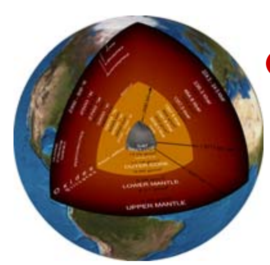
Evolution of Complex Earth Systems

Lynn S. Fichter and Eric J. Pyle, 2010, Department of Geology and Environmental Science, James Madison University, Harrisonburg, Virginia, 22807



Dead Planets

Without life, evolution to a lifeless equilibrium atmosphere and geologically dead planet like Mars or Venus

Virginia 6th Grade Science Standards of Learning

Evolution by increasing . . . 6.1 i

> complexity

> diversity

> interconnectedness

By the complex systems mechanisms of . . .

> elaborating evolution

Elaborating evolution begins with a seed, an ancestor, or a randomly generated population of agents, and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function; those that do not measure up selected out. The fitness function may be a real environment, an abstract environment, or another "species" of agents.

> self-organizing evolution

Self-organizing evolution begins with an initial state of random agents that through the application of simple rules of interaction among the agents (e.g. an algorithm, or chemical/physical laws)evolves a system of ordered structures, patterns, and/or connections without control or guidance by an external agent or process; that is, pulls itself up by its own boot straps—Local Rules leads to Global Behavior.

