocks are still relatively cool (although they are about 180 degrees Celsius – about as hot as a bread oven), they are brittle. Except in subduction zones, where two tectonic plates collide, most of the world's earthquakes occur within the upper crust within a few kilometers of our present depth. If we had begun our journey above a deep sedimentary basin, we might find petroleum deposits (oil or natural gas within the pore spaces of sandstones or other porous rocks) at this depth. If we had begun our journey at the surface of the ocean, we would be near the base of the oceanic crust at this depth. The oceanic crust consists of marine sediments overlying rocks of approximately basaltic composition.

If there are no questions, we'll go to the next depth.

Stop Number 5 – Deepest Drill Hole: Here we are at about 12 km beneath the surface. This is the depth of the world's deepest drill hole (in the Kola peninsula of Russia). The pressures and temperatures are so great that it is difficult to build drill bits and drilling equipment that will penetrate these rocks. The rocks are also so compacted that there is almost no space between the crystals or grains that make up the rocks. We definitely couldn't survive here.

Although our next stop is the base of the continental crust, it's only about one half of one percent of the way along our journey! We shouldn't delay.

Stop Number 6 – Base of the Crust: We've reached the base of the crust. It is also called the crust/mantle boundary, or "Moho", after Andrija Mohorovicic the Croatian seismologist who discovered this prominent boundary in 1909. If you'll look back toward the Earth's surface, you'll notice that we really haven't gone very far on our journey to the center of the Earth. The depth to the Moho averages about 35 km beneath continents but is about 10 – 15 km depth beneath oceans. The Moho is an abrupt boundary in composition and properties. Just above the Moho, the lowest layer of the crust consists of more mafic (higher in Magnesium and Iron) rocks than the granitic rocks that we've been traveling through in the upper crust. Below is the mantle – a thick layer that forms about 82% of the Earth's volume; so we'll be traveling through the mantle for a long time. Like the crust, the mantle is also made up of silicate (high percentage of Silicon and Oxygen) rocks. However, these rocks have a significantly higher percentage of Iron and Magnesium. A common material in the mantle is Olivine – an olive green mineral that is commonly found as large crystals in basaltic volcanic rocks such as in Hawaii.

Let’s go to the next stop.

Stop Number 7 – Base of the Lithosphere: Here we are at the base of the lithosphere. Notice that the lithosphere consists of the crust *and* the uppermost part of the mantle. This boundary is gradual with depth, not an abrupt “discontinuity”. The depth (~50 – 300 km) to the base of the lithosphere is controlled by temperature. Where temperatures in the upper mantle are higher than average, such as beneath mid ocean ridges and in active tectonic zones in continental areas, the lithosphere is thinner. Old, relatively cool lithosphere is much thicker. The lithosphere forms the tectonic plates that separate, collide, and slide past each other to create the Earth’s landscape and produce mountain ranges, faults, earthquakes and volcanic eruptions. Below the lithosphere, temperatures are hot enough to partially melt the mantle rocks, forming the asthenosphere – the primary source of magma that erupts from volcanoes on the surface.

The asthenosphere is our next stop.

Stop Number 8 – Asthenosphere: Except beneath areas that are very old (over about one billion years) and have relatively cool upper mantle, at our current depth of 150 km, we would find ourselves within a very hot (about 1300 degrees Celsius) mantle that is partially (probably less than 1-2 percent) molten and flowing. Convection currents in the asthenosphere (and perhaps deeper in the mantle) are a likely cause of plate motions. Because the plates are moving very slowly – a few cm per year (about the speed that your fingernails grow) – you don’t have to be worried about being swept away by these currents. Because seismic shear waves travel through the asthenosphere, we classify this part of the mantle (as well as the rest of the mantle) as a solid even though it flows. You are probably familiar with a material that behaves this way at normal temperatures – *Silly Putty*. Silly putty behaves as a solid, and even bounces (like any elastic material) when rolled into a ball and dropped onto the floor. However, it can be stretched, and slowly flows over longer periods of time. It even flows slowly into the form of the plastic egg-shaped container that it is sold in. This behavior, over longer periods of time, is more like a liquid.

