Air and Rock: Changing Climates at Grand Canyon

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The Grand Canyon offers one of the Earth's most dramatic views of geologic time. The layers of rock in the Canyon walls preserve snapshots of the distant past, stretching back 1,840 million years. Each layer is unique, with its own distinct assemblage of minerals, structures, and appearance, and each one gives modern geologists a different glimpse of the Earth's history. Some of these ancient environments are boldly illustrated by mud cracks and ripple marks, by water-worn cobbles or sand dunes cemented into rock. Other aspects of these ancient environments are more subtle, revealed in the minerals and even the mix of atoms making up the rocks. The Canyon's rock layers are the most obvious records of the past. But Grand Canyon contains much younger material, including cave deposits, packrat middens, and river terraces, that shed light on changes as the modern landscape has taken shape.

To appreciate the Grand Canyon, we must look through air, often, a lot of air. This ocean of air is usually ignored, unless pollutant hazes or weather conditions are obscuring the view. Yet, without air, Grand Canyon would not exist, and even the rocks though which the Canyon is carved would never have formed. The air filling the Grand Canyon, surrounding us and blanketing the globe has its own history. In the short term, our air may be carrying various particles and gases that record its passage across oceans, deserts and cities around the world. This history may only stretch back hours or days for some compounds, but weeks or years for others. Over much longer timeframes, the atmosphere has evolved dramatically over the course of the Earth's history. The air that we peer through to see the Grand Canyon is a product of cyanobacteria billions of years ago and tailpipes in the parking lot today.

The Grand Canyon's rocky records of past environments include evidence of how this other, fundamental environmental factor, air, has changed through time. Today, we face the challenges of understanding and dealing with changes humanity has imposed on our atmosphere. Taken together, the Canyon's rock and air help us piece together the evolving drama of Earth's history, and provide hints of what the future may hold.

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Earth's first atmosphere(s)

The Earth has been around for 4.54 billion years (Dalrymple 1991), and its oldest surviving rocks are about 4.28 billion years old (O'Neil et. al 2008, p. 1828). The rocks exposed in the walls of the Grand Canyon only cover the last 40% of Earth's history (see Figure 1). For the first 60% of Earth's history, the elements that make up the rocks of the Grand Canyon were very much a part of the Earth, but they were "somewhere else," part of other rocks that formed and eroded away, or melted (some many times) before coming together in the rocks we see today. Grand Canyon's coverage of its 1.8 billion year span is quite sporadic, with gaps in the record that lasted hundreds of millions of years. Even so, the Canyon's rocks provide us with "snapshots" that we can combine with information from other locations to create an "album" of Earth's evolving climate.

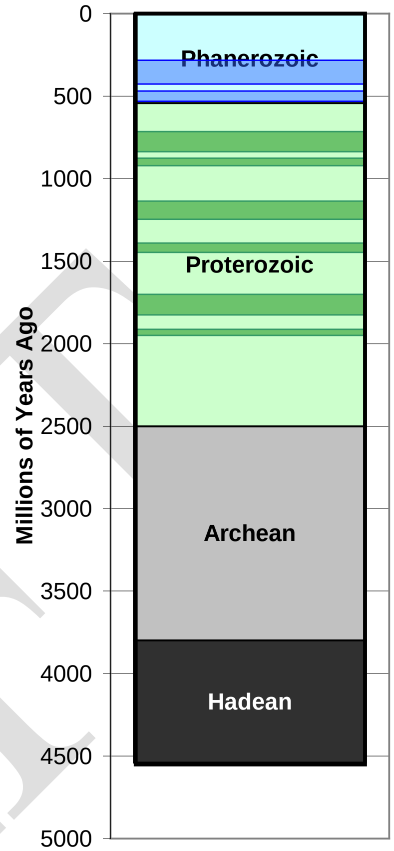

Figure 1: Only a small part of Earth's long history is recorded in the rock layers of Grand Canyon (shown as darker colored areas, modified from Timmons & Karlstrom 2007)

The Origin of the Atmosphere and Hydrosphere. The rocks of Grand Canyon are far too young to provide "first hand accounts" of the formation of Earth's oceans of air and water. We have to rely on evidence gathered elsewhere (and not just on the Earth!) to piece together this story. The young Earth grew through violent impacts of "planetesimals," the chunks of rock, ice and frozen gases that condensed from the Solar nebula and gave birth to our Solar system. The Hadean Eon applies to this formative stage of the Earth's history. When the growing Earth reached a third its current size, it was big enough to at least partially vaporize incoming comets and meteors, adding to its growing oceans and atmosphere. Their development was not a smooth progression. The most massive meteor strikes, especially the one forming the Moon 4.54 billion years ago (Bottke *et al.* 2007, p. 203), may have driven off the entire early atmosphere and oceans. Any such losses were only temporarily (Kastling & Catling 2003, p. 431-434; Catling & Zahnle 2009, 36-43). These impacts did decline for about 500 – 600 million years after the Earth's formation, but then increased dramatically during the "Late Heavy Bombardment." By this time, the outer planets (Jupiter, Saturn, Neptune, and Uranus) had grown into giants. They had become so massive that their orbits began changing in response to gravitational harmonics (models even show Uranus and Neptune switching orbits). As the outer planets moved about, their shifting gravity fields disrupted the orbits of comets and asteroids, slinging many toward the inner Solar System. These incoming bodies pelted the planets of the inner Solar System. The Moon still retains its scars from this period as dark maria (or "seas"), although weathering, erosion and plate tectonics have removed any such scars from the Earth (Bottke & Levison 2007).

The Earth's orbit is so close to the Sun that water and gases should have evaporated from the planetesimals that collided to form most of our planet. Ocean waters and atmospheric gases may have been delivered from bodies formed in cooler, more distant orbits, such as the outer asteroid belt, and some contributions from even farther out via comets. This "import" model is supported by the compositions of comets and asteroids, linked with models of the Solar nebula. Thus, some researchers believe the Late Heavy Bombardment delivered much of our planet's air and water, although there is evidence that Earth was wet before this time as well (Cowen 2008, p. 28; Bottke & Levison 2007). The Hadean Eon ended about 3.8 billion years ago, when the last large bodies (over 60 miles or 100 km. in diameter) smashed into the Earth and Moon (Kastling & Catling 2003, p. 431-434). By the end of the Hadean and its Late Heavy Bombardment, the Earth had an atmosphere that was rich in nitrogen (as it is today), with some carbon dioxide and water, but virtually no oxygen gas (Wayne 1991, p. 339).

The Moon itself is an important influence on Earth's climate. Current hypothesis suggest the Moon formed 4.54 billion years ago (Bottke *et al.* 2007, p. 203), when a Mars-sized body slammed into the early Earth (Belbruno & Gott 2005, p. 1724). Without the stabilizing effect of the Moon's gravity, the tilt of the Earth's axis (which drives the changing seasons) could vary from 0° to 85° in just tens of millions of years. The wildly chaotic "seasons" that would result from such a wobbly planet would make life on land difficult, if not impossible (Kastling & Catling 2003, p. 431). The Moon has also caused the Earth's rotation to slow down through geologic time. The Moon's gravity pulls the tides across the Earth, which has the double effect of slowing the Earth's rotation (making days longer), and causing the Moon to slowly spiral away from the Earth. It now appears that some of the earlier, fossil-based estimates of a fast-spinning Earth are not accurate, projecting them back in time produces a cataclysmic close approach of the Earth and Moon (for which there is no geologic evidence). More recent estimates, based on rhythmic tidal variations in fine sediment deposition (called "varves") and other data still show Earth's rotation slowing down, although estimates vary (adapted from Williams 2000, p. 50):

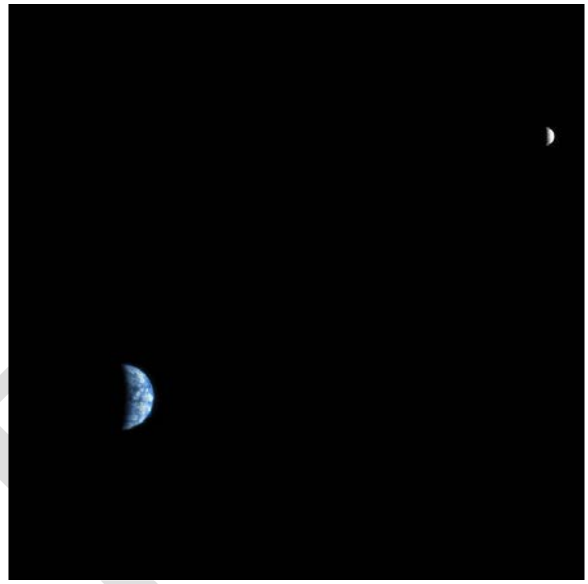

Figure 2: The Earth - Moon system. Like a "gravitational outrigger," the Moon has stabilized and slowed Earth's rotation through geologic time (NASA/JPL-Caltech / University of Arizona photo)

Table 1: Earth's Slowing Rotation through Time

	2,450 Ma (older than Grand Canyon's rocks)		**~ 900 Ma** (concurrent with Grand Canyon's Nankoweap Frm.)		**~ 620 Ma** (prior to Tapeats Ss.)	**Modern**
	(Estimate A)	(Estimate B)	(Estimate A)	(Estimate B)		
Solar days/year	514 ± 33	466 ± 15	464 ± 13	422	400 ± 7	365.25
Hours/ solar day	17.1 ± 1.1	18.8 ± 0.6	18.9 ± 0.5	20.8	21.9 ± 0.4	24.00

A faster-spinning Earth would have important consequences for temperature. Shorter days and nights should mean more even temperatures, with less time to heat up during the day or cool down at night. However, so far as the author is aware, no analysis has been done to relate changing day length to weather or climate in the distant geologic past.

<u>The Young, Dim Sun.</u> The Sun is the ultimate source of virtually all light and warmth on the Earth. The Sun shines because its thermonuclear fire fuses hydrogen fuel into helium ash. Since helium is denser than hydrogen, pressures in the solar core have increased through geologic time as this heavier helium ash accumulates. This mounting pressure causes the Sun to grow slowly brighter (Gough 1981, p. 21, 28). Superimposed on this slow, steady brightening are short-term variations in solar output, with some minor variations apparent on a time-scale of only decades or millennia. For example, the 11-year sunspot cycle seems to influence weather and climate on Earth, even though the magnitude of these effects as well as the mechanisms and details are still being worked out (Rind *et al.* 2008, p.

23104). Billions of years ago, at the center of its new Solar system, the young Sun only shone about 70% as brightly as it does today. Eventually, billions of years from now, the Sun will brighten into a nova, and Earth will no longer be habitable. In spite of our Sun's variability, fossils show that the Earth has been a habitable planet for billions of years, and we anticipate its habitability far into the future. What are the mechanisms that have kept the Earth "just right" for life?

Staying warm: the Global Greenhouse and Carbon Dioxide

Exo-biologists have to grapple with almost existential questions about the requirements of life on other planets. But here on Earth, we know what life needs, and perhaps the most fundamental need is liquid water. We also know that life arose early in Earth's history. It is true that paleontologists argue over the validity of specific chemical signatures, isotopic fractionations, and problematic fossils. But all of the evidence points at life on the Earth more that 3 billion years ago, and contested claims reach back almost 4 billion years (Kastling & Catling 2003, p. 437). Even under the dimmer Archean Sun, the Earth must have been warm enough to support liquid water. How? The answer lies in Earth's atmosphere, and specifically, the greenhouse gases in the atmosphere that let sunlight through to heat the ground (and to a much lesser extent, the air), but trap the outgoing heat, thus warming the planet. Although the exact composition of the Earth's early atmosphere is still being investigated, it contained important greenhouse gases, especially water vapor, carbon dioxide, and methane.

Just how powerful is an atmosphere's greenhouse effect? Our Moon receives the same amount of warming sunlight that we do, but without a significant atmosphere, lunar temperatures swing between -250 °F at night and 250 °F during the day (-157 to +121 °C). Venus receives almost twice the solar energy Earth does, and with a "super-greenhouse" atmosphere of 96% carbon dioxide, Venusian temperatures don't vary between night and day, holding at a toasty 867 °F (464 °C; NASA 2005). Venus and Earth seem to have about the same amount of carbon (Wayne 1991, p. 6). Venus stores its carbon in the atmosphere as carbon dioxide to create its super-greenhouse. Earth stores most of its carbon (79.95%) in carbonate rocks, a lot (19.99%) in coal and shale, and virtually none (0.07%) in the atmosphere, ocean, soil, and life (Berner 1999b, p.6). It is Earth's weak greenhouse that keeps our planet habitable.

Carbon dioxide was an original component of the Earth's atmosphere, and today it remains as a "trace gas." In every 10,000 molecules of modern air, about 3 are carbon dioxide. This whiff of carbon dioxide is essential for plants, along with water and sunlight, it is the raw material for photosynthesis (providing all of us animals with the food we eat). In spite of its low concentration, carbon dioxide is also an important "greenhouse gas," that is, it lets incoming sunlight pass through the atmosphere to warm the Earth's surface, but traps outgoing heat. Our atmosphere has traces of other greenhouse gases (methane, nitrous oxide and halocarbons are the strongest). Water vapor is Earth's most powerful greenhouse gas, responsible for about two thirds of the 58°F (33°C) the greenhouse effect adds to surface temperatures (Kastling & Catling 2003, p. 438). Unlike other greenhouse gases, water at the Earth's surface is so close to its boiling point that it easily moves in and out of the atmosphere through evaporation and condensation/precipitation. Since the water vapor content of the air responds instantly to temperature, it can not "force" climate changes like long-lived greenhouse gases – carbon dioxide, methane, nitrous oxide and halocarbons (Solomon et. al 2007, p. 23). The following table shows the relative contributions of long-lived gases to the modern Earth's greenhouse (halocarbons are not shown – although their current warming effect is somewhat less than methane's, they are not a significant natural component of the Earth's atmosphere; data from Solomon *et. al* 2007, pp. 24-28, 32):

Table 2: Major greenhouse gases in Earth's Atmosphere

Greenhouse Gas		Radiative Efficiency W / m^2 / ppb	Preindustrial		2005	
			Concentration (ppb)	Warming (W / m^2)	Concentration (ppb)	Warming (W / m^2)
Carbon Dioxide	CO_2	0.000014	280,000	3.92	379,000	5.31
Methane	CH_4	0.00037	730	0.27	1,774	0.66
Nitrous Oxide	N_2O	0.00303	270	0.82	319	0.97
Total Greenhouse				5.01		6.93

Rocks and Air: The Carbon Cycles. None of the Grand Canyon's rocks record the Earth's earliest history during the Hadean and Archean eons. But the Canyon's rocks do relate to climate and the atmosphere, and the processes that they illustrate are similar to the processes that occurred in the early Earth as well. Especially interesting are the family of minerals called "carbonates," named for the carbonate ion ($CaCO_3^{++}$) these minerals are built around. Carbonates are the major ingredient in the limestone layers of the Canyon walls, like the Redwall and the Kaibab. Carbonates also cement mineral grains together in other rocks. For example, they bind the sand grains in the sandstones of the Supai Group. Even the ancient Vishnu Schist is about 1% carbonate (Babcock 1990), including some bands of almost pure marble near Gneiss Canyon (Clark 1972). How can a rock or mineral relate to a gas in the atmosphere? When carbon dioxide from the atmosphere dissolves in water, some of it forms weak carbonic acid (H_2CO_3). Carbonate minerals form when certain metals (especially calcium or magnesium) react with the carbonic acid. Many organisms, from single-celled foraminifera to giant clams, form their shells from these carbonate minerals (usually calcite and aragonite, both $CaCO_3$), the primary ingredient in limestone. The thick layers of limestone and other carbonate rocks in the Grand Canyon and around the world "lock up" more than 100,000 times as much carbon dioxide as is in the Earth's atmosphere (Wayne 1991, p. 6).