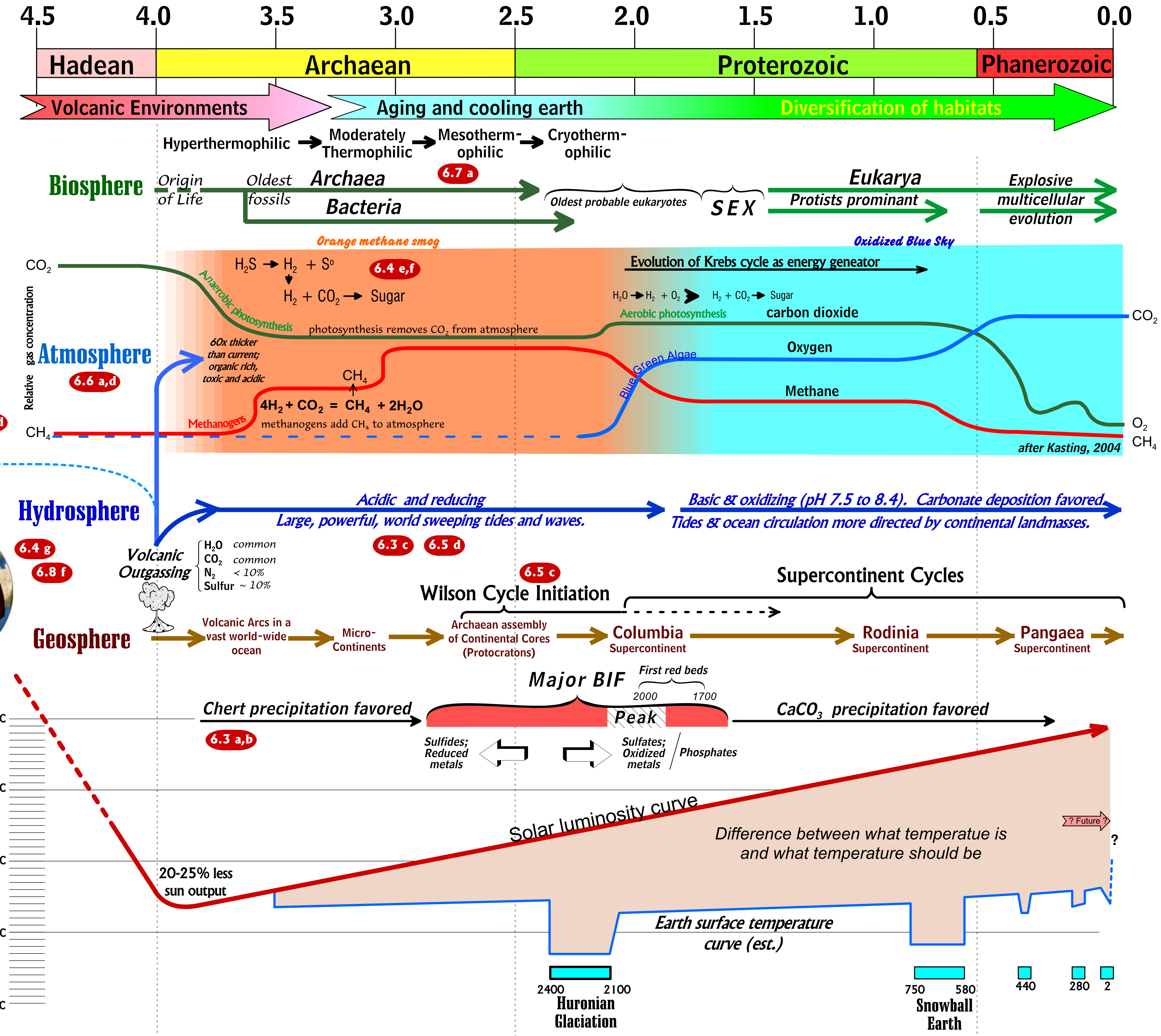
> fractionating evolution

Fractionating evolution begins with a complex parent which is physically, chemically, or biologically divided into fractions—through the addition of the right amount of energy—because of differences in the size, weight, valence, reactivity, etc. of the component particles.

The designators in cartouches refer to the Virginia 6th grade Standards of Learning items that are specifically germain to different parts of this complex Earth systems model.

Other Standards of Learning, usually existing as prerequisite knowledge to the SOLs listed here, are implied in this diagram, but not directly outlined here.

FROM: Final Review of Proposed Revised *Science Standards of Learning;* January 14, 2010; Ms. Paula Klonowski, Science Coordinator



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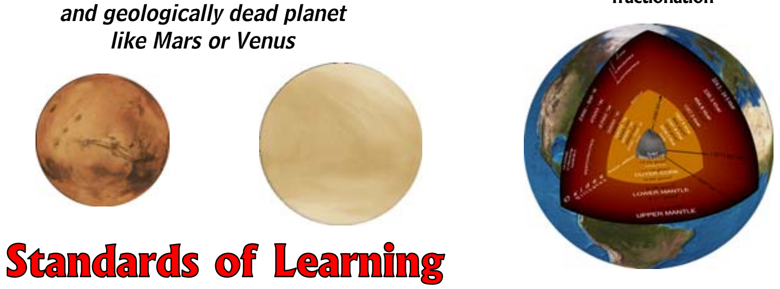

Virginia Standards of Learning

ES.2a Earth Sciences LS.3a Life Sciences BIO.8 Biology

Evolution by increasing . . .

> complexity ES.2a ES.10c LS.3a

> diversity LS.3b LS.4a-c

> interconnectedness ES.2a LS.6a-d LS.7a LS.8a-e

By the complex systems mechanisms of . . .

> elaborating evolution LS.13a-c

Elaborating evolution begins with a seed, an ancestor, or a randomly generated population of agents, and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function; those that do not measure up selected out. The fitness function may be a real environment, an abstract environment, or another "species" of agents.

> self-organizing evolution ES.2a ES.3b LS.3 LS.6 LS.7 LS.8 BIO.8a,c

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> fractionating evolution ES.10b-c ES.11

