Evolution of the Earth

The First Billion Years

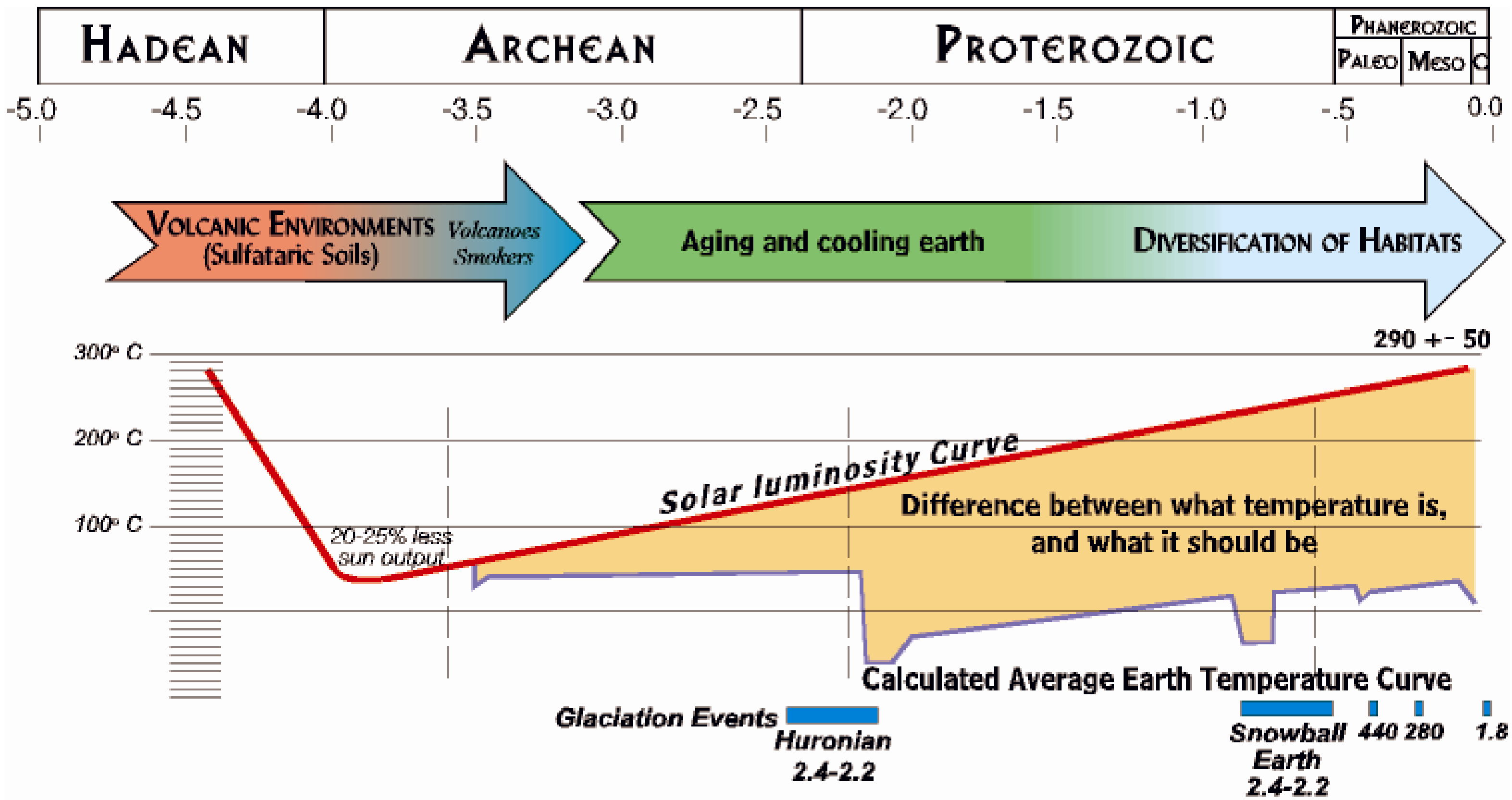
The Earth is a Unique Planet

The Earth is a unique planet

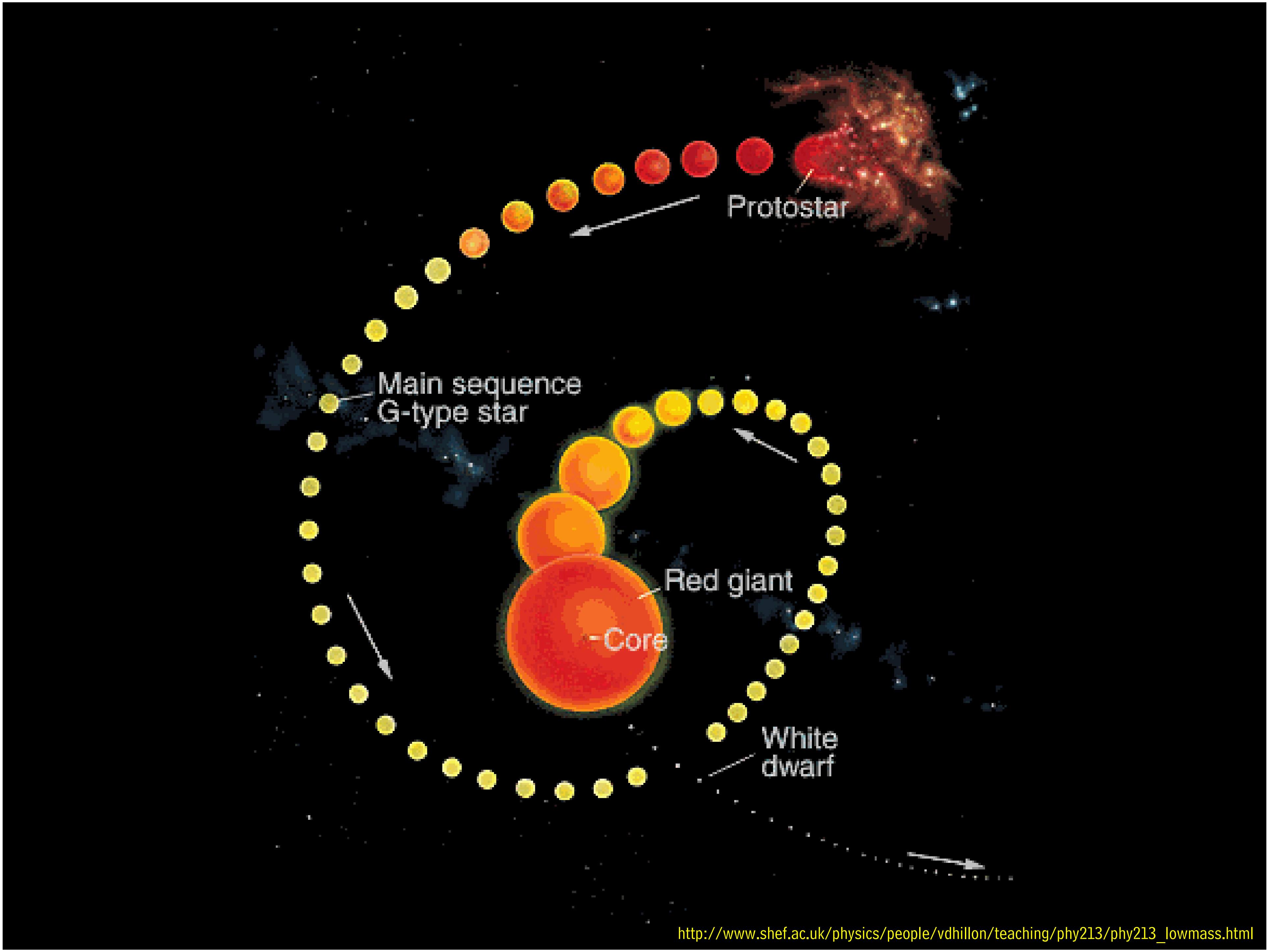
1. Earth remains geologically active on its own internal energy source after 4.0 billion years of history. Seen today in earthquakes (16,500/year greater than 4.0) , volcanoes (4-500 active now or in the recent past), and the building of mountains (Mt. Everest is still rising about an inch a year).

Unique things about the Earth we need to explain

2. Surface temperature allows liquid water to exist, even though the energy the Earth receives from sun the has increased 30% in past 4 billion years. Surface temperatures should be a couple of hundred degrees above what they are today. Something is actively regulating the temperature.



In contrast, temperatures on Venus are about 900 F, on Mars about -193 F, on Jupiter -243 F, and on Saturn -301 F.


Protostar
Main sequence
G-type star
Red giant
Core
White
dwarf
http://www.shef.ac.uk/physics/people/vdhillon/teaching/phy213/phy213_lowmass.html

An artist's Vision of the Red Giant phase of the sun about 4 billion years in the future.

http://www.cosmographica.com/gallery/portfolio/portfolio151/pages/172-RedGiantSun.htm

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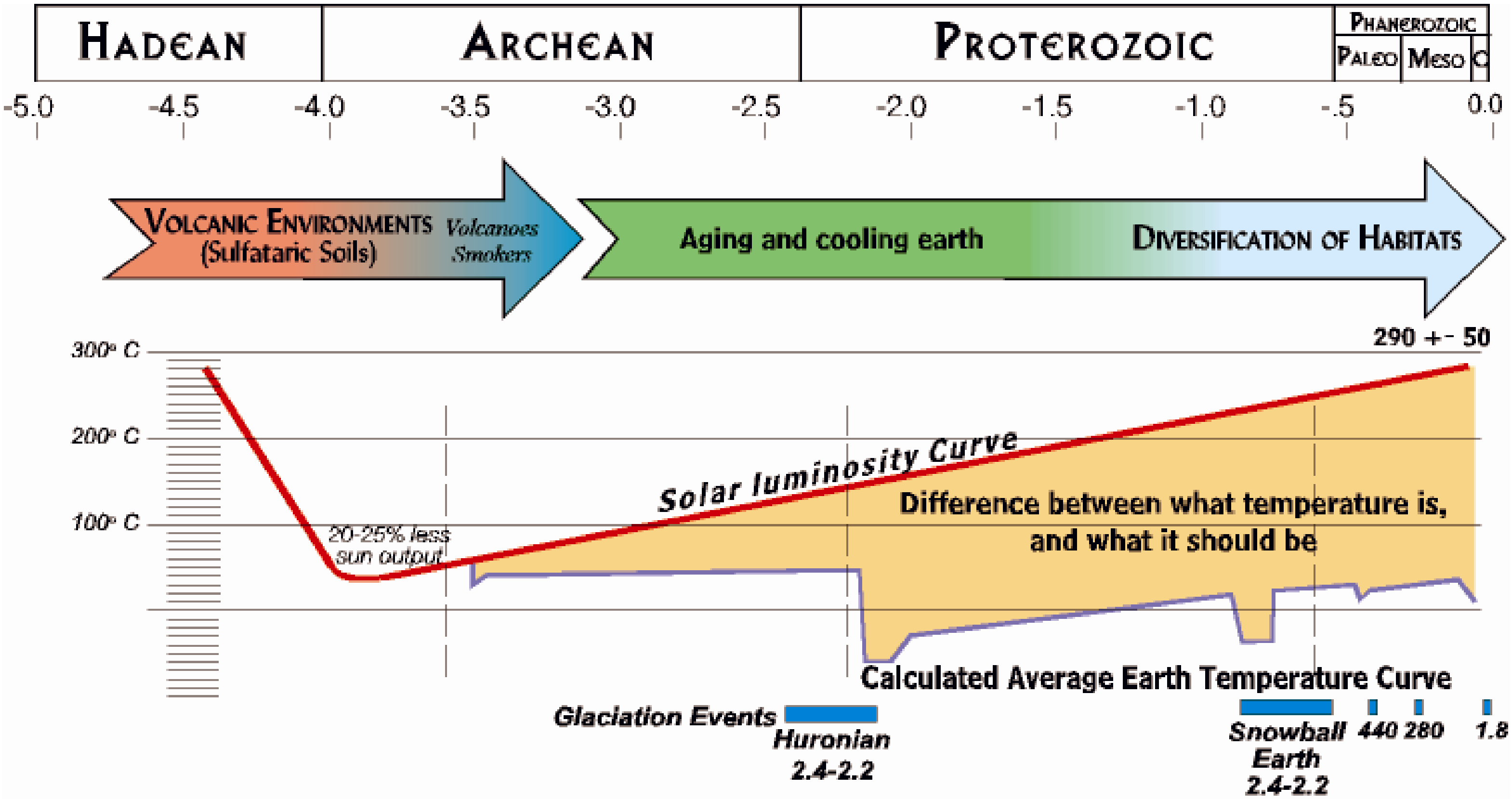
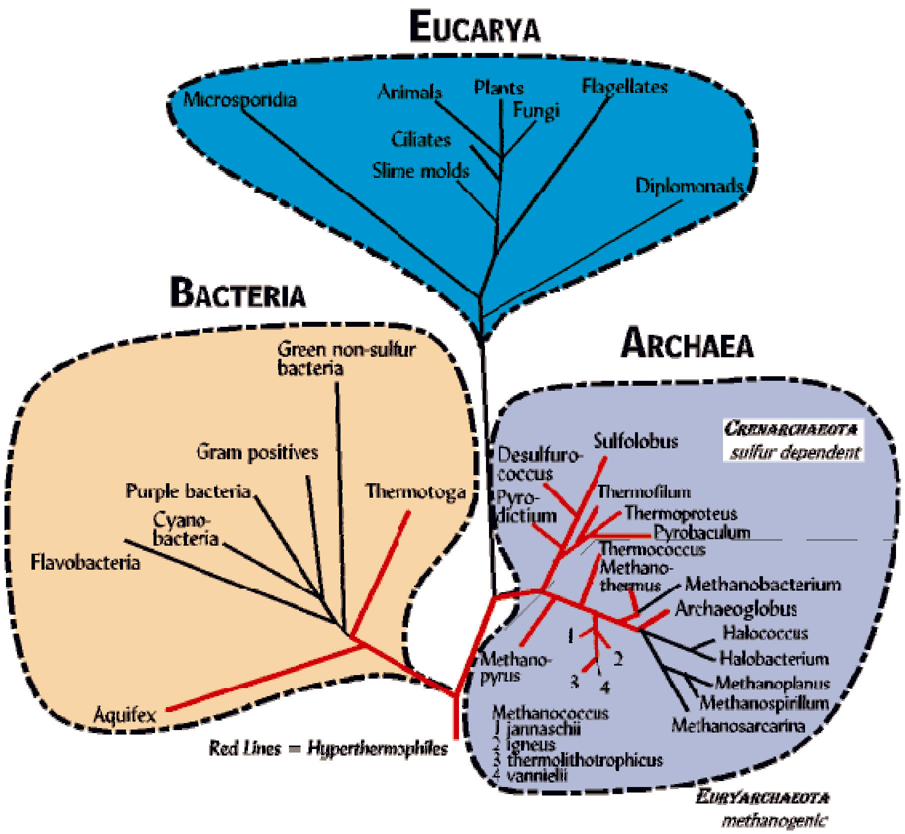


In contrast, temperatures on Venus are about 900 F, on Mars about -193 F, on Jupiter -243 F, and on Saturn -301 F.

Unique things about the Earth we need to explain

3. Earth has abundant life., What is more this life has increased in complexity, diversity, and abundance with time.



Meanwhile life has adapted to most extremes of the earth's environments, such as 1 1/2 times the boiling point of water, 50º below zero, 2 miles below ground, and, more remarkably, normal conditions.

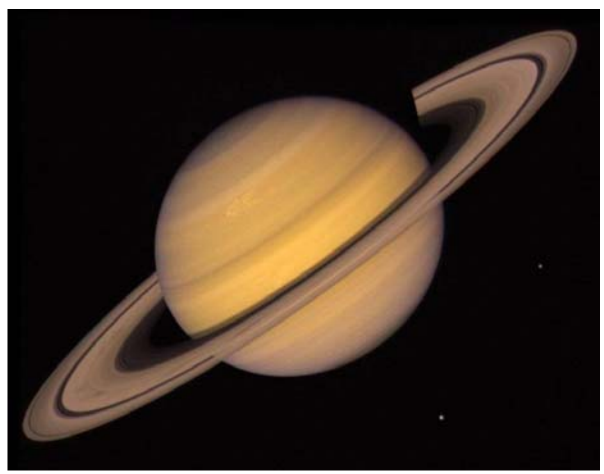
Unique things about the Earth we need to explain

4. The atmosphere is oxygen rich even though oxygen is extremely chemically reactive. Left alone all oxygen would disappear in less than 1000 years. Something is actively maintaining an oxygen rich atmosphere.

Nitrogen	*79%*
Oxygen	*19%*
CO2	*0.03%*
Argon	*1.0%*
Water vapor	*variable*

Earth

Hydrogen	*75%*
Helium	*25%*
Methane (CH4)	*trace*
Ammonia (NH3)	*trace*
Water ice	*trace*



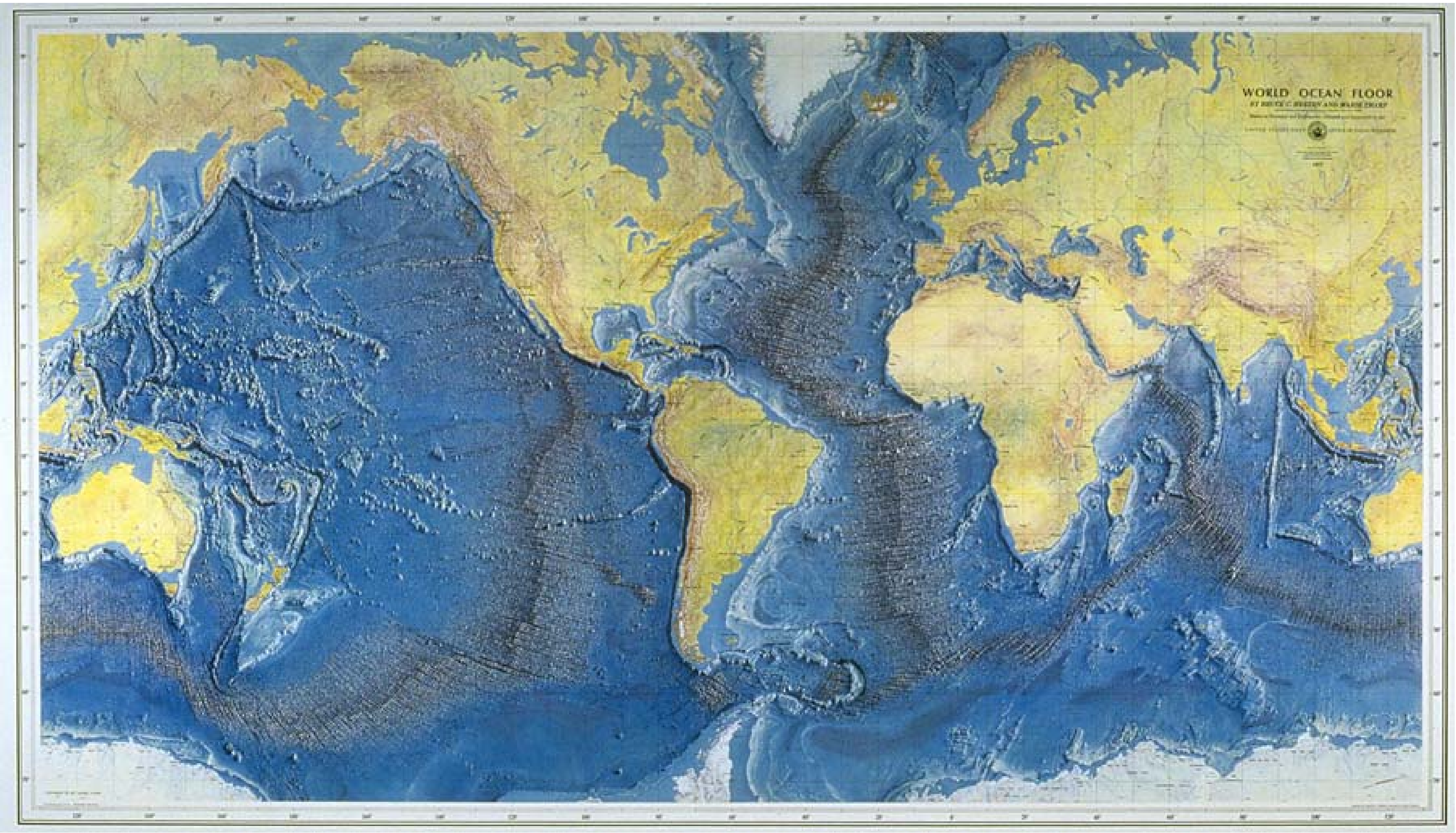
Saturn

CO2	*95.3%*
Nitrogen	*2.7%*
Argon	*1.6%*
Oxygen	*0.15%*
Water vapor	*0.03%*

Mars

Unique things about the Earth we need to explain

5. A crust with two distinct divisions – continents and ocean basins



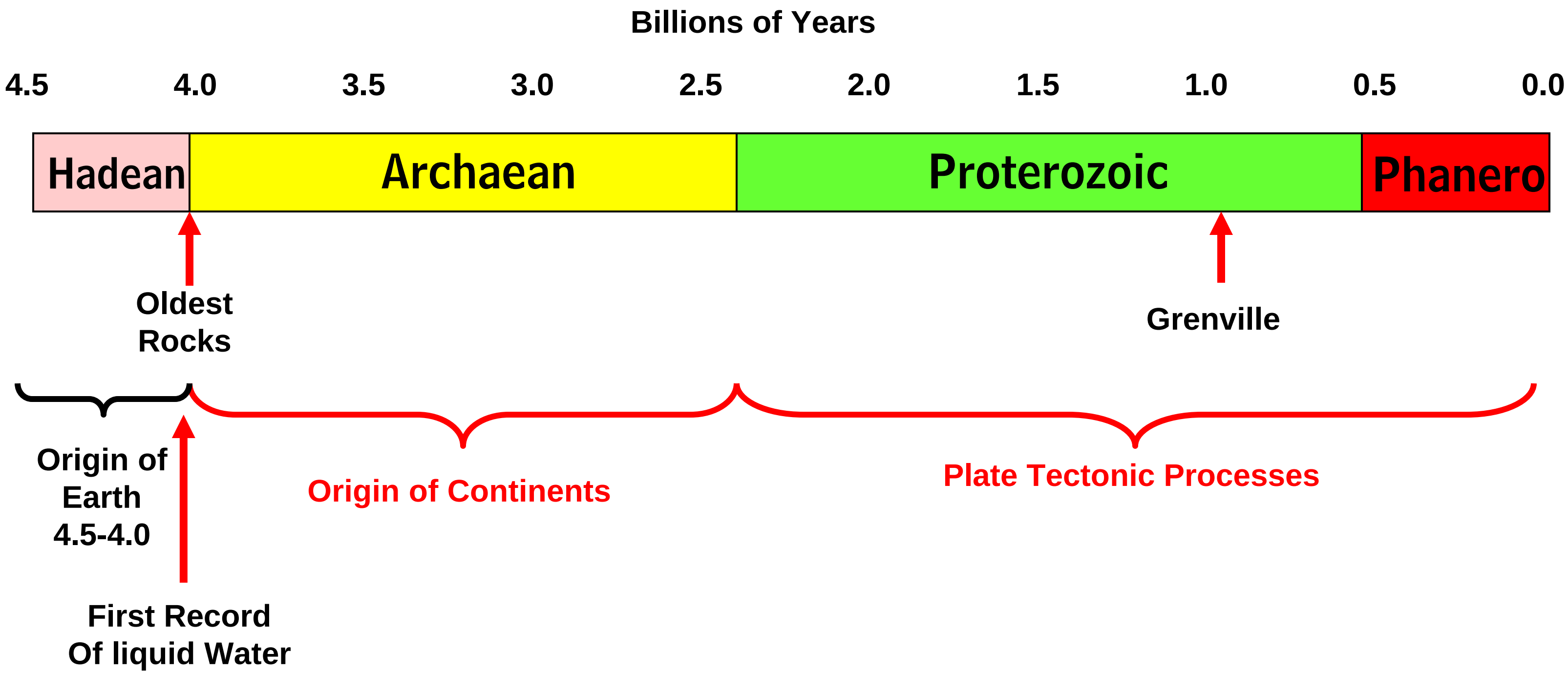
In contrast, nearly 90% of Venus' surface appears to consist of recently-solidified basalt lava. Mars, despite evidence for sedimentary rocks, is also mostly basaltic in composition

The Earth is a Unique Planet

The questions . . .

- What can we learn from the Earth's past that will help us understand the present and the future?
- We want to look at the norm, and at the extremes – what is the Earth capable of?
- Many of these are at time scales longer than humans have experienced or can imagine.
- But, right now we are not so much about narrowly human concerns, but about how this planet, our home, lives and behaves.

Just How Long is Earth History ?
And When Did the Important Things Happen ?



The First Half Billion Years

4.5 – 4.0

Origins

The Solar Nebula

The solar system began as a spinning cloud of gas and dust, called the solar nebula, which collapsed under its own weight to form a new star, our Sun. As the solar nebula spun and churned, dust grains stuck together to form dustballs, and huge bolts of lightning melted them into small spheres. These solidified into rocky balls called chondrules. (Painting by Don Dixon, NASA JSC photo S76-25001)

Click for web site for description of solar system formation

http://www-curator.jsc.nasa.gov/outreach1/expmetmys/slide set/Slides16-20.htm

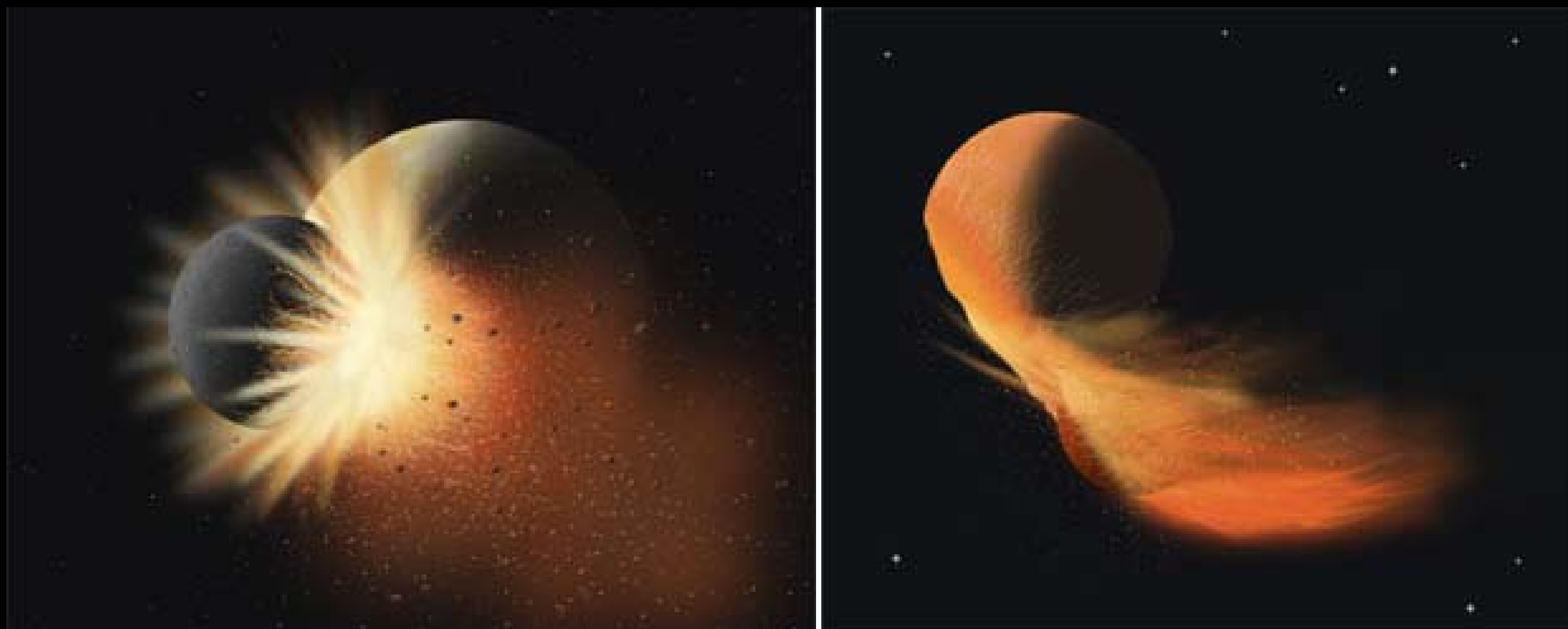
Embryonic planets emerge from the chaos of the protoplanetary disk. They endured constant bombardment by a progression of ever-larger objects.

http://www.howardastro.org/documents/HET607Essay.htm

http://www.psrd.hawaii.edu/Feb08/EarthMoonFormation.html

Formation of the Earth-Moon System

A Mars-sized planet collided with Earth, vaporizing, melting, and throwing debris from the impactor and Earth's outer layer into orbit around Earth, creating an encircling debris ring



http://www.lpi.usra.edu/education/timeline/gallery/slide_10.html

~ 4.5 Ga

~ 4.5 Ga

~ 4.5 Ga

At ~4.5 Ga the Earth-Moon collision provided enough energy to melt them and begin their physical evolution.

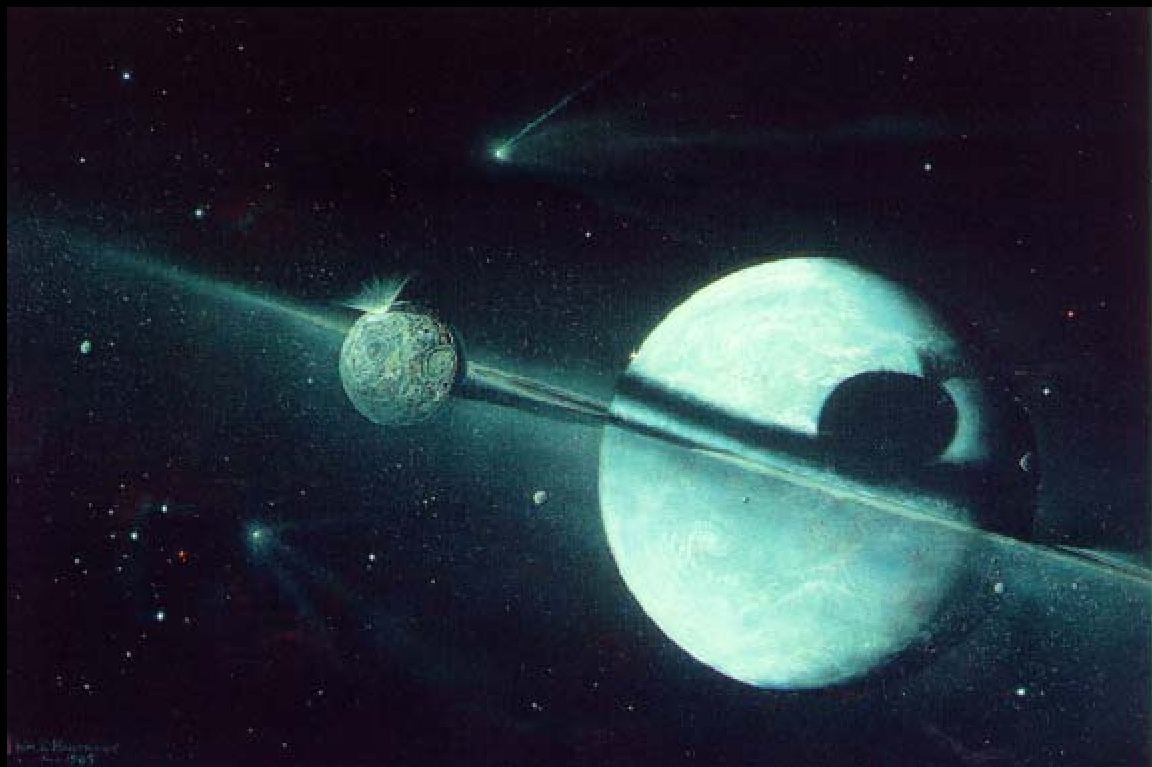
http://www.psi.edu/hartmann/pic-cat/images/72.jpg

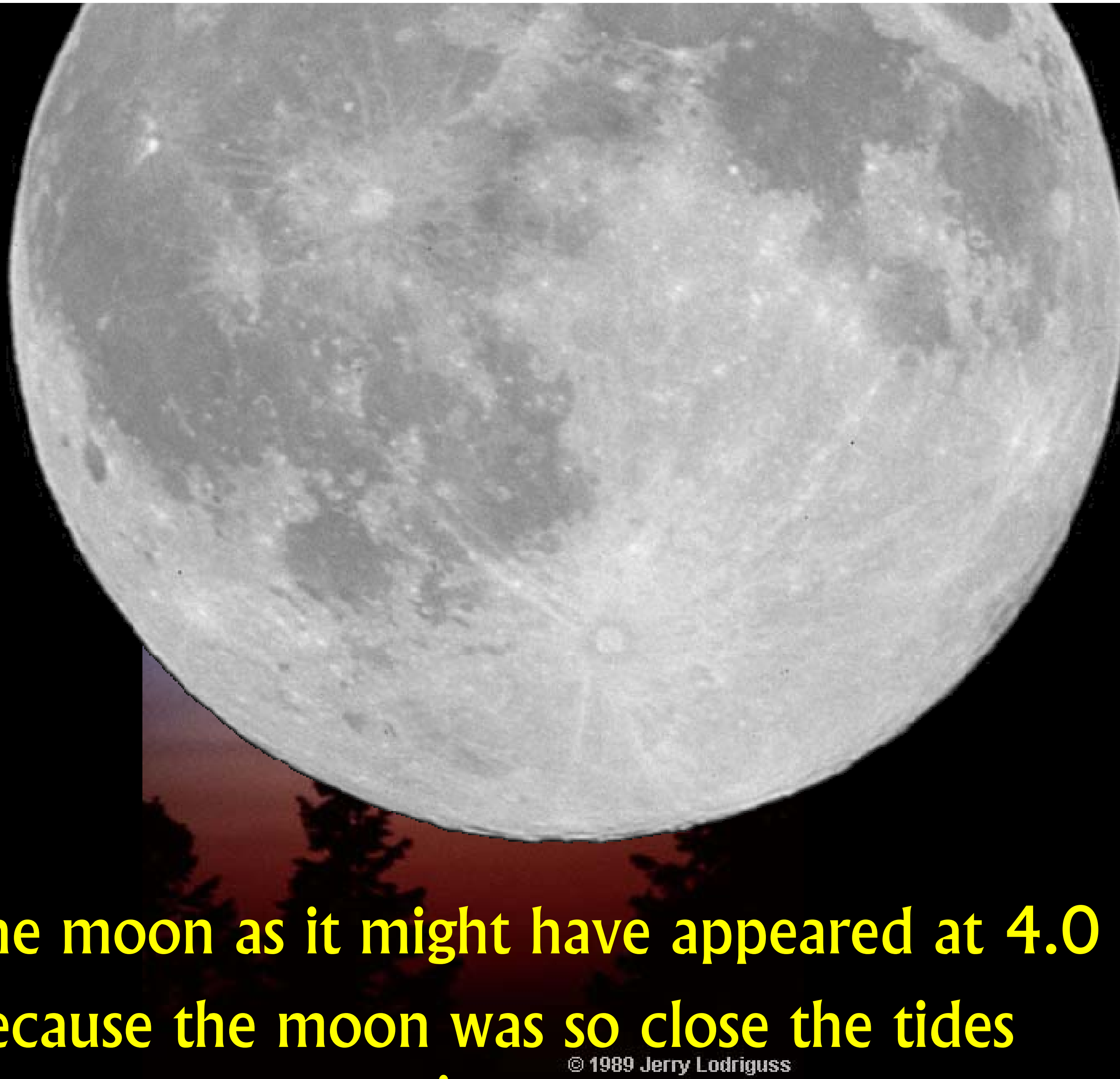
Early Earth From the Moon About 4.4 billion years ago

http://www.psi.edu/hartmann/pic-cat/images/72.jpg

~ 4.3 Ga ~ 4.3 Ga ~ 4.3 Ga

At ~4.3 GA the Earth-Moon system reach this stage. The Earth is already stratified by density, convection cells are operating, and tectonic processes have begun.





The moon as it might have appeared at 4.0

Because the moon was so close the tides were immense

Formation of the First Solid Ground

~ 4.0

~ 4.4 Ga
~ 4.4 Ga
~ 4.4 Ga

Earth About 4.4 billion years ago

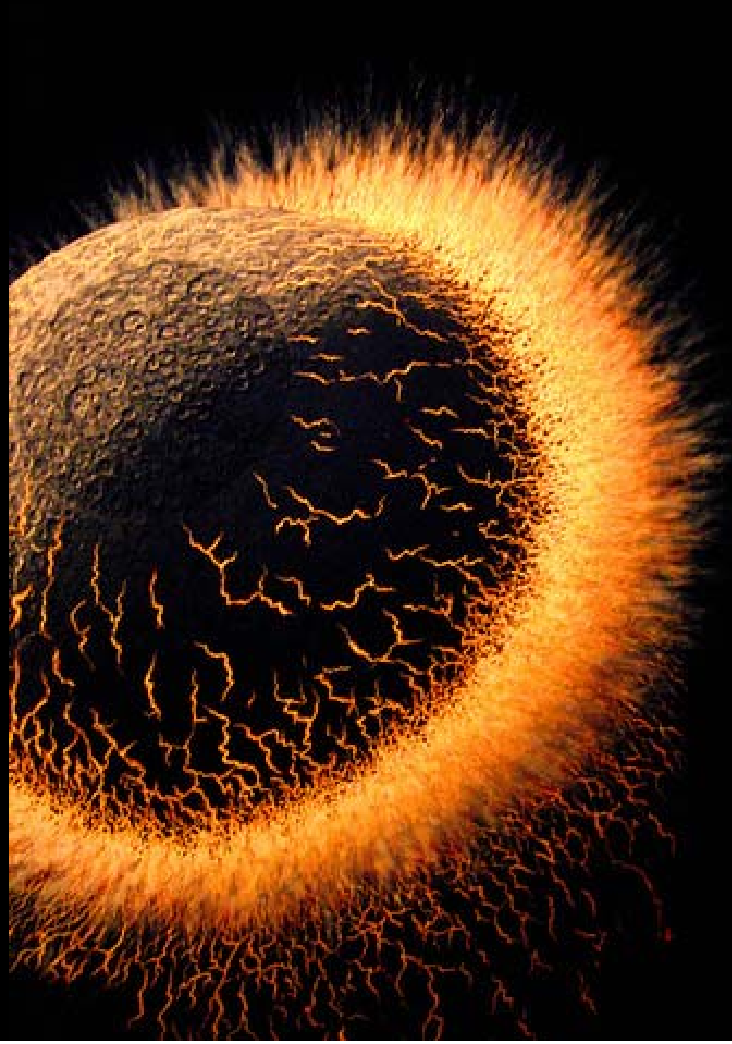
Still molten hot, without water or life, being bombarded continuously by meteorites.

http://www.space-art.co.uk/pages-en/debris/Bombardment.htm

~ 4.4 Ga ~ 4.4 Ga ~ 4.4 Ga

Earth About 4.4 billion years ago

Molten hot, without water or life, surface just beginning to solidify, being bombarded continuously by meteorites.



//www.flickr.com/photos/killbyte/318021281/

Earth About 4.2 billion years ago

Still molten hot, without water or life, being bombarded continuously by meteorites.

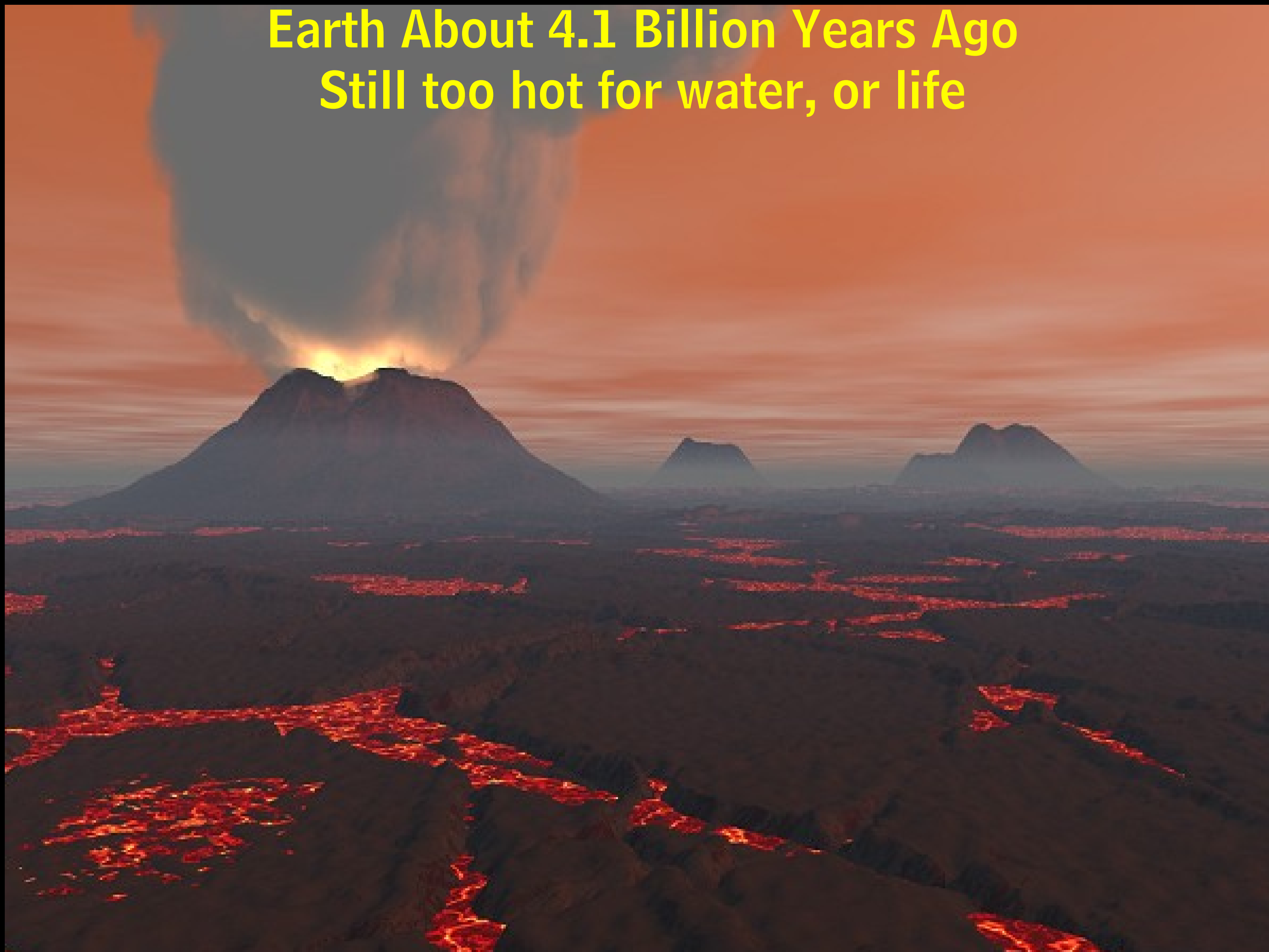
http://www.gps.caltech.edu/~mjwillis/research/bugbuster.html

~ 4.2 Ga ~ 4.2 Ga ~ 4.2 Ga

Earth About 4.2 Billion Years Ago

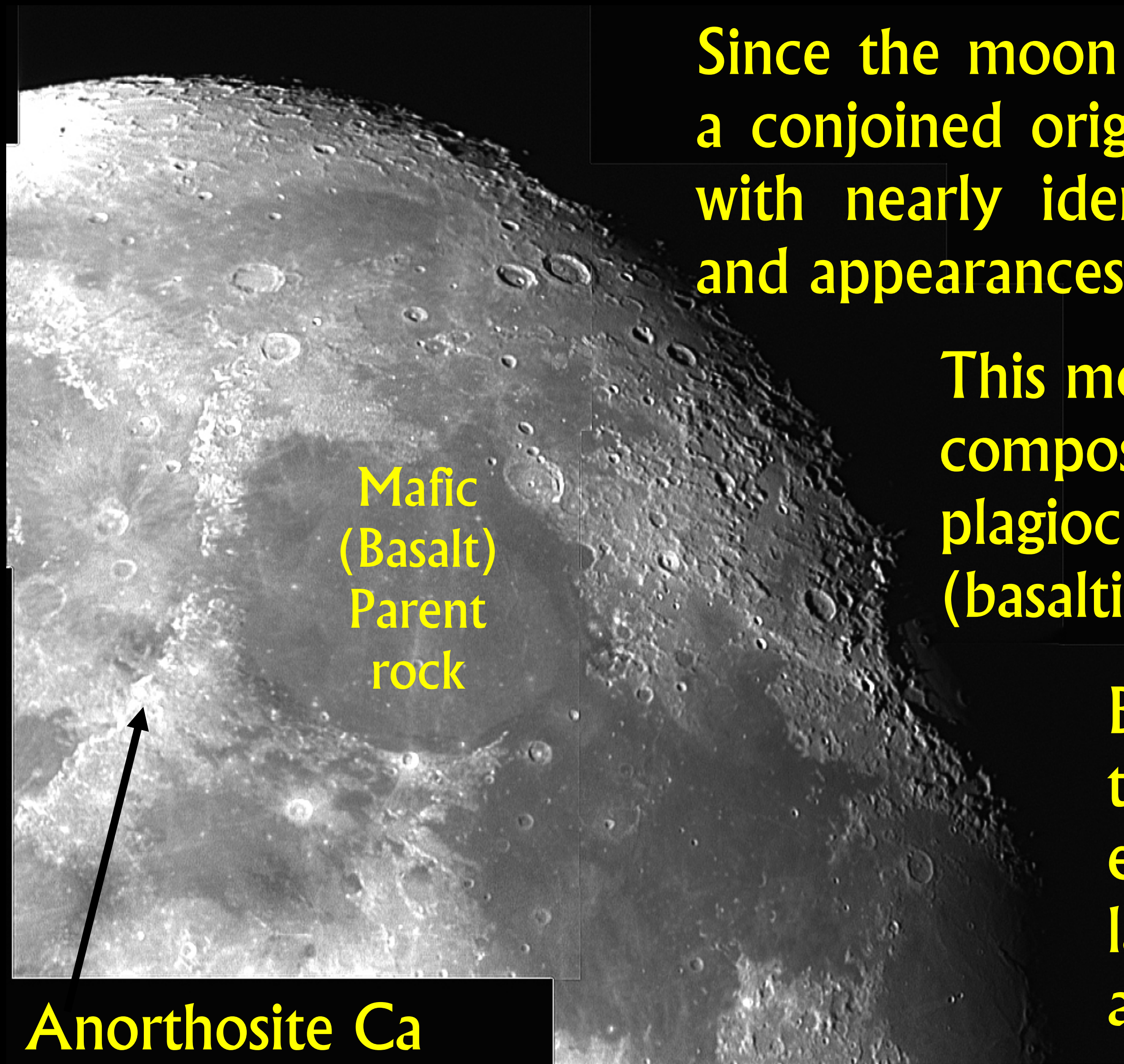
http://mysite.wanadoo-members.co.uk/mearca/pictures.htm

~ 4.1 Ga ~ 4.1 Ga ~ 4.1 Ga



http://www.arcadiastreet.com/cgvistas/earth_010.htm

Since the moon and the Earth had a conjoined origin they started out with nearly identical compositions and appearances.



This means they both were composed of anorthosite (Ca plagioclase) and the mafic (basaltic) parent rock.

But, the Earth, unlike the moon, kept evolving because it is larger, and it had abundant water, and it established convection cells to dissipate its heat.

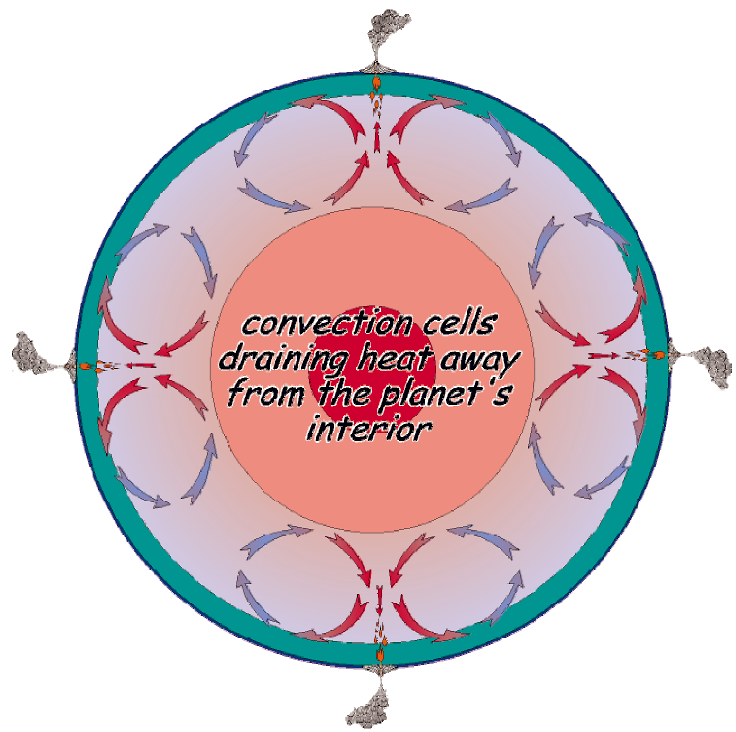
http://www.nightskyobserver.com/images.htm

Dissipation of the The Tectonic Energy

Heat is transferred from the center and escapes to space a couple of ways.

Convection: transfer of heat by the circulation or movement of the heated parts

This is what is happening on Earth, and is the only known place it is occurring.



And, it is the cause of plate tectonics (but requires special conditions, like the presence of abundant water).

The Origins of the Atmosphere and Oceans

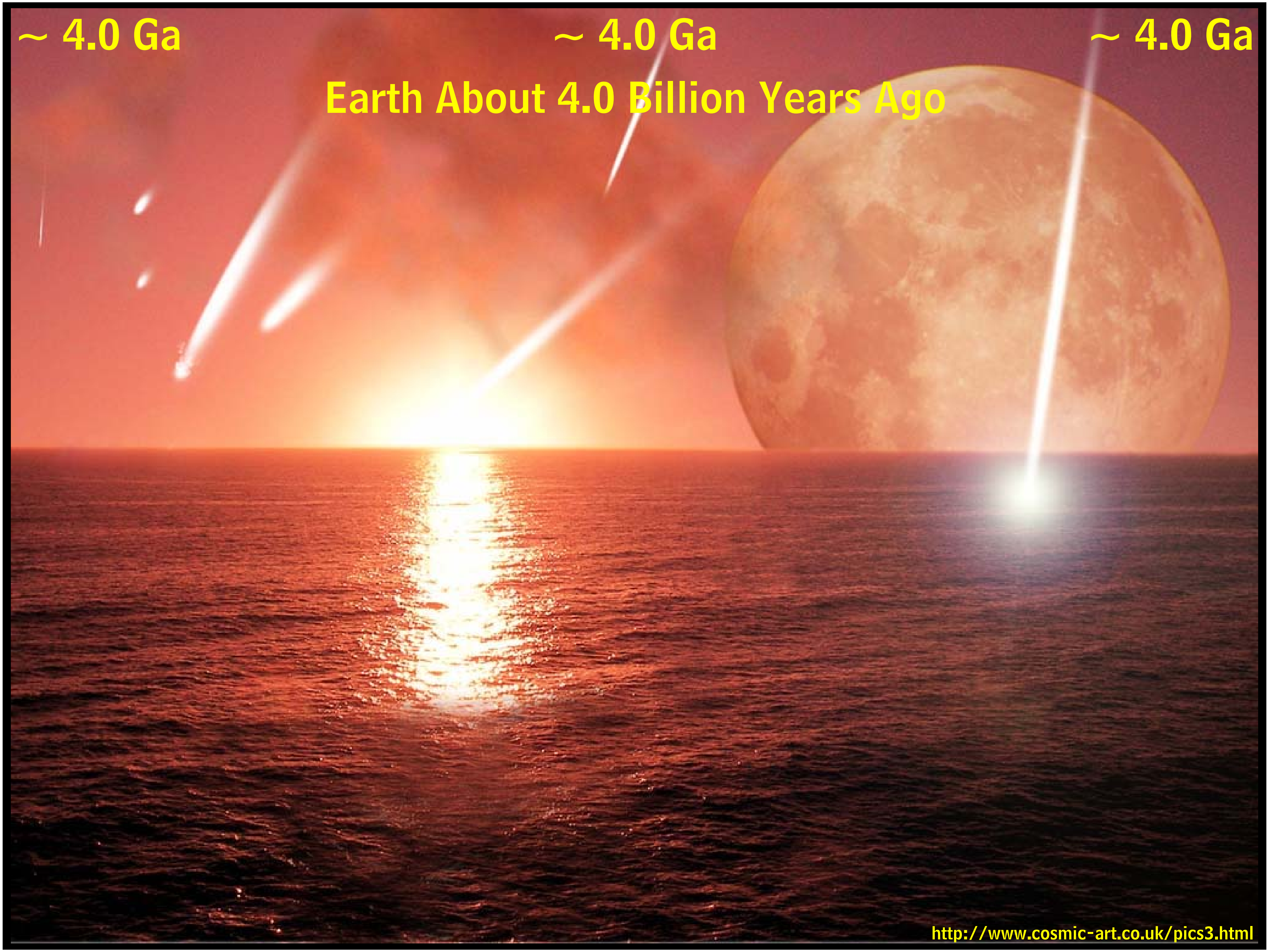
4.1 – 4.0

~ 4.0 Ga

~ 4.0 Ga

~ 4.0 Ga

http://www.dailygalaxy.com/my_weblog/2007/07/a-second-genesi.html


~ 4.0 Ga
~ 4.0 Ga
~ 4.0 Ga
Earth About 4.0 Billion Years Ago
http://www.cosmic-art.co.uk/pics3.html

~ 4.1 Ga

~ 4.1 Ga

~ 4.1 Ga

One source of water were ice-rich asteroids colliding with the Earth during the early bombardment

http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/earth.htm

~ 4.0 Ga

~ 4.0 Ga

~ 4.0 Ga

A second source of water is volcanic degassing of the Earth's interior

http://www.lpi.usra.edu/education/timeline/gallery/slide_18.html

Origin of Atmosphere and Oceans

The closest we can get to the composition of the Earth's early atmosphere is to look at out gassing from modern volcanoes.

Kilauea Volcanic Gasses

H_2O	67.7%
CO_2	12.7%
N_2	7.65%
SO_2	7.03%
SO_3	1.86%
S_2	1.04%
H_2	.75%
CO	.67%
Cl_2	.41%
Ar	.20%

Observe the following:

There is no free oxygen coming from the volcano, but oxygen is not rare. In fact, 90% of the gasses have oxygen in them.

Water must have been as common or more common in in the past in volcanic outgassing (otherwise there would be no oceans.)

Carbon dioxide is very common.

Sulfur is very common, almost 10%.

In addition:

Hydrogen must have been in much greater abundance in the past than today since hydrogen has been continuously lost to space over the past 4 billion years.

~ 4.0 Ga ~ 4.0 Ga ~ 4.0 Ga

Moonrise: 4 billion BCE . . . a much-closer moon stirs huge tides on the primeval earth.

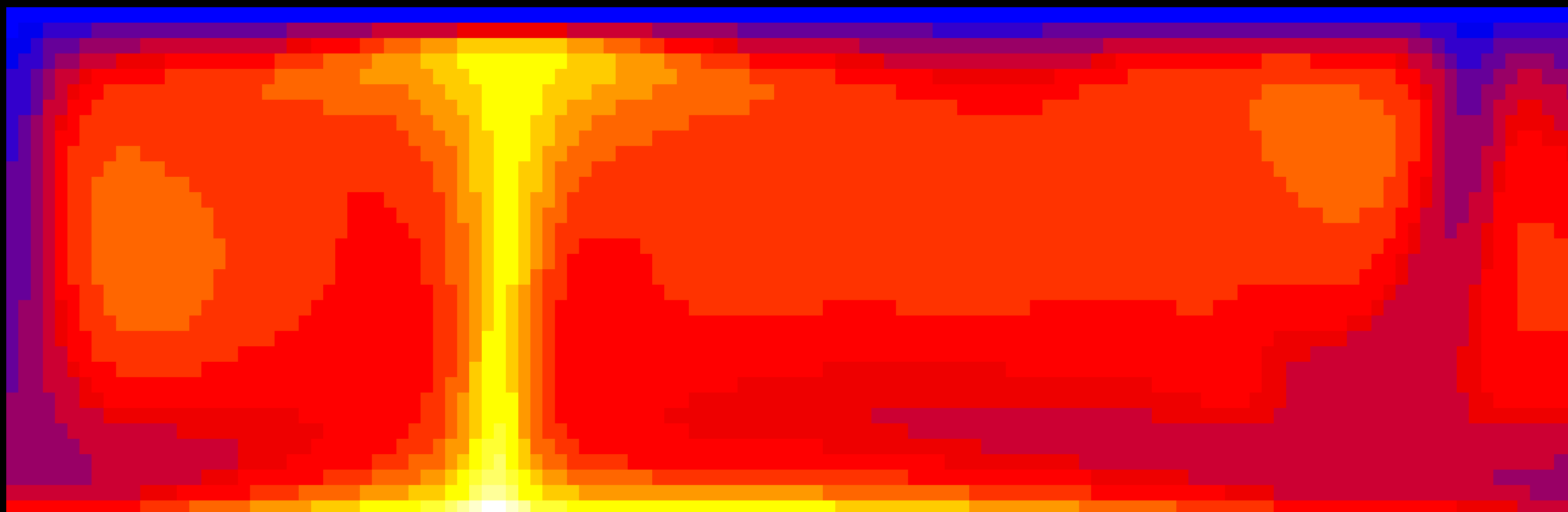
~ 3.9 Ga ~3.9 Ga ~ 3.9 Ga

Earth About 3.9 billion years ago

Moonrise 2 - the nearby moon draws huge tides on the early earth, sending the early ocean waters violently sloshing all around the globe uninterrupted because there are no continental landmasses to slow them down.

http://www.cosmographica.com/gallery/portfolio2007/content/194_Moonrise2_large.html

The First Dry Land

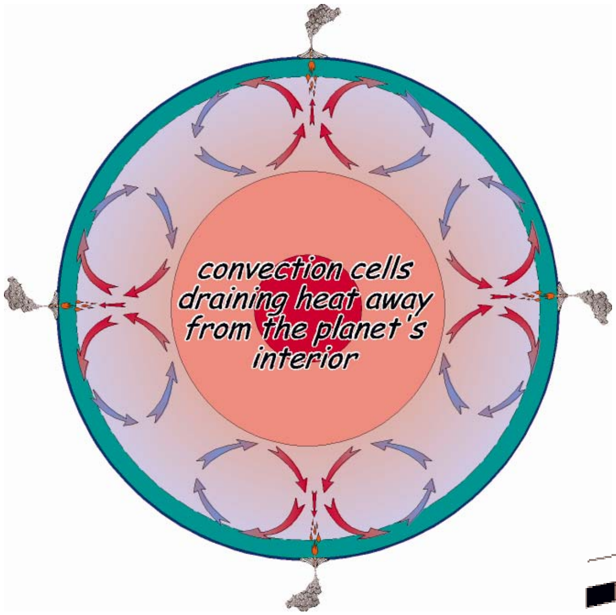


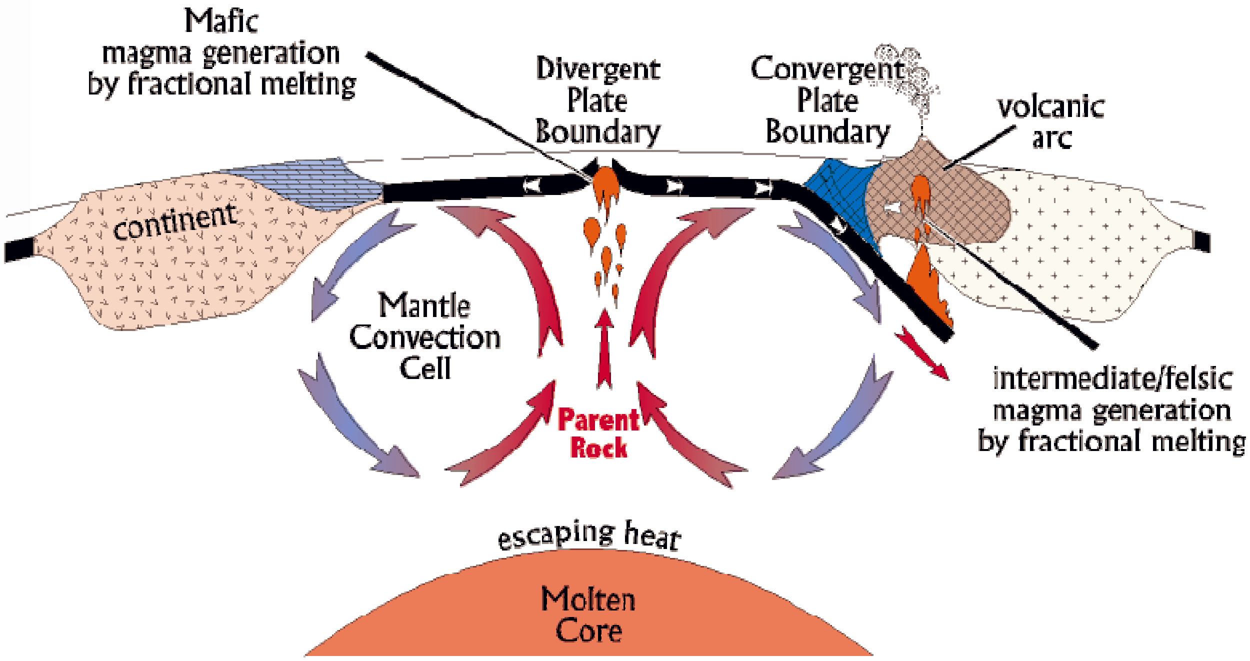
A simulation of convection in the mantle of the earth. Hot rock (yellow) rises and cool rock (blue) falls. The rock is at 1000 to 2000° C and creeps slowly; the rate of motion is a few centimeters per year (the simulation shows millions of years).

Volcanic Islands

http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/earth.htm

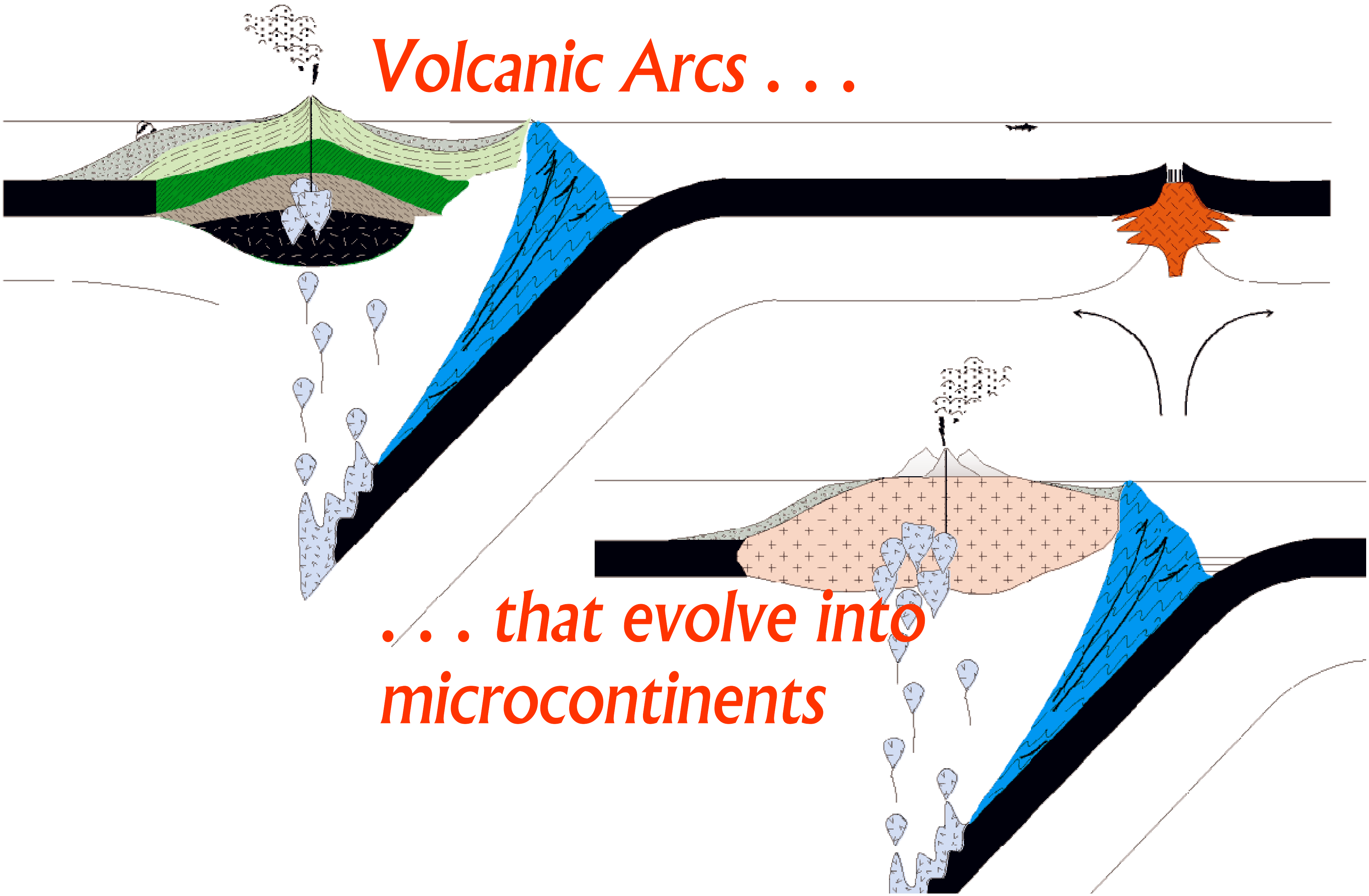
Convection cells in the mantle set up divergent and convergent plate boundaries where igneous rock evolution by fractionation takes place





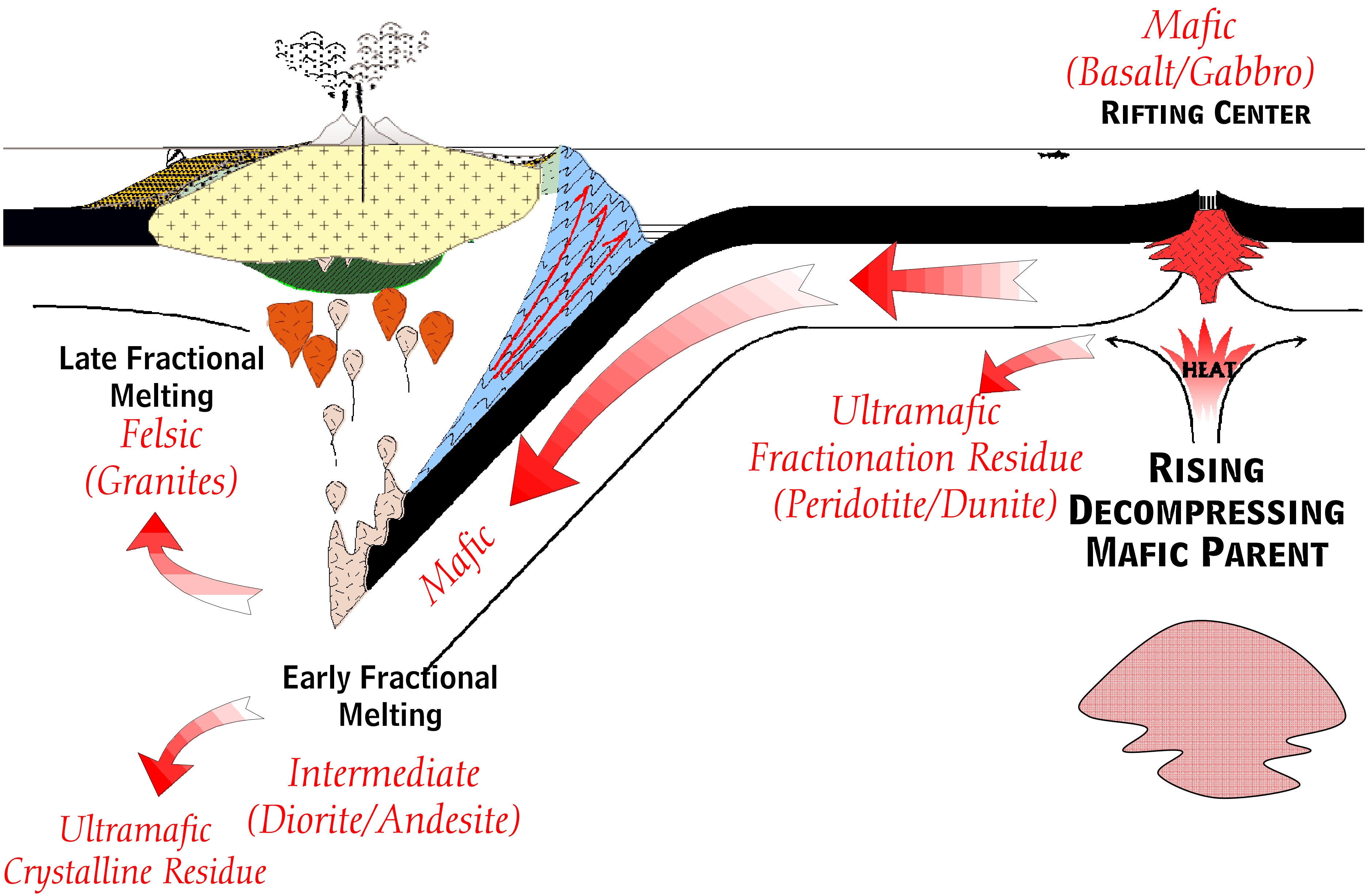
The result was the formation of . . .

Volcanic Arcs . . .

