

**Three Mechanisms/Theories of Evolutionary Change:** Fichter, Whitmeyer, and Pyle (in press). Expanding Evolutionary Theory Beyond Darwinism: Elaborating, Self-Organizing, and Fractionating Evolutionary Mechanisms, *Journal of Geoscience Education*.

The four major systems of Earth are the geosphere, hydrosphere, atmosphere, and biosphere (3.1; these numbers refer to the “Big Ideas” from the Earth Science Literacy Principles developed by the Earth Science Literacy Initiative, National Science Foundation, updated version May 22, 2009; these numbers are positioned where they apply on the “Evolution of Complex Earth Systems” flow model, Appendix ), and all Earth processes are the result of energy flowing and mass cycling within and between these Earth’s systems (3.2, 3.3, 3.6, 4.2, 4.3). The energy for these exchanges is derived from the sun and the Earth’s interior (3.2). The result is, over the past 4.5 billion years these four systems have increased in diversity, complexity, and interconnectedness (4.1); that is, they have evolved. Evolution takes place through three distinct mechanisms: elaboration (including biological evolution), fractionation, and self-organization. To understand Earth systems we must understand for each sphere the evolutionary mechanisms operating and their results, and then how the evolutionary processes in one sphere affect the evolutionary processes in the other spheres (3.4, 4.1).

**Elaborating evolution** begins with something simple (e.g. the first cell) but results in increases in diversity, complexity, and abundance with time due to adaptation to ever diversifying environments (evolving by fractionation and self-organization). Darwinian evolution is the best known example (6.2), but not the only; for example, businesses in an economy also evolve by elaboration. What is common to all elaborating evolutionary systems is the General Evolutionary Algorithm: 1) differentiate (i.e. elaborate), 2) select, 3) amplify, 4) repeat. Elaborating evolution is characterized by experimentation—lots of experimentation; and failure—lots of failure (natural selection and extinction). On the other hand, there is no limit to the adaptations that are possible; elaborating evolution is open ended.

The increase in abundance and diversity from elaborating evolution is driven by the increasing differentiation (fractionating evolution) of Earth environments, including the geosphere, hydrosphere, and atmosphere (6.4). Conversely, the evolution of Earth environments has also been driven by elaborating evolution. It is the interplay among these that constitutes Earth evolutionary history (6.8).

**Fractionating evolution** begins with a complex parent which is physically or chemically divided into fractions through the dissipation of sufficient energy because of differences in the

size, weight, valence, reactivity, etc. of the component particles. Large components of Earth evolution is by fractionation, including the compositional evolution of the atmosphere and oceans, the evolution of rocks, and isotope fractionations, such as  $^{13}\text{C}$  used in radiometric dating, and  $^{18}\text{O}/^{16}\text{O}$  used to measure ancient temperatures from ice cores. For example, igneous rock evolution, and by extension the origin and evolution of the continents, begins with a chemically complex parent that in hand specimen resembles a basalt. Through successive stages of partial melting the initial rock is divided into fractions, an unmelted fraction that is more mafic than the parent, and a melted fraction that is more felsic than the parent. These processes occurring along subduction zones generate the intermediate and felsic magmas that eventually make the continents.

Weathering and sorting that results in sedimentary rocks is also fractionating evolution (4.8). The evolution of the atmosphere from a dominantly  $\text{CO}_2$  rich state (still present on Venus and Mars), to a methane and  $\text{CO}_2$  mixture in the Archaean, to the nitrogen and oxygen composition today is via fractionating evolution. In most of these evolutions, biology is an essential mediating step, and as biological systems have evolved they have driven geological, atmospheric and hydrospheric evolution, while changes in geological, atmospheric and hydrospheric systems has fed back to drive biological evolution.

Although lots of diversity may be created by fractionating evolution, there is always a finite—and sterile—end state to the fractionation determined by the chemistry and physics of the system. An important geological implication of fractionating evolution is that the circular rock cycle so commonly taught in Earth science classes, leaves out a most important component—that the geological Earth is a fractionating evolutionary rock cycle, and rather than just going round and round in a circle has undergone directional and irreversible change (Whitmeyer, Fichter, Pyle, geosphere paper as a reference.)

**Self-organizing evolution** is the ability of a system to develop structures and patterns in the absence of control or manipulation by an external agent. All these phenomena begin with random or less ordered initial states which increase in organization and/or complexity by the interaction of entities with their near neighbors, following simple locally-acting rules, which are usually the laws of chemistry and physics, and/or mathematical algorithms. Unlike elaborating evolution, where much diversity is created, after which selection eliminates—or fails—much of it, self-organization is a growth-based strategy. Starting with a seed, or random initial conditions, the system progressively expands into and adapts to the available space, following the local rules for the system.

Self-organizing evolution is one of the most pervasive, and its mechanisms are used to explain how networks evolve (from the World Wide Web to social networks, to ecosystems, to how termites without central leadership build a colony that looks like it has design and purpose.) Alternatively, self-organizing theories explain turbulence in fluids, cross bedding in sediments, river drainage patterns, evolution of earthquake systems, crystal growth, patterns in animal pelts and shells, the shape of spiral galaxies, and a host of others. Also, the question of the origin of life is self-organizing, unlike the “evolution” of life, which once in existence, is elaborating.

Thinking about and modeling changes in Earth systems as evolutionary processes—explicating the different evolutionary processes within each domain of lithosphere, atmosphere, hydrosphere *and* biosphere as well as how evolutionary processes in one sphere affects the other spheres— gives a central, unifying theme to all the changes we see in Earth systems evolution by providing rational and testable mechanisms that explain the complexity and interactions that we see.