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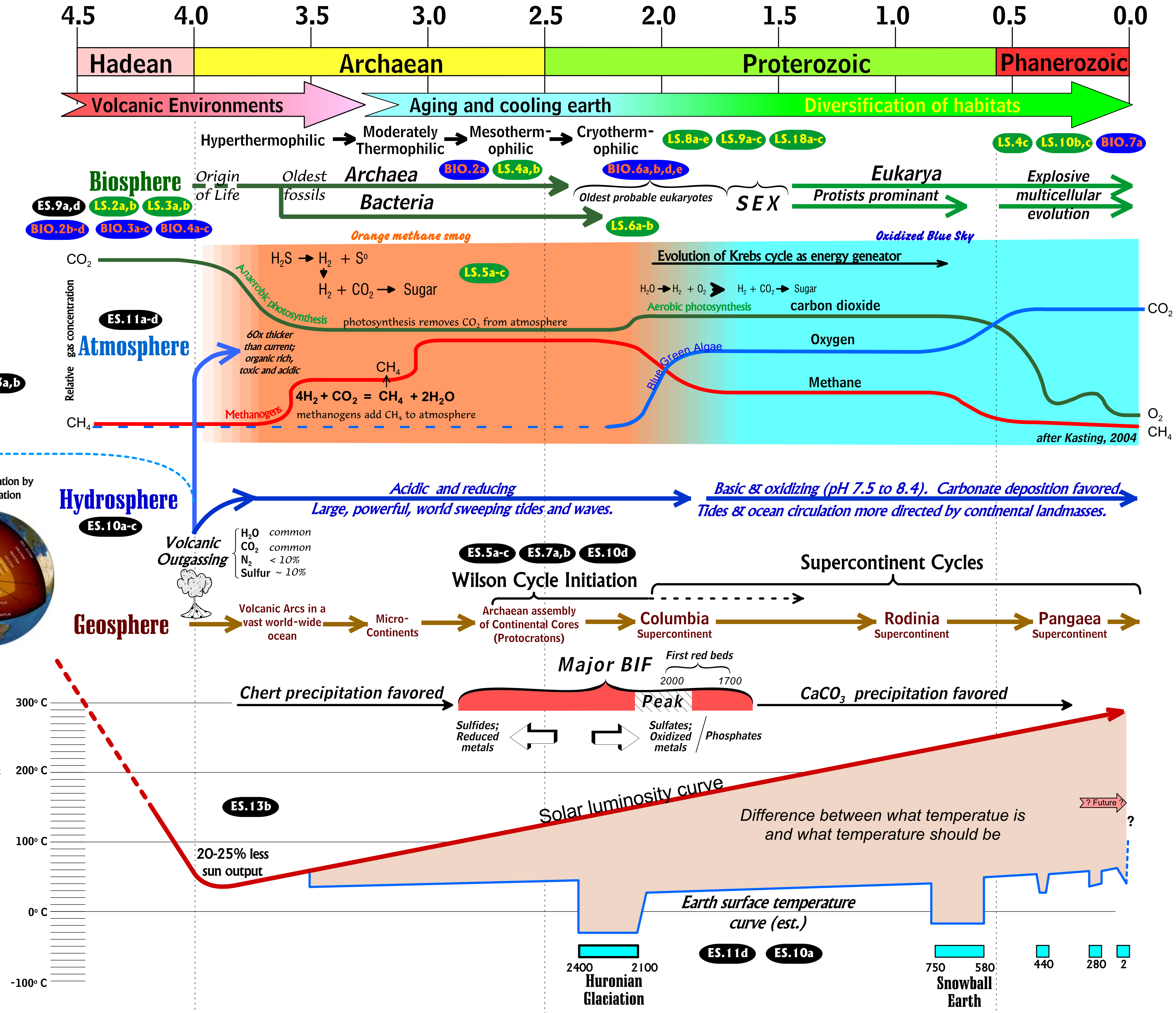
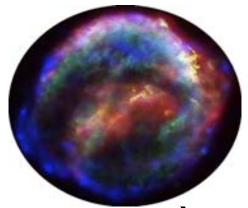


JAMES MADISON UNIVERSITY



supernova creating elements and scattering them into space 2.2

Evolution of Complex Earth Systems

gas and dust clouds collapsing into solar systems

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solar nebula and planet fractionation 2.3

stratification by fractionation

Dead Planets

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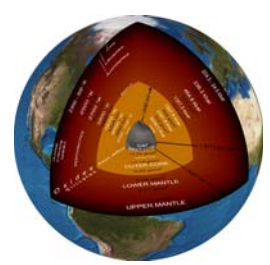

National Science Foundation, Earth Science Literacy Principles - Big Ideas

Evolution by increasing . . .

- > complexity 3.7
- > diversity 6.4 6.5
- > interconnectedness 3.2 3.5 3.7

By the complex systems mechanisms of . . .