The amount of carbon dioxide in the atmosphere is far from constant. Every year, global levels drop in the northern hemisphere's spring as the annual rush of new plants and leaves pull carbon dioxide from the air to fuel their growth and reproduction (with far less land in the southern hemisphere, there is not a corresponding drop six months later). From an early summer low, carbon dioxide levels gradually climb back to their winter high. This annual cycle is the most obvious effect of the constant exchange of carbon dioxide between plants, animals, soils, oceans and atmosphere. It creates the "sawtooth" pattern seen in the gradually rising carbon dioxide levels of the last 50 years (Figure 3).

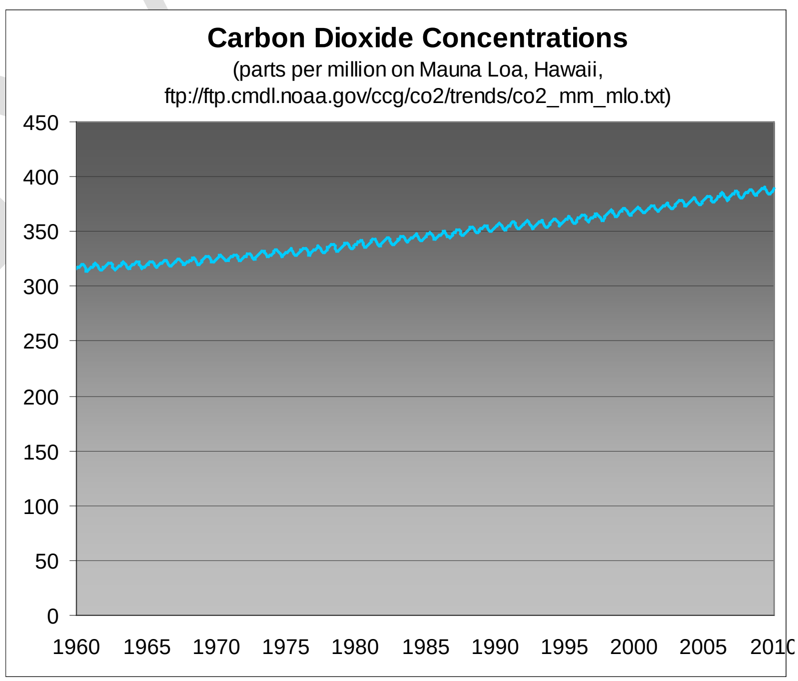

Figure 3: Carbon dioxide concentrations in parts per million, measured at Mauna Loa, Hawaii (NOAA 2010)

Superimposed on this short term cycling

of carbon, there is a long-term carbon cycle operating over millions of years. It does not have the steady annual "beat" of the short-term organic cycle. The long-term, or geochemical carbon cycle responds to slower processes, as carbon is removed from the organic cycle by the burial of organic material (to form oil or coal, for example), and by the formation of carbonate minerals. Carbon returns to the atmosphere as carbon dioxide in the geochemical cycle through volcanism, metamorphosis or the exposure and weathering of organic-rich rocks (Berner & Kothavala 2001, p. 183). The rates of carbon removal and return vary through geologic time. The position of the continents and the Sun's energy output (which is slowly increasing through geologic time; Gough 1981) affect temperature, which in turn affects precipitation and thus, weathering and erosion. Occasionally, weathering and erosion can release some carbon dioxide when a carbon-rich rock (like coal) is weathering. But more often, weathering frees the calcium and magnesium needed to form carbonate minerals. Thus, the most important result of weathering is actually to remove carbon dioxide from the air and lock it into carbonate minerals. Plate tectonics can affect carbon dioxide through mountain building (and thence weathering and erosion) and volcanic activity. The dominant gases in a typical volcanic eruption are water vapor (73%) and carbon dioxide (12%), with lesser amounts of sulfur dioxide, nitrogen, sulfur trioxide, carbon monoxide, hydrogen, argon and chlorine (Dott & Batten 1971, p. 98).

Geologists and climatologists have woven this complex interplay of factors into computer programs that model carbon dioxide levels in the Earth's past. One, the GEOCARBSULF model illustrated below, also predicts prehistoric oxygen levels (Berner 2006). Such models do not provide precise "year by year" carbon dioxide values, but are valuable for examining multi-million year trends. These models are not a record of past concentrations, but rather, a prediction of what those levels would have been, modeled on geologic and biologic events that would have affected the amount of carbon dioxide and other gases in the atmosphere. During this long time span, carbon dioxide levels have varied from lows near modern levels to peaks as much as 25 times that amount. Of course, the rock layers of the Grand Canyon's walls are far from a complete record of the Paleozoic, but they do reflect the environment during the intervals in which they formed. Considering the Canyon's "rock-recorded" history in light of trends seen in the computer model predictions provide interesting insights into the Earth's climatic history.

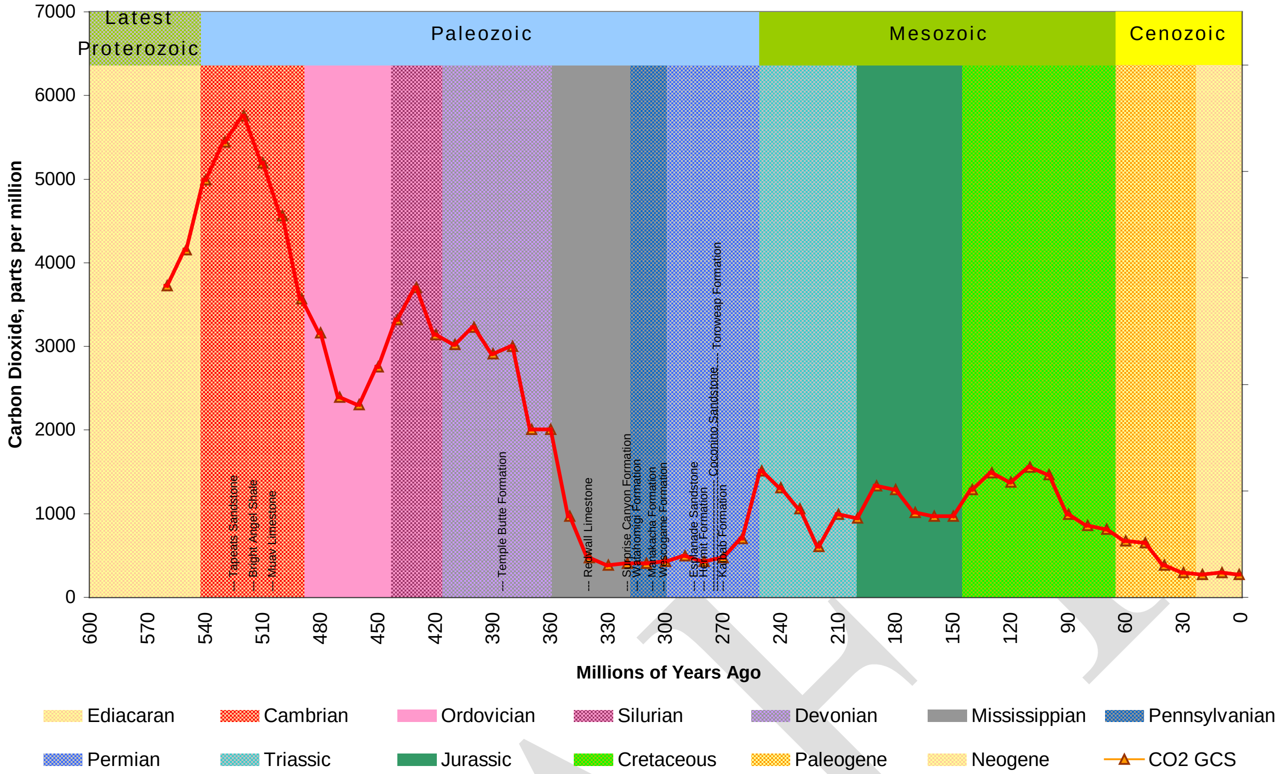

Figure 4: Carbon dioxide levels predicted over the last 570 million years by the GEOCARBSULF model (Berner 2006)

Before the Basement Rocks: The Rise of Oxygen

Unlike carbon dioxide, oxygen gas (O_2) was not present in the Earth's early atmosphere. Instead, oxygen atoms were chemically bound with other elements in molecules like carbon dioxide, water, and many mineral species. Today, free oxygen makes up 21% of the atmosphere (Kump 2008, p. 277). Evidence of this free oxygen is all around us, from the rusty red rocks of the Grand Canyon to every life-sustaining breath we take. Where did this oxygen come from – how did it escape its "chemical bondage?" As yet, there is no definitive answer, but a number of different processes may have contributed to this fundamental change.

Some oxygen-enrichment processes are "abiotic." Since its birth, Earth's atmosphere has been "leaking" into space, usually at a slow rate (although meteor impacts can literally blast away significant amounts). In the highest reaches of the atmosphere, ultraviolet light from the Sun can shatter water molecules (H_2O) into hydrogen and oxygen. Oxygen atoms are relatively heavy, and Earth's gravity is strong enough to hold most of them down. Hydrogen, the lightest element, is the most likely to escape into space. Thus, the Sun itself slowly enriches the Earth's atmosphere in oxygen. It is a slow process to both dehydrate and oxygenate the Earth this way. Water vapor is heavy, so there is very little of it in Earth's upper atmosphere where ultraviolet light can shatter it (although smaller Mars may have lost its hydrogen this way). Eventually, Earth may lose enough hydrogen to transform the planet into an arid red world like Mars, but this fate lies a couple billion years in the future (Catling & Zahnle 2009, 36-43).

Physical changes as the Earth's interior cooled may have teamed up with microorganisms to help oxygen accumulate in the air as well. As the Earth's mantle cooled, volcanoes pumped less nickel to the surface. This metal is a critical component for various microbial enzymes that produce methane. In the atmosphere, this methane would have reacted with any oxygen gas to produce carbon dioxide and water (in other words, the methane would "burn," molecule by molecule). Of course, the Earth cools slowly, and nickel concentrations took nearly two billion years to fall from their high Archean levels, 2.7 billion years ago, to reach modern levels about 550 million years ago. As nickel levels fell, so did the microbial methane production, thus helping set the stage for oxygen to accumulate (Konhauser *et al.* 2009, p. 750; Barazesh 2009, p. 14).

Biological processes, and photosynthesis in particular, occupy "center stage" in producing and maintaining atmospheric oxygen today. Evidence in Australian rocks suggest bacteria-like organisms evolved the ability to use sunlight to create sugars from carbon dioxide and water, and releasing oxygen as a "waste" product by about 2,700 million years ago. Around 2.3 billion years ago, free oxygen (O_2) began accumulating in the atmosphere (Kastling & Catling 2003, pp. 431, 457). Oxygen is a highly reactive (in other words, "poisonous") gas and posed a critical challenge for life. Its chemical reactivity makes it a "bull in the chemical china shop," ripping apart other molecules in processes including fire. These sometimes violent chemical reactions make oxygen extremely dangerous to living things. But some microorganisms developed an incredible power source by harnessing oxygen's explosive potential into the complicated chemical reactions called "oxidative respiration." Modern yeast illustrates the powerful potential. In the absence of oxygen, yeast can obtain energy by fermenting the sugar glucose into alcohol. In the presence of oxygen, yeast can "burn" glucose into carbon dioxide, producing almost 7 times as much energy as fermentation to alcohol (57 kcal/mole vs. 380 kcal/mole; Brock 1970, p. 104, 113). Poisonous but powerful, free oxygen in the air and water could have caused a tremendous "mass extinction," dwarfing the more familiar extinction of the dinosaurs 65 million years ago, or the "Great Dying" 251 million years ago. Little is known of this extinction some 2.3 billion years ago. Its victims would have been much like today's bacteria – poor prospects for fossilization and preservation through the ensuing billions of years.

Recent research suggests oxygen levels may have increased in a stepwise fashion over billions of years, rather than in a single long rise. The very low oxygen levels (less than a thousandth current concentrations) of the infant Earth persisted until about 2.45 billion years ago. Then, with the advent of photosynthesis, oxygen levels rose to at least 1%, and perhaps to as much as 40% of current levels. Much later, during the late Proterozoic Eon (about 600 million years ago), oxygen levels rose again, reaching near current concentrations by 420 million years ago (Kump 2008, p 278). Why this step-wise increase? In true cyclic fashion, photosynthesis removes carbon dioxide from the atmosphere and releases oxygen, but oxidative respiration (what our cells do with our food to gain energy from it) simply removes the oxygen from the air we breathe and returns the carbon dioxide. So, the photosynthesis – respiration cycle is "closed" with respect to oxygen. It results in no net change to oxygen levels in the air, unless some of the photosynthesized material is never consumed. During the late Proterozoic, there was an increase in the amount of organic material deposited in deep ocean basins as "black shales" and other carbon-rich rock (see Figure 5). Burying this organic carbon without burning or respiring it allowed oxygen levels in the atmosphere and oceans to climb. This last rise in oxygen may have been just what was needed to trigger the appearance of multicellular animals (Knoll 2003, p. 218). The precise timing and causes of oxygen's debut and importance in Earth's atmosphere is still a subject of lively scientific investigation, with many discoveries and refinements probably yet to come.

Figure 5 Black shales in Grand Canyon's Proterozoic Kwagunt Formation get their color from organic carbon. Freshly broken pieces even give off an oily, fetid smell (NPS Photo – Bowman).

Oxygen is not a greenhouse gas (although in the form of ozone it does contribute to the greenhouse, Solomon *et al.* 2007, p. 32). Methane is a potent greenhouse gas, about 25 times as insulating as carbon dioxide (see Table 2). With free oxygen in the atmosphere, flammable methane does not last long. As oxygen levels rose in the early Earth's atmosphere, methane levels fell, and climatic shifts would be expected. In the latest Archean and earliest Proterozoic eons, there is indeed evidence for cold climates, by 2.2 billion years ago, glaciers even reached the tropics (Kopp *et al.* 2005, p. 11131). While exact causes of the loss of Earth's early methane greenhouse are still being investigated, the impact of that loss seems clear.

