

## THE BIOGENIC TRANSFORMATION OF THE EARTH (Part 1: Earth's Environmental Setting)

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Earlier this year while birding at some artificial salt ponds in Costa Rica, I was reminded that the life processes which converted our planet into the temperate, oxygen-rich environment that we take for granted, and which started billions of years ago, are still at work. While my companions scanned the ponds of the small-scale salt-making enterprise for wading shorebirds, or peered into the surrounding foliage hoping for a glimpse of the rare Mangrove Hummingbird, my attention was directed instead to some dirty-looking lumps and mounds barely breaking the water surface in some of the shallow pools. The brown-and-ochre sludge covering the bottom surface of these bodies of water made them as

different from the surrounding lagoon as these pools were from the final salt-encrusted evaporation ponds into which their waters would eventually be directed. Apparently the placid waters and elevated saline content of these intermediate concentration ponds provided the perfect environment to promote the growth of microbial mats, which in places had built up thicker domed mounds several feet in diameter. I was looking at the relicts of a bacterial kingdom that had ruled the Earth by itself for most of our planet's history, that had paved the way for the 'more advanced' forms of life, and whose petrified mound-structures in the exact forms I saw that day (called stromatolites by geologists) have been discovered around the globe in sedimentary rocks up to 3.4 Ga in age.<sup>1</sup> Flat bacterial mats are a common enough feature of every marsh and estuary of the world, but living dome-structured stromatolites are quite rare in today's environment, so it was an unusual privilege to view this ancient lineage that helped transform the world.

The science of paleobiology has existed as a formal, stand-alone discipline for only the last twenty years or so. In this short time, on their own and by drawing upon the work of researchers in many other branches of science, the paleobiologists have made great strides. But be cautioned, as a young science, the theories put forward in this essay are bound to change, for they are based on evidence that becomes ever more fragmentary as it is projected farther back into deep time.

### The Illusion of Stability

In 1785, seventy-four years before Charles Darwin severed biology from its roots in supernatural history, Scottish scientist James Hutton accomplished the same for geology with the presentation of his 'Theory of the Earth' to the Royal Society of Edinburgh. In it he stressed that the most reliable method for understanding events of the distant past is through knowledge of ongoing processes that we can observe today. Formalized by later geologists as 'the present is the key to the past,' this axiom, while not excluding rapid or catastrophic changes, forever removed geology from the dogma of Noah's Flood and the six days of Creation in 4004 BC. Building upon this foundation, Sir Charles Lyell (1797-1873), postulated that geological events were attributed to uniform processes occurring at uniform rates. This 'Principle of Uniformitarianism' was to dominate geology for more than a hundred years and was taught in most college geology courses until only a few years ago. This comfortable 'gradualistic' view of a slowly evolving Earth proved useful by providing key insights into erosion processes, mountain building, glaciation, and even plate tectonics.<sup>2</sup>

<sup>1</sup> The oldest confirmed stromatolites are from the Pilbara Sequence in Western Australia, dated to 3.45 Ga [Schopf (1999), p. 196]. There will be much more to say about stromatolites in Part 2 of this essay.

<sup>2</sup> Powell provides a thorough discussion of Hutton and Lyell and their dominant roles in the history of geology. Also see Drury, Hartmann, McPhee, Lunine, and Lamb.

But what of events such as an asteroid impact that may have exterminated the dinosaurs? Despite Lyell's Uniformitarianism, geologists time and again called upon catastrophes whenever they were stumped.<sup>3</sup> Like 'the little boy who cried wolf too often,' catastrophism fell into extreme disfavor, and throughout most of the 20<sup>th</sup> century no self-respecting Earth scientist would espouse any argument that hinted of large changes effected over short time periods. However, the accumulating record of worldwide catastrophic events, culminating in the verification of the Alvarez theory of the Cretaceous-ending asteroid impact, has brought catastrophism back into the limelight.<sup>4</sup>

The long-term, or uniformitarian, factors with which life has contended fall into six broad categories: (1) solar output; (2) Earth's internal heat engine; (3) variations in continental configurations as driven by plate tectonics; (4) volcanism; (5) a 30 million-year cycle involving geological and astrophysical dynamics; and (6) biogenic effects driven by large-scale life processes. Three principal types of catastrophic events have punctuated these long-term effects: (1) bombardment by cosmic bodies; (2) volcanic upheavals; and (3) run-away climatic change.<sup>5</sup>

We should note that a long-term factor, such as the Earth's internal heat engine, can drive or greatly influence other factors, in this case both long-term plate tectonics and short-term volcanic upheavals. We should also observe that some factors have been extremely beneficial to life, while others have presented extreme challenges. And finally, that in an article of this brevity, we can barely touch upon these factors to give but a hint of their relevance to life on Earth.

### Long-term (Uniformitarian) Factors

**(1) Solar Output:** The radiation emitted by a star varies over its lifetime. In its youthful stage, the Sun produced only about 70 percent of the heat output we receive today. The net effect should have been the creation of a snowball Earth consisting of frozen glaciers of water and carbon dioxide.<sup>6</sup> Fortunately, carbon dioxide (CO<sub>2</sub>) is a greenhouse gas *par excellence*, and the thick blanket of the gas, as on Venus, trapped enough heat to prevent what would have been the ultimate freeze-up. As the Sun warmed up, life intervened to drastically draw down CO<sub>2</sub> levels and prevent a run-away Venus-type situation.<sup>7</sup>

<sup>3</sup> For an example of this 'back against the wall' recourse to catastrophism, we have to look no further than our own Golden State and its able and forceful first Director of the California Geological Survey, Josiah Dwight Whitney. Rather than admit that glaciers had carved out the deep valley of Yosemite as propounded by that 'ignorant sheep herder' John Muir, Whitney laid the creation of the valley to a catastrophic earthquake.