- > elaborating evolution 6.3 6.4 3.2 6.2 6.8

  Elaborating evolution begins with a seed, an ancestor, or a randomly generated population of agents, and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function; those that do not measure up selected out. The fitness function may be a real environment, an abstract environment, or another "species" of agents.

- > self-organizing evolution 2.3

  Self-organizing evolution begins with an initial state of random agents that through the application of simple rules of interaction among the agents (e.g. an algorithm, or chemical/physical laws)evolves a system of ordered structures, patterns, and/or connections without control or guidance by an external agent or process; that is, pulls itself up by its own boot straps—Local Rules leads to Global Behavior.

- > fractionating evolution 2.1 2.2 2.3

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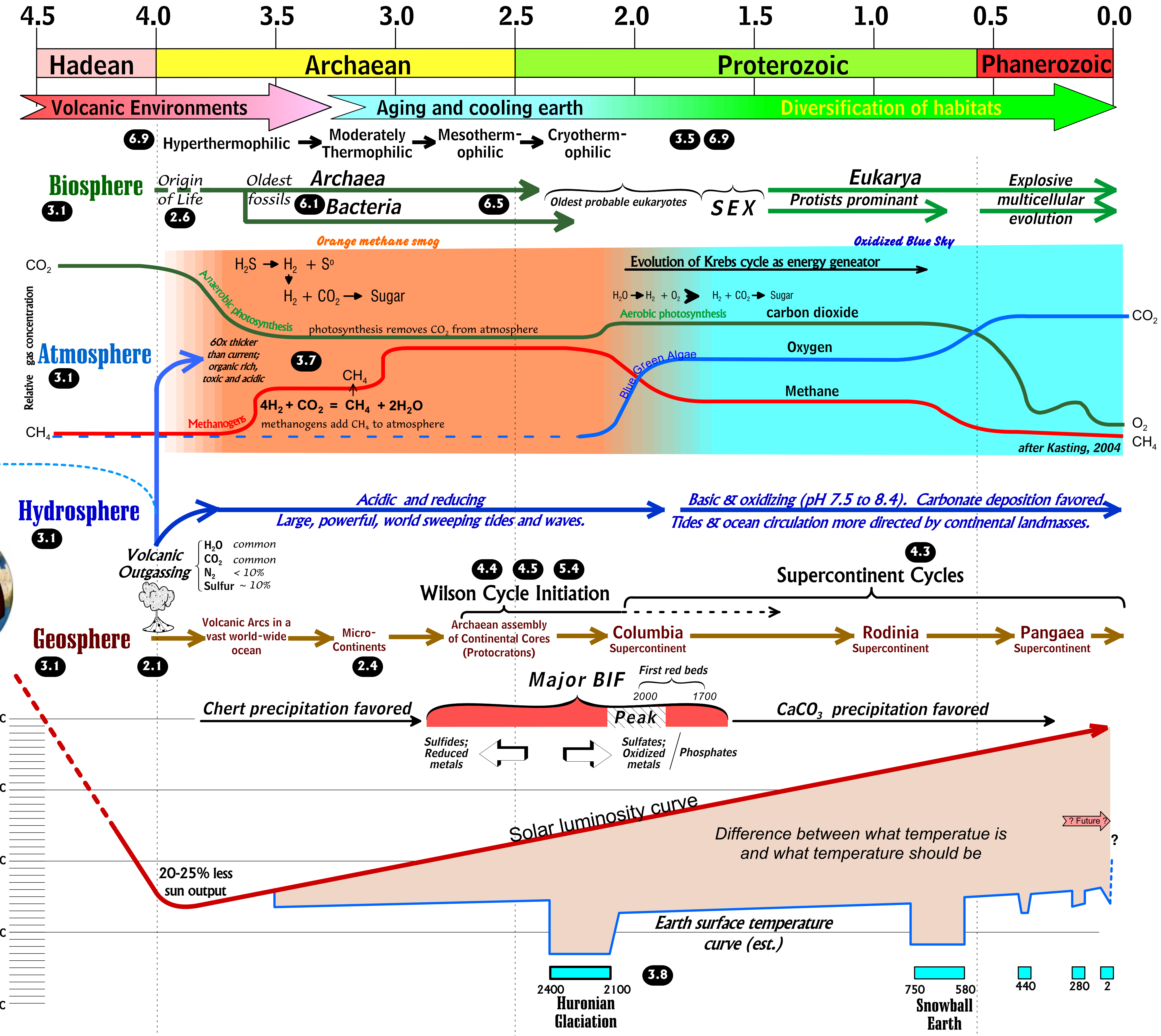
3.6 3.7 4.1