Alas, none of the rocks exposed in the Grand Canyon are old enough to record the beginning of this "oxygen revolution." The Elves Chasm Gneiss formed about 500 million years after the first appearance of free oxygen ("only" 1,840 million years ago; Hawkins *et al.* 1996, p. 1167). Consequently, evidence of free oxygen shows up throughout the Canyon's rocks. The most obvious indicator of free oxygen is the Canyon's many red rock layers. Their color is the result of minute amounts of iron oxide, or rust. In an oxygen-free environment, iron can't rust. But even the Canyon's oldest mudstone, the 1,200 million year old Mesoproterozoic Hakatai Shale, clearly shows bright red and orange evidence of free oxygen in the atmosphere (see Figure 6). At this time, oxygen levels were probably only 1% to 10% of modern levels (Kastling & Catling 2003, p. 458), but rising. By the end of the Proterozoic, oxygen made up 20% of the atmosphere, nearly modern concentrations. Since then, oxygen has remained a major gas in Earth's atmosphere.

Figure 6 Iron oxides (essentially rust) give the Hakatai Shale its brilliant color (NPS Photo – Bowman).

The GEOCARBSULF model used for carbon dioxide, also predicts oxygen levels through "recent" geologic time. Its modeled levels vary from about 31% during the Permian to about 12% in the early Jurassic (Figure 7, Berner 2006). The model predicts times when there was insufficient oxygen in the atmosphere to support wildland fire. The presence of fossil charcoal during the Jurassic Period's low oxygen interval that began about 190 million years ago suggests some remaining uncertainty about both the computer modeling and the nature of wildland fire (Gramling 2008, p. 27). However, low oxygen levels 380 million years ago during the Devonian Period have been linked to a "gap" in the evolution of early land arthropods and vertebrates (Ward *et al* 2006, p. 16821).

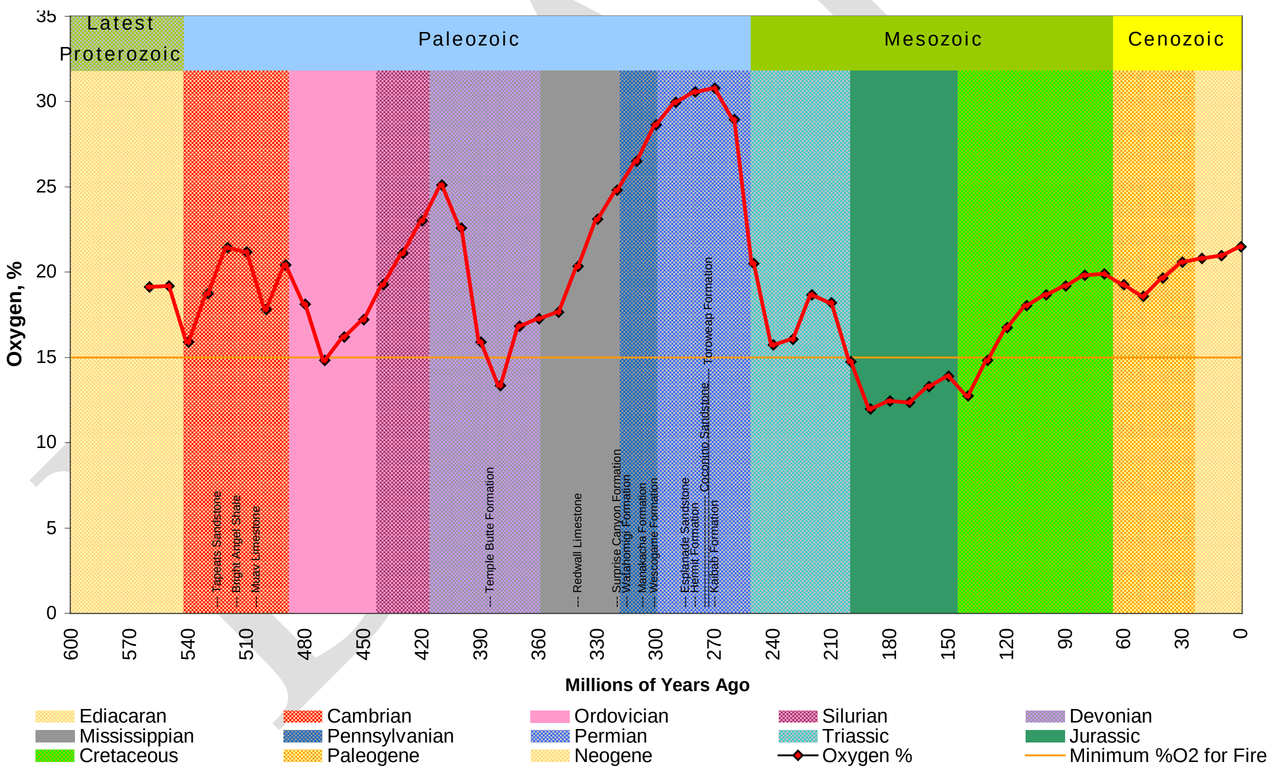

Figure 7: Oxygen levels predicted by the GEOCARBSULF Model (Berner 2006)

Broken windows in the Greenhouse: Snowball Earth

The Proterozoic rocks of the Grand Canyon Supergroup hint at the Earth's evolving atmosphere and changing climates. Even in the basement rocks, the Vishnu Schist contains carbonate rocks, including marble (Clark 1972). In the younger Grand Canyon Supergroup, colorful redbeds, especially the Hakatai and Dox formations, are the rusty evidence of free oxygen. Limestones and dolomites in the Supergroup contain the Grand Canyon's oldest fossils. These carbonates are clear evidence of "carbon sequestration," that is, carbon removed from the atmospheric reservoir of carbon dioxide and stored as rock in carbonate minerals. Near the top of the Supergroup, the Kwagunt Formation also contains black shale beds, colored by the carbon in their abundant microfossils (over 10,000 per cubic centimeter in some beds; Ford & Dehler 2003, p. 69). The rock can be as much as 4.7% carbon, enough that the Chuar Group could be a source of the oil trapped in the Tapeats Sandstone under Grand Staircase-Escalante National Monument in Utah (Reynolds 1986, Allison *et al.* 1997). In the Grand Canyon, freshly broken samples of black shales in the Kwagunt have a strong "fetid" or oily smell (Bowman, pers. obs.). The "biological drawdown" of carbon dioxide into carbonates and black shales seems to be a local example of a world-wide process in Neoproterozoic time (Nield 2007, p. 243), and could have contributed a rise in oxygen levels (Knoll 2003, p. 218).

Deposition of the upper Supergroup, specifically the Chuar Group and the overlying Sixtymile Formation, records a period of extension in the Grand Canyon area. The crust stretched and sagged along the Butte Fault to create the Chuar Basin north of Desert View. Evidence of similar processes of extension are found in the Yukon and Northwest Territories (Little Dal Group, Rapitan Group), California (Kingston Peak Formation) and Arizona (Chuar and Sixtymile). All these appear to be related to the breakup of the supercontinent Rodinia, as a continental mass (which included Australia) rifted away from the western margin of ancestral North America (Timmons *et al.* 2001, p. 178), opening a "paleo-Pacific Ocean." The Chuar Basin itself did not evolve into this new ocean basin; rather, it shows that stretching and collapse reached well inland from the continental fracture. The actual separation hypothesized between ancestral North America and ancestral Australia was probably close to the modern position of Death Valley, CA (Dehler *et al.* 2001, p. 492).

Chilling climate changes of the Chuar. The Chuar Basin was filling even as it formed. Within its rock formations are cyclic deposits of mud and carbonates that reflect modestly rising and falling sea levels, probably caused by glacial advances and retreats that become more pronounced with time (Dehler *et al.* 2001, p. 487, 491). There are no glacial deposits within the Chuar itself, since the future Grand Canyon area was well within the tropics, only 5° - 20° north of the Equator (Dehler *et al.* 2001, p. 469), roughly the same as modern Central America or Indochina. Indeed, most of the supercontinent Rodinia was near the equator, and there was little or no ice accumulation on land. Any polar ice caps would have been floating, and thus having no effect on sea level. As these polar ice caps grew, white ice and snow would reflect solar energy back into space. Cooling and reduced evaporation as open sea was replaced by ice increased would have made even the tropics drier. Periodic aridity is indeed reflected in Chuar sediments (Dehler *et al.* 2005, p. 43). At the end of Supergroup deposition, sea level fell

Figure 8 These large rocks needed energetic streams to transport them to the Sixtymile Formation's depositional basin at the end of Grand Canyon Supergroup time (NPS Photo – Bowman).

enough (or maybe the land rose) that land appeared east of the Butte Fault as the “Grand Canyon Disturbance” got underway. A fall in sea level as glaciers began “locking up” water on land seems a likely cause for this emergence. Although movement along the Butte Fault is often cited as the cause of the sea’s retreat, the fault had already been moving during earlier Chuar times (Karlstrom *et al.* 2000, p.620), so this movement cannot be the only reason. The coarser sediments eroded from the exposed upland accumulated as the Sixtymile Formation (see Figure 8). Viewed together, the upper rock layers of the Grand Canyon Supergroup, with their evidence of fluctuating and falling sea levels hint at glaciers and falling carbon dioxide levels (Dehler 2005). They were a prelude to one of the Earth’s most dramatic climate shifts.

<u>The Snowball Earth Hypothesis.</u> The breakup of the equatorial supercontinent Rodinia may have led to a draw-down of atmospheric carbon dioxide. As the supercontinent slowly shattered, moist winds could blow from the opening seaways across the broken shorelines. Rain fell, picking up carbon dioxide on the way down, and forming weak carbonic acid (H_2CO_3). This carbonic acid combined with elements in the rock (especially calcium), and eventually formed carbonate minerals (like calcite, $CaCO_3$). At the same time, shallow seas were spreading across newly formed continental shelves. These marine platforms supported diverse ecosystems, as evidenced by the rich fossil content of the Chuar Group. Photosynthetic bacteria and algae consumed carbon dioxide in these shallow seas, and some of the carbon remained trapped in organic mud settling on the sea floor. Atmospheric carbon dioxide was disappearing, sequestered in carbonate minerals, organic structures (like stromatolites) and black shales.

During the Chuar’s Neoproterozoic Era, the Sun was about 6% dimmer than today (Nield 2007, p. 239; Hoffman & Schrag 1999). A weaker Neoproterozoic Sun, disappearing carbon dioxide, and growing polar ice caps were sending global climates spiraling out of control.

In the late Neoproterozoic, glacial deposits are found in many places around the world. Hints of this approaching “Sturtian Ice Age” seem to appear in sea level records of Chuar Group rocks of the Grand Canyon Supergroup. What may be surprising about this ice age is its apparent severity – some of the glacial deposits are found near sea level *and* near the paleo-Equator! This led some geologists to hypothesize a “Snowball Earth.” Global glaciation had happened before, with the loss of the methane greenhouse in the late Archean and early Paleoproterozoic (see above). The most recent happened just after Chuar time, in the late Neoproterozoic. Declining levels of carbon dioxide led to lower temperatures, which led to increasing sea ice and snow cover, which led increased reflection of solar radiation, which led to lower temperatures. Once the polar ice caps reached a latitude of 30°, this feedback loop is so strong that the entire Earth might have frozen over (Hoffman & Schrag 1999). Plate tectonics continued under this icy shroud, and volcanoes pumped carbon dioxide back into the atmosphere, slowly restoring the greenhouse and thawing the Earth. But, to overcome the almost total reflection of solar radiation by a brilliant white Snowball Earth, carbon dioxide would have to rise to about 350 times its modern concentration, a process that would take millions of years (Hoffman & Schrag 1999). Once land and sea emerged from the ice and began absorbing, rather than reflecting, solar radiation, these high carbon dioxide levels

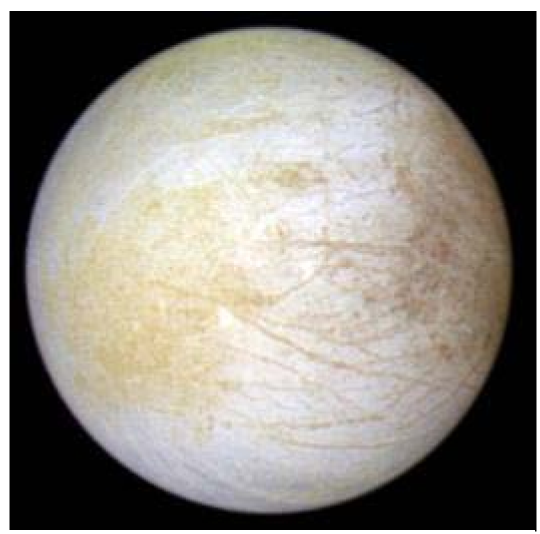

Figure 9 At its worst, did Snowball Earth look like Jupiter's frozen moon Europa? Scientists are still collecting data and discussing the ramifications (NASA/JPL/University of Arizona photo).

would have triggered a runaway greenhouse. Sea-surface temperatures could have reached 120° F (50° C) before carbon sequestration removed enough carbon dioxide from the atmosphere to apply the brakes. Snowball Earth may have happened as many as four times before the cycle was completely broken (Nield 2007, pp 239-244).

There have been ice ages since Snowball Earth, but none covered the whole Earth with ice. What made the Neoproterozoic different? The Sun has continued to warm since then, making ice ages "more difficult." But the fundamental answer may be geography. Rodinia was the last supercontinent that didn't extend to the poles. In subsequent ice ages, growing polar glaciers covered more and more land as they expanded. The frozen, buried rock was no longer subject to chemical weathering, and stopped drawing down atmospheric carbon dioxide. The global greenhouse may have weakened in later ice ages, but it didn't break.

Snowball Earth is really not a single hypothesis, and this group of hypotheses is not accepted by all geologists. For example, another way to explain equatorial glaciers is to tip the Earth's axis of rotation closer to "horizontal" (much like Uranus' today). Under this scenario, each pole gets alternating 6-month days and nights, and through much of the year, the sun barely skims the horizon above a frigid equator. But this hypothesis has its own suite of problems, not the least of which is tipping the planet over (Hoffman & Schrag 1999). Other researchers using geo-climate models have found that finding atmospheric conditions that completely cover the oceans with ice are very difficult to model (and hence less likely to be "real"). Specifically, feedback loops in the Neoproterozoic carbon cycles tend to keep enough of the greenhouse intact that the oceans do not completely freeze over. Instead, their models of the Neoproterozoic Earth favor a "slushball Earth," with tropical glaciers on land, but a belt of open sea water near the equator (Ridgwell & Kennedy 2004).

One of the early stumbling blocks to accepting Snowball Earth was the persistence of life through this crisis – ten million years is a long time to wait for spring. Different hypotheses have tropical "windows" in the ice (Nield 2007, p. 246) to allow limited photosynthesis to continue. A slushball Earth would have allowed life access to the Sun and limited gas exchange with the atmosphere. Paleontologists have pointed to the diversity of life seen around hydrothermal vents on the sea floor. Even under kilometers of water and ice, these vents would have been (and still are) a source of energy for many life-forms and could have been refugia during the Proterozoic ice ages.