Take a close look at the rocks here. You might find diamonds! Diamonds form in the upper mantle from Carbon atoms at high pressure at depths greater than about 150 km. The diamonds can be deposited closer to the surface in “Kimberlite pipes” – narrow vents that are created in brief explosive eruptions.

Well, we’ve got a long distance to go to our next stop, so we’d better start walking.

Stop Number 9 – Upper Mantle Transition Zone: We’re well below the asthenosphere now at about 670 km depth. The pressure is so great at this depth that some of the minerals that form mantle rocks undergo a transformation in their crystal structure that results in a tighter packing of the atoms that make up the mineral. Because of this tighter packing, mantle rocks in the upper mantle transition zone (about 400 – 700 km) become denser with depth even though the chemical composition of the rocks is virtually the same. Therefore, lower mantle rocks are similar in composition to the olivine-rich rocks of the upper mantle but are of higher density. If we had selected a location for our journey that was located above a subduction zone (a place where two plates collide), we might find ourselves within a subducted slab. These parts of lithospheric plates descend, normally at steep angles and at typical plate tectonic velocities – about 2-10 cm/year, from the collision zone at the surface into the mantle. Therefore, these slabs formerly were near the Earth's surface. Because the slabs remain cooler than the surrounding mantle for tens of millions of years, deep earthquakes occur within or at the edges of these slabs. The deepest earthquakes occur at about 670 km depth.

I know that you can feel the intense heat and pressure that are present at this depth, so we need to move on. Our destination, the center of the Earth, is still very distant; in fact, we've only traveled just over 10 percent of our journey. We'll make fewer stops for the rest of the journey.

Stop Number 10 – Core/Mantle Boundary: We're now 2885 km below the surface and at the core/mantle boundary. Let's turn around and look at the Earth's surface to see how far we've gone and to see how much of the Earth is mantle. Let's also look further down in depth to the Earth's center to see how far we have to go. This boundary is the most prominent boundary in the Earth's interior. It is a dramatic boundary in composition, and therefore density, with silicate rocks of the mantle above and dense iron and nickel below. In addition, the mantle above is solid and the outer core below is liquid. The boundary probably varies laterally, and in detail is a transition zone above the liquid outer core that is about 200 kilometers thick. The transition zone has been interpreted to consist of the bottom of mantle plumes where heat flowing from the outer core causes partial melting of the mantle rocks above the core mantle boundary and lithospheric plates (old subducted slabs) that have descended to the bottom of the mantle. The temperature here is about 3500 degrees Celsius, about 2 –3 times hotter than a blast furnace and hot enough to melt iron even under the great pressure that exists at this depth. Because of the dense rocks and high pressure, compressional seismic waves (P-waves) travel at nearly 14 km/s in the mantle just above this boundary. Because the outer core is liquid, the P-wave velocity decreases to about 8 km/s and shear (S) waves cannot propagate in the outer core. Also, the hot, electrically-conductive outer core liquid flows by convection, generating the Earth's magnetic field. It is this magnetic field that aligns the needle on our compass at the Earth's surface.

You may wonder why the temperature is so high in the Earth's interior. Most of the heat comes from radioactive decay of Uranium, Thorium and Potassium atoms that are found in the mantle. These elements are of fairly small concentration in the mantle, so the level of radioactivity is low. However, there are enough radioactive atoms in the mantle to generate significant heat. Some of the Earth's heat was also generated at the time of formation of the planet by bombardment of planetesimals (causing melting) during the accretion of the Earth. Because rocks are not good conductors of heat, the temperature in the interior has remained high.

Well, it's really getting hot, so I'm sure that you're anxious to complete our journey and get back to the Earth's surface. Let's hurry to our next stop.

