IS4

Physics in the Universe Instructional Segment 4: Nuclear Processes and Earth History

Energy [CCC-5] related to changes in the nuclei of atoms drives about 20 percent of California's electricity generation (California Energy Commission Energy Almanac 2016) (from fission in nuclear power plants), half the heat flowing upwards from Earth's interior (from the radioactive decay of unstable elements) (Gando et al. 2011), and all of the energy we receive from the Sun (from nuclear fusion in its core). In this instructional segment, students will develop **models [SEP-2]** for these processes.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 4: NUCLEAR PROCESSES AND EARTH HISTORY

Guiding Questions

- What does $E=mc^2$ mean?
- How do nuclear reactions illustrate conservation of energy and mass?
- How do we determine the age of rocks and other geologic features?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-ESS1-5. Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks. [Clarification Statement: Emphasis is on the ability of plate tectonics to explain the ages of crustal rocks. Examples include evidence of the ages oceanic crust increasing with distance from mid-ocean ridges (a result of plate spreading) and the ages of North American continental crust increasing with distance away from a central ancient core (a result of past plate interactions).] (Also addressed in the High School Chemistry in the Earth System course)

HS-ESS1-6. Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. [Clarification Statement: Emphasis is on using available evidence within the solar system to reconstruct the early history of Earth, which formed along with the rest of the solar system 4.6 billion years ago. Examples of evidence include the absolute ages of ancient materials (obtained by radiometric dating of meteorites, moon rocks, and Earth's oldest minerals), the sizes and compositions of solar system objects, and the impact cratering record of planetary surfaces.] (Also addressed in the High School Living Earth course)

HS-ESS2-1. Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features. [Clarification Statement: Emphasis is on how the appearance of land features (such as mountains, valleys, and plateaus) and sea-floor features (such as trenches, ridges, and seamounts) are a result of both constructive forces (such as volcanism, tectonic uplift, and orogeny) and destructive mechanisms (such as weathering, mass wasting, and coastal erosion).] *[Assessment Boundary: Assessment does not include memorization of the details of the formation of specific geographic features of Earth's surface.]* (Also addressed in the High School Living Earth course)

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 4: NUCLEAR PROCESSES AND EARTH HISTORY

HS-PS1-8. Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay. [Clarification Statement: Emphasis is on simple qualitative models, such as pictures or diagrams, and on the scale of energy released in nuclear processes relative to other kinds of transformations.] *[Assessment Boundary: Assessment does not include quantitative calculation of energy released. Assessment is limited to alpha, beta, and gamma radioactive decays.]*

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-2] Developing and Using Models [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-7] Engaging in Argument from Evidence	ESS1.C: The History of Planet Earth ESS2.A: Earth Materials and Systems ESS2.B: Plate Tectonics and Large-Scale System Interactions PS1.A Structure and Properties of Matter PS1.C: Nuclear Processes	[CCC-1] Patterns [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-7] Stability and Change

Highlighted California Environmental Principles and Concepts:

Principle I The continuation and health of individual human lives and of human communities and societies depend on the health of the natural systems that provide essential goods and ecosystem services.

Principle II The long-term functioning and health of terrestrial, freshwater, coastal, and marine ecosystems are influenced by their relationships with human societies.

Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter.

Principle IV The exchange of matter between natural systems and human societies affects the long-term functioning of both.

Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes

CA CCSS Math Connections: MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.4; RST.11–12.1, 8; WHST.9–12.2.a–e, 7, 9

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

Students will need to apply an understanding of the internal **structure [CCC-6]** of atoms and be able to read the periodic table. These topics are introduced in the High School Three-Course Model Chemistry in the Earth System course and no longer presented in the middle grades. If students have not yet taken the High School Three-Course Chemistry in the Earth System course, teachers can use nuclear processes to introduce these topics.

