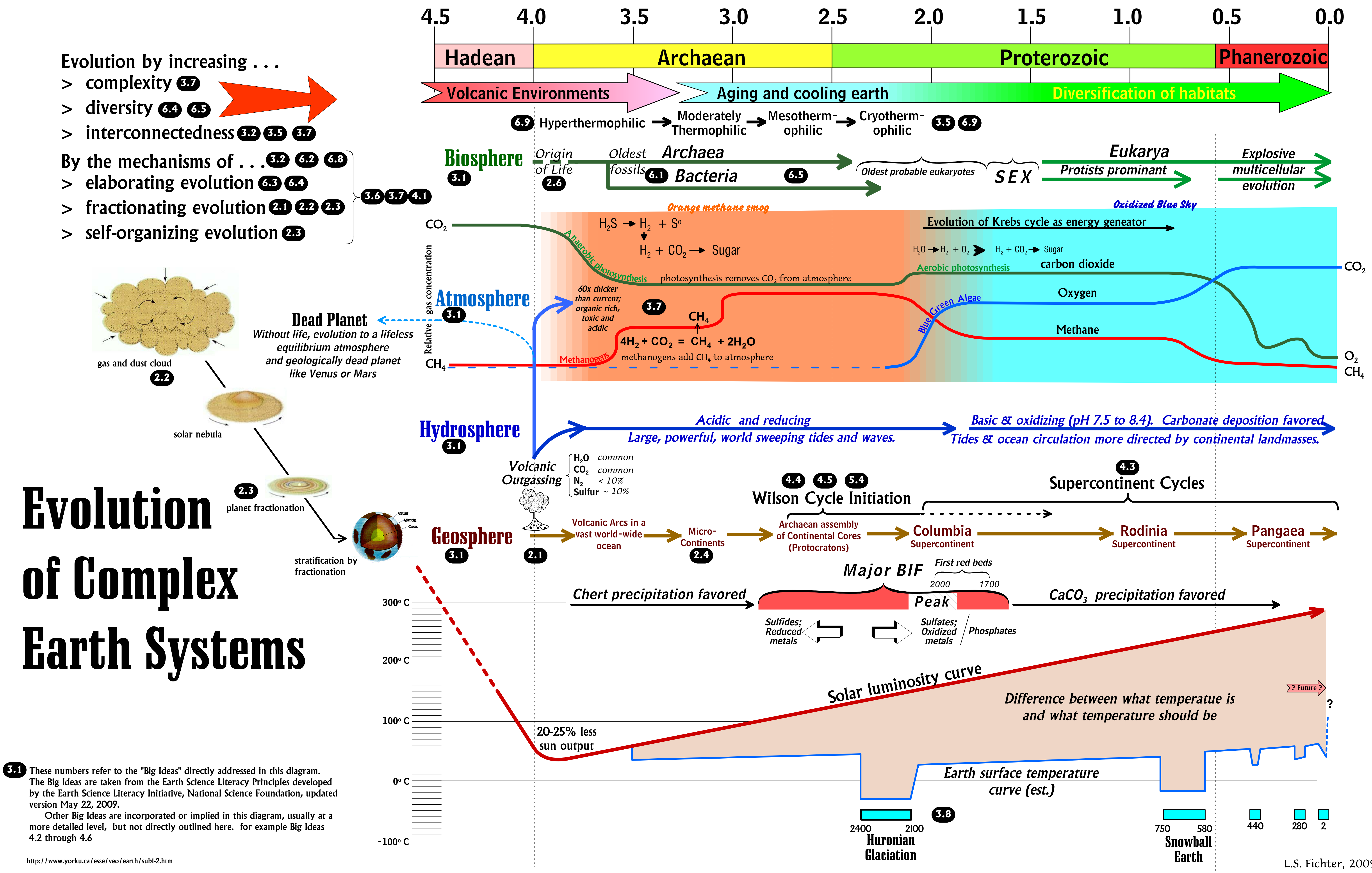
Evolution of Complex Earth Systems



3.1 These numbers refer to the "Big Ideas" directly addressed in this diagram. The Big Ideas are taken from the Earth Science Literacy Principles developed by the Earth Science Literacy Initiative, National Science Foundation, updated version May 22, 2009.

Other Big Ideas are incorporated or implied in this diagram, usually at a more detailed level, but not directly outlined here. for example Big Ideas 4.2 through 4.6

http://www.yorku.ca/esse/veo/earth/sub1-2.htm

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MAESTRO: Evolution of Complex Earth Systems: Flow Diagram of Evolutionary Changes and Relationships

To have Earth Science literacy it is not enough to just have knowledge of geology, biology, meteorology, and/or oceanography by themselves. More important, one must understand how these four systems have interacted through 4 billion years of history to result in the Earth we have today. The flow model ***"Evolution of Complex Earth Systems"*** summarizes the systems, history, and relationships that lie behind and support MAESTRO. Knowledge of these complex interactions is not only essential to understanding the past, it is also essential to understanding our present and future environmental conditions.