Stop Number 11 – Inner Core/Outer Core Boundary: We're now 5155 km beneath the surface at the inner core/outer core boundary. The material both above and below us is iron, along with a small percentage of nickel and probably oxygen or sulfur. Above us the iron-nickel outer core is molten. Below us the pressure is so high that, even though it is very hot, the iron-nickel inner core is solid. Although the radius of the inner core is 1216 km (look toward the center of the Earth in our model; that's how far we have to go), the inner core is only 0.7 percent of the Earth by volume.

Let's hurry; only one more stop!

Stop Number 12 – Center of the Earth: Well, we made it. Congratulations, we're at the center of the Earth! It's 6371 km back to the surface. Take a look at how far we traveled from the surface. The temperature is about 5500 degrees Celsius. The pressure is over 3.6 million times the pressure at the Earth's surface. HOWEVER, I MUST WARN YOU TO HOLD ON! Because there is approximately the same amount of Earth all around us (we're in the center of a nearly spherical planet), Earth's gravity here is ZERO. *If* there was an opening here, we would feel weightless! However, the pressure and temperature are very high, so we could not survive. It's a good thing this is a *virtual* journey!

It's now time to go back to the surface. It's been a long journey, so let's go directly back.

Back at Stop Number 1 – Earth's Surface: Thank you for being such a good tour group! I hope that you've enjoyed our Journey to the Center of the Earth and that you've learned some interesting things about the Earth's interior. If you have any additional questions about our journey or about the interior of the Earth, I'd be glad to try to answer them for you.

[1] There are several places in the narrative that can be personalized for your use.
[2] The narrative is written assuming the playground or hallway (1:100,000, or 63.7 m long) scale model (Table 1). If the classroom (1:1,000,000, or 6.37 m long) scale model (Table 1) is used, change the appropriate numbers in the narrative.

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Acknowledgments: We thank Michael Wysession, Barry Marsh and John and Kathy Taber for providing information or assistance. The development of this activity was partially supported by the National Science Foundation.

Tour Guide: Provide each student in the class with a copy of the "Tour Guide" that can be produced by printing the next two pages of this document. Trim each image and enlarge each one to fit on one page. Or, print the Tour Guide from the .doc (recommended; margins are better) or .pdf files: guide.doc or guide.pdf. Copy (in color or black and white) on the front and back of a sheet of paper. Make copies for the class. Folding the page in "thirds" creates a small brochure that each student can use on the tour and take home to help them remember the information that they learned and their experiences on the Journey to the Center of the Earth.

To generate additional interest in the Journey to the Center of the Earth tour, one can make a construction paper "hardhat" (Figures 4 and 5) for the tour leader or for each participant in the tour (the idea of wearing a hat for the tour was provided by John and Kathy Taber).

Labels: A set of labels for the stops along the Journey tour is available in the MS Word document: http://web.ics.purdue.edu/~braile/edumod/journey/labels.doc. The labels include a single page to mark the first five stops. Labels that can be placed at the appropriate scaled distance for Stop 1 and Stops 6-12 are also included. The label for the first five stops is designed for the 1:100,000 scale (63.7 m scale model). The labels should be printed on card stock paper. Labels for Stops 1 and 6-12 can be folded to make a convenient and visible sign.

This document at:
MS Word format: http://web.ics.purdue.edu/~braile/edumod/journey/journey.doc
HTML format: http://web.ics.purdue.edu/~braile/edumod/journey/journey.htm
PDF format: http://web.ics.purdue.edu/~braile/edumod/journey/journey.pdf
PPT: http://web.ics.purdue.edu/~braile/edumod/journey/journey.ppt