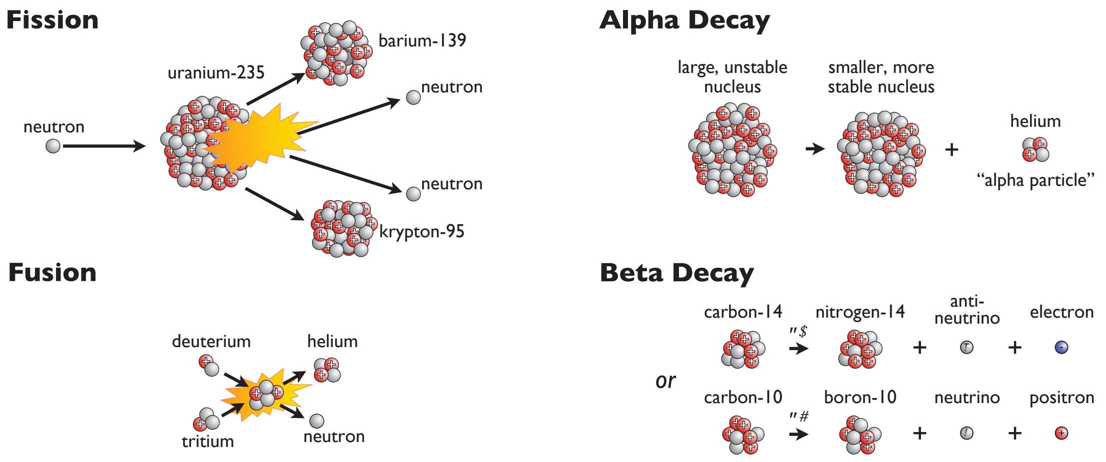
Changes in the nucleus occur at a length **scale [CCC-3]** too small to observe directly, but students can detect **evidence [SEP-7]** of these processes by looking at energy and matter that radiate out of the nucleus as a result of these changes. One can think of these emissions as an **effect [CCC-2]** and **develop a model [SEP-2]** that **explains [SEP-6]** the **cause [CCC-2]**. Students begin the instructional segment by making observations of a cloud chamber (see MIT Video, *Cloud Chamber* at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link49, as a video clip or classroom demonstration). Strange streaks whiz through the cloud chamber. Students can measure background radiation using a Geiger counter or even a smartphone app (see Australian Nuclear Science and Technology Organization, Smartphone radiation detector app tests positive at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link50). With these observations, students now **obtain information [SEP-8]** about the discovery of radioactivity and how scientists in the late 1800s like Becquerel and the Curies determined that the particles emitted during radioactivity had mass, were often charged, and emanated in high concentrations from different types of natural materials. Over time, this understanding has led to the modern **models [SEP-2]** of radioactivity and the modern tools for measuring its effects. These concepts can generally not be explored in direct experimentation in the classroom, so students will need to **analyze data [SEP-4]** from external sources and simulations to develop their own understanding of these models.

Scientists have identified only four fundamental interactions, known as fundamental forces: gravitational, electromagnetic, strong nuclear, and weak nuclear. All interactions between matter in the universe involve one of these forces. Students studied the first two during IS2, and the focus in this instructional segment is on the effects of the remaining two. The strong force ensures the **stability [CCC-7]** of ordinary matter by binding the atomic nucleus together, while the weak mediates radioactive decay. Although the strong and weak nuclear forces are essential for matter as we know it to exist, they are difficult to conceptualize and relate to because they operate at **distance scales [CCC-3]** too small to be seen. As the nucleus gets larger, forces holding nuclei together are overcome by electrostatic repulsion, which is why the largest atoms on the periodic table are unstable. It is this instability that result in the nuclei changing in various ways.

The Earth receives more **energy [CCC-5]** from the Sun in an hour and a half than all of humanity uses in a year, but this energy does not come from nothing. Nuclear reactions, too, must obey **conservation [CCC-5] laws**, but now students must apply the principle of mass-energy equivalence ($E=mc^2$) to revise the view that matter is conserved as atoms, to a more accurate view that the number of nucleons (sum of protons and neutrons) is conserved. Neither mass, nor the number of atoms of each type are conserved in nuclear processes, and although such mass conservation laws are applicable to gravitational and electromagnetic processes they must be revised and refined as we examine nuclear processes. This revision and refinement process should be stressed as an essential part of the nature of science.