Numbers in cartouches refer to the "Big Ideas" directly addressed in this diagram. The Big Ideas are 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



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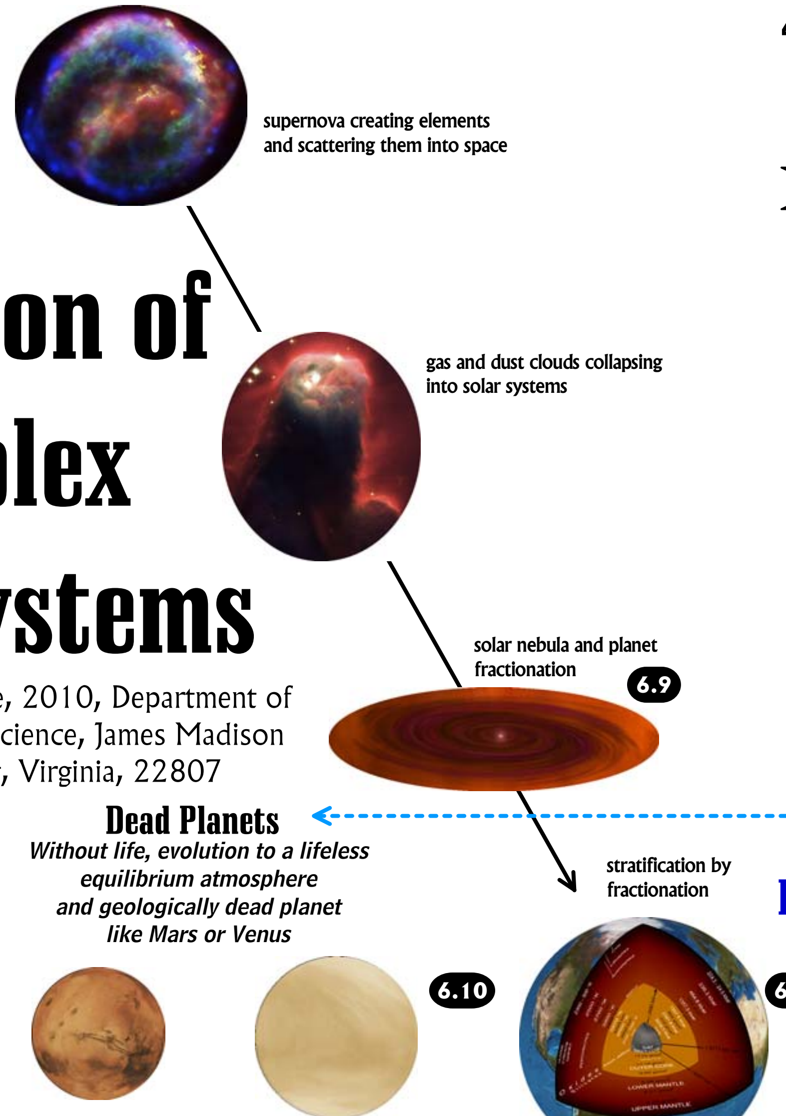