<sup>4</sup> The father-son team of Luis and Walter Alvarez presented their ground-breaking theory of an asteroid strike causing the extinction of the dinosaurs in 1980 (Ward). Their discovery is the subject of two full-length book treatments (see Alvarez and Powell). See Powell's *Night Comes to the Cretaceous: Dinosaur Extinction and the Transformation of Modern Geology* for an excellent treatment of catastrophism vs. uniformitarianism and the way modern science works, or sometimes doesn't work.

<sup>5</sup> There are a dozen or more catastrophe candidates that could be added to this list. My personal favorite is the occasional star that explodes in our neck of the woods as the Solar System travels through the galaxy. According to Hartmann (p. 234), the likelihood of a supernova occurring within 100 light-years of Earth, close enough to appreciably damage our ecosystems, is about once every 1 Ga, and therefore has probably happened at least four times during the history of the Earth.

<sup>6</sup> The 'Weak Sun Paradox', as it is called, is described in Lamb (pp. 230-231), Drury (p. 180), Lunine (p. 165-166), and Schopf (1983)(pp. 263-264).

<sup>7</sup> Estimates of CO<sub>2</sub> in the early atmosphere vary from 1/10 atmosphere to 7 atmospheres—a wide range, but significantly more than the fraction of a percent of

<p><b>Time Notation</b>  <b>Ga = 1,000 million years</b>  <b>(a billion in the American lexicon)</b>  <b>Ma = one million years</b></p>
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**(2) Earth's Internal Heat Engine:** When Lord Kelvin computed the age of the Earth in 1899 based on rates of heat transfer, he came up with a figure of 20-40 Ma. His mathematics and understanding of thermodynamics were sound, but the science of his day was unaware of the heat engine contained in the radioactive elements bound up in the very substance of our planet.<sup>8</sup> Radiogenic heat, generated by the Earth's nuclear engine, expresses itself through the slow-but-steady convection of heat through the lithosphere, through volcanism, and indirectly through planetary plate tectonics as the power source that drives continental motions. This last expression of planetary thermodynamics is responsible for sea floor spreading and the resultant 'Ring of Fire' around the Pacific Ocean<sup>9</sup>. Plate tectonics and volcanism have been critical factors in the history of life, so it is important to acknowledge their ultimate source and to realize that this engine has been consuming its fuel and is today producing only one-sixth of the heat it generated when life may have originated nearly 4 Ga ago<sup>10</sup>. Geologically, Earth was far more dynamic in the ancient past.

**(3) Plate Tectonics:** The continents, as we now know, are not fixed upon the face of the globe; they have been colliding and splitting and coasting across the surface of the Earth for billions of years. Continental configurations have great effects on ocean currents and weather patterns. Today we live in a 'slice-world', where the great north-south masses of the Americas and Europe-Africa span the globe like two orange slices and disrupt the large-scale Coriolis effects in both the atmosphere and the oceans. World environmental conditions were much different during the part of the Precambrian when the original supercontinent of Rodinia lay along the equator forming a 'ring-world,' allowing free circulation in the higher latitudes. Earth

experienced yet another extreme when the remnants of a fragmented Rodinia re-sutured themselves to form another supercontinent, the more familiar Pangaea. At the beginning of the Permian Period, Pangaea seems to have been centered on the South Pole, forming a 'cap-world.' The realignment of Pangaea from cap-world to ring-world over the next 40 Ma could well have encouraged global warming. When linked to

**Precambrian:** the span of time from the origin of the Earth about 4.56 Ga to the appearance of the first organisms with hard parts in the fossil record at 570 Ma. The Precambrian encompasses nearly 90 percent of the history of Earth.

today's atmosphere, and also considerably less than that found on Venus [Drury (p. 241)]. Per Hartmann (p. 106), if all the CO<sub>2</sub> that is currently 'trapped' in limestones around the world was liberated, the atmosphere would be dominated by this hothouse gas to the extent that the pressure at sea level would run close to 70 atmospheres! Even at today's higher levels of solar radiation, the predicted average surface temperature of Earth would be -15C were it not for the presence of a tiny fraction of greenhouse gases in the atmosphere [Drury (p. 140)]. It's easy to see why climatologists are vitally concerned over the issue of greenhouse gas emissions [Hartmann (p. 223)]. Also see Schopf (1983, 1999), Ward, and Lamb.<sup>8</sup> William Thompson, later Lord Kelvin, was the preeminent physicist of the Victorian era. Macdougall (p. 82) relates the following amusing story about Ernest Rutherford, an early British researcher on radioactivity: 'Rutherford was giving a lecture about the heat produced by radioactive decay, but was nervous because Lord Kelvin, still a powerful force in British science, was in the audience. In a smooth twist, he announced during his talk that Kelvin had in fact anticipated the discovery of radioactivity because his calculation of the Earth's age had been made with the proviso that the result would be different if a new source of internal heat were to be found. It is said that Lord Kelvin, then eighty, had nodded off during the lecture but awoke with a broad smile when he heard Rutherford's pronouncement.'

see Macdougall (p. 82), Drury (p. 103), McPhee (p. 96), and Lamb (pp. 21-23).