Nuclear **changes [CCC-7]** all release large amounts of **energy [CCC-5]**, but they do so by different mechanisms. Scientists have recognized several classes of nuclear processes, including combining small nuclei to make larger ones (fusion) and larger nuclei emitting smaller pieces (fission, alpha decay, and beta decay). Students **develop models [SEP-2]** to illustrate the **changes [CCC-7]** in the composition of the nucleus of the atom and the **energy [CCC-5]** released during each of these processes (HS-PS1-8). Such models could be in the form of equations or diagrams (figure 7.53). Although it is not necessary to include quantitative calculations, the models should communicate the conservation of the combined mass-energy system.

Figure 7.53. Models of Nuclear Processes in Atoms



Sources: Adapted from Stefan-XP 2009; adapted from Pbech 2008; adapted from Thomas Jefferson National Accelerator Facility—Office of Science Education 2015a, 2015b

In fusion, small nuclei combine together to form larger ones. Since all nuclei have positive charges (made only of positive protons and neutral neutrons), electrostatic forces will tend to repel nuclei apart from one another. The closer nuclei get to one another, the stronger the electrostatic repulsion. Nuclei can get very close to one another if they collide when they are moving very fast. If they manage to get close enough to one another, another interaction becomes important: the strong nuclear force, which holds nuclei together in the first place. Like creating a new chemical bond, creating new strong-force interactions releases **energy [CCC-5]**. Students will revisit fusion and apply their qualitative model of it to stars in IS6, since stellar cores are the only place where fusion naturally occurs. Efforts have been made to use fusion to make energy on Earth, but the engineering task is challenging. If scientists and engineers can succeed in making it work, fusion would be cleaner and safer than just about any other known energy source and is therefore a worthwhile area of research. Even though fusion can be recreated in laboratories, a large amount of energy is required for nuclei to reach speeds fast enough to achieve fusion. Unless the fusion device is extremely efficient, it ends up taking more energy to start the fusion process than the fusion actually releases. California hosts the most advanced fusion experiment in the world at the Lawrence Livermore National Laboratory where scientists and engineers are working daily to make breakthroughs. Students could explore an interactive computer simulation of the experiment in which they adjust the speed at which atoms are accelerated until fusion is achieved, making measurements about the amount of energy used in the device and the amount of energy released by fusion.

Weak interaction processes (beta decay) should be introduced as **changes [CCC-7]** in which neutrons transform into protons or protons transform to neutrons. Beta decay allows atoms to move closer to the optimal ratio of protons and neutrons, and is key to understanding why all stable nuclei have roughly equal numbers of protons and neutrons, with a few more neutrons as nuclei gets bigger. Protons have an electric charge while neutrons are neutral and have a slightly larger mass. Conservation laws dictate that the charge and extra mass cannot just appear or disappear but must come from somewhere. Applying the reasoning from conservation laws, students recognize that other subatomic particles like positrons and neutrinos must exist along with protons, neutrons, and electrons.

Sometimes the competition between different forces within the nucleus causes it to spontaneously split apart to form two or more smaller nuclei. One of these smaller products is often a helium nucleus composed of two protons and two neutrons. This particle is called an alpha particle, so this type of fission is referred to as *alpha decay*. The smaller nuclei require less total binding energy, so some of that energy is converted into kinetic energy causing the smaller nuclei to rapidly fly away from one another. These nuclei are also usually unstable because smaller nuclei require a different ratio of protons to neutrons to be more stable than the original larger nucleus. These smaller nuclei will often release even more energy, either undergoing beta decay or by releasing energy by gamma radiation when their component protons and neutrons rearrange to a lower, more stable, energy configuration.