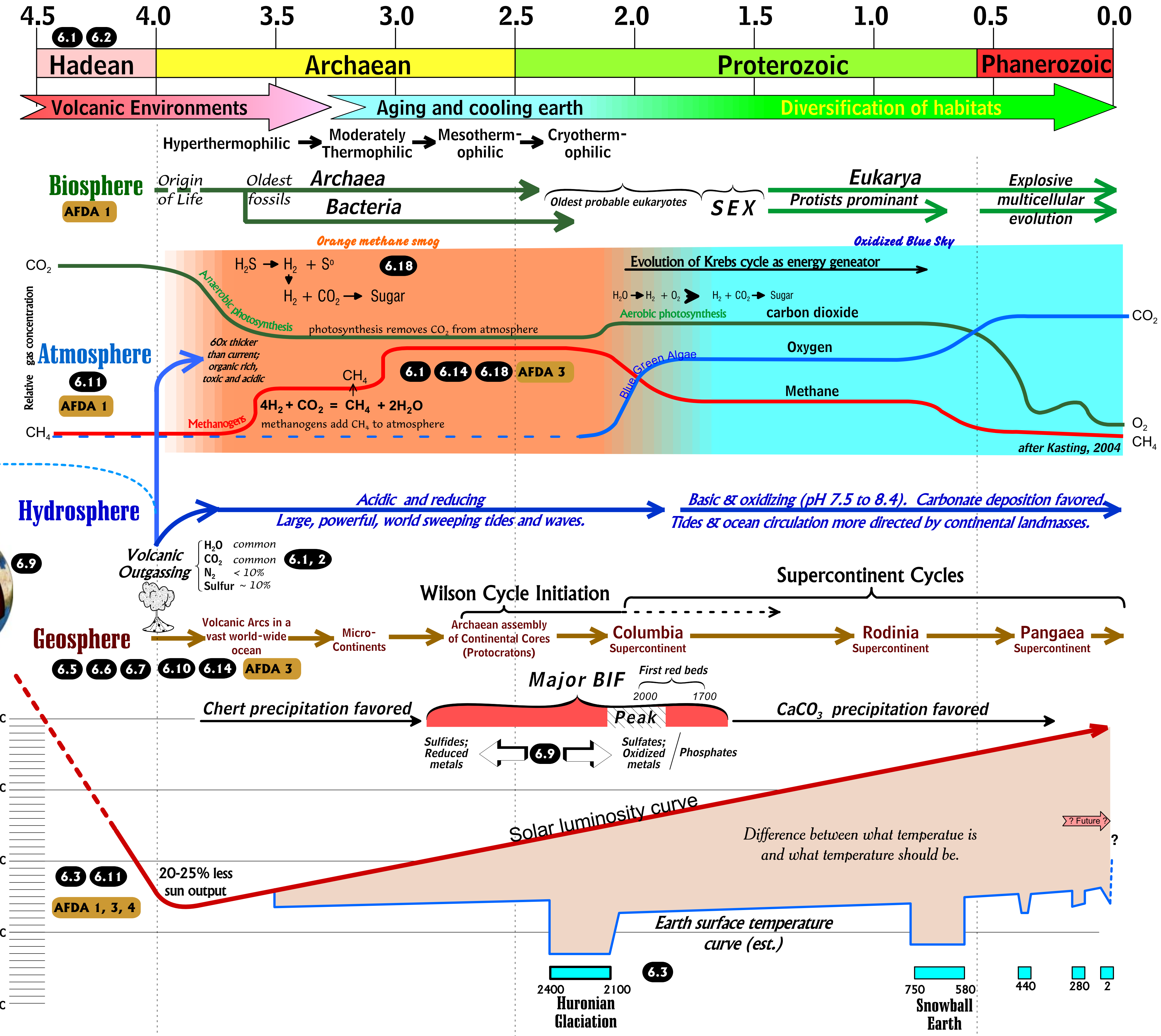

Virginia Math Standards of Learning

6.1 Sixth Grade AFDA 1 Algebra, Fuctions and Data Analysis

Evolution by increasing . . .

> complexity 6.1 6.16

> diversity AFDA 1, 2, 4, 6, 7

> interconnectedness

By the complex systems mechanisms of . . .

> elaborating evolution

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The math Standards of Learning, are usually stated in terms of pure mathematical concepts. We have identified places where those concepts can be used to describe or explain parts of this model, without here specifying specifically what they would look like. These will be the foci of workshop discussions.

FROM: Virginia Standards of Learning for mathematics. Final Review of Proposed Revised Science Standards of Learning; January 14, 2010.

