Earth System Science: The Big Ideas

Like all scientific disciplines, the Earth sciences continually evolve over time. New discoveries fuel new ideas, providing and ever-increasing understanding of the planet. But of the overwhelming number of observations, theories, and principles that form the foundation of Earth **system** science, what is essential for every American to understand? All too often, curricula are too ambitious and, as a result, may fail to cover topics in any substantial depth. An alternative approach is to build one's curriculum upon a foundation of focused, interconnected <u>big ideas</u>. A well-designed set of big ideas can provide an all-encompassing conceptual framework for any discipline, including Earth system science. Developed alongside scientists and Earth science teachers, this coherent set of big ideas illuminates what is fundamental to the Earth sciences:

1. The Earth is a system of systems.
2. The flow of **energy** drives the cycling of matter.
3. Life, including human life, influences and is influenced by the environment.
4. Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system.
5. To understand (deep) time and the scale of space, models and maps are necessary.

These ideas are designed to cover the breadth of any Earth science curriculum, but they must be dissected to build deep understanding. Each idea is essentially bottomless; that is, while a meaningful understanding of these ideas is readily attainable, the details contained within are endless. Each of the ideas can be understood, but the depth of understanding can vary greatly.

Introduction of these ideas also invites discussion of the <u>nature of science</u>. As curricula are designed and implemented, the traditional topics of Earth system science should be complemented with ideas on *how* we have come to know what we know about the natural world. Within our big ideas framework, we draw attention to the nature of science with two overarching questions:

1. How do we know what we know?
2. How does what we know inform our decision making?

These questions, when addressed in concert with the big ideas, provide a gateway into the nature and utility of the range of scientific ideas.

system • *a set of connected things or parts forming a complex whole.*

energy • *the power derived from the use of physical or chemical resources.*

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Big Ideas

Big Idea 1:
The Earth is a system of systems

plate tectonics • *the way by which the plates of the Earth's crust move and interact with one another at their boundaries.*

weathering • *the breakdown of rocks by physical or chemical means.*

erosion • *the transport of weathered materials.*

uplift • *upward movement of the crust due to compression, subduction, or mountain building.*

plates • *large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.*

heat • *the transfer of energy from one body to another as a result of a difference in temperature or a change in phase.*

metamorphic rocks • *rocks formed by the recrystallization and realignment of minerals in pre-existing sedimentary, igneous, and metamorphic rocks when exposed to high enough temperature and/or pressure.*

The Earth is composed of many systems, which cycle and interact in both space and time. It is also part of a multitude of systems, nested in larger systems such as the solar system and the universe. Systems are composed of an untold number of interacting parts that follow simple rules; they can and do evolve. For example:

Outlining the geologic history of any region demonstrates the concept of the Earth as a system of systems. **Plate tectonics** drives the formation of mountains. Subsequent **weathering** and **erosion** of the **uplifted** mountains leads to the formation of deltas in the adjacent shallow seas. And with uplifted continents, shorelines change and the distribution of marine communities are altered.

The planet's systems are intimately connected: the forces of one system affect other systems nested within it. As **plates** collide, systems that drive plate tectonics are obviously linked to the formation of mountains, but they are ultimately linked to and influence much smaller systems. The intense **heat** and pressure resulting from collisions can lead to the **metamorphism** of existing strata, or it can melt existing rocks to later form **igneous rocks**.

As **glaciers** extended down from the north, they cut into river valleys in the upper portion of North America. This glacial system shaped the landscape, deepening and widening the river valleys and creating huge lakes that later emptied in great torrents like the Missoula Floods, leaving impressive scars on the landscape as well as huge deposits that accumulated in mere days. Had the glaciers never advanced so far south, the erosional forces that led to the formation and draining of these lakes would have never been set in motion. This interplay of **climate**, rock, and water has shaped every natural landscape on the planet. Humans and other living things build upon (or tear down) the foundations lain down by these other systems, furthering the interplay of systems.

See Chapter 4: Topography for more on the Missoula Floods and other ways in which glaciers shaped the Western Landscape.

Each of the remaining ideas operates across multiple systems within the larger Earth system.

Big Ideas

Big Idea 2: The flow of energy drives the cycling of matter

The Earth is an open system. Energy flows and cycles through the system; matter cycles within it. This cycling is largely driven by the interaction of the differential distribution of solar radiation and internal heat: the constant flow of solar radiation powers much of Earth's ocean and **atmospheric** processes on the surface of the system, while the flow of heat from **radioactivity** within the Earth drives plate tectonics. For example:

> One of the fundamental processes known to Earth system scientists is the rock cycle. The rock cycle illustrates the steps involved in the formation of one type of rock from another. It is a system that has operated since the Earth's origin, and it continues today. The energy that drives weathering and erosion, melting, or an increase in heat or pressure, drives the continuation of the rock cycle.
>
> The landscape of the West that we see today has been shaped by the geologic forces of the past, and these forces are still active today. The movement of Earth's plates is driven by plate tectonics, illustrating how the flow of energy drives the cycling of matter—the flow of heat from radioactivity within the Earth drives plate tectonics. Evidence littered throughout the West's terrain tells a story that began billions of years ago with the formation of tectonic plates, and continues today as the Pacific and Juan De Fuca Plates slide underneath and along the North American plates. This plate movement creates the volcanoes of coastal Oregon, Washington, and Alaska, **earthquakes** along the Pacific's Ring of Fire, and features on the seafloor, like the Juan De Fuca Ridge off the coast of Oregon and Washington.
>
> During the most recent **ice age**, glaciers advanced and retreated many times during the past two million years. One of the great questions in the Earth sciences revolves around the causes of these glacial cycles, with the general consensus pointing toward cyclic variations in the planet's tilt, movement about its axis, and its orbital shape around the sun. These variations lead to changes in the amount of solar radiation that reaches the Earth, which in turn affect global climate.
>
> The rock cycle, plate tectonics, and the water cycle are all **convection**-driven. Without convection, Earth would be extraordinarily different.

See Chapter 6: Glaciers to learn more about the West during the ice age.

igneous rocks • *rocks derived from the cooling of magma underground or molten lava on the Earth's surface.*

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

climate • *a description of the average temperature, range of temperature, humidity, precipitation, and other atmospheric/hydrospheric conditions a region experiences over a period of many years (usually more than 30).*

atmosphere • *a layer of gases surrounding a planet.*

radioactive • *when an unstable atom loses energy by emitting radiation.*

ice age • *a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and glaciers.*

convection • *the rise of buoyant material and the sinking of denser material.*

Big Ideas

Big Idea 3: Life—including human life—influences and is influenced by the environment

greenhouse gas • *a gas in the atmosphere that absorbs and emits heat.*

global warming • *the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere.*

Across its four-billion-year history, the course of life's evolution has been intimately tied to the Earth's physical environment. Global cooling led to the relatively recent spread of grasslands, which then triggered an evolutionary shift in many herbivorous mammals from browsing to grazing. Conversely, the evolution of life has altered the physical environment. Photosynthetic bacteria released free oxygen into the early oceans and atmosphere, making Earth habitable for later types of organisms. Humans, with their increasing population and expanding technology, have altered the landscape and the distribution of flora and fauna, and they are changing atmospheric chemistry in ways that affect the climate. Earth system processes also influence where and how humans live. For example:

> With human populations increasing the world over, the emission of **greenhouse gases** has also increased dramatically. These gases alter the chemical composition of the atmosphere and directly influence the planet's climate. It is generally agreed that the rapid and immense pouring of carbon dioxide into the atmosphere will lead to **global warming**, which will have incredible impacts throughout the world.

See Chapter 9: Climate to learn more about the effect of greenhouse gases.

> Around three million years ago, a land bridge formed between North and South America. For the first time in more than 150 million years, the two continents were linked, and the mammals inhabiting both lands migrated across the bridge. Horses, mastodons, cats, and dogs moved south, while opossums, porcupines, ground sloths, and armadillos moved north (to name a few). Today, half the mammal species in South America are descended from North American migrants.

Big Idea 4:
Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system

The Earth processes operating today—everything from local erosion to plate tectonics— are the same as those operating since they first arose in Earth history, and these processes are obedient to the laws of chemistry and physics. While the processes that constantly change the planet are essentially fixed, their rates are not. Tipping points are reached that can result in rapid changes cascading through Earth systems. For example:

> During the **Precambrian**, the evolution of photosynthetic organisms led to significant changes in the planet's atmosphere. Prior to this event, there was little free oxygen in the atmosphere, but with photosynthesis producing oxygen as a waste product, the very existence of these organisms flooded the seas and atmosphere with free oxygen, changing the planet forever. But life's evolution represents just one of the processes working upon Earth systems.
>
> The San Andreas Fault is a **transform boundary** that separates the North American plate from the Pacific plate and runs almost the entire length of California, from the Salton Sea in the south to Cape Mendocino in the north. The relative motion of the plates shifts most of the continent to the southeast, while a relatively thin sliver of California (and the very large Pacific plate to which it is connected) shifts to the northwest. While the **fault** itself is relatively young (thought to be between 5 and 30 million years old at different points along its length), the processes at play have been at work in the same way for billions of years, opening and closing oceans and building up and tearing down landscapes.
>
> Today, the **ice sheets** of Greenland and Antarctica make up some 95% of all the current glacial ice on Earth. The study of these modern glaciers and their influences on the environment, such as through the formation of U-shaped valleys, is key to interpreting glacial deposits of the past, which are thought to have formed under the same processes as those operating today.