Nuclear power plants rely on the release of **energy [CCC-5]** from nuclear **changes [CCC-7]** in uranium (and sometimes plutonium). Nuclei of these atoms are unstable and naturally decay very slowly, primarily by alpha, beta, and gamma decay. Reactors produce most of their energy by inducing fission, accomplished typically by separating uranium-235 (a nucleus with 92 protons and 143 neutrons) from other isotopes of uranium with different numbers of neutrons. The naturally occurring mix of uranium isotopes absorbs neutrons, preventing the fission process from occurring too quickly. However, when fission occurs in one atom of purified uranium-235, neutrons that are emitted are likely to collide with other uranium-235 atoms and induce fission. As a result, energy release can be maintained at a rate far above the typical background level for naturally occurring mixtures of uranium isotopes. This energy is used to heat water just like other thermoelectric power plants. Students can use an online simulator to model the fission process and can be given the challenge to adjust the simulator settings to find the minimum concentration of uranium-235 required to maintain a certain energy output from fission (see PhET, *Nuclear Fission* at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link51).

Using Radioactive Decay to Understand Earth Processes

How old is the Earth? How long ago did human civilizations arrive in California? How long has this boulder been exposed at the Earth's surface? Practically any time scientists want to know about the age of events older than the written historical record, they turn to radioactive decay to help them find out. This section shows how students can **apply their model [SEP-2]** of microscopic radioactive decay to answer such real-world questions. None of the performance expectations related to radiometric dating require that students perform calculations of decay rates. The emphasis is instead on a qualitative model of the radiometric dating process and, more importantly, on the **analysis [SEP-4]** of results from radiometric dating to identify **patterns [CCC-1]** that provide **evidence [SEP-7]** of processes shaping Earth's surface.

When an atom has an unstable nucleus, it decays at a random time. Different elements behave differently as the number protons and neutrons in a nucleus affects the probability that an atom will decay in a certain time period, but it is not possible to predict when any given nucleus will decay. Science usually strives to find **cause and effect [CCC-2]** relationships to predict when future events will occur, but having decay being largely based on fixed probabilities means that it is not sensitive to external triggers (at least under most natural conditions). Scientists have learned to calibrate radiometric clocks by measuring the proportion of radioactively unstable atoms (often called *parent products*) to stable products that are produced following decay (so-called *daughter products*). In a simple system of pure uranium-235 (a nucleus with 92 protons and 143 neutrons), about 50 percent of the atoms will have decayed after 700 million years (defined as its *half-life*). This probability has been calculated from much shorter observations of radioactive decay in laboratories. By contrast, pure carbon-14 (a nucleus with six protons and eight neutrons) decays at a much faster rate with 50 percent of the atoms decaying into nitrogen-14 within just 5,730 years. Students can visualize what is meant by half-life using a computer simulation (see PhET, *Radioactive Dating Game* at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link52) or classroom activity with pennies representing individual atoms that decay as they flip from heads to tails (Center for Nuclear Science and Technology Information of the American Nuclear Society, Half-Life: Paper, M&M's, Pennies, or Puzzle Pieces: http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link53), or even using a physical model of ice melting (Wise 1990).

Real materials on Earth rarely involve pure chunks of uranium-235, carbon-14, or any other radioactive parent product. There are initial amounts of other types of atoms, including daughter products. A rock can be thought of as a **system [CCC-4]** with parent and daughter products, but this system may not be closed and a portion of the daughter product may escape. Extra or missing daughter products that are not properly accounted for would alter the calculated age if not properly recognized. Scientists have developed sophisticated tests involving comparisons of multiple parent–daughter systems to account for these issues and ensure accurate date measurements.

Scientists use these radiometric clocks to calculate the age of natural materials and learn about the past. Using data collected by geologists, students can compare the concentration of radioactive elements in different samples from Earth's rocks, meteorites that have crashed into Earth's surface, and moon rocks. Meteorites have compositions similar to what we expect the core of the Earth to look like, and are therefore interpreted to be pieces of other planetary objects that formed around the same time as Earth's core. Students can **calculate [SEP-5]** and **compare [SEP-4]** the age of these samples (see Keyah Math Project, "Keyah Math Module 8, Level 2: Age of the Earth" at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link54). Many of these meteorites have similar ages of around 4.5–4.6 billion years and none have been found with ages older than that. Ages on the Moon are also similar, though a bit younger (4.4–4.5 billion years old). Students can use all this information as **evidence [SEP-7]** for making a claim about the age of Earth itself and use information about the age of the Moon to construct an account of the timing and possible mechanism by which it formed (HS-ESS1-6). A detailed assessment task for this performance expectation was written by the authors of the NGSS as a model of how the three-dimensional learning appears in the classroom (see Achieve, Unraveling Earth's Early History—High School Sample Classroom Task at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link55).