<u>The Great Unconformity – what are we missing?</u> Snowball or just a severe ice age, either way, life survived. During the very latest Neoproterozoic, the Ediacaran Period (630-542 million years ago; all chronostratigraphic ages from ICS 2004), only about 40 million years after the last snowball would have melted, multicellular life explodes in the fossil record. The first, Ediacaran explosion seems a bit muted, since its mysterious creatures were soft-bodied and poorly fossilized. They soon gave way to the hard bodied creatures of the subsequent Cambrian Period explosion. It is from this Cambrian explosion that we can trace the genealogy of all living creatures. Red algae and protist fossils show that eukaryotes (animals, plants and fungi, organisms whose cells have a nucleus to contain their DNA) had been around since the beginning of Grand Canyon Supergroup time, 1,000 to 1,200 million years ago (Knoll & Carrol 1999, p. 2130). Various hypotheses have been studied to explain the timing of their delayed abundance. Perhaps it took evolution a while to reach some critical point where they had the genetic or biochemical "toolkits" to develop into diverse forms. Atmospheric oxygen concentrations may have finally risen high enough to support active, macroscopic animals (Knoll & Carrol 1999, p. 2135). Some paleontologists see the harsh conditions and genetic isolation of the Neoproterozoic ice ages and their hothouse interludes as evolutionary drivers that pushed life from the single celled and simple colonial forms of the pre-Snowball Chuar fossils, to the diverse multicellular

creatures we find fossilized in the Cambrian rocks of Grand Canyon, and still living around us today (see Nield 2007, pp 248-256).

In the Grand Canyon, rocks of the Grand Canyon Supergroup give us a tantalizing glimpse of the approaching Neoproterozoic ice ages, and the fossil record of its aftermath in the Tonto Group. But a 215 million year gap between the Sixtymile Formation and the Tapeats Sandstone means the Grand Canyon has no rocks from any Snowball Earths, or fossils of strange Ediacaran creatures, and the record resumes just a few million years after the Cambrian explosion of about 530 million years ago (Knoll & Carrol 1999, p. 2129). Why this gap below the Tapeats Sandstone, the Great Unconformity?

Simply stated, the Great Unconformity is a period of non-deposition. In fact, the eroded surface of the underlying Grand Canyon Supergroup rocks clearly show that not only was there a gap in deposition, but that very active erosion occurred, enough erosion to plane off thousands of feet of rock. This deep erosion, combined with the block tilting of underlying rock layers, has been described as a period of mountain building in western North America – the "Grand Canyon Disturbance." With increased understanding of the Neoproterozoic ice ages, falling sea levels (as ice locked up more of Earth's water supply in ice sheets) probably played an important role in this apparent uplift (Karlstrom *et al.* 2000, p.620). At least some of the uplift was probably "real" as well, as heat from the Earth's interior powered the break-up of Rodinia. New mid-ocean ridges grew on the floor of the paleo-Pacific, and probably displaced seawater onto the continental margins. Opening of the proto-Pacific also left the fractured continental crust warm, and consequently less dense, than it had been. Only the thin edge of the new North American continent (for example, in the future Death Valley region) rode low enough to be under the new ocean, with thicker warm crust to the east (including the future Grand Canyon region) floated higher. "Warm" would have been a relative term, as the mountains in the Grand Canyon area would have been covered by glaciers and ice fields grinding away at the Supergroup. Erosion continued after the Neoproterozoic ice ages, erasing any glacial topography (moraines, cirques, etc.) that may have formed. The "warm," buoyant crust continued to cool slowly during the latest Neoproterozoic and early Cambrian times, slowly sinking as it did. This allowed the paleo-Pacific to spread east across the new continental margin (Baldridge 2004, p. 83), depositing the sandstones that eventually "ended" the Great Unconformity in the Grand Canyon's rock record.

Grand Canyon rocks of the Paleozoic: Layers of Climate and Life

Tonto Group Greenhouse? During the Cambrian Period (542-488 million years ago, ICS 2004), carbon dioxide levels were high (Berner & Kothavala 2001), suggesting warm "greenhouse" climates. In northern Arizona, the dawn of the Cambrian saw continued erosion of highlands remaining from the opening of the western "paleo-Pacific" ocean millions of years earlier. Most of the rocks of the Grand Canyon Supergroup had eroded away. Remaining ridges of Supergroup rocks still rose as much as 800' (244 m) above hills and plains of exposed basement rock – the Granite Gorge Metamorphic Suite (the Vishnu, Brahma and Rama schists) and various granite intrusions. By late in the early Cambrian Period, the western ocean began encroaching into northwestern Arizona. The initial river and beach deposits, now the Tapeats Sandstone, buried this ancient topography. The Precambrian rocks being buried under the Tapeats were heavily weathered in many locations. Chemical weathering can extend up to 50' (15m) below this buried "soil" surface, although in most places, it is less than 10' (3m). This thick layer of "regolith" has prompted many geologists to suggest a humid environment. Since large land plants had not yet evolved, the Cambrian weathering processes would differ from modern chemical weathering (Middleton & Elliott 2003, pp. 92, 100). The weak carbonic acid formed from carbon dioxide and rainwater is an important factor in chemical weathering (Leet & Judson 1971, p. 110-118), so the high carbon dioxide levels in the Cambrian could have increased the rates of chemical erosion and contributed to the thick weathering zone inundated by the Cambrian sea.

As the Cambrian Period progressed, the paleo-Pacific continued its advance over northern Arizona. The sea's advance was driven by non-climatic forces, of which two seem most important. First, the continental crust in northern Arizona was cooling after the breakup of the Rodinian supercontinent and accompanying igneous activity. Cooler being denser, the continental margin was sinking. Second, sea levels were rising world-wide, again as a result of Rodinia's breakup and the relatively new, hot sea floor created as the new oceans widened. This buoyant sea floor displaced water onto the continental margins, called the Sauk sequence in North America (Baldridge 2004, p. 89). The Tapeats Sandstone was buried under the offshore muds of the Bright Angel Shale, and eventually the Muav Limestone.

Formation of the Muav Limestone was driven by earth movements (including plate tectonics) on local and regional scales. While not climatic in origin, the Muav may be part of a larger picture climatically. Sea levels rose world-wide, and limestones like the Muav were forming on the continental margins, perhaps leading to the decline in carbon dioxide concentrations in the later Cambrian.

Temple Butte Formation and the Devonian upheavals. After depositing the Muav Limestone and undifferentiated dolomites, the Cambrian sea retreated to the west. No rock layers are preserved in the Grand Canyon record for about 120 million years, until the 385 million year old Temple Butte Formation (all Grand Canyon strata ages from Mathis & Bowman, 2005) was deposited in the middle to late Devonian Period (416 – 359 million years ago). During this time, the first forests began growing on the continents, like those fossilized near Gilboa, New York, about 385 million years ago (Perkins 2007). The appearance and spread of large land plants triggered a tremendous reduction in the amount of carbon dioxide in the atmosphere, a trend that extended into the following Mississippian Period. Simple plants had been growing on land for millions of years, there is evidence for algal soil mats (perhaps like modern soil crusts) as far back as 1.2 billion years ago in the Mescal Limestone of central Arizona (Beeunas 1985, the Mescal may correlate to Grand Canyon's Bass Limestone, based on similar age and rock types, see Dalton 1972). However, it was not until late Silurian and early Devonian time that vascular land plants diversified and slowly began spreading across the landscape. Two developments in particular, trees and seeds, had profound impacts. Trees were a big, new form of biomass in the organic carbon cycle. They require support, and their roots not only increased this biomass, but, by extending deeper into the ground, increased soil development. Then, in the latest Devonian, seeds allowed more plants to spread to drier upland habitats (Algeo *et al.* 1995, p. 64). Trees themselves may be a consequence of declining carbon dioxide levels. The earliest land plants had tiny leaves or no leaves at all. With a strong greenhouse, this small surface area was a survival tactic. There was plenty of carbon dioxide, but with warm temperatures, a large leaf surface area would have lead to lethal overheating. As carbon dioxide levels fell, leaves needed more stomata ("breathing pores") to collect the scarce gas. A side effect was greater evaporative cooling from transpiration, helping the larger leaves avoid cooking in the sun. Larger leaves captured more light, leading to more biomass, reducing carbon dioxide, leading to cooler temperatures and more stomata. Leaf and plant size grew and carbon dioxide levels fell through the late Devonian Period and into the subsequent Mississippian (Osborne *et al.* 2004, p. 10362, Beerling & Berner 2005, p. 1302).

The "greening of the continents" during the late Devonian was another crisis for life on the Earth. The organic carbon cycle suddenly had a new "reservoir" to fill, as carbon was incorporated into the new forests. Some of this carbon was transferred out of the organic and into the geochemical carbon cycle as coal beds began forming. Carbon dioxide levels in the atmosphere fell, reducing the "greenhouse effect." By late Devonian time, glaciers appeared in South America (Dott & Batten 1971, p. 392). The Temple Butte Limestone does not show evidence of this glaciation (thanks to continental drift) because the southwestern U.S. was drifting into the tropics (Blakey n.d.). However, it still shows some evidence of environmental upheavals. When freshly broken, samples of Temple Butte Limestone can have a "strong fetid smell" (Billingsley 1978), indicating organic matter. Elsewhere around the world, even more organic material accumulated in thick layers of black shale being deposited in shallow seas. These deposits may indicate massive blooms of marine algae, over-fertilized by the rapid release of nutrients as forests expanded across the land. As trees grew bigger, their roots dug deeper, breaking down more rock and releasing more nutrients to be carried to the sea (Algeo *et al.* 1995, p. 66). Today, the flush of nutrients from the Mississippi River creates a "dead zone" in the Gulf of Mexico. The nutrients fuel algal blooms, whose decay consumes oxygen from the water to the point where animals can no longer survive.

In addition to the challenges posed by falling carbon dioxide levels, oxygen levels fell during the early Devonian. Arthropods had colonized the land in the Silurian (over 400 million years ago), when the atmosphere's oxygen content rose above 20% (the modern atmosphere is about 21.5% oxygen). A few vertebrate species followed in the Devonian. During the late Devonian extinctions (specifically, the Frasnian/Fammenan event), atmospheric oxygen levels fell to about 13.5%. The low oxygen levels seem to have stopped animals from colonizing the land (Ward *et al.* 2006). Marine waters became anoxic, and there is even evidence that forest fires ceased (the "charcoal gap;" Kump 2008, p. 278). Late in Temple Butte Limestone time, oxygen levels began to rise. Only after oxygen was again more than 20% of the atmosphere did the arthropods and vertebrates resume diversifying on the land (Ward *et al.* 2006). Thus, the animal conquest of the land is tied to the air, specifically, rising oxygen levels.

Of course, none of these processes happened overnight. The spread of forests, the drawdown of atmospheric carbon dioxide, oxygen's negative spike, and the growth of ice caps all take time. The extinctions of the late Devonian were also drawn out over about 20 million years, with at least eight extinction events. But by the opening of the Mississippian Period, marine life had lost around 21% of its families and 50% of its species (Algeo *et al.* 1995, p. 45). The Devonian is one of the "big five" mass extinctions in Earth history (Raup & Sepkoski 1982, p. 1502).

<u>Redwall Limestone and Surprise Canyon Formation dodge the icy bullet.</u> During the following Mississippian Period (359 – 318 million years ago), carbon dioxide levels continued to fall and the

Gondwanan ice age continued. But you wouldn't know, just looking at Grand Canyon's Redwall Limestone. The Redwall was formed in a huge carbonate bank (similar to the Bahaman Banks of modern time) along the continental shelf of North America from Mexico to Canada. Other limestones forming at the same time include the Escabrosa Group of southern Arizona and New Mexico (Geolex), Nevada's Monte Cristo Group and Blue Point Limestone (Billingsley 1978), the Madison Limestone of Wyoming and Utah (Hansen 1969), and the Leadville Limestone of Colorado (Baars 1983). Western North America was now fully tropical, with northwestern Utah, Wyoming and North Dakota on the Equator itself (Blakey n.d.). Even so, the Redwall contains some evidence of world conditions. Subtle cycles of coarse and fine-grained limestone in the Redwall may be related to changes in water depth (McKee 1974). Such changes would be expected as ice sheets in southern Gondwana expanded and contracted. In Utah, the Redwall/Leadville Limestone produces oil in the Kaiparowits Basin (Allison 1997, Fig. 4) and Lisbon Valley (Baars 1983). The source of this oil could be in the Redwall itself (Thunder Springs Member; Allison 1997), or it could have migrated from other rocks. This oil represents un-decayed organic material, some of the carbon transferred from the short-term organic carbon cycle to the long-term geochemical cycle, thus contributing to the drop in carbon dioxide levels.

By the last few million years of the Mississippian Period, the Redwall "sea" had retreated back to the west. Northern Arizona was a broad, limestone platform, very similar to today's Yucatan Peninsula (Huntoon 2003, p. 227), with average temperatures of about 80°F (27°C; Kenny 1998, p. 22). Like the modern Yucatan, this exposed Redwall platform was riddled with caves. Stream valleys up to 400' (120 m) deep cut into the limestone. The Surprise Canyon Formation was deposited on this ancient "karst topography" about 320 million years ago. Red mudstones fill some of the ancient caves, and valley deposits contain abundant fossils, including tree fossils and pollen from early terrestrial ecosystems, and more than 60 species of marine life from later times when the valleys flooded to form estuaries (Beus 2003, pp. 126, 129). The evidence of weathering, erosion, and diverse life preserved by the Surprise Canyon Formation reflect the tropical environments. Changing sea levels are a reminder of the ice caps around the distant South Pole as glaciation spread from South America to Africa and Antarctica as continental drift carried Gondwana across the South Pole (Dott & Batten 1971, p. 392).

<u>Supai Group and Hermit Formation tropical redbeds.</u> Through the Mississippian, Pennsylvanian and Permian, carbon dioxide levels continued to fall and remain at very low levels. Oxygen levels did just the opposite. While the spreading forests initiated in the Devonian drew down carbon dioxide levels, they boosted oxygen levels in the atmosphere. The organic carbon cycle suggests this oxygen would have been consumed as the trees rotted, but during the Mississippian and Pennsylvanian periods, much of this material did not. Why? There are possibilities, but not definitive answers. It could be that microbes took time to evolve the ability to digest wood (especially lignin). The ebb and flow of the Gondwanan glaciers may have periodically inundated vast, poorly drained lowlands, filling them with stagnant, oxygen-poor water that inhibited decay. Whatever the reason, the Mississippian, Pennsylvanian and Permian periods saw the highest rates of coal formation in Earth history (Berner 1999, p. 10956). In fact, through most of the world, the Mississippian and Pennsylvanian periods are combined into a single "Carboniferous Period." So, oxygen levels rose as carbon was transferred from the organic to the geochemical cycle. The "greenhouse planet" was done, for a while…

The deep red color of Grand Canyon's Pennsylvanian and Permian rocks are a reminder of this oxygen-rich atmosphere. The Supai Group and the Hermit Formation are red throughout, but even the mudstones in the upper Toroweap and Kaibab formations tend toward red colors, stained by oxidized (rusted) iron. Another clue to rising oxygen levels can be found in the animal life of the times. The

Hermit Formation has produced a fossil dragonfly wing about 5" (127 mm) long. The 10" wingspan of the Hermit dragonfly is small compared to the 30" (762 mm) wingspan of Pennsylvanian dragonflies (Dott & Batten 1971, p. 347), but illustrates the size insects could achieve in the oxygen-rich atmosphere.