Precambrian • *a geologic time period that spans from the formation of Earth (4.6 billion years ago) to the beginning of the Cambrian (541 million years ago).*

transform boundary • *an active plate boundary in which the crustal plates move sideways past one another.*

fault • *a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.*

ice sheet • *a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

Big Idea 5:
To understand (deep) time and the scale of space, models and maps are necessary

compression *• flattening or squeezing as a result of forces acting on an object from all or most directions.*

The use of models is fundamental to all of the Earth sciences. Maps and models aid in the understanding of aspects of the Earth system that are too big or small for direct observation, or where observation is not possible. They also help make complex systems comprehensible through strategic simplification. When compared to the size and age of the universe, humanity is a speck in space and a blip in time; models assist in the comprehension of time and space at both sub-microscopic and immense scales. For example:

> Much of scientists' understanding of the inner workings of our planet is derived from mathematical modeling. It is not possible to directly measure the movement below Earth's surface, but modeling of convection currents brings us closer to the true nature of these monumental geologic phenomena.
>
> The observation of natural phenomena today, such as deposition along a streambed, is critical for interpreting the geologic record. But for processes that operate on much larger, slower scales, modeling within the lab is required. The formation of mountain ranges, such as the Cascades, is better understood by examining the effects of stress and strain in the laboratory.
>
> What is the effect of a two-kilometer-thick (1.2-mile-thick) glacier on the terrain? In addition to changes related to deposition, the shear weight of such an object depresses the continental mass. Understanding this **compression**—and the rebound that occurs upon the glacier's retreat—is improved through modeling in the laboratory.

In Conclusion

Taken individually, these big ideas and overarching questions represent important aspects of Earth system science, but together they are more significant. Keeping these ideas in mind—and considering how they arose through scientific methods and investigation—is invaluable as one proceeds throughout his or her curriculum, and it can provide a conceptual framework upon which to build an enduring understanding of the discipline.

Resources

Books

Donovan, S., & J. Bransford, 2005, *How Students Learn: Science in the Classroom,* National Academies Press, Washington, DC, http://books.nap.edu/catalog.php?record_id=10126.

Wiggins, G. P., & J. McTighe, 2005, *Understanding by Design, 2nd edition*, Association for Supervision and Curriculum Development: Alexandria, VA, 382 pp.

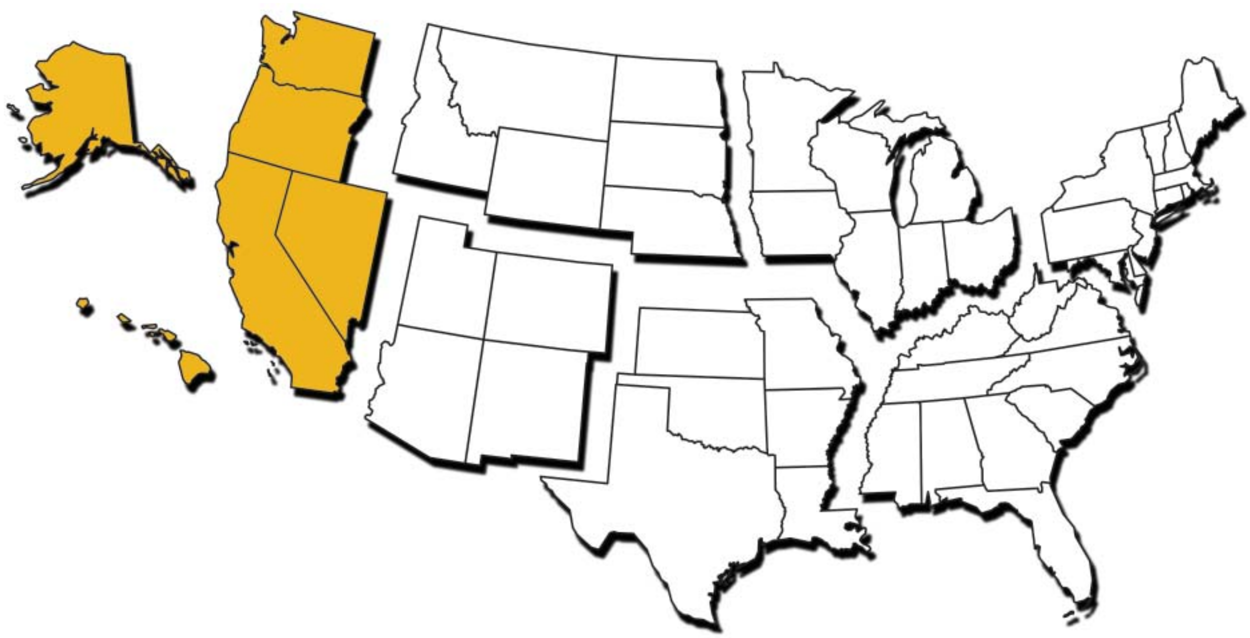
Wiske, M. S., ed., 1998, *Teaching for Understanding: Linking Research with Practice,* Jossey-Bass, San Francisco, CA, 379 pp.

Websites

Exploring Geoscience Methods with Secondary Education Students, by J. Ebert, S. Linneman, & J. Thomas, http://serc.carleton.edu/integrate/teaching_materials/geosci_methods/index.html.

The **Teacher-Friendly** Guide™

to the Earth Science of the Western US



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On the back cover: Blended geologic and digital elevation map of the Western US. Each color represents the age of the bedrock at the surface. Adapted from Barton, K. E., D. G. Howell, & J. F. Vigil, *The North America Tapestry of Time and Terrain*, US Geological Survey Geologic Investigations Series I-2781, http://pubs.usgs.gov/imap/i2781.