MSP Targeted Partnership

MAESTRO

Proposal Descriptions/Explanations for the Evolution of Complex Earth Systems Model

October, 2010 Version

The central premise of MAESTRO is that the lithosphere, biosphere, atmosphere, and hydrosphere (henceforth the "spheres") are intimately interconnected and have evolved in unison throughout the Earth's history. The Complex Earth System Model serves as a framework to explore and relate various ideas and standards of learning incorporated in MAESTRO. We do not mean to imply that all of the ideas in the model are necessarily incorporated into Secondary education classrooms. What these models are meant to demonstrate is that there is a strong theoretical framework supporting MAESTRO, and that there is a rich source of ideas to draw upon.

Below we describe three ideas relating MAESTRO and the Evolution of Complex Earth Systems Model. The first describes the Complex Earth System Model, the second how various science standards relate to the model, and the third, the three mechanisms (computational algorithms) of evolutionary change by which the solar system and Earth systems evolved.

1. 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/climatology, and/or oceanography by themselves. More important, one must understand how the spheres have interacted through 4 billion years of evolutionary history to result in the Earth we have today. Furthermore, one must be able to articulate the physical and chemical principles behind these processes, and the mathematics that analyzes and explicates them. 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 (see Earth systems model), 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 Earth System Model) .

The essence of understanding the Earth is explaining how the geo-, hydro-, atmo-, and biospheres interact—have transferred energy and materials between and among 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. 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 that drive MAESTRO: 1) Follow the energy; 2) No rock is accidental; 3) All the systems increase in diversity, complexity, and interconnectedness through three distinct evolutionary mechanisms (described below.)

Because solar luminosity increases at a known rate (see Earth systems model, 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 methanogenic Archaebacteria and anaerobic photosynthetic bacteria, life began to regulate the surface temperature by adjusting atmospheric gasses. 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 Earth systems model). As Watson and Lovelock (1983) and Lenton and Lovelock (2001) have 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 Earth systems 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 abundant water, which the Earth has retained since its formation compared to Mars and Venus *because of* life processes. Hazen, et al. (2008) and Hazen (2010) also demonstrate that a non-evolving planetary body, like the moon, is limited to about 250 minerals, but on Earth life processes have created environments that have resulted in the ~4000 minerals now on Earth. 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 using the Krebs cycle as a respiratory pathway. 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 kinds and 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 Earth systems 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 Earth systems 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 Earth systems model, although at more detailed levels. The important point of this Earth systems 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 efficacious to build a teaching curriculum that taps all the sciences and mathematics around these interrelationships.

2. Complex Earth System Model and Science Standards

As a model demonstrating how the four spheres have interacted, the model ***The Evolution of Complex Earth System*** stands on its own. For the purposes of MAESTRO, however, we need to demonstrate that the model is a consistent and applicable medium to provide examples for science learning standards. To illustrate the connections between the Complex Earth Systems Model and science standards we provide four version of the chart. The Earth systems model in each chart is identical, but each contains notes illustrating how specific points in different standards of learning are incorporated into the model, and how the model can be used to explicate those standards. The place where each specific standard of learning applies is designated by a cartouche containing the alphanumeric indicator of the standard. We include only those standards that are specifically germane to different parts of the Earth systems model. Other standards of learning, usually existing as prerequisite knowledge to a standard, are implied in the diagrams, but not directly outlined.

The four learning standards MAESTRO applies to the Complex Earth Systems Model are:

- Virginia 6th Grade Science Standards of Learning. Final Review of Proposed Revised Science Standards of Learning; January 14, 2010.
- Virginia Standards of Learning for Earth Science, Life Science and Biology. Final Review of Proposed Revised Science Standards of Learning; January 14, 2010.
- Virginia Standards of Learning for mathematics. Final Review of Proposed Revised Science Standards of Learning; January 14, 2010.
- National Science Foundation, Earth Science Literacy Principles - Big Ideas; May 22, 2009.

3. Evolutionary Processes in the Complex Earth System Model

The essence of Earth history is that the four spheres that compose the Earth have evolved with time, where evolution is defined as an increase in complexity, diversity, order, and/or interconnectedness with time. We acknowledge these changes when we observe that rocks have evolved, life has evolved, the atmosphere has evolved, and environments have evolved. But, it is clear that not all these systems evolve by the same mechanism; rocks and life become more complex and diverse with time by different mechanisms.