North America (now firmly embedded in the supercontinent Pangaea) slowly drifted, and northern Arizona crossed the Equator and into the northeast trade winds. Before reaching Arizona, these winds had blown across the wide expanse of Pangaea to the east, and were dry. Because the continent was rotated a bit clockwise (compared to our modern orientation), Arizona's coastal plains were downwind of the Ancestral Rockies. These mountains rose when North America crumpled into Africa and South America during the assembly of Pangaea (Huntoon 2003, p. 227). Their long rain shadow reached west, contributing to the steady drying trend in northern Arizona. Marine waters had deposited the thin Watahomigi Formation limestones about 315 million years ago. After they withdrew to the west, dry winds piled dunes of the Manakacha Formation. These dunes contain sand derived from both quartz and carbonate minerals, probably picked up as the wind blew over lowlands and beaches. They represent the first of many wind-blown sand deposits that make "desert" a recurring theme of ancient environments on the Colorado Plateau from the middle Pennsylvanian Period to the late Jurassic Period some 150 million years later. Dune sands, cemented into sandstone, also form prominent cliffs at the base of the Watahomigi Formation and near the top of the Esplanade Sandstone, as well as smaller cliffs throughout all three formations. Even the Hermit Formation contains a few dune deposits among its riverbed and floodplain deposits (Blakey 2003, p. 161-162), and caliche suggests precipitation of only 4-20" per year (Duffield 1985). These dunes were not the sole deposits in a sterile, lifeless environment. The dune deposits are separated in space (horizontally) and in time (vertically) by floodplain deposits. These deposits of mud and fine sand contain scattered plant fossils and animal tracks. Fossil leaves in the Hermit show adaptations to at least a seasonally arid climate with thick, leathery leaves, hairy or scaly coverings, their pinnae (leaflets or fronds) rolled into quills to reduce evaporation (White 1929). The top of the Hermit Formation has huge cracks, filled with sand from the overlying Coconino Sandstone. Usually referred to at "giant mud cracks," these features are actually far larger than mud cracks that form as mud dries in the sun. They are more likely "giant desiccation cracks," which form as clay-rich sediment as much as 50' below the surface dries and shrinks, initiating the crack. Desiccation cracks then grow toward the surface. When the surface soil is wetted, it looses strength as water reduces the clay's "stickiness" (cohesion), and it collapses into the underlying crack (Harris 2004).

The equatorial arid climates revealed by Grand Canyon's Supai and Hermit redbeds makes it easy to forget the Gondwanan ice age. But these formations, and the Coconino, Toroweap and Kaibab formations above them, still contain evidence that the Earth's climate had cooled. The Gondwanan ice age lasted a long time, from the latest Mississippian (Surprise Canyon Formation time) until the middle Permian (Kaibab Formation time). There were two major glacial maxima when the ice cap reached its greatest (and, presumably, sea levels were lowest), once during the mid-Pennsylvanian, and again in the early Permian. The first maximum is not even represented in Grand Canyon's rocks. Falling sea levels as the ice caps grew may be related to the onset of arid conditions seen in the Manakacha. The first peak of the Gondwanan ice age (and lowest sea levels) occurred during the unconformity (gap) between the Manakacha and Wescogame formations (the Desmoinesian Stage; Gastaldo *et al.* 1996, p. 4). Sea level fell far enough that the top of the Manakacha Formation began to erode away (Blakey 2003, p. 143).

The second glacial maximum, in the early Permian ("Wolfcampian Stage") peaked at the same time Esplanade dune sands were deposited. Sea level again fell, and arid floodplains of the Hermit reached west to at least Las Vegas, NV (Rowland 1987).

On fine scales, cyclic deposition patterns seen in the Supai Group are likely to reflect the rise and fall of sea level as the glaciers advanced and retreated. The cycles are not always recorded as outright marine deposits, they can also appear as changes in sediment size and composition. Sea level changes are also "base level changes" (the level streams and rivers cut down toward). A change in base level can change a flowing river into a sluggish waterway, changing the size and type of sediments it deposits (or erodes). Throughout the Pennsylvanian and Permian, the western sea was never really that far away, all the formations of the Supai grade into limestones to the west (Blakey 2003, p. 141). Although the pattern within each formation differs, in the Las Vegas areas the Watahomigi, Manakacha and Wescogame formations have become the Callville Limestone, and the Esplanade Sandstone has graded into the Pakoon Limestone. In the Grand Wash Cliffs, the desert sands of the Coconino Sandstone thin and disappear into salt flat and tidal deposits (Blakey 1986). Only the Hermit remains a terrestrial deposit so far to the west (Rowland 1987).

Coconino Sandstone, Toroweap and Kaibab Formations, the desert seas. By Coconino Sandstone time (early Leonardian Stage, 275 million years ago; Mathis & Bowman 2005), the Gondwanan ice sheets were retreating, and by Kaibab time, the Gondwanan ice age was almost over (Gastaldo *et al.* 1996). The Kaibab Formation does still show some cyclic deposition patterns which are likely due to glacial sea level changes, rather than crustal movements (Hopkins & Thompson 2003, p. 209). Arid climate was the rule, even as the Toroweap and Kaibab "seas" advanced across the shelf to deposit layers of limestone. The shoreline deposits of both formations contain evidence of extensive salt flats and gypsum deposits. Subsequently, groundwater has dissolved much of this gypsum, leaving the upper, muddier portions of both formations (Woods Ranch Member of the Toroweap and Harrisburg Member of the Kaibab) contorted and distorted (Turner 2003, Hopkins & Thompson 2003). Distortion of the upper Toroweap was severe enough that geologists initially thought it was an erosion surface separating the Toroweap and Kaibab. Later work indicates there is no, or only a localized, unconformity between the two (Hopkins & Thompson 2003, p. 199). To the east, the Toroweap Formation becomes indistinguishable from the desert dunes of the Coconino Sandstone (Turner 2003, p. 189). In the Grand Canyon Village area, the limestones of the Kaibab transition from open marine deposits to restricted circulation and interbedded salt flat deposits (Guerrera *et al.* 1997). Overall, the shallow desert seas of the Kaibab and Coconino were probably similar to the modern Persian Gulf, surrounded by the salt flats and dunes of the Arabian Desert. In spite of the (waning) ice age, Arizona's equatorial location still meant "desert."

The Great Dying. The Kaibab Formation is the last Permian rock layer exposed at Grand Canyon, but about 20 million years remained before the Permian Period itself ended 251 million years ago. During this time, other limestone layers were deposited in surrounding areas. However, if any rock layers formed in the Grand Canyon area, they were removed by erosion before the Moenkopi Formation spread across the Colorado Plateau in Triassic time, about 245 million years ago. One of the most dramatic events in the Earth's biologic and climatic history, the "Great Dying," unfolded during this 75 million year gap. The Great Dying was such a profound extinction event that it defines the end of the Permian Period and the Paleozoic Era in general.

Even as the Kaibab Formation was being deposited on the shallow continental shelf, environmental stresses were building in the deep ocean basins. Specifically, oxygen levels were falling in these deep basins. As oxygen levels fell, anaerobic ("oxygen-fearing") bacteria began to thrive. Some of these bacteria produce hydrogen sulfide (H_2S), and during the late Permian hydrogen sulfide poisoning ("euxinia") began decimating deep sea creatures (Bottjer *et al.* 2008, p. 7).

During the late Permian, 100 genera of bryozoans became extinct, and only four survived into the Triassic (Gilmour 1995). Indeed, the end of the Permian was also the end for 52% of all families of marine organisms (Raup & Sepkoski 1982, p. 1502). Extinction of marine plankton caused marine food chains to collapse (Eshet 1995). On land, more than 70% of vertebrate species became extinct, in the sea, over 85% of the species disappeared (Monastersky, 1998). Photosynthetic land plants were decimated and fungi "spiked," followed by a slow return of gymnosperms. The Great Dying is the greatest extinction in the entire fossil record.

Why? Periodically, arguments for a meteor or comet strike are advanced (for a recent example, see Davis 2008). Much later in geologic time, at the end of the Mesozoic Era (the "Age of Dinosaurs"), there is good evidence for a fatal impact. Around the world, ejecta from the Chicxculub crater in the Yucatan forms a distinctive deposit rich in the rare metal iridium. However, evidence for a meteor impact ending the Permian Period remains elusive and questionable (see Ward 2007). The end of the Permian did see an incredible eruption of flood basalts, up to 12,000' (3,700 m) thick, in Siberia. In just one million years (or less), up to 750,000 cubic miles (3,000,000 cubic kilometers) of lava poured out to form these "Siberian Traps" (Renne 1995, Alper 1994). In China, volcanic ash beds from this time were deposited in less than 160,000 years, perhaps as little as 10,000 years (Bowring 1998). Since carbon dioxide makes up 12% of the gas released in an "average" volcanic eruption (Dott & Batten 1971, p. 98), these eruptions would have caused carbon dioxide levels in the atmosphere to soar (Berner 2006, p. 5661). Conditions in the sea deteriorated further, with the potential for acidification and carbon dioxide poisoning on top of the low oxygen levels and hydrogen sulfide buildups already underway (Bottjer et. al 2008, p. 7). The stage was set, and it was the last act for most of the life on Earth.

A "worst case scenario" may be entirely appropriate in the extreme case of the Great Dying. One scenario is laid out by Ward, 2007 (p. 137). As eruption of the Siberian Traps drove carbon dioxide levels up at the end of the Permian, the atmospheric greenhouse returned with a vengeance. The Earth's atmosphere is a giant heat engine, its weather driven by the temperature differences between the poles and the tropics. Warming greenhouse temperatures evened out average temperature differences between the tropics and the poles. The winds weakened, as did surface water circulation in the oceans. This greenhouse warming didn't shut down oceanic circulation, but changed it. Before (and again today), cold, dense, oxygen-rich waters sinks to the sea floor in polar regions. But as Earth, and especially the poles warmed, it was salty, dense, oxygen-poor water that sank to the sea floor in the tropics. Individuals, species, genera, and families began to suffocate and die as anoxic water slowly filled the ocean basins. Eventually, the anoxic bottom water filled the ocean basins to a level where light could penetrate. Anaerobic bacteria, which would die in oxygenated waters, now proliferated. Some begin using the sunlight to produce hydrogen sulfide instead of oxygen. Some hydrogen sulfide escapes from seawater today, but during the Great Dying, the oceans may have vented 2,000 times as much of this poisonous gas. As if anoxic oceans and poison gas weren't enough, hydrogen sulfide also destroys ozone. As concentrations rose, the stratospheric ozone layer thinned, and increasing amounts of ultraviolet radiation began reaching the Earth's surface. Land plants and the photosynthetic plankton near the ocean's surface died, and atmospheric oxygen levels plunged. Extinctions spread as conditions deteriorated, not as quickly as they did after the end-Cretaceous meteor impact in the Yucatan, but more thoroughly than any other recorded extinction before or since.

Yet, if the Great Dying is the result of Earth-driven processes (in this case, volcanism), rather than a chance extra-terrestrial encounter (a meteor impact), are there other examples? As it turns out, four of the "big five" mass extinctions (in the Ordovician, Devonian, end-Permian, and end-Triassic), and some lesser extinctions as well (e.g., end-Cambrian, end-Jurassic, Paleocene), are marked by high global carbon dioxide concentrations (Ward 2007, pp. 18, 138).

Bridging the gap, Mesozoic rocks

In most accounts, the Kaibab Formation ends the "classic" rock record of the Grand Canyon some 270 million years ago. However, this view is rather myopic. Just as our ancestral line (somehow) continued through the Great Dying, so did the evolution of the Grand Canyon region. Younger rocks are exposed all around the Grand Canyon. Patches of the 245 million year old Triassic Moenkopi Formation are found on the rim in the western Grand Canyon (Billingsley & Wellmeyer, 2003), and additional Mesozoic layers tower above the Colorado at Lees Ferry. Within and near the Canyon itself, latest Mesozoic and Cenozoic rocks record uplift and erosion of the modern landscape. Indeed, the rock record overlaps biological remains with lava flows near Tuweep only a thousand years old.

The rock record of the early Mesozoic is dominated by desert sands of the Jurassic Period's Wingate, Navajo, Page and Entrada sandstones, just to name a few. During the early Mesozoic, the continents were relatively exposed above sea level (Dott & Batten 1981, p. 434). Because land heats up and cools down faster than water, this led to generally arid "continental" climates. The American southwest was also drifting into the "Horse Latitudes" (30° – 35°), where global air currents foster aridity (the modern Sahara, Arabian, Atacama, Kalahari and Australian deserts all lie in this belt). The Jurassic deserts reflect the combined effects of exposure and latitude. Interspersed with these sand dune deposits are silty mudstones, including the Triassic Chinle, Triassic/Jurassic Moenave and Jurassic Summerville formations. These mudstone deposits certainly represent river systems, and their fossils suggest a moist environment. However, the extent of the water still remains under scrutiny. Was the climate moist, or do these deposits represent riverside oases? With evidence suggesting both conditions, it seems likely both environments were present at different times.

During the Jurassic Period, North America began pulling out of the supercontinent Pangaea. Narrow seaways to the south and east formed and grew into the Atlantic Ocean. To the west, island arcs were colliding with North America. Rock layers formed on the old marginal shelf were crushed and thrust east. Although northern Arizona was not caught up in this "Sevier Orogeny," mountain-building was as close as the Las Vegas area. Volcanoes similar to the modern Cascades (Mt. Rainier, Mt. Saint Helens) erupted near the active western continental margin. Sediments eroded from these western mountains, dusted heavily at times with volcanic ash, spread across the future sites of the Colorado Plateau, southern Rocky Mountains, and western Great Plains. The Morrison Formation records this savanna environment with its famous dinosaurs and other fossils.

During the Cretaceous Period, another shallow seaway began to slice the continent from south to north. Unlike the continental rifting that had split Pangaea; this was a shallow, "epicontinental" sea, with continental crust under its shallow bottom. Unlike the Paleozoic "seas" that had deposited so many rock layers now exposed in the Grand Canyon, this Cretaceous seaway was connected to the new Atlantic Ocean to the southeast. This new seaway is called the "Western Interior Seaway." Modern epicontinental seas are much less impressive, but include Hudson Bay and the Baltic and Bering seas. North America was not breaking up, it was just being flooded as global sea levels rose and ultimately covered about one-third of the modern continental land area (Dott & Batten, 1981, p. 429). Although different in detail, this continental flooding is a reprise of the flooding that had occurred some 400 million years earlier, during the Cambrian (Grand Canyon's Tonto Group). Then, breakup of the supercontinent Rodinia had created new, hot, and thus buoyant sea floors. This time, it was buoyant sea floor formed in the wake of dispersing fragments of the supercontinent Pangaea that displaced sea water onto the continents (Baldridge, 2004, p. 83). High sea levels and ice-free poles during the Cretaceous suggest a warm climate, even though carbon dioxide levels generally fell throughout the Mesozoic Era. This seeming contradiction is likely the result of sea currents freely distributing solar heat from the tropics to the poles, an "oceanic climate" in contrast to the "continental climate" of the early Mesozoic.