http://web.ics.purdue.edu/~braile
braile@purdue.edu

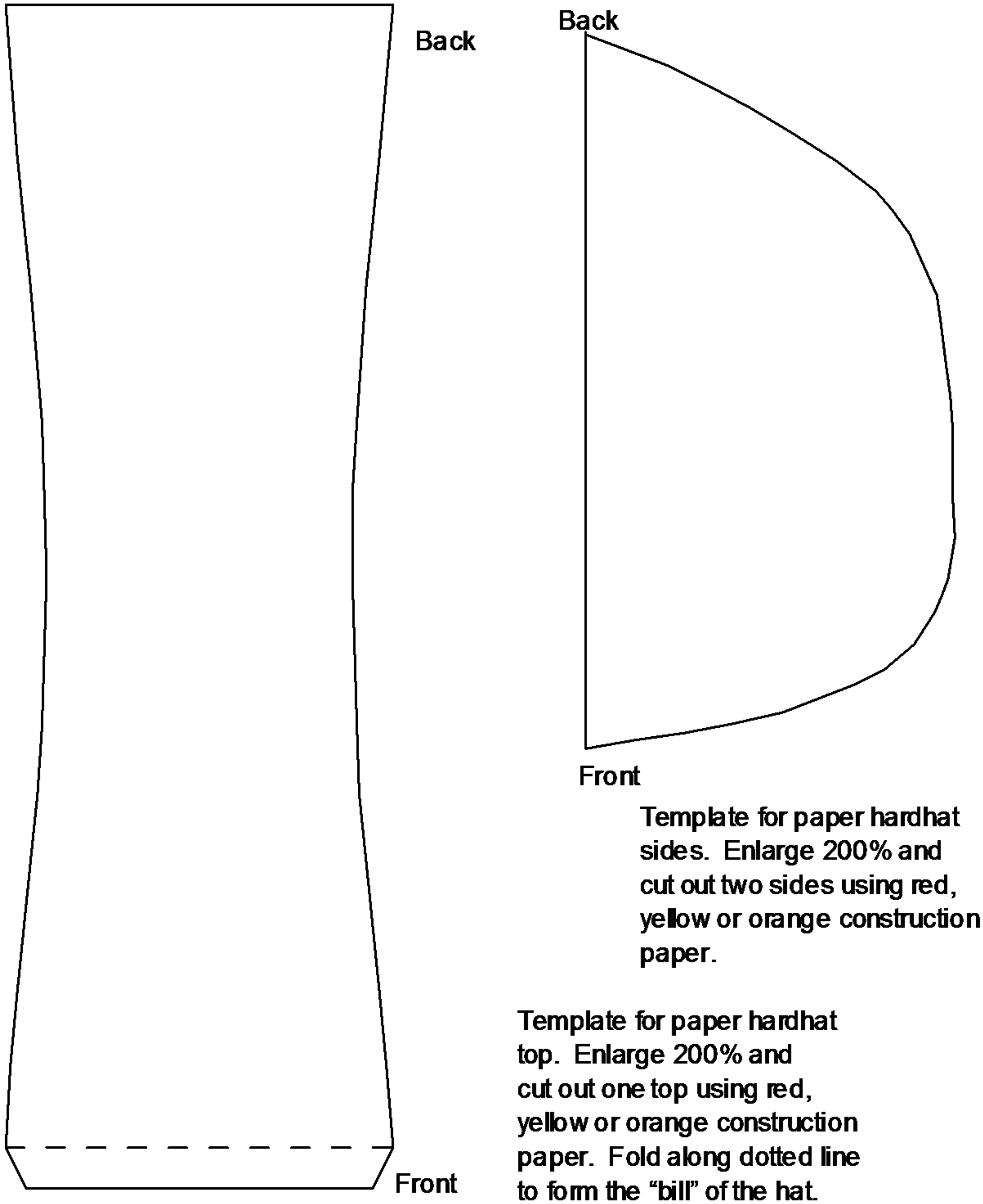


Figure 4. Template for making a "hardhat" (Figure 5) out of construction paper for the Journey to the Center of the Earth tour.

Figure 5. Photograph of completed construction paper "hardhat." The templates for the sides and top are given in Figure 4. The two sides are joined to the top with small pieces of transparent tape in the inside of the hat. The Journey to the Center of the Earth logo (below) is taped to the front of the hat with two-sided tape.