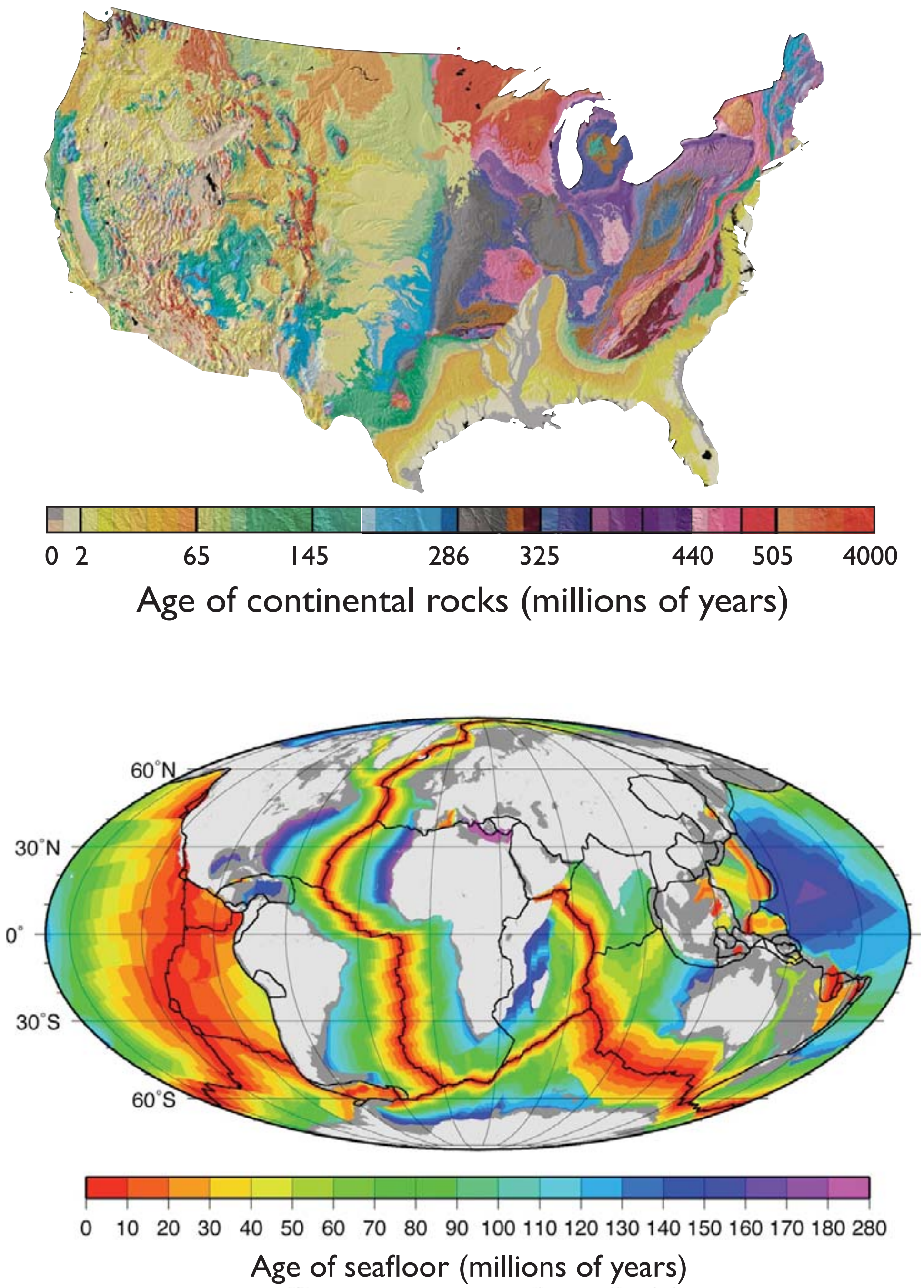
Since Earth formed, its surface has been constantly reshaped. We know this, in part, by evidence from radiometric dating. Plate tectonics is one process that actively moves and deforms rocks, and students **analyzed [SEP-4]** a range of data types supporting this theory in the middle grades (MS-ESS2-3). In high school, students evaluate the theory to see if it is consistent with evidence from rock ages calculated using radiometric dating. They use evidence from rock ages to refine their model of the processes that shape earth's landforms (HS-ESS2-1).