If we model the mechanisms by which systems increase in complexity, diversity, order, and/or interconnectedness with time—for example, writing computer algorithms to simulate them—we find three distinct computational strategies. These are elaborating, fractionating, and self-organizing evolution, briefly described below (see Fichter, Pyle, and Whitmeyer, 2010A, and 2010B)

Elaborating evolution begins with a seed, an ancestor, or a randomly generated population of agents, and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function; those that do not measure up are selected out. Those that survive are reproduced—with mutations—and run through the fitness function again. The fitness function may be a real environment, an abstract environment, or another "species" of agents. Neo-Darwinian evolutionary mechanisms are a specific example of elaborating evolution, but non-biological examples also exist, including optimizing computational algorithms in computer science.

Self-organizing evolution begins with an initial state of random agents that through the application of simple rules (e.g. an algorithm, or chemical/physical laws) evolves a system of ordered structures, patterns, and/or connections without control or guidance by an external agent or process; that is, pulls itself up by its own boot straps. These mechanisms are pervasive in physical and chemical systems, but also some biological patterns are self-organizing. Computational models include, for example, Self Organized Criticality (Bak, 1996, Bak, et al., 1987), cellular automata, oscillating chemical reactions, and boids.

Fractionating evolution begins with a complex parent which is physically, chemically, or biologically divided into fractions through the addition of sufficient energy because of differences in the size, weight, valence, reactivity, etc. of the component particles. These processes are pervasive in industrial applications, but are also used to explain rock evolution (e.g. solid solution and binary eutectic phase diagrams), and the evolution of the atmosphere and ocean compositions (one specific application is the use of O^{16}/O^{18} isotopes to determine past Earth temperatures from glacial ice and carbonate shells.)

Earth systems are not simple systems (e.g. classical mechanics), or systems of disorganized complexity (classical thermo dymanics). They are what Warren Weaver called problems of organized complexity, and Ilya Prigogine called dissipative structures, and we call complex systems, in which a half-dozen and even several dozen quantities are all varying simultaneously and in subtly interconnected ways. The variables are many, but they are not helter-skelter; they are interrelated into an organic whole.

To approach Earth systems from a complex systems viewpoint we are interested in how the evolutionary processes in one sphere influences the evolutionary processes in another sphere. A few examples of these interactions are:

- The fractionating evolution of atmospheric gasses over geologic time has been largely mediated by biological processes, but not all fractionations are biological (e.g. fractionation of atmospheric oxygen isotopes, and many but not all mineral fractionations).
- Over short geologic time scales (e.g. thousands of years), elaborating evolutionary change has little influence on how fractionation occurs, but at longer geological time scales the evolution of biological elaboration mechanisms has changed the way that chemical fractionation occurs. For example, the switch from an anoxic atmosphere to an oxic atmosphere fundamentally changed the geochemical processes operating on the Earth.
- The fractionating evolution of the atmosphere has at times changed opportunities for elaborating evolution and subsequently the long-term evolution of life on Earth.
- Meanwhile, the origin of life, and development and structure of ecosystems are not elaborating mechanisms, but self-organizing systems, and they influence how Earth environments have evolved through time.

By using Earth materials and processes as examples of evolutionary change we gain multiple advantages. The Earth provides an expansive set of examples in geo-, bio-, atmo-, and hydro- we can explore in classes at nearly all levels. But, also Earth evolution can only be understood by understanding how the biosphere, atmosphere, and hydrosphere have influenced, driven, and modulated its geochemical processes. And, the biosphere, atmosphere, and hydrosphere can only be properly understood by relating them back to the Earth processes that are driving their evolution. The evolutionary model provides a common thread by which multiple science disciplines, often taught separately, can be brought to bear on a single set of integrated processes and problems. This common thread will connect the subjects students learn, spread across five or six years of their education into a common reference point. Meanwhile, growing mathematical sophistication applied to these systems will allow ever more precise mathematical description and modeling skills. Looking at evolution through these concepts we will see new dimensions and new possibilities that might not have occurred to us before. A whole new vision of teaching based on complex evolutionary Earth systems lies before us.

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