Table 2. Photographs of rock samples that can be used to represent possible rock types for selected stops in the Earth's interior*.

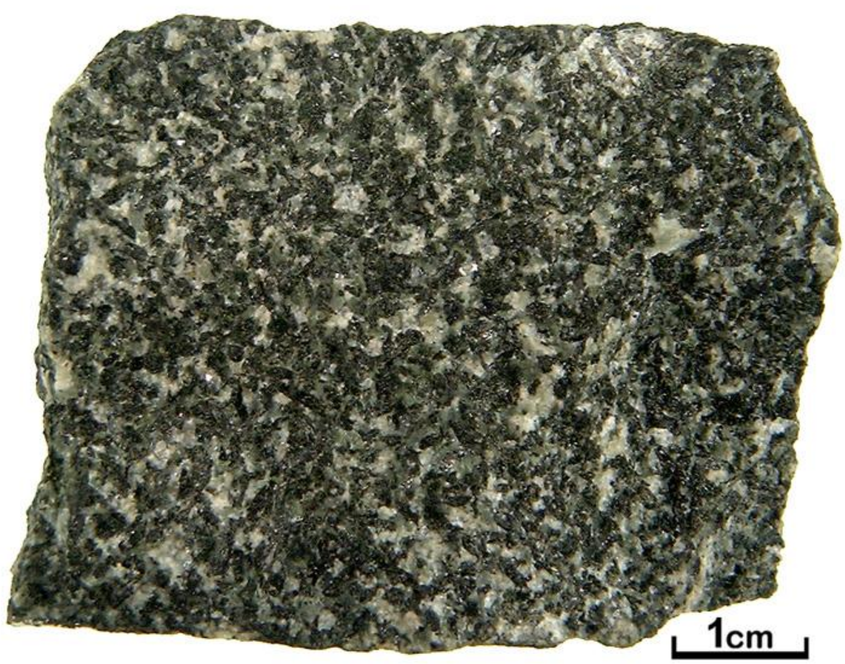
1. Sandstone

Close up of central area

2. Granite

2. **Gneiss**

3. **Gabbro**



5. Olivine

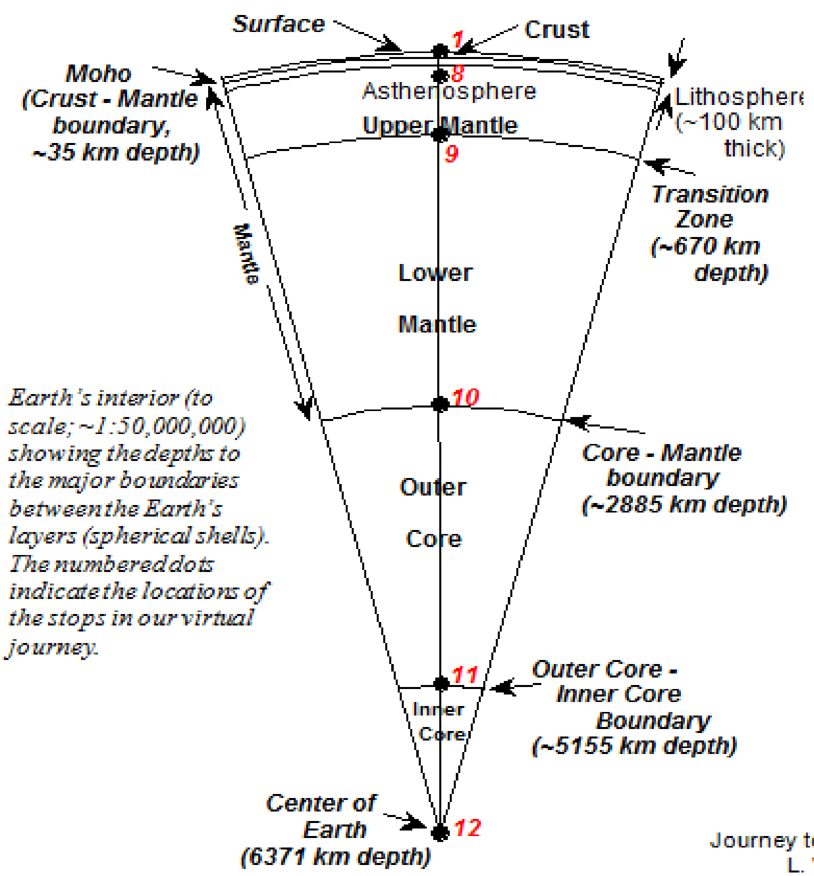
6. Iron-Nickel Meteorite

* Photos 1 – 5 courtesy of Barry Marsh, School of Ocean and Earth Science, Southampton Oceanography Center, University of Southampton, UK; used with permission. For more information and additional rock and mineral sample photographs, see http://www.soes.soton.ac.uk/resources/collection/minerals/. Photo 6 is from NASA, http://www-curator.jsc.nasa.gov/outreach1/expmetmys/slideset/Slides35-42.htm.

Table 3. "Journey to the Center of the Earth" and the National Science Education Standards (NSES; National Research Council, 1996).	
NSES Standard	**How standard is addressed in Journey to the Center of the Earth activities (see Procedure and Teaching Strategies section for more details)***
Science Teaching Standards	Activities include inquiry and opportunities for student involvement (A, B) and provide opportunities for ongoing assessment of student learning (C).
Professional Development Standards	The activity provides opportunities and appropriate resource material for teachers to learn about an Earth science topic that is not likely to have been included in their previous educational experiences and that build on their previous knowledge (A, C) and includes suggestions for effective teaching strategies (B).
