Earth System Science: The Big Ideas

Like all scientific disciplines, the Earth sciences continually evolve over time. New discoveries fuel new ideas, providing an 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 big ideas. 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 nature of science. 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

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 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 and a wide range of landscape types, not just mountains. Much of the terrain in the Southwestern US is rugged and mountainous, reflective of relatively recent tectonic forces at work. Mountains and plateaus rise and fall; **rifts** open; and basins form. These forces have also driven movement of Earth's tectonic plates, such that the Southwestern US sits between 30° and 40° North latitude.

Inland from the Pacific Ocean, the **climate** is largely arid, producing vast desert landscapes. The 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 their interplay.

See Chapter 8: Climate to learn how climate has affected the Southwest's life and landscape.

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

plate tectonics • *the process 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.*

delta • *a typically wedge-shaped deposit formed as sediment is eroded from mountains and transported by streams across lower elevations.*

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

rift • *a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.*

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 we see today in the Southwest has been shaped by the geologic forces of the past, and these forces are still active today. Evidence throughout the Southwest's terrain tells a story that began billions of years ago with the formation of tectonic plates, and this story continues to evolve. 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. Through **geologic time**, the Southwestern US has been shaped by the collision of the North American Plate with the Pacific Plate in a process driven by **convection** within the **mantle**. In addition to tectonic processes, energy flows and cycling matter also shape the landscape through erosion, deposition, sea level change and the direct action of humans.

See Chapter 1: Geologic History for more about the tectonic processes that led to the formation of North America as we know it today.

In the recent geologic past, the Colorado River's water has moved a tremendous mass of sediment from the interior of North America into the Gulf of California. Other Southwestern rivers, including the Rio Grande, Brazos, and Mississippi (through major tributaries like the Arkansas and Red), have moved great quantities of sediment to the Gulf of Mexico. The flow of sediment is, of course, driven by the water cycle, and, especially for the Colorado River, greatly affected by human activity. Like the rock cycle, and plate tectonics, the water cycle is convection driven. Without convection, Earth would be extraordinarily different, if it were here at all.

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.*

radioactivity • *the emission of radiation by an unstable atom.*

geologic time scale • *a standard timeline used to describe the age of rocks and fossils, and the events that formed them.*

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

mantle • *the layer of the Earth between the crust and core.*

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.*

hectare • *a metric unit of area defined as 10,000 square meters.*

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, the flow of rivers, the distribution of flora and fauna, and 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.

Throughout the Southwest, water diversion for agriculture and other uses has changed and continues to change remarkably. The Colorado River effectively no longer reaches the Gulf of California due to a series of dams and diversions along its course. Much of its flow is diverted outside of its basin, for use in California and Nevada. Water is also taken to quench the thirst of nearby cities like Denver and Phoenix. The Colorado River serves the needs of 30 million people in seven US states and Mexico, and 70% of its flow is diverted to irrigate 2.2 million **hectares** (5.5 million acres) of land. It also supports production of 4,200 megawatts of electric generating capacity. These changes coupled with long-standing drought in the region—likely enhanced by human-induced climate change—have brought a wide range of changes to the basin. When we ask, "Why does this place look the way it does?" the role of humans must be central to our answer.

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's 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.
>
> Tectonic processes have been at work in the same way for billions of years, opening and closing oceans and building up and tearing down landscapes. The Grand Canyon offers a large cross-section of Earth history—a window into nearly two billion years of North America's formation. Some 3900 meters (13,000 feet) of **lava** and sediment are exposed there, and though these rocks date back over a huge span of Earth's history, the processes that made them are still at work today. **Schists** still form from other rocks put under heat and pressure; sediments still become **limestones** and **sandstones**, and lavas still cool to form **basalts**. Rocks born from all of these processes are visible in a number of places throughout the Southwestern US.

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

lava • *molten rock located on the Earth's surface.*

schist • *a medium grade metamorphic rock with sheet-like crystals flattened in one plane.*

limestone • *a sedimentary rock composed of calcium carbonate ($CaCO_3$).*

sandstone • *sedimentary rock formed by cementing together grains of sand.*

basalt • *an extrusive igneous rock, and the most common rock type on the surface of the Earth.*

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

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 that occurs 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 riverbed, 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 like the Rocky Mountains and basins like the Gulf of Mexico is better understood by examining the effects of stress and strain 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.

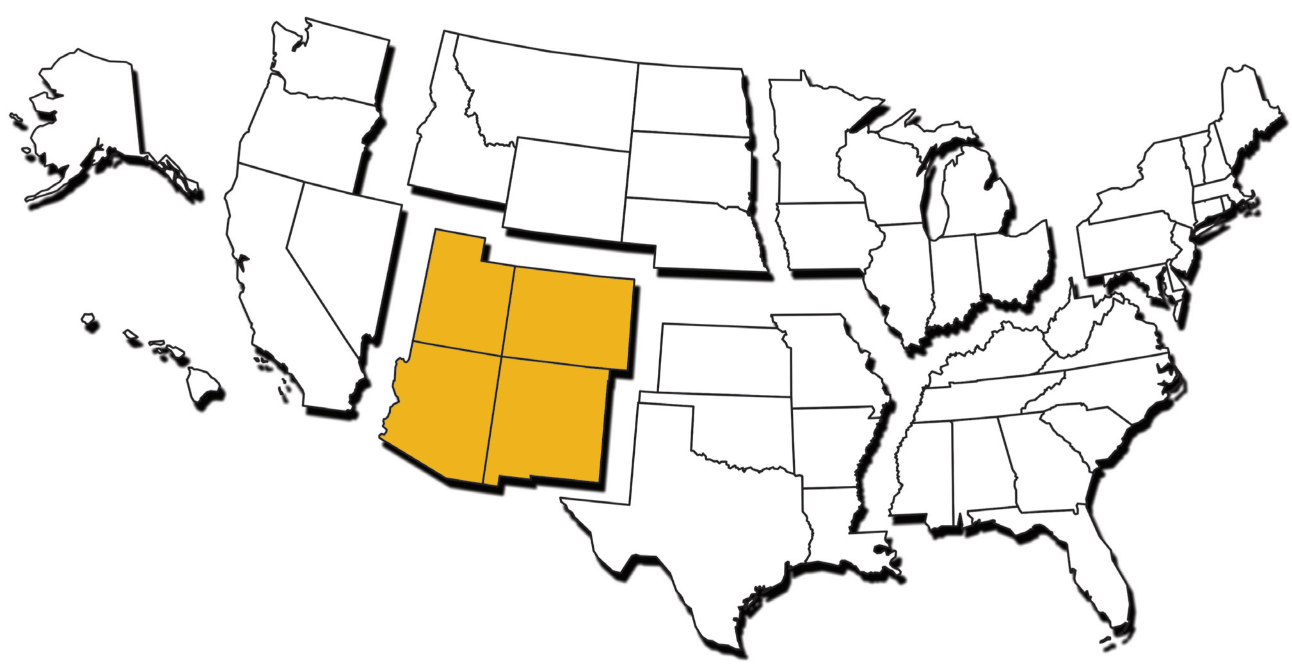
Wiske, M. S., ed., 1998, *Teaching for Understanding: Linking Research with Practice*, Jossey-Bass, San Francisco, CA, 379 pp.

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 Southwestern US



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