The American southwest was under the fluctuating western shoreline of the Western Interior Seaway. Rivers flowing from (and eroding) the Sevier mountains to the west entered bands of near shore swamps, coastal beaches and marine muds. The shoreline was constantly migrating, producing a complicated interweaving of the three environments. The near shore swamps produced the coal beds of Arizona's Black Mesa, New Mexico's Gallup and San Juan basins, and Utah's Price and Kaiparowits areas. This coal locked away carbon that today is being returned to the atmosphere from burning coal seams (the Smoky Mountain of Utah's Kaiparowits Plateau) and electric power plants throughout the southwest. The sandy beach deposits form cliffs in the Mesa Verde Group and Mancos Shale throughout the Four Corners region, while gray marine mud makes up most of the Mancos, Tropic, and other shales.

The end of the Cretaceous Period, and the end of the Mesozoic Era, is marked by the Chicxculub Impact on Mexico's Yucatan Peninsula, and by the extinction of the dinosaurs 65.5 million years ago. Most paleontologists agree the two events are related, and research into the effects of this catastrophic impact closely mirror the research into the effects of a nuclear winter. While this subject is fascinating, neither dinosaurs nor impact ejecta occur at Grand Canyon.

More relevant to the Grand Canyon story is the Laramide uplift that began in the late Cretaceous and continued well into the Cenozoic, or "Age of Mammals." Uplift started the erosion cycle that ultimately resulted in the Grand Canyon itself. It also plays a key role in the evolution of modern climatic patterns.

The Age of Mammals: From the Greenhouse to the Icehouse

The Laramide uplift of the western U.S. was not uniform. The Rocky Mountains arched up east of the Colorado Plateau, and long, stairstep-like folds cut across the Plateau itself. Highlands also rose to the west and south. As blocks of the crust rose, streams struggled to adjust, but drainage was disorganized on this young landscape. Enclosed lake basins and aprons of debris accumulated layers of sediment that record the life and climate of the latest Cretaceous and early Cenozoic. This record is one of very warm, humid times. The Green River Formation of central Utah and southwestern Wyoming contains fossil crocodiles and palm fronds (Baer 1987). South of the Grand Canyon on the Hualapai and Coconino plateaus, red Laramide gravel deposits also illustrate this subtropical to tropical climate. Although these gravels were deposited in areas with abundant limestone (for example, exposures of the Kaibab, Toroweap, Redwall and Muav), the gravels themselves contain few limestone fragments. In the warm, moist environment, most carbonate fragments would have been destroyed by chemical weathering, rather than surviving to be part of the Laramide beds (Young 2001, p. 12).

Why so warm? Locally, computer models suggest the warm, moist climates were partially dependent on the effects of the large Eocene lakes of Utah (for example, Lake Flagstaff; Caroll 1994). But, by the early Cenozoic, continental drift had already carried the Colorado Plateau north and out of the tropics (Blakey no date), so it was not just Grand Canyon country that was warm, but the whole world. Some of this warmth may have been the result of the carbon dioxide released into the atmosphere as the "Tethys Ocean" closed. Half a world away, Tethys lay between the then-island continent of India and "mainland" Asia. Plate tectonics was carrying India north toward Asia and slowly closing this tropical seaway. Metamorphism of carbonate minerals as Tethys closed would have released substantial amounts of carbon dioxide, strengthening the Earth's greenhouse (Kerrick 1994). Warming reached its peak, and indeed, spiked, at the boundary between the Paleocene and Eocene epochs, an event called the "Paleocene – Eocene Thermal Maximum" or PETM (Nash 2008, p. 15) about 55 million years ago.

The PETM is not one of the "Big 5" mass extinctions, but it did see extensive extinctions of deep sea floor fauna, and a change in land mammals (Ward 2007, p. 49). Prior to the PETM, mammals included "holdover" types from the Cretaceous and some strange "experimental" types for the new Age of Mammals. After the PETM, mammals became much more "familiar." For example, early "primitive" horses and primates appear in the fossil record. The PETM itself is not preserved in the rocks of Grand Canyon country. Our red Laramide deposits stop at an unconformity, on top of which are tawny rocks from the mid-Cenozoic that reflect cooler, drier conditions, much more like modern climates (Young 2001, p. 12). For the cause of the PETM, evidence from elsewhere around the west, and computer models of various Earth systems point to an abrupt release of carbon dioxide.

During the Paleocene, the Earth was already warm, its greenhouse carbon dioxide stoked by volcanic eruptions around the closing Tethys and opening Atlantic oceans. On top of these moderately high carbon dioxide levels, isotopic analysis shows an additional pulse of carbon. Deep in the oceans, there is a strange kind of "ice" called "methyl hydrate" that forms around natural gas seeps. Cold temperature and high pressure keeps this amalgam of water and methane frozen. Reducing the pressure or increasing the temperature causes the methyl hydrate to decompose and release methane, a potent greenhouse gas. Warm Paleocene climates may have caused some of this methyl hydrate to decompose, gradually adding to the planet's greenhouse. Computer modeling (Bice & Marotzke 2002) suggests that gradual warming and the shifting continents eventually reached a "tipping point." This tipping point caused deep ocean currents to change. Deep currents of icy cold water descending from the Antarctic coast were replaced with somewhat warmer water from the North Atlantic. The temperature increase was enough to decompose the remaining methyl hydrates, releasing bursts of greenhouse gases that drove planetary temperatures up.

The PETM was a “spike,” not a fundamental change in Earth’s climate – why? If the methyl hydrate hypothesis is correct, the answer is simple. Once the oceans’ methyl hydrates decomposed, that source of greenhouse carbon gas (either as methane, or oxidized to carbon dioxide) was gone. The carbon cycles began removing it from the atmosphere, and the Earth cooled again. In fact, this period of cooling carried the Earth temperatures from the PETM all the way down to the “icebox” conditions of the Ice Age and the first continental glaciers since the Paleozoic ice sheets of Gondwana some 200 million years earlier.

As the Cenozoic progressed, the climate gradually cooled, slowly transforming from greenhouse to icebox. This transition was strongly punctuated about 45 million years ago, when the island continent of India finally, and firmly collided with Asia. When India had been approaching Asia, the seafloor separating the two continents was forced down into the Earth’s mantle (just as it is today in the deep ocean trenches). This “subducted” crust fueled volcanoes similar to those of the Andes and Cascade mountain ranges. Since carbon dioxide is an important component of volcanic gases, these eruptions had helped to keep the planetary greenhouse’s thermostat high during the Paleocene, helping set the stage for the PETM. But, the collision of India with Asia ended that process during the Eocene epoch. The ancient Tethys Ocean closed and mountains, the beginnings of today’s Himalaya, began to crumple upward along the collision zone. The sea-side volcanoes were deprived of their old magma sources since there was no longer any seafloor descending between India and Asia. The volcanoes went extinct, no longer pumping carbon dioxide into the atmosphere. Instead of a source of carbon dioxide, the newly forming Himalaya became a carbon dioxide sink as their newly exposed rocks began to weather. South of the new ranges, India had also carried thick layers of basalt north, the Deccan Traps. Eruption of the Deccan Traps 65 million years ago had been a huge event. This eruption was not as large as the Siberian Traps (implicated in the Great Dying at the end of the Permian 250 million years ago), but still much larger than the flood basalts of the Columbia Plateau in Idaho, Washington and Oregon. In fact, some geologists considered (and a few still consider) the eruption of India’s Deccan Traps as a major player in the extinction of the dinosaurs 65 million years ago. Carried into the tropics for the first time during the Eocene, chemical weathering attacked these huge layers of basalt, consuming carbon dioxide in the process.

<u>The “Ice Age”</u> The almost-final closure of the Tethys Ocean (the remnant Mediterranean Sea and Persian Gulf are still closing) drove climatic cooling world-wide. Weathering rock consumed atmospheric carbon dioxide, reduced its greenhouse effect, and the Earth began to cool. It took more than lower carbon dioxide levels to drive the ice ages at the end of the Cenozoic. The weak greenhouse was the “backdrop” against which other factors drove the advance and retreat of continental glaciers, especially in the northern hemisphere. The most fundamental of these cyclic processes are the “Milankovitch cycles.” The Earth spins in space like a slow but massive top as it swings around the Sun. But, the Earth’s spin axis is not perpendicular to its orbital plane. Instead, Earth’s axis is tilted by about 23°, a tilt that gives us summer (when our half of the Earth tilts toward the Sun) and winter (when we tilt away). Earth’s orbit around the Sun isn’t a perfect circle, either – it is an ellipse. So, part of our orbit swings closer to the Sun, part farther away. None of these spins and swings are constant. Earth wobbles on its axis, our elliptical orbit around the Sun stretches and contracts. And, these variations are not synchronized, either. Today, the northern hemisphere tilts toward the Sun at the same time our orbit has carried us farthest from the Sun (in 2009, the northern hemisphere reaches its maximum tilt toward the Sun, the Summer Solstice, on June 21, while its

orbital path was farthest from the Sun, "aphelion," on July 4; http://aa.usno.navy.mil/data/docs/EarthSeasons.php).

All this spinning and twirling and stretching means that different parts of the Earth get more or less intense sunlight. Over the course of the year, these variations drive the changing seasons. Over longer terms, these variations can conspire to grow ice sheets or melt them away. Although it may seem odd, it is cooler summers that drive the northern hemisphere into its periodic ice ages. Northern winters are always cold enough for snow. When cool summers allow the snow to persist, year after year, the ice sheets begin to form and grow (Elias 1997, p. 48). Thus, a weak greenhouse (from low carbon dioxide levels) and Earth's changing tilt and orbit usher in glacial "icehouse" conditions. But the picture is not complete until we factor in where the continents themselves are.

By the early Oligocene Epoch, about 33.6 million years ago, falling carbon dioxide levels allowed Earth to cool enough for continental glaciers to begin forming in Antarctica, soon locking that continent in the "deep freeze" that has held it ever since (DeConto *et al.* 2008, p. 652). The ice cap began as mountain glaciers in a landscape like the modern Alps. Ice-penetrating radar reveals glacial valleys and cirques in the Gamburtsev Mountains buried below Ice Dome A. It took millions of years for these glaciers to grow and coalesce into the massive ice sheet covering the continent today (Perkins 2009, p. 15). The Antarctic cold is further intensified by the Southern Ocean that neatly encircles the continent. Icy ocean currents and howling winds circle the globe unimpeded, cutting Antarctica off from tropical warmth. It is interesting to remember the ancient ice age from the Pennsylvanian and Permian periods (especially the Supai Group in Grand Canyon), when the southern supercontinent Gondwana drifted over the south pole at a critical time to produce an ice age.

In contrast to Antarctica's cold isolation, the northern continents did not ice up as quickly. The earliest definitive evidence for widespread continental glaciers in the northern hemisphere does not appear until about 2.7 million years ago in the later Pliocene Epoch. Models of carbon dioxide concentrations and variations in Earth's orbit suggest earlier glaciation was possible, perhaps as long ago as the Oligocene – Miocene boundary 23.03 million years ago. But early glaciation of the northern hemisphere was probably limited to mountain glaciers and small, temporary ice sheets in western North America, northeastern Asia and eastern Greenland (DeConto *et al.* 2008, p. 653).

Ice sheets have advanced and retreated many times across the northern hemisphere during the last 2.7 million years. The most recent glacial maximum of the late Pleistocene is called the "Pinedale" in the Rockies (or the "Wisconsin" for the continental glacier in the north and east). The Pinedale/Wisconsin glaciation lasted from 110,000 years ago until about 10,000 years ago. It contained several glacial "maxima," the most recent one peaked about 18,000 years ago. Various indicators suggest temperatures were 9-18 °F (5-10 °C) cooler than modern. Climate models show a strong temperature gradient around the southern edge of the North American continental ice sheet, with a strong jet stream blowing to the east above the American southwest. This jet stream would have encouraged winter precipitation but helped suppress the summer monsoon. Although models disagree on precipitation increases at this time, the lower temperatures reduced evaporation and water demand, resulting in rain-fed lakes in the Great Basin and basins in southwestern deserts (Connin *et al*. 1998, p. 186).

The modern Southwestern Monsoon develops each year as rising warm air from the Four Corners region draws moisture from the Gulf of Mexico and Sea of Cortez into the southwest. During the ice age, three factors may have combined to inhibit the monsoons. The bright, white glaciers and late spring snowpacks would reduce the seasonal warming over the Four Corners by reflecting away the warming sunlight. Lower sea levels would have reduced the water surface areas in the Gulf of Mexico and the Sea of Cortez, reducing moisture the evaporate into the air. And, the Pleistocene jet stream was further south, blowing high over Arizona (about 30-35°N). There is some evidence for summer moisture, especially south of the Colorado Plateau. It is possible that the southerly jet stream was able to steer tropical storms generated off the southwest coast of Mexico into the southwestern U.S. (today, they typically move in a more northwesterly direction; Connin *et al*. 1998, p. 191; Anderson *et al.* 2000, p. 50).

<u>The Pleistocene Grand Canyon</u> Visually, a glacial Grand Canyon as much different from the landscape we see today. Our best glacial records come from the most recent, Pinedale Glaciation (110,000 to 10,000 years ago; Elias 1997, p. 68). There were no glaciers in the Grand Canyon, the closest were on the San Francisco Peaks near Flagstaff. The Grand Canyon was, nevertheless, about 12° F (6.7° C) cooler, and water was more available (about 24% more precipitation on the South Rim, 41% more at Phantom Ranch; Cole 1990, p. 255). As glaciers advanced in its Rocky Mountain headwaters, the Colorado River had deposited as much as 125 feet (38 m) of gravel along its channel, and its course wandered over this somewhat flatter Canyon bottom (perhaps somewhat like the River's modern course across the Lake Mead delta in lower Grand Canyon today). At the same time, soils were beginning to cover the slopes in the Canyon walls. Soil development was the result of several processes, all operating together. Suppression of the summer monsoon meant fewer flash floods to scour away loose material from the hillsides. More available moisture (from at least lower temperatures, if not additional winter precipitation) increased plant cover. Plants not only helped hold the developing soils in place, their roots helped weather they underlying rock. The soils themselves then helped the process by absorbing and storing precipitation, allowing further plant growth and bedrock weathering (Anders *et al.* 2005, p. 2442). As glaciation waned, the Colorado began cutting down through its recent fill deposits. Tributary streams in the side canyons didn't respond to the River's fall immediately. Perhaps there was enough soil developed on the Canyon's slopes to keep them supplied with sediment. Eventually, the River's incision, drier conditions, and the return of the monsoon combined to trigger erosion. Soils were stripped away, bedrock exposed, and the Canyon gradually became the rocky desert environment we see today.