Assessment Standards	Authentic assessment activities are suggested (C).
Science Content Standards	
- Unifying Concepts and Processes in Science	Activity provides experience with observation, evidence and explanation, and constancy, change and measurement.
- Science as Inquiry	Includes discussion of observations and evidence that result in conclusions about properties and conditions in the Earth's interior.
- Physical Science Standards	Activity explores properties and changes of properties in matter (Grades 5-8, B). Activity explores structure and properties of matter (Grades 9-12, B).
- Earth and Space Science	Activity explores structure of the Earth system (Grades 5-8, D). Activity relates to energy in the Earth system, origin and evolution of the Earth system (Grades 9-12, D).
- History and Nature of Science	Activity includes discussion of history of science, science as a human endeavor (and a connection to literature) (Grades 5-8, G). Activity includes discussion of science as a human endeavor and historical perspectives (and a connection to literature) (Grades 9-12, G).

Return to Braile's Earth Science Education Activities page:

Journey to the Center of the Earth
(Deep Earth Stops)



Earth's interior (to scale; ~1:50,000,000) showing the depths to the major boundaries between the Earth's layers (spherical shells). The numbered dots indicate the locations of the stops in our virtual journey.

"To conclude, I may say that our journey into the interior of the earth created an enormous sensation throughout the civilized world." (Jules Verne, *A Journey to the Center of the Earth*, 1864)