<sup>9</sup> On a planet such as Venus, it appears that core-generated heat builds up over a period of approximately 500 Ma with little going on in the way of tectonic action to provide a safety valve. At a critical juncture the whole planet seems to turn 'inside-out', resulting in a complete resurfacing of the planet with a fresh ocean of lava [Drury (pp. 175-176)]. On smaller Mars, the engine seems to have generated a few great volcanoes (among them the largest in the Solar System) but was insufficient to drive plate tectonics [Drury (p. 91)]. The geology of Venus is covered in more detail by Lunine, and Ward. A discussion of Martian geology may be found in Lunine and in Schopf (1983).

<sup>10</sup> Slow-down of Earth's heat engine, see Drury (p. 122); also Lamb (pp. 217-218).

massive volcanism of the late Permian, this may have created a run-away greenhouse effect that was at least partly responsible for "The Great Die-Off" at the end of the period.<sup>11</sup>

**(4) Volcanism:** During all the time in which continents were forming and reforming and sliding around the globe like jigsaw puzzle pieces during an earthquake, volcanism was acting, as it continues to act, as the major convective heat transfer mechanism for Earth's nuclear engine. We owe our very atmosphere and the oceans to the prolonged volcanism that has played out on Earth. The outgassing that occurred during the molten period of Earth's earliest years created the original reserves of carbon dioxide and water, but both would most likely have dwindled to insignificance without restocking from the chemical cupboard of the mantle via volcanism<sup>12</sup>. Water molecules are too heavy to escape Earth's gravity, even when excited to high energy levels (turned to super-heated steam). However, water can spontaneously dissociate under ultraviolet stimulation into its separate oxygen and hydrogen components, and while the heavier oxygen molecules remain earthbound, free hydrogen formed this way in the upper atmosphere literally floats off into space. This is one theory now being propounded to explain the evidence of water-formed features on Mars where no surface water is to be found today. Through photodissociation, the Red Planet's ancient seas were 'evaporated'—hydrogen escaping to space and oxygen bonding to iron to create the rusty-red oxidized surface that gives Mars its alternate name.<sup>13</sup>

Large-scale volcanism has presented some extreme challenges to life, as we shall see. In our long-term view of a changing Earth environment, we recall here the earlier observation that Earth's nuclear engine has cooled to where it produces only one-sixth of its original heat output. Think of those ancient times when volcanoes and their eruptions were six times more common and undoubtedly more powerful!

**(5) The 30 Ma Cycle:** One of the most recent and controversial theories of long-term perturbations affecting planet Earth is the observation of cyclicity in the astrophysical, geological, and climatological record of our planet. In 1983, University of Chicago researchers John Sepkoski and David Raup published their discovery of a 26 Ma pattern of mass extinctions for the last 260 Ma, based on a survey of 3,500 families and 30,000 species in the fossil record. Further refinements over the years show the period to be closer to 30 Ma. To mass extinctions, Sepkoski, Raup and other scientists have added a host of other phenomena. As earth scientist Stephen Drury explains:

<sup>11</sup> For effects of 'slice-world' vs. 'ring-world' vs. 'cap-world', see Drury (Chapters 16 and 17). For effect of Pangaea realignment, refer to Drury (p. 267). Lunine devotes many pages to descriptions of continental configurations.

<sup>12</sup> Paleontologist Richard Fortey, of the British Museum of Natural Science, has coined an apt and certainly the most colorful metaphor to describe the outgassing of our atmosphere as "... the consequence of a vast, terrestrial flatulence risen from the bowels of the Earth." See Fortey (p. 32). [Editorial comment: There will always be an England.] For origin of Earth's early atmosphere, see also Lunine (pp. 75-76). See also Lamb (p. 217), who states that the atmosphere was largely in place by 4.35 Ga years ago.

<sup>13</sup> Today, the net gain of gasses (mostly water and CO<sub>2</sub>) to Earth's atmosphere from terrestrial volcanoes is minor compared to the amounts generated at the volcanic spreading centers located beneath the oceans and which drive planetary plate tectonics. With tectonic-generated volcanism absent on Mars, even the huge Martian volcanoes were unable to stem the tide of slow but steady loss of its ancient surface water. See Drury (p. 140); also Lunine (p. 183). However, Lamb (p. 228), thinks that UV radiation at the Martian distance from the Sun is too weak to drive the reaction at significant levels. Photodissociation of water vapor in the upper atmosphere of Earth currently liberates 1,000,000,000 kilograms of oxygen per year [Lunine (p. 241)].

The pace itself is not exclusive to life, but carries through other features of the evolving Earth system for the Mesozoic and Cenozoic [Cenozoic, ed] Eras. The timing of major mountain-building events on all continents over the Phanerozoic [from Cambrian (570 Ma) to the present, ed] shows a periodicity of between 30 and 36 Ma. Igneous events that involve the deep mantle to generate flood-basalt provinces come in 30 Ma bursts. The curve of sea-level change . . . has many superimposed periods, the strongest of which comes out at 33 Ma. Oxygen-isotope records of climate for the last 130 Ma show 30 Ma repetitions. Even the record of changes in the Earth's magnetic field, produced in the fluid outer core, has a 30 Ma signal. For good measure we can also throw in the occurrence of evaporite deposits, pulses in sea-floor spreading, and times when unoxidized organic matter built up on the ocean floor. Even the most optimistic poker player would gibe at such a run of coincidences, especially since all these seeming unrelated processes share the same 30 Ma episodicity—they all happened roughly together.<sup>14</sup>

Astronomers have come up with three principal theories for cosmological drivers for the observed patterns. These include: (1) The possibility that the Sun is really half of a binary star system (like most stars that we observe) with our partner being on a highly eccentric orbit that periodically disturbs the Oort cloud sending showers of long period comets into the inner Solar System some of which strike Earth with catastrophic results.<sup>15</sup> (2) There might be an undiscovered tenth planet performing much the same function. (3) The observed periodicities could be related to the passage of the Solar System through the plane of the Galaxy, which appears to be on the same 30 Ma cycle.<sup>16</sup>

**(6) Biogenic Effects (Life Processes):** Last but not least on our summation of uniformitarian forces affecting life are those imposed by life itself. These biogenic effects will be the subject of most of Part 2 of this essay, but suffice it to say that life has intervened in a major way to alter the oceans, the surface of the land, the atmosphere and our climate. In all likelihood Earth would have been incapable of supporting any higher forms of life today had not life itself altered the environment through the activities of 'the little things that run the Earth',<sup>17</sup> the microbes.

### Short-Term (Catastrophic) Factors

**(1) Meteorite (Asteroid) Impacts:** Most of us are aware of the theory that the impact of a large meteorite may have caused the extinction of the dinosaurs, thus terminating the Cretaceous Period 65 Ma ago.<sup>18</sup>

**Cretaceous Period:** Spanning 136 to 65 Ma, the Cretaceous was named for the thick deposits of chalk laid down during this period (*creta* is Latin for chalk). Although associated with dinosaurs due to their sudden demise at the end of the period, dinosaurs had arisen many millions of years earlier. It should be more properly celebrated as the age in which flowering plants first appeared.

Geophysicists have even located the remnant crater on the northern coast of the Yucatan Peninsula, naming it Chicxulub after a nearby Mexican village. We know of no impacts of similar magnitude since then, and the oceans and

erosive processes on the continents would have obscured collisions from deep time. But of the 130 or so identified impact features on Earth, at

least 11 possess diameters in excess of 50 kilometers, including Chicxulub.<sup>19</sup>

The power expended in a few seconds when an object the size of a mountain slams into the Earth is impressive, as is the repertoire of energy release. For example, since asteroids and comets travel at speeds up to 200 times that of sound in air, by definition the air in front of one of these incoming objects cannot move out of the way and becomes compressed, with about two percent of the kinetic energy of the meteorite being converted into adiabatic heating of the compressed atmosphere. Dr. Drury explains the consequences:

For an object larger than a few hundred metres, air temperature will rise to the order of 60,000 K, ten times hotter than the Sun's surface. This entry flash would emit hard gamma rays from horizon to horizon. Air molecules would be destroyed, their component atoms stripped of electrons to form a plasma. As with lightning bolts, high-energy, low-frequency radio waves would pass unhindered through the entire planet, perhaps to interfere with electrical activity in the fluid outer core that generates the Earth's magnetic field. Huge pressure gradients in the air eventually force a blast effect. As well as sideways, blast models suggest an upward one at velocities that approach those where matter can escape the Earth's gravitational field. The synthesis of unusual gas molecules as the atmosphere cools is a distinct possibility. Nitrogen and oxygen molecules can combine to form a variety of gaseous oxides of nitrogen, all of which dissolve in water, eventually to form nitric acid.<sup>20</sup>

As anticipated, a major impact represents a real blow to life. Kill mechanisms can be separated into short-term and long-term. The flash of heat, hard gamma-radiation and follow-on blast wave would immediately kill all larger surface organisms in the event of a land hit. If the object struck the ocean, shock waves traveling through the water would destroy all larger marine animals. Resulting acid rains would result in kill-off of land plants, plankton, and shallow-water marine organisms, including coral reefs. Solar blocking from smoke and aerosols would severely impact phytoplankton and photosynthetic plants. Tsunamis would destroy coral reefs and estuarine systems.

Longer-term effects on life are much less certain. Scenarios include both global warming due to CO<sub>2</sub> increase (and from water vapor in the event of an oceanic impact), and global cooling from the so-called 'nuclear winter' effects. These in turn could result in sea-level fluctuations due to glaciers melting or growing.<sup>21</sup>

Given immense amounts of time and the huge numbers of asteroid-sized bodies within the Solar System and its enveloping Oort Cloud (source of long-period comets), the Earth cannot avoid all the bullets in the cosmic shooting squad.<sup>22</sup> By studying the fossil cratering record of

<sup>19</sup> The Chicxulub impact of an object estimated to have been 10 km in diameter resulted in a 180 km-wide crater [McPhee (p. 85)] and liberated the energy equivalent to detonating a one megaton bomb for every square kilometer of the Earth's surface [Lamb (p. 197)]. Powell states that the crater could actually be up to 300 km in diameter (p. 194), and may have released up to 7 billion times the energy of Hiroshima (p. 125), or 100 million megatons (p. 179). The classic circular fracture patterns are shown in a false-color gravimetric image in Lamb (p. 198). Powell presents a gravimetric map (p. 105) and references web page <<http://dsaing.uqat.quebec.ca/~mhiggins/MIAC/chicxulub.htm>> for other pertinent images. See Hartmann (pp. 168-177) for full discussion of Chicxulub, including artist's representations. See also Schopf (1999), Lunine, and Macdougall. For maps showing location of major impact features, see Drury (p. 168) and Powell (p. 49); also web page <[http://gdcino.agg.emr.ca/crater/world\\_craters.html](http://gdcino.agg.emr.ca/crater/world_craters.html)>.

<sup>20</sup> Quote on impact effect from Drury (p. 170).

<sup>21</sup> For short-term vs. long-term effects, see Drury (p. 297). Lamb gives a good description of effects specific to the Chicxulub event (pp. 197-199), as does Hartmann.

<sup>22</sup> In addition to the Oort Cloud, there is the less well-known Kuiper Disc, circling the Sun just beyond the orbit of Neptune and believed to be the source of most short-period (SP) comets, such as Halley's. All told, there are probably several thousand billion sizable objects lurking in space with the potential of visiting our

<sup>14</sup> Quote from Drury (pp. 292-293).

<sup>15</sup> The Oort Cloud consists of a shell of deep space debris located at the periphery of the Solar System which makes itself known by supplying a never-ending source of the so-called long-period (LP) comets [Drury (pp. 89-90); Lunine (p. 6)].

<sup>16</sup> Powell devotes a whole chapter (Chapter 12) to long-term periodicities. Also see Drury (pp. 292-294)

<sup>17</sup> For a consideration of life from the point of view of 'the little things that run the Earth', see Wilson, who coined this phrase.

<sup>18</sup> Extinction was not limited to the dinosaurs. At least 50 percent of known species of that time disappeared forever at the end of the Cretaceous [Ward (p. 181)]

the Moon, which stretches back 4.5 Ga, scientists can estimate the probabilities of impacts on Earth.

The Moon looks like Swiss Cheese, full of holes from every angle. The lunar body's lack of tectonics and erosion has preserved the ravages from millions of hits.<sup>23</sup> Now here's where it begins to get scary. Earth is a far larger target than the Moon, possessing greater mass and gravity; so much so that frequencies of lunar impacts of all sizes must be scaled up by a factor of nearly thirteen-and-a-half times for Earth. Scientists have been counting lunar craters for decades. Extrapolating these to Earth results in estimates of our home planet having been struck 27 times in its long history by bodies that would have resulted in craters larger than 1000 km across, with over 3000 other hits greater than 100 km across. Since the Moon was struck once with sufficient bulk and energy to create a crater larger than 1000 km across, extrapolation for the Earth implies the probability of a one-time hit that could have made a crater around 5000 km in diameter, 'large enough to span the Atlantic or engulf the whole of North America.'<sup>24</sup> There's a record of an even greater impact around 4.5 Ga, and again the Moon provides the most striking evidence. The current most widely held theory for the creation of the Moon proposes that a planet about the size of Mars struck the Earth, resulting in a 'splash-out' of mantle material that condensed to become the lunar body.<sup>25</sup>

Before leaving this subject, let's take a brief tour of Canada's Lake Manicouagan in Quebec Province. A circular feature about 65 km across, the geologic formations of the immediate area bear all the unmistakable signs of an asteroid impact 214 Ma ago. The geology can best be interpreted by the delivery of  $5 \times 10^{20}$  Joules of energy in less than a second, or roughly five times the energy locked up in the world's nuclear arsenals.<sup>26</sup> The lunar frequency studies indicate that strikes smaller than the Lake Manicouagan event, but still capable of instantaneous delivery of the entire nuclear arsenal have happened on the average of every 400,000 years—a possible 10 times while humanity evolved.<sup>27</sup> Earth has passed through a number of 'nuclear winters' through which life has persevered.

**(2) Large-Scale Volcanic Eruptions:** The Deccan Traps of western India are a series of basaltic outflows, each lying on top of another to form a series of steps ('trap' is a Swedish word for stairs) up to two kilometers thick. The flows cover an area of half a million square kilometers, having eroded from an original acreage of perhaps three times that when they ceased erupting 64 Ma ago. Even the smaller sized mass of today contains a staggering 2.5 million cubic kilometers of basalt. Many of the

**Carboniferous Period:** Spanning the time from 360 Ma to 290 Ma, the Carboniferous Period derives its name from the thick deposits of carbon laid down when shallow seas flooded widespread tropical forests. Through the mechanism of plate tectonics, these deposits, now coal, were moved with the continents to North America and Europe.

individual eruptive events that created the Traps were characterized by torrential outpourings of lava that welled up from the mantle at rates of tens to hundreds of thousands of cubic meters per second. It took only 2 million years to build the Traps, perhaps a long geologic blink of the eye, but nevertheless a relatively brief period that qualifies as a 'catastrophe' in geologic terms. The pulses during this period must have resulted in huge discharges of carbon dioxide and sulfur dioxide, the powerful greenhouse gases that break down in the atmosphere to form carbonic and sulfuric acid.<sup>28</sup> One can imagine the potential disruption in climate as well as the detrimental effects of 2 million years of off-and-on acid rains. As if this were not enough, at about the same time similar basalt floods broke out in northwest Britain and east Greenland. The dinosaurs, and the ecosystems that supported them, clearly had the deck stacked against them.<sup>29</sup>

If the Deccan Traps are implicated in the mass extinction at the end of the Cretaceous, what about other flood basalt events? As so happens, the largest terrestrial flood basalt known, the Siberian Traps, poured forth during the Permian-Triassic boundary 247 Ma ago, when up to 95% of species disappeared in the greatest mass extinction of all time. Interestingly, shocked grains of probable impact debris show up in Antarctica and southeast Australia also at the same time boundary. And in the most curious coincidence of all, an examination of the globe reveals that the Siberian Traps and the Deccan Traps are located at the antipodes of the probable Antarctic impact event and of the Chicxulub crater in the Yucatan, respectively. Questions abound, without definitive answers: Did both the Permian and Cretaceous mass extinction episodes involve asteroid impact *and* volcanic super-eruptions as the causative agents? Does the effect of a major impact generate disruptive geophysical forces at the opposite side of the planet setting up conditions for superplume magma-generation and consequent floods of deep-mantle basalt?<sup>30</sup>

As is the case with asteroid impacts, basalt floods are spaced far apart in terms of human history, but nevertheless show up frequently in the geologic record, dating back to at least 2.8 Ga.<sup>31</sup> They have occurred on every continent and beneath the oceans as well. As impressive as the Indian and Siberian events were, there are larger flood basalt provinces. The huge Ontong Java Plateau, credited with some of the highest lava discharge rates ever computed, occurred 120 Ma ago under the western Pacific Ocean.<sup>32</sup>

**(3) Run-away Climate:** The last catastrophic process we shall consider is climate—specifically run-away scenarios resulting in periods when

part of the Solar System some day [Drury (pp. 89-90); Lunine (p. 6)]. For graphical illustration of the Kuiper Belt and Oort Cloud, see Lunine (pp. 109-110).<sup>23</sup> Astronomers have reported observing flashes of light from the Moon during last year's Perseid meteor storm, apparently the result of impacts with the debris trail of comet Swift-Tuttle, the 130-year-period comet that is the source of the Perseids (from recent L.A. Times article). Typical velocities computed for objects striking the moon are in the range of 100,000 miles per hour [Lunine (p. 19)].

<sup>24</sup> For estimated frequency of asteroid impacts, see Drury (Chapter 10); also Hartmann (p. 228).

<sup>25</sup> The theory of the moon being the result of a collision between Earth and another cosmic body (the "giant impact theory") has a long history, and geochemical analysis of rocks brought back from the Moon as well as other astrophysical data have reinforced this view. The modern interpretation was established by planetary researcher William K. Hartmann. See Hartmann (Chapter 5), for detailed arguments and excellent painted renditions of this cosmic event. See also Lunine (pp. 127-129). For a one-page summation with good illustrations, see *Natural History*, Vol. 109, No. 1, February 2000, p. 20. *The Moon's Violent Birth*.

<sup>26</sup> The Lake Manicouagan impact event is fully described in Drury (pp. 136-137).

<sup>27</sup> Regarding impact frequency estimates, see Drury (Chapter 10) and Hartmann (p. 228). For those of you now worried about returning to a parking lot to find a large smoldering crater in place of your car, the frequency of 1 km events is about once every 1500 years [Drury (p. 296)]. Ward (p. 165), presents a plot relating rates of occurrence, energy involved (kilotons), and resultant crater diameter.

<sup>28</sup> Drury (p. 298) quotes volcanologists' estimates of 10 trillion tons of sulfur dioxide and a like amount of CO<sub>2</sub> having been emitted into the atmosphere during the short eruptive phase of the Deccan Traps. Powell (p. 88) gives estimates of 30 trillion tons of CO<sub>2</sub>, 6 trillion tons of sulfur dioxide, and 60 billion tons of halogens.

<sup>29</sup> Many scientists prefer to attribute mass extinctions to multiple causes. Macdougall (pp. 175-176), for example, renders an especially good discussion of the additive effects of the Chicxulub impact and the Deccan Traps eruptions on world climate. This more encompassing approach is sometimes called the Murder-on-the-Orient-Express-model, named after the Agatha Christy novel in which Hercule Poirot correctly adduces that the 12 individual knife wounds made in the victim's body were the work of all 12 of the suspects on the train. This also provides some insight into the recreational reading habits of the scientific community.

<sup>30</sup> For potential role of the Siberian Traps in the Permian extinction, and antipodal relationship of flood basalt provinces with asteroid impacts, see Drury (pp. 300-302). Drury estimates that the Siberian Traps were capable of liberating  $5 \times 10^{15}$  kg of CO<sub>2</sub> along with twice as much sulfur dioxide (source of sulfuric acid rain) over the course of less than a million years. Since the Traps consist of about 45 separate massive flows, there is the potential for a like number of world-wide pulses of acid rainfall during this time [Drury (pp. 244-45)].

<sup>31</sup> For earliest date of flood basalts, see Drury (p. 134).

<sup>32</sup> On flood basalts in general, see Drury (pp. 134-136) and Powell (pp. 88-90).

extreme thermal conditions dominated the entire planet. In the long history of Earth there have been thousands of fluctuations in world climate: ice ages and hot-house ages. Most of the coal of the world was formed during the 70 Ma hot-house run called the Carboniferous Period. Any discussion of climate can quickly become contentious because there are so many factors that are involved: continental configurations, ocean and atmospheric currents, the albedo or solar reflecting characteristics of land, water, snow and ice, the constituent gases of the atmosphere, and on and on. Most authorities emphasize the role of greenhouse gases. Curiously, although greenhouse heating can cause serious disruptions in local ecologies, there seems never to have been a truly worldwide life-threatening episode related to overheating. This is not to say that a build-up of greenhouse gases could never trigger an irreversible Venusian type situation, but perhaps our greater distance from the Sun has raised the threshold beyond the reach of any 'normal' Earth process.

Deepfreezes, on the other hand, resulting in a so-called 'snowball Earth,' have occurred at least two times—the first deep in the Precambrian at 2.5 Ga, and again during the late Precambrian in a series of episodes dated to 800-650 Ma. Glacial deposits are distinctive, so geologists have been able to map these phenomena with a fair degree of reliability. During each, it appears that snow- and ice- covered landscapes spread from the poles toward the equator, perhaps during periods of extreme drawdown of CO<sub>2</sub> and other greenhouse gases accompanied by a slow-down in the restocking of these gases from volcanic sources. The increasing albedo of the planet (from areas covered by white snow and ice) resulted in greater reflection of solar radiation and continued lowering of planetary temperatures. This runaway positive feedback loop was ultimately responsible for massive glaciation even at the equator. Some scientists believe that the entire ocean froze over, perhaps to a depth of half a kilometer, for thousands or even a few million years. Paleobiologists, pointing to the absence of evidence of mass extinctions among the primitive life-forms of that time, imply that open ocean and a somewhat milder climate must have prevailed at least in the immediate equatorial regions. Whatever the cause and extent of the snowball episodes, they all ended by restocking of the greenhouse gases and subsequent re-heating of the atmosphere.<sup>33</sup>

### The Hadean Environment

The evidence from astrophysics and radiometric dating of rocks from the Earth, Moon, and meteorites, suggests that the Earth is a by-product of the gravitational collapse of a stellar cloud of almost pure hydrogen which resulted in the formation of the Solar System about 4.6 Ga ago.<sup>34</sup> This is only about a quarter of the estimated age of the Universe, which

**Hadean Epoch:** The Hadean Epoch covers the earliest part of Precambrian time, from the formation of the Earth until the end of the period of heavy bombardment 3.9 Ga ago. Since the Earth was molten throughout most of this period, the derivation of the name from the Greek Hades seems most apropos.

allowed plenty of time for earlier stars to form, grow to old age while forming small percentages of heavier elements within their cores, and disperse them throughout the cloud via supernovae explosions.

The planets, including Earth, are still comprised of large amounts of hydrogen, and also the residue of heavier elements that were not blown off into space by the early solar wind.

These heavier elements coalesced to

form bodies called planetesimals, which accreted in time to form the planets and their moons. The proto-Earth was subjected to heavy bombardments of planetesimals and lesser bodies for hundreds of

millions of years. As mentioned earlier, the largest of these collisions is believed to have been with a Mars-sized object, creating the Moon and accounting for the Lunar body's unique astrophysical characteristics.

A beneficial aspect of the early Hadean Epoch was the partial and sometimes complete melting of the forming planet, causing chemical compounds to fractionate and differentiate according to densities and chemical properties. The result was a planet with a solid inner-core of mostly nickel-iron, a liquid outer-core of heavy molten elements dominated by iron, a thick mantle of dense-yet-deformable matter, a thin rind of lighter-weight rocks called the lithosphere (the continents and ocean-floors), and the thinnest of all layers, the atmosphere.<sup>35</sup>

Earth and the other planets effectively vacuumed up the inner Solar System such that the period of heavy bombardment ended about 3.9 Ga.<sup>36</sup> The last oceans of lava cooled sufficiently that the chemical component of Earth's atmosphere with the highest boiling point condensed into liquid form. The gaseous form of di-hydrogen oxide—water—changed from steam to liquid, forming the oceans in floods that dwarfed the accounts of Gilgamesh and Noah.<sup>37</sup> To answer the question of what the early Earth was like, we need rocks from that period. As you can guess, the dynamic nature of Earth processes makes this a difficult proposition; but generations of diligent field geologists, along with the advent of radiometric dating, have resulted in significant finds. Rocks, including sedimentary deposits, dating in excess of 3.5 Ga have been found on all the continents.<sup>38</sup>

Of particular interest in the sedimentary record are stream-worn lumps of iron sulfide, FeS (iron pyrites or fool's gold). Whenever this mineral is worn out of rocks in today's environment, it rapidly breaks down and becomes oxidized; hence scientists conclude that the earliest atmosphere was depauperate in oxygen<sup>39</sup>. The most likely dominant gas in the atmosphere was carbon dioxide, still the most abundant of gases emitted from volcanoes.<sup>40</sup> The greenhouse characteristics of CO<sub>2</sub> have been alluded to previously and, if present in sufficient quantities, would have prevented a rapid transition from molten Earth to snowball Earth.

<sup>35</sup> Formation of the Earth by the accretion of planetesimals and the subsequent heating, melting and differentiation of the primal Earth is described in more detail in Lunine (Chapter 11) and Hartmann (Chapters 3 and 4, with excellent illustrations).

<sup>36</sup> For discussions on period of heavy bombardment, see Drury (p. 165), Lunine (pp. 69-70), Schopf (1999)(pp. 166-168), and Hartmann (Chapter 3).

<sup>37</sup> Our view as surface dwellers leaves us with the impression that water is everywhere. It actually comprises only one-half of one percent by weight of the Earth [Ward (p. 208)], which is still impressive when most of it is pooled on the surface. The source of all this water, on the order of 1.4 billion cubic kilometers [Drury (p. 51)], is still an area of debate. One authority [Lunine (pp. 103-131)] cites the early bombardment by icy comets as a primary source, while another [Hartmann (p. 43)] states that isotopic analysis shows that most of the water in the oceans of today originated from Earth's original inner-Solar System building materials and not from outer-solar-system comets. See also Ward (p. 58). According to Lamb (p. 220), substantial oceans had formed within 150 Ma after Earth's formation due to outgassing alone.

<sup>38</sup> The oldest rocks found so far on Earth, excluding meteorites, are from northwest Canada. They solidified some 3.96 Ga years ago, as dated by analysis of radioactive isotopes [Macdougall (p. 18); Drury (p. 106)]. However, minute crystals composed of zirconium silicate, called zircons, dated to between 4.1 Ga and 4.3 Ga, have been found imbedded in 3.6 Ga-old sandstones from Western Australia, and it is presumed that these were eroded out of igneous rocks formed at the earlier time. For a discussion of zircons, their amazing toughness, and their value in dating geologic formations, see Macdougall (pp. 18-19), and Drury (p. 107).

<sup>39</sup> Pyrites as evidence of lack of oxygen is mentioned in most of the sources [see Drury (pp. 130, 144), Lunine (p. 131), Schopf (1999)(p. 173), Lunine (pp. 213-214), Lamb (p. 181)]. Discussions of the early atmosphere may be found in Schopf (1983, 1999); and Macdougall (1996). Besides yielding valuable evidence on the earliest Terran atmosphere, iron sulfide is thought to have played a key role in the evolution of life. A number of proteins essential to life, and particularly in photosynthesis, involve Fe-S linkages [see Drury (pp. 211)].

<sup>40</sup> CO<sub>2</sub> as dominant volcanic gas, see Drury (p. 239); also Hartmann (pp. 66-67).

<sup>33</sup> For 'snowball Earth', see Ward (p. 112), and Hartmann (pp. 105-106)

<sup>34</sup> Lunine (pp. 52-52, 75-76) presents a thorough discussion on the age of the Earth, including the long and fascinating search for this elusive date. For a technical discussion, see Schopf (1983) (Chapter 2, *The Nature of the Earth Prior to the Oldest Known Rock Record: The Hadean Earth*). Other references with strong geophysical bents include Lamb, Macdougall, Schopf (1999), Hartmann (p. 17), Osterbrock, and Lambert (1988, 1994).

Several lines of evidence point towards an early 'reducing' atmosphere with high CO<sub>2</sub> content, as opposed to the rusting iron-oxidizing environment of today.<sup>41</sup> In our story of life, the extended presence of a reducing environment may have been a prerequisite for the formation of the rich 'primordial soup' of increasingly complex molecules theorized as a necessary precursor of life. Although Earth is and always has been oxygen-rich, the unmatched oxidizing potential of the element means that most of it is safely under lock and key, firmly combined in the minerals comprising the mantle and lithosphere, as well as in water molecules and in biomatter. It is well that this is so, because oxygen is hazardous to life, even to us oxygen-breathers—it is the basis of molecular fragments called 'free radicals' that can wreak havoc upon unprotected cells. In too great a concentration it can stoke the fires of basic metabolism to the point of self-combustion.<sup>42</sup> Free oxygen is especially adept at embracing iron in a powerful grip, and since iron is central to the proteins involved with photosynthesis and in hemoglobin, the molecular chemistry for the creation of these proteins may only have arisen in a reducing environment.<sup>43</sup>

By 3.9 Ga the period of heavy bombardment has ceased; the oceans have formed; and a strongly reducing atmosphere believed rich in carbon dioxide blankets the planet and through the greenhouse effect keeps temperatures from plummeting. The early, weaker Sun rakes the surface with lethal doses of UV<sup>44</sup> yet produces insufficient long-wave radiation to cause a run-away Venusian effect. Hundreds of millions of years go by while minerals leach from the first proto-continents<sup>45</sup>, lightning flashes through the air billions of times, and strong doses of UV excite a growing suite of complex molecules forming in Earth's aqueous environments. The stage is set.

### Next Installment: Part 2: Life Takes Charge

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<sup>41</sup> Whether an environment is chemically reducing or oxidizing in nature depends on whether it is dominated by elements or compounds that are easily stripped of some of their normal complement of electrons (electron donors, such as iron) or by elements/compounds that have a strong affinity for bonding with available electrons (electron acceptors, such as oxygen). Iron will never rust in a reducing environment.

<sup>42</sup> Oxygen comprises 21% of our atmosphere today. Plants will self-combust from their own metabolic processes at an oxygen level of 35%. Drury (pp. 141-143) cites the increased size of flying insects during the Carboniferous Period and the evidence of a great conflagration at the end of the Cretaceous as indicators of higher levels of atmospheric oxygen in the past.

<sup>43</sup> For necessity of a reducing environment in generating critical life-developing molecules, refer to Drury (p. 178).

<sup>44</sup> The ozone barrier to ultra violet radiation is comprised of oxygen combined in a three atom molecule (O<sub>3</sub>). If this protective shield was removed, virtually all terrestrial life would be exterminated. Even 20 meters of water would be insufficient against these lethal Solar emissions [Drury (p. 181)].

<sup>45</sup> These proto-continents were really just chains of islands. Stanford University researcher Don Lowe estimates that prior to 3 Ga land comprised less than 5 percent of the Earth's total surface area [Ward (p. 262)].