At the height of glaciation, vegetation in the Grand Canyon started turning its red slopes green. At first glance, it would have appeared that the various plant communities we see in and around the Grand Canyon today simply moved downslope by 2,600-3,300 feet (800-1,000 m.). On closer examination, things were more complicated. Engelmann spruce (*Picea engelmannii*) forests dominated the North Rim. Douglas fir (*Pseudotsuga menziesii)* and limber pine (*Pinus flexilis*) grew from the South Rim down to the top of the Redwall. The Tonto Platform supported an open juniper (*Juniperus sp.*) woodland containing sagebrush (*Artemisia*), agave (*Agave utahensis*), and wild rose (*Rosa sp.*). Desert shrub communities of blackbrush and snowberry were found at the lowest elevations in the western Canyon. During peak glaciation, this "desert" community even included beargrass (*Nolina microcarpa*) and gooseberry (*Ribes montigenum*; Elias 1997, pp 103-105; Anderson *et al.* 2000, p. 45).

The plant communities of glacial Grand Canyon were similar to, but still different from, the communities we see today. The three pines of Grand Canyon provide some good examples. Limber pine was the most widespread conifer during glacial periods, its needles are quite common in packrat nests. Yet, it doesn't grow in the Grand Canyon at all today. Ponderosa pine (*Pinus ponderosa*), on the other hand, is found today at higher elevations throughout the region. Ponderosa doesn't mind the cold, but it needs the Southwestern Monsoon (which was marginal at best during glacial periods). Ponderosa pine's absence may reflect a lack of summer moisture (Elias 1997, p. 106), late summer cold limits on growth and reproduction, and/or the absence of fire (Anderson *et al.* 2000, p. 47). Ponderosa and limber pines probably didn't compete directly, since limber pine fossils disappear about

12,000 years ago, while ponderosa doesn't appear until about 9,000 years ago (Cole 1990, p. 248). The third pine of Grand Canyon is piñon (*Pinus edulis)*. Today, piñon grows with juniper at middle elevations throughout the Grand Canyon region, but piñon fossils are very rare in glacial-age packrat middens, in this area it only appears in Wupatki National Monument and a couple sites in far western Grand Canyon (Anderson *et al.* 2000, p. 45). It seems that today's "piñon-juniper woodland" is not a biological entity, but rather, a modern overlap in habitat requirements of two, independent species, one of which was essentially absent during the ice age. Thus, Grand Canyon's pines illustrate how climate change is not a particular effect, but rather, a broad suite of related effects. Any of these effects, including temperature, moisture and seasonality, affect various species differently.

Changes in vegetation also imply changes in wildlife, and fossils from the Grand Canyon help illustrate these changes as well. Many of these fossils are from dry cave deposits, the most famous (and before the 1976 fire, the most extensive) of which is Rampart Cave near the Grand Canyon's mouth. Desiccated sloth dung, packrat nests and other deposits provide a faunal record stretching back more than 40,000 years. Cave deposits have produced fossils of over 200 animal taxa, including a tortoise, lizards, snakes, water birds (ducks, geese, coots, grebes), quail, turkey vulture, and California condor (*Gymnogyps califorianus*), bats (including the vampire bat *Desmodus stocki*), packrats (*Neotoma* spp.), mice, wolf (either the modern *Canis lupus* or the extinct *C. dirus*), bison (*Bison*), and bighorn (*Ovis canadensis*). While many of these animals may not be unexpected in today's climate, porcupine (*Erethizon dorsatum*) and marmot (*Marmota flaviventris*) have also been found. The caves also contain the remains of recently extinct species such as the Shasta ground sloth (*Nothrotheriops shastensis*), Harrington's mountain goat (*Oreamnos harrintoni*), mammoth (*Mammuthus*), an American camel (*Camelops*) and a small American horse (*Equus*). In all, Grand Canyon's dry caves have protected a wealth of ice age fossils (Santucci *et al.* 2001, p. 16-24).

Although species (both plant and animal) each have their own habitat requirements, and must seek them out (either actively or passively) to survive, interactions between species are also important. Joshua trees were widespread, mostly west and south of Grand Canyon, during the Pleistocene, but their range is much more restricted today. Shasta ground sloth dung often contains abundant Joshua tree seeds and fruits. It is possible that the extinction of the sloth at the end of the Pleistocene robbed the Joshua tree of an important, perhaps primary, seed dispersal mechanism (Cole *et al.* 2011, p. 138). Arrival of the Ponderosa pine seems to be linked with the post-glacial development of the summer monsoon, and the monsoon, fire, and Ponderosa seem to go together, perhaps to the detriment of limber pine.

From our modern perspective, it is tempting to view the glacial periods as aberrations of the present. But the fossil record actually suggests the opposite. Plant remains preserved in packrat middens suggest the vegetation communities were quite stable during the Wisconsin / Pinedale glaciation and well-adjusted to the prevailing climate when compared to more recent records (Cole 1990, p. 253). Considering that just the entire Wisconsin glaciation lasted about 100,000 years (although it did contain some warm spells), the ecological flux of the brief, 10,000 year-long Holocene Epoch should probably be expected.

The retreat of the Pinedale ice sheets was not the end of the Ice Age. Indeed, in the absence of human greenhouse gas emissions, it is possible we would already be (barely) entering the next glacial advance (Ruddiman *et. al* 2005, pp. 2, 6). But during the last 11,500 years, since the final "cold snap" of the Pinedale / Wisconsin (the "Younger Dryas"), the overall trend in Grand Canyon climate has been warming and drying. By 8,000 years ago, woodland species like juniper and single-leaf ash (*Fraxinus anomala*) had disappeared from the lower Canyon (near Rampart Cave; Phillips *et. al*, p. 6). Desert plants like the creosote bush (*Larria tridentata*) and Joshua tree (*Yucca brevifolia*) ventured from their Ice Age refuges in the lower Colorado River valley to colonize the Grand Canyon. At the same time, plants requiring more moisture have retreated upslope onto the surrounding plateaus, and in some cases, have disappeared.

Superimposed on this migratory pattern, other plants have moved into the region based on specific climatic patterns. These kinds of adjustments have continued to the present day, and the Grand Canyon actually provides a snapshot of the developing interglacial communities.

Future trends in Grand Canyon Climate

Today, "global warming" is a summary phrase used to describe future climatic conditions. While scientists look at future climate on a "global" scale, the term "warming" only describes part of the picture. Current research predicts limited cooling in some areas, and changes in precipitation and sea level may be the dominant concern for many people and locations. Consequently, "climate change" is a somewhat more accurate umbrella under which to examine the future. Along with the physical and biological changes driven by climate change, there will be socioeconomic impacts. All of these changes will affect the Grand Canyon we know today.

Most of the concern with climate change tends to focus on the greenhouse gas carbon dioxide, and on the period since 1750, the approximate start of the industrial revolution. Other gases and other times have not been ignored. Climate researchers have looked at the advent of rice farming (which increases methane) and Eurasian deforestation (which increases carbon dioxide) over the last 8,000 years. Their computer modeling suggests that without these human-caused changes, ice caps would already be growing on Baffin Island, Canada (Ruddiman *et. al* 2005, pp. 2, 6). Nevertheless, the burning of fossil fuels and increases in carbon dioxide concentrations are the "big players" in contemporary climate change (see Solomon *et. al* 2007).

In trying to predict the future climate of Grand Canyon, we can rely on the past to a certain extent, but the future will be driven by a combination of unique conditions. It has been warmer (and cooler) in the past, drier (and wetter). Today's carbon dioxide levels (383.7 in 2007, NOAA 2008) are higher than they have been for the last 800,000 years (Lüthi et. al. 2008, p. 380). The unique combination of today's plants and animals, increasing human populations (along with agriculture and urbanization), and changing climates will produce completely new environments in which our future will unfold.

Understanding the future global climate relies heavily on computer modeling. The increasing sophistication of the models, and the data from which they draw, allow greater and greater confidence in their predictions. Still, scaling these predictions down to an area as small as Grand Canyon invites uncertainty. Given these limitations, what should we expect?

<u>Temperature</u>

In spite of local conditions and year-to-year weather variation, "warming of the climate system is unequivocal" (IPCC 2007, p. 5), and current conditions are unusual for at least the last 1,500 years (IPCC 2007, p. 9). There is a 90% probability that human-produced greenhouse gases are to blame (IPCC 2007, p. 10). Comparing temperature changes from 1900 to 2005, climate models for North America show an excellent match with observed temperature increases. If human-caused influences like greenhouse gas production are removed, these models predict natural influences, especially volcanic eruptions and a very slight increase in solar output could have caused a very slight *decline* in temperature over the last century (IPCC 2007, pp. 32, 121).

Changes in climate are, by definition, changes in average conditions. Weather can be seen as the short-term expression of climate. As climate (average conditions) changes, weather will change, which implies a change in extreme weather as well. Simple statistics show that increased average temperatures would mean extreme low temperatures would be warmer, and extreme highs would be hotter. But the weather's response to climate shift is not simply to "move the curve up." Climate models suggest the western U.S. has more than a 90% chance of longer, hotter, and more frequent heat waves and hot spells over the next century (IPCC 2007, p. 862).

In the western U.S., temperatures have climbed steadily since the 1890's, in spite of cooling trends in the teens and 60's. The 11-year running mean temperature of the Colorado River Basin of 53.5° F in 2000 was about 1.5° F warmer than the 1900 mean, and the Basin has warmed more than any other region in the U.S. (NRC 2007, p. 82-83). From 2003-2007, Arizona averaged 2.2° F warmer than the 20th century average (Saunders et. al., 2008, p. 41).

Going out on a modeling limb, what will future temperatures be at Grand Canyon? During the 21st century, average temperatures in the southwest are expected to increase by about 6° F (3.5° C). Summers will be even a bit warmer, by 8° F (4° C), with the very hottest days becoming even hotter (IPCC 2007, p. 887, 890). Temperature extremes that now occur every 20 years could occur every three years by the middle of this century, and every other year by the century's end (CCSP 2008, p. 99). Since the current rise in temperatures is most likely driven by greenhouse gas emissions, changes in those emissions affect predicted temperature increases. If carbon dioxide emissions are stabilized by 2100, models predict annual average temperature increases as small as 3.6° F, but if they grow relatively unchecked, temperature increases could be as high as 14.4° F (NRC 2007, p. 87).

<u>Precipitation</u>
Precipitation in Grand Canyon is generally concentrated in two seasons, winter with its cyclonic storms and the late summer's monsoon storms. Year to year variations can be dramatic, and are often blamed (right or wrong) on the El Niño / La Niña pattern. The La Niña's cold water in the eastern equatorial Pacific is linked to droughts in the American southwest. Warm waters during an El Niño may cause increased rainfall in the southwest, but not always. Although precipitation is critical in the arid southwest, we still have much to learn about what drives it, even under normal conditions (Collier & Webb 2002, p. 78).

Warm air can hold more water than cold air. Rain or snow falls when the air temperature cools enough that the air can no longer hold the water it absorbed at higher temperatures. As global temperatures rise, more water evaporates from the world's oceans, but will the air cool enough that it falls out as rain and snow on Grand Canyon? And, with warmer temperatures, how much of that precipitation will quickly evaporate? Precipitation is much more difficult to model, and the IPCC report considers 21 different models. Although uncertain, these models suggest a 5% to 10% decrease in annual precipitation for the Grand Canyon area (IPCC 2007, p. 890). In the early fall, tropical storms from the eastern Pacific can produce rainfall at Grand Canyon. Since 1980, the number of east Pacific hurricanes has declined, but the storms have moved slower so that rainfall (measured along the west Mexican coast) actually increased as a result (CCSP 2008, p. 6). Regarding precipitation over the Colorado River basin as a whole, "no appreciable trend…has been detected or currently is projected" (NRC 2007, p. 86). However, climate models of the southwestern U.S. suggest a transition to a drier climate may already be underway, and conditions like those of the Dust Bowl, the droughts of the 1950's and since the late 1990's may become the norm in the 21st century (Seager *et al.* 2007, p. 1181). Based on long-term tree ring data, these recent droughts are not as severe as those of the Medieval Warm Period (from about AD 900 – 1300). If increased medieval aridity is the natural response to warmer temperatures in the southwest, it has important implications for future conditions in a warmer southwest (Cook *et al.* 2004, p. 1015).

Increasing temperatures and decreasing, or even stable precipitation will result in increasing water stress. Snowfall will begin later and end earlier. Water storage will be reduced with less snow and reduced infiltration into the soil. Growing seasons will lengthen, with increasing water demands by plants.

The final piece of the precipitation puzzle, after water supply and water demand is water reliability. Specific weather events can not "prove" or "disprove" changes in climate. However, changing climate can make particular weather events more likely to occur. For example, the current drought in the southwestern U.S. is consistent with climate change predictions, including changes in atmospheric and marine circulation, even though current understanding can not provide an ironclad link between the two (Saunders 2008, pp. 10-11). It is very likely (more than a 90% chance) that during the 21st century, more precipitation will come in heavy events (IPCC 2007, p. 52). For an area like Grand Canyon, where precipitation is expected to decline only slightly, this means that gentle, soaking rains (or snowfall) will become less likely and dry spells will last longer between more intense downpours. Based on the last 63 years in northern Mexico, the southwestern monsoon now comes 10 days later, wet spells (consecutive days with rain during the monsoon) have shortened from four days to three, but the intensity of the precipitation has increased 17% (CCSP 2008, p. 51). Unfortunately, such downpours are less likely to soak into the land and more likely to run off, increasing the likelihood of flooding.

Specific implications of climate change for Grand Canyon

Grand Canyon is facing a warmer, drier future. In spite of whatever is done to stabilize or reduce greenhouse gas emissions, the climate will remain in flux for centuries to come. With just the excess carbon dioxide already in the atmosphere (i.e., if emissions stopped today), we are already committed to some climate changes over the next 1,000 years. It takes 30,000 to 35,000 years for the oceans to reach equilibrium with the atmosphere (IPCC 2007, p. 77). Every year will not be hotter or drier than the last, and the effects will not be evenly distributed. Synergistic effects will occur, some that we are not aware of. The listings below outline some of the specific changes that can be expected.

Biotic communities. As conditions warm and dry, it is natural to assume that plant communities will simply "move uphill" to escape heat and drought. In the Santa Rosa Mountains above Palm Springs, California, researchers have documented such a migration. Between 1977 and 2006, temperatures there rose 0.9 – 1.4°F (0.5 – 0.8°C), and variability in annual precipitation doubled. Transects showed the ten most widespread species migrated upslope an average of 212 feet (64.7 m). However, a simple migration is not the whole story, since the 95% confidence interval range was 101 – 323 feet (30.9 – 98.5m) of uphill movement (Kelly 2007), some species moved more than others.
It is probably over-simplistic the treat biological communities as biological "units" of inter- or co-dependent species. Rather, in the face of changing conditions, there appears to be an adaptive advantage for individual species to follow their own ecological requirements. What we perceive as "communities" are the intersection of those requirements among a number of species (Dickenson 1995, p. 2). Ten thousand years ago, it is doubtful that any current communities existed, rather, they have been assembled as individual species were shuffled in response to changing environments (Jablonski 1991, p. 756) For an example in the Grand Canyon area, a model of future plant distributions under climates with double the carbon dioxide concentrations predicts piñon pine and one-seeded juniper will end their familiar association over the next 100 years. Piñon will be restricted to the Upper Basin (south of Desert View), while juniper will occur farther to the southeast, near Wupatki National Monument (Cole n.d., p. 9). The recent die-off of piñon in the southwestern U.S. in response to the recent drought is a good example of the type of vegetation changes triggered by changing climate. Although the immediate cause of death for many of the trees was bark beetle infestation, this infestation was closely tied to the ongoing drought. Unlike a similar drought in the 1950's, temperatures during the 2000-2003 period were higher as well, increasing water stress. Mortality rates reached 66% for piñon in the Flagstaff area. While the die-off of a dominant, overstory tree is readily apparent, other species have been affected. In a New Mexico piñon-juniper study site, blue grama

grass declined 50%, and the more drought-tolerant one-seeded juniper was reduced from 2% to 26% at study sites in the 4 corners states (Beshears et. al. 2005).

Migration to new habitats as old ones become untenable can be a response to climate change. The ability to migrate depends on a number of factors, including contiguous suitable habitat, methods (or vectors) of dispersal, and barriers. Animals are generally more mobile than plants, but there is wide variability in their ability to disperse. Compare, for example, the opportunities available to two endangered species breeding in the park, the Kanab Ambersnail and the California condor. The tiny Ambersnail creeps through the foliage around a single spring through its brief life, while condors soar many miles a day in their search for food, nesting sites and other necessities. For plants, migration is limited by how quickly a new individual can become established and mature to the point of reproducing, and how widely seed is dispersed. Since the last major climate change 11,500 years ago, piñon has migrated an average of 43 meters per year (Cole n.d., 4). During the same period, Joshua trees' migration has been only about 1 to 2 meters annually, making its survival in the western Grand Canyon area unlikely without "assisted migration." The plateaus around Grand Canyon are likely to develop suitable Joshua tree habitat within the century as temperatures rise, but without its ground sloth seed spreader, Joshua trees simply can't colonize their way across the landscape fast enough (Cole *et. al.* 2011, p. 141, 146). In contrast to the slow migration rates of these tree species, some plants (especially those whose seeds are dispersed by the wind, tamarisk for example) can migrate rapidly. Overall, the Grand Canyon itself illuminates the process of plant migration. During the Holocene (the last 11,500 years), desert plant species have been colonizing the Grand Canyon from the open deserts to the west. Some desert plants, like brittlebush, occur along the entire length of the Canyon. Ocotillo has extended its range to just upstream of Havasu Canyon. Creosote dominates lower Canyon slopes below Mohawk Canyon. Joshua trees are still seen only near the Canyon's mouth. And, in just the last century, tamarisk has spread throughout the Canyon. Of course, these few species can not cover all the variables in plant migration, but they do help illustrate the fallacy of assuming a plant community (Mohave Desert, Piñon-juniper Woodland) will respond as a unit to climate change.

Habitat fragmentation (natural or human-caused) can limit horizontal migration. The rugged topography of the southwestern U.S., with its mountainous "sky islands," can easily isolate plant and even animal populations (e.g., the Abert and Kaibab squirrels). However, the steep gradients also make vertical migrations possible. For example, Utah agave has migrated up and down the walls of Grand Canyon throughout the last 20,000 years in response to changing climate (Cole & Arundel 2005, p. 714). There is a limit to vertical migration. Grand Canyon rose (*Rosa stellata*) has already migrated up from its Redwall Limestone habitat during the Pleistocene to a few isolated populations on Kaibab limestones today. With no higher limestone habitat "retreats," it could be eliminated by further warming (Cole n.d., p. 2).

Animals are more mobile than plants, giving them somewhat greater flexibility in responding to climate change. However, many animal species have very specific habitat needs that may not be met as biological communities migrate and reform under new climatic regimes. Seasonal relationships may become disrupted as those that respond to changing day length diverge from those that follow temperature. European studies have found that in the early 1970's, winter moth (*Operophtera brumata*) eggs hatched just as oak trees were leafing out to provide the young caterpillars their primary food. Warmer temperatures now cause the caterpillars to hatch up to 3 weeks before the oak buds open, and many caterpillars starve. This lack of caterpillars occurs just when songbirds such as the Great Tit (*Parus major*) rely on it as a food source for their nestlings (Perkins 2003, p. 152). Climate-related factors, elevation, precipitation, and dependable springs are strongly linked to the persistence of desert bighorn populations in the isolated mountain ranges of southern California. These environmental factors were much more important than the area of suitable habitat in each subpopulation's range. Because of this environmental influence, the risk of a subpopulation becoming extinct increases with increasing temperature and declining precipitation, even with no change in surface-water availability (Epps *et al.*, 2004).

Warmer winters and a longer frost-free season can also increase insect populations and/or the number of insect generations per year. These increases have been tied to tree mortality (CCSP 2008, p. 13).

Carbon dioxide fertilizes plants, allowing them to synthesize more fiber and starch, but these tissues are relatively protein-poor. In experiments, the lower concentrations of protein in faster growing plant tissues caused caterpillars to eat up to 40% more, yet weigh less than caterpillars eating plants growing in normal atmospheric carbon dioxide. Sheep rely on bacteria in their rumen to process plant material. These rumen bacteria are limited by the protein content of the food eaten by the sheep, and the bacteria take longer to digest protein-poor feed like the carbon dioxide-fertilized plants. The ecological ramifications of such changes in natural ecosystems are still not clear (Hesman 2000, pp 200-202).

Wildland Fire. The role of wildland fire in maintaining, and even sustaining some park plant communities is well known. Human activities, whether promoting or excluding wildland fire, also help shape these plant communities. The impacts of fire exclusion can compound, and confuse, the impacts of climate change. In Bandelier National Monument, drought in the 1950s caused a rapid shift of two kilometers or more in the boundary between ponderosa pine forests and piñon-juniper woodlands. Ponderosa pine mortality resulted from the drought, compounded by competition with the piñon-juniper understory, and an infestation of bark beetles. The resulting shift in forest types has persisted to the present. There, fire exclusion intensified the effects of a drought, allowing a piñon and juniper understory to develop in the ponderosa forest. The persistence of the change illustrates the importance of mortality (which can be relatively sudden compared to seedling establishment and growth) in defining new vegetation patterns (Allen & Breshears 1998, p.14840). Various environmental factors, like drought in this case but also including generalized "climate change," may prime a system for change, although the immediate cause of change may be fire, or insect infestation. Even without the effects of climate change, fire exclusion may have created an ecologically "novel" environment in which new plant communities would replace existing North Rim forests after stand-replacing fires, rather than re-establishment of current or historic forest types (Fulé et. al 2004, p. 246).

Wildland fire is not only one of the agents carrying out the effects of climate change. Fire itself is affected by and may affect changing climates. At Grand Canyon, where precipitation levels in the 21st century are predicted to decline only slightly, warming temperatures can extend the dry season by reducing the size of the snowpack (more precipitation falling as rain), and melting the snowpack earlier (extending the spring drought). Increasing wildfire activity since the mid-1980s has been greatest in the vast forests of the central and northern Rockies. But the Kaibab Plateau shows a similar, though lesser vulnerability to increased wildfires due to climate during that period (Westerling et. al. 2006, p. 3). At the same time, wildland fires release a tremendous amount of greenhouse gases, thus affecting climate change themselves. Nearly all is carbon dioxide, and these releases are part of the short-term, organic carbon cycle. Nevertheless, once in the atmosphere, this carbon dioxide is still a greenhouse gas, contributing to climate change. Overall, forests are a "carbon sink," absorbing more carbon dioxide than they emit, storing most of the surplus as wood. Indeed, forests in the west account for 20% to 40% of all the carbon "sequestered" in the U.S. However, increasing levels of wildland fire could turn these forests from a sink to a carbon dioxide source (JFSP 2007, p. 2).

Colorado River Flow. The Colorado is a regional water resource. Many studies have examined the River's flow, and tried to place the current drought in a historical perspective. The flow of the Colorado has been gauged at Lees Ferry, AZ since 1921. Numerous studies of tree rings throughout the Colorado Basin have been used to estimate the River's flow, some dating back to the late 15th century. Although the models differ in the absolute amount of water they project, the pattern of wet and dry periods are remarkably consistent. They agree that the early 20th century had relatively high flows, perhaps the wettest in the entire reconstruction. The models also suggest the current drought is within the range of past droughts in terms of Colorado River flow at Lees Ferry, and that even longer periods of low flows (10-11 years) have occurred in the past (NRC 2007, p. 102-107).

Based on the Colorado River's already highly variable flow, and the potential impacts of climate change, future water flows in the Colorado are of great concern. The historical record shows droughts exceeding the severity of the current drought, and suggests they will happen again. Even predicting the duration of the current drought is problematic, with some climate patterns suggesting it is also over, while others could extend it for decades (Webb et. al 2004, p. 4). A wet year may not necessarily restore flows, even temporarily. The Colorado Basin as a whole received normal snowfall during the 2004-2005 winter, but runoff was only 75% of normal. Preceding drought years had depleted soil moisture and high-elevation aquifers, absorbing much of the year's runoff. High late-winter temperatures combined with this absorption to reduce runoff (CCSP 2008, p. 22). Barnett and Pierce (2008) offer a 10% chance that Lakes Mead and Powell will be at "dead pool" by 2013, and a 50% chance by 2023. In making these projections, they assume no changes in River allocation and reservoir operations, combined with decreasing flows due to climate change. If Colorado River flows drop to their long-term averages (as opposed to the generally high flows of the 20th century), or decline further due to climate change, the Colorado River system can still maintain its ability to mitigate droughts if its 27 million users develop ways to reduce their demands on the river (Barnett & Pierce 2009, p. 7334)

Major floods downstream of Glen Canyon Dam can make a significant contribution to the Colorado's flow though Grand Canyon. A flood on the Little Colorado almost washed away the USGS Birdseye Expedition below Lava Falls September 18, 1923. Flooding events may become more common in a warmer future (IPCC 2007, p. 52), but most of the time, Glen Canyon Dam will continue to control Colorado River flows. Management of dam releases to benefit Grand Canyon are still the subject of both research and criticism. In a warmer future, many of the assumptions on which management is based may come into question. As long as Lake Powell is deep enough to allow power generation, it will be deep enough to allow high flows. The river outlet works (jet tube) intakes are below the power plant's penstock intakes, and if both are completely open, up to 48,200 cfs (15,000 and 33,200 respectively) can be released from the dam. If Lake Powell is full, up to 208,000 cfs can also be released through the spillways (USGS 2005). Even when physically possible (i.e., enough water in Lake Powell), other factors influence decision-making when Colorado River high flows are contemplated, and may assume new importance in the future. The hydropower generated by Glen Canyon Dam is essentially "carbon-free," and releases in excess of the 33,200 cfs power plant capacity represent water from which no carbon-free power is generated. If average flows of the Colorado continue to decline, water storage may become increasingly important (although any water released from Lake Powell is captured below Grand Canyon in Lake Mead). Even while high flows remain possible, changing perceptions and priorities may challenge their implementation.

Park Infrastructure and Operations: Rising temperatures and erratic precipitation patterns have the potential to disrupt park facilities (including NPS, concession, and residential developments). These changes are expected to occur gradually, not as a sudden shift from a "previous condition" to a "new condition." Simple annual variability in the weather will make change seem halting and uncertain, but overall anticipated impacts could include:

- Increased damage from flooding, rockslides and wash-outs as more precipitation occurs in "extreme events." Such events may overwhelm design capacities deemed adequate in the past. For example, historic-based criteria like "50 year floods" may no longer provide accurate predictions of runoff patterns. Existing bridges, culverts and diversions may become inadequate. Some facilities will have increased risk of flooding (e.g., Corridor developed areas, Xanterra General Offices and historic railroad depot along Bright Angel Wash, individual buildings where local terrain or landscaping may funnel runoff).
- Higher levels of air pollution can result from increasing temperature. Most air pollution in the park comes from upwind sources, but the temperature-dependent changes will apply to both regional and local pollution sources. Anticipated effects include
  - Greater production of nitrogen oxides (precursors of ozone, haze, and nitrogen deposition ["acid rain"]) from internal combustion engines (Lindhjem & Yarwood 2004, p. 1-1). Nitrogen deposition has been increasing in Grand Canyon, but the trend is not statistically significant (Bowman 2008).
  - Higher ozone concentrations as chemical reactions to form ozone in the atmosphere accelerate (Stedman 2004, p. 65). Ozone concentration in Grand Canyon are already very close to exceeding health standards established by the U.S. EPA, and already exceed levels known to damage sensitive plant species. Unfortunately, Grand Canyon continues to see a statistically significant rise in ozone concentrations (Bowman 2008).
- Increased need and demand for air conditioning as temperatures rise (and associated rise in utility expenditures).
- Increasing emergency service needs for visitors (and employees / residents) due to heat-related illnesses, flash floods and increasing wildland fire activity.
- Increasing vulnerability of utilities due to wildland fire (especially electric service) and flooding (especially water supply). Note that power and water are single supply lines into the park.
- Overall (multi-year) decline in snow removal as temperatures warm and declining precipitation is more likely to fall as rain, but occasional heavy snowstorms are likely occasionally.
- Will isolation or insularity increase between park operations? Climate change may not physically "cut off" different park operations from each other, but efforts to manage greenhouse gases may make travel and commuting more difficult and/or costly. Implications include telecommunications, vehicle fleets, office locations, and housing.

Socioeconomic changes are extremely difficult to predict. They will be the result of a complex interplay of environmental conditions, legal and regulatory requirements, and societal responses. In this kaleidoscope it will be difficult to identify the primary drivers of socioeconomic changes. Take, for example, the current (2008) concern over gasoline prices. Monetary drivers (taxes, profits, etc.) are mixed with concerns about "peak oil" as well as the climatic impacts of burning fossil fuels. Broad issues like urban planning and sprawl, research and development of alternatives fuels, and global equity issues are often brought into the discussion. With so many interrelated variables, questions may be more appropriate than answers regarding the volume and demographics of Grand Canyon visitors:

- Will visitation via more fuel-efficient modes (rail, bus) increase, and will that increase be tied to declines in less fuel-efficient modes (air, private vehicle)?

- Will seasonal utilization change as winters become milder, and summers hotter? This has implications for the North Rim season, seasonal closures on the South Rim, and demand for backcountry and river use.
- How will campground utilization change in response to
    - motor homes and trailers coupled to rising transportation costs,
    - milder winter and hotter summer temperatures?
- Will return visits decline?
- Will length-of-stay increase as people cut back on driving to multiple destinations?
- Will spending patterns (food, lodging, incidentals) change as transportation costs rise?
- Will shuttle bus ridership rise in relationship to overall visitation as visitors conserve fuel? How will any proportional change relate to overall visitation? For example, if a higher percentage of visitors ride shuttles, but overall visitation drops, will more shuttle buses be needed? This could have implications for the adequacy of transportation fees, shuttle routes, and the size of the shuttle fleet

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