Journey to the Center of the Earth©
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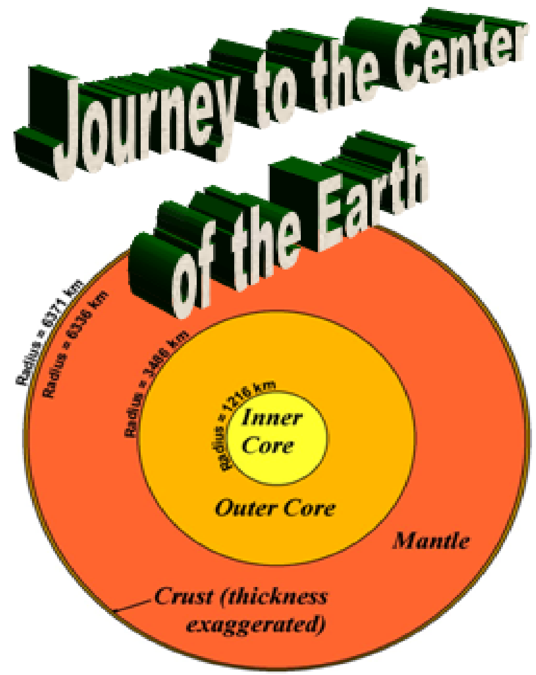
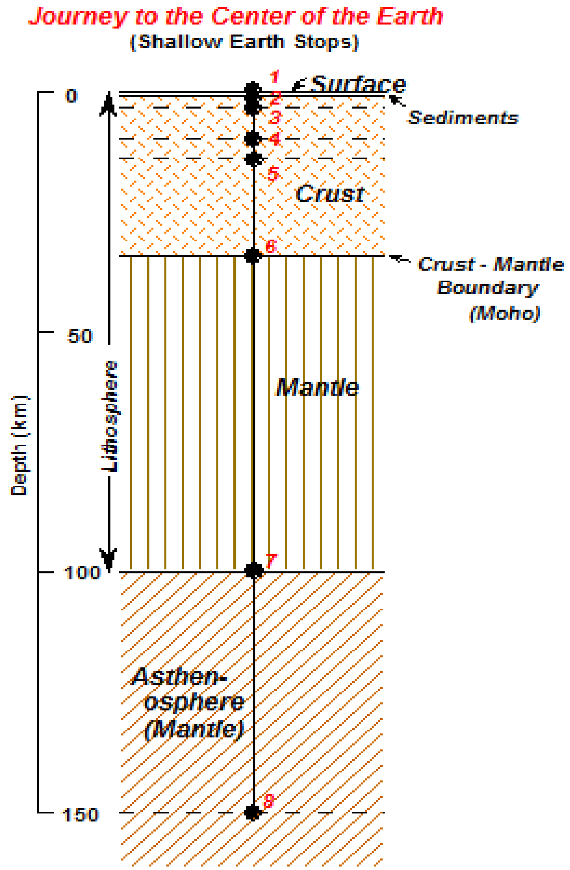
Explorations in Earth Science

A once in a lifetime opportunity!!! Join us in a…



Tour the inside of the planet in under one hour! Discover the structure of the Earth's interior! Experience the conditions deep below the surface!



Shallow Earth structure showing the depths to boundaries in the upper 150 km of the Earth. The numbered dots indicate the locations of the first 8 stops in our virtual journey.

Scheduled stops on our *Journey to the Center of the Earth* (Depth in kilometers in parentheses):

Shallow Earth stops:

1. Earth's surface (0 km) – Atmosphere above, Earth below.
2. Top of crystalline basement (~1 km) – Granitic igneous and metamorphic rocks.
3. Depth of deepest mine (3.6 km) – Temperature is ~50° C here.
4. Upper crust (10 km) – Many earthquakes occur near this depth.
5. Depth of deepest drill hole (12 km) – Drilling used for scientific study and oil exploration.
6. The Moho – crust/mantle boundary (~35 km [beneath continents]) – Crust is a thin shell; mantle is ~82% of Earth.
7. Base of the lithosphere (~100 km) – The Earth's plates (lithosphere) are moving at centimeters per year!
8. The asthenosphere (150 km) – Partially molten mantle and convection currents here.

Deep Earth stops (see diagram on back page):

9. Upper mantle transition zone (~670 km) – Increased pressure transforms minerals to more compact crystal structure and higher density. This depth is only a little more than 10% of our journey.
10. Core/mantle boundary (2885 km) – Solid mantle (iron/magnesium silicate rock) above; liquid iron and nickel below in outer core.
11. Inner core/outer core boundary (5155 km) – Pressure is so great that the iron inner core is solid. Density is about 13 g/cm^3.
12. Center of the Earth (6371 km) – Temperature is ~5500° C, pressure is over 3.6 million times the pressure at the surface.

Thanks for joining us on our Journey to the Center of the Earth! We hope you've enjoyed the tour and will come back again soon!