The oldest individual minerals in some of Earth's oldest rocks are about 4.4 billion years old, though these rocks form only a tiny fraction of the planet's surface. Few rock formations are older than even three billion years, and those rocks are only found on the continents. The spatial distribution of the ages of rocks on continents has complicated **patterns [CCC-1]**. For example, some of the oldest rocks in California are located just outside the Los Angeles area in the San Gabriel Mountains. These rocks formed 1.8 billion years ago and are literally touching rocks just 85 million years old. This jumble of ages is evidence of California's complicated geologic history where faults slice up rock formations and move them across the state. Some might be surprised to find that the rest of the United States does not appear that much different (top of figure 7.54). In fact, all continents show evidence of very complicated geologic histories where rocks of very different ages are mixed as continents are built up by the collision of smaller pieces and then broken back apart by later episodes of motion in a different direction. Students can observe maps of different rocks in California or North America (see USGS, "The North America Tapestry of Time and Terrain" *Geologic Investigations Series* I-2781 at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link56) and **ask questions [SEP-1]** about the **patterns [CCC-1]** they notice. Why do the patches of color take up so much space in the eastern half of the continent while the western United States looks much more speckled with color? Why are there no metamorphic rocks in the middle of the country? Why does Florida have so many young rocks?

The seafloor, however, is much younger (no rock being older than 280 million years) and shows a clear pattern. We know that there must have been oceans older than 280 million years ago because we have found fossil marine creatures in rocks that are much older than those found on today's continents. So what happened to the rest of the old seafloor? A clue comes from the fact that ages of rocks on the seafloor typically progress in a logical order in a symmetrical **pattern [CCC-1]** from the middle of the ocean outwards (bottom of figure 7.54).

Students should be able to use data from radiometric ages to collect evidence that the crust is moving (HS-ESS1-5). Running along the center of the ocean is a band of rock with zero age. This means that there has been no accumulation of daughter product from radioactive decay (above the background level). How can this be when the unstable parent isotopes are present and therefore constantly decaying into the daughter products? When rock is hot, atoms can move around relatively easily and daughter products for radioactive decay can therefore escape or equilibrate with the background concentration of that element. As a rock cools, atoms are locked into their positions in crystal lattices; this is the moment when the geologic clock starts ticking. The new crust in the center of the ocean was therefore very hot in the recent past, which is evidence that it rose up from Earth's interior. As new crust is progressively forming, it also must constantly move away from the middle of the ocean. At the same time, older crust must therefore be sinking. This is expected because the crust becomes denser as it cools over time. Ultimately, the seafloor is subducted at an active plate boundary, which explains why there are no older seafloor ages). Students can measure the length of crust from the mid-ocean ridge and they know its age at different points; with this information they can **calculate [SEP-5]** how quickly the crust is moving in different ocean basins and even how those rates have changed over geologic history. Do ocean basins with faster moving seafloor experience more earthquakes each year?

Figure 7.54. Rock Ages in the Continental US and Seafloor



Map of rock ages in the continental United States (top) and seafloor (bottom). Continental rocks are as old as 4 billion years and are a jumbled mix of ages. Seafloor rocks show a consistent pattern and are never older than 280 million years. *Sources*: Adapted from Vigil, Pike, and Howell 2000; National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2008