The Earth formed from the same gas and dust cloud and from similar processes as its nearest neighbors Venus, and Mars. Venus and Mars are, however, lifeless, dead, equilibrium planets while the Earth remains thermodynamically open, geologically active, and rich with life. The Earth could have evolved to an equilibrium state like Venus/Mars, with an atmosphere of ~95% CO_2, a lithosphere composed mostly of basalt, and no liquid water, but it did not. Instead the Earth has large oceans, an atmosphere that evolved from CO_2 rich, to CH_4/CO_2 rich, to nitrogen/oxygen, a crust divided into distinct ocean basins and continents, while at the same time maintaining a surface temperature that has allowed liquid water to exist, despite the fact the energy received from the sun has increased steadily through the solar system's history (solar luminosity curve at bottom of foldout) .

The essence of understanding the Earth is explaining how the geo-, hydro-, atmo-, and biospheres interact—have transferred energy and materials with each other—through 4.5 billion years to result in an Earth that evolves and changes continuously, allowing all the systems to increase in diversity, abundance, complexity, and interconnectedness with time (see Three Mechanisms of Evolution Change). These facts are not accidents; they are the result of complex and evolving interactions among the four spheres. The history of these interactions are preserved in the rocks; without rocks there would be no history: every rock results from the convergence of processes within each sphere. This leads to the three precepts: 1) Follow the energy; 2) No rock is accidental; 3) All the systems increase in diversity, complexity, and interconnectedness through three distinct evolutionary mechanisms.

Because solar luminosity increases at a known rate (see flow, bottom), temperature conditions at the Earth's surface could have–should have–risen steadily over the past 4.6 billion years from a level 20-25% below present to a current projected temperature of ~ 300^o C. That this temperature increase has not occurred is evident, and the reason is the Earth, unlike Mars and Venus, has sustained life over the past 3.6 (oldest fossils) to 4.0 billion years (depending on when life appeared). Beginning with methanogen Archaebacteria and anaerobic photosynthetic bacteria, life began to regulate the surface temperature. Both methanogens and photosynthesizers draw down CO_2 from the atmosphere, reducing the greenhouse effect, leading to lower temperatures. Conversely the methanogens in obtaining energy from the reaction $CO_2 + H_2 \rightarrow CH_4 + H_2O$ release CH_4 as a waste product into the atmosphere leading to greenhouse warming (biosphere and atmosphere paths at top of model). As Lovelock has shown in the Daisyworld models, CH_4 and CO_2 act as positive and negative feedbacks to regulate temperature in spite of rising solar luminosity, the long term effect of which is CO_2 has declined from its initial ~95% to today's .03%. One reason Venus is so hot today is because it retains its initial ~95% CO_2 greenhouse atmosphere.

These changes are an example of the Earth systems modeling that is part of MAESTRO, and although the connections between atmosphere and hydrosphere are not as well known for the ancient Earth, similar deductions based on evidence from the ancient rocks are part of this thinking (flow model).

The geosphere has its own evolutionary trajectory, both by itself, but also closely interacting with the other three spheres. For example, the tectonic evolution of rocks on Earth is dependent on the presence of water, which the Earth has retained since its formation compared to Mars and Venus because of life processes. Changes in atmospheric composition and ocean chemistry also respond to and at the same time change life evolution and processes. For example, the development of aerobic photosynthesis about 2 billion years ago put oxygen into the atmosphere—resulting in one of the largest environmental cataclysms in Earth history—while at the same time leading to the evolution of consuming organisms with the Krebs cycle. These changes also changed the geochemistry of the Earth (for example an acidic ocean—pH ~5.5) to a basic one—pH 7.5-8.4) which led to changes in the abundances of sedimentary rocks being formed.

Meanwhile, as the geosphere has evolved from a planet dominated by isolated, scattered volcanoes in a worldwide ocean, to one with microcontinents and then continents, tectonic processes evolved from the development of Wilson cycles to finally supercontinental cycles (see flow model). Conversely, as the Earth aged and cooled (began to use up its tectonic energy) the environments available for life to diversify into expanded from hyperothermophilic to mesothermophilic, to cryothermophilic (see flow model; top). From the Proterozoic on then, and with the final evolution of eukaryotes and multicellular life, expanding continental land masses, shallow epicontinental seas, and finally terrestrial environments opened up further environments for life's evolution.

Many other connections are known among the four spheres, and virtually every Earth process can be related back to the interrelationships shown in the flow model, although at more detailed levels. The important point of this flow model is to demonstrate that the four spheres are tightly interlocked with each other via positive/negative feedbacks, and have been from the beginning of Earth history, and therefore it is wise to build a teaching curriculum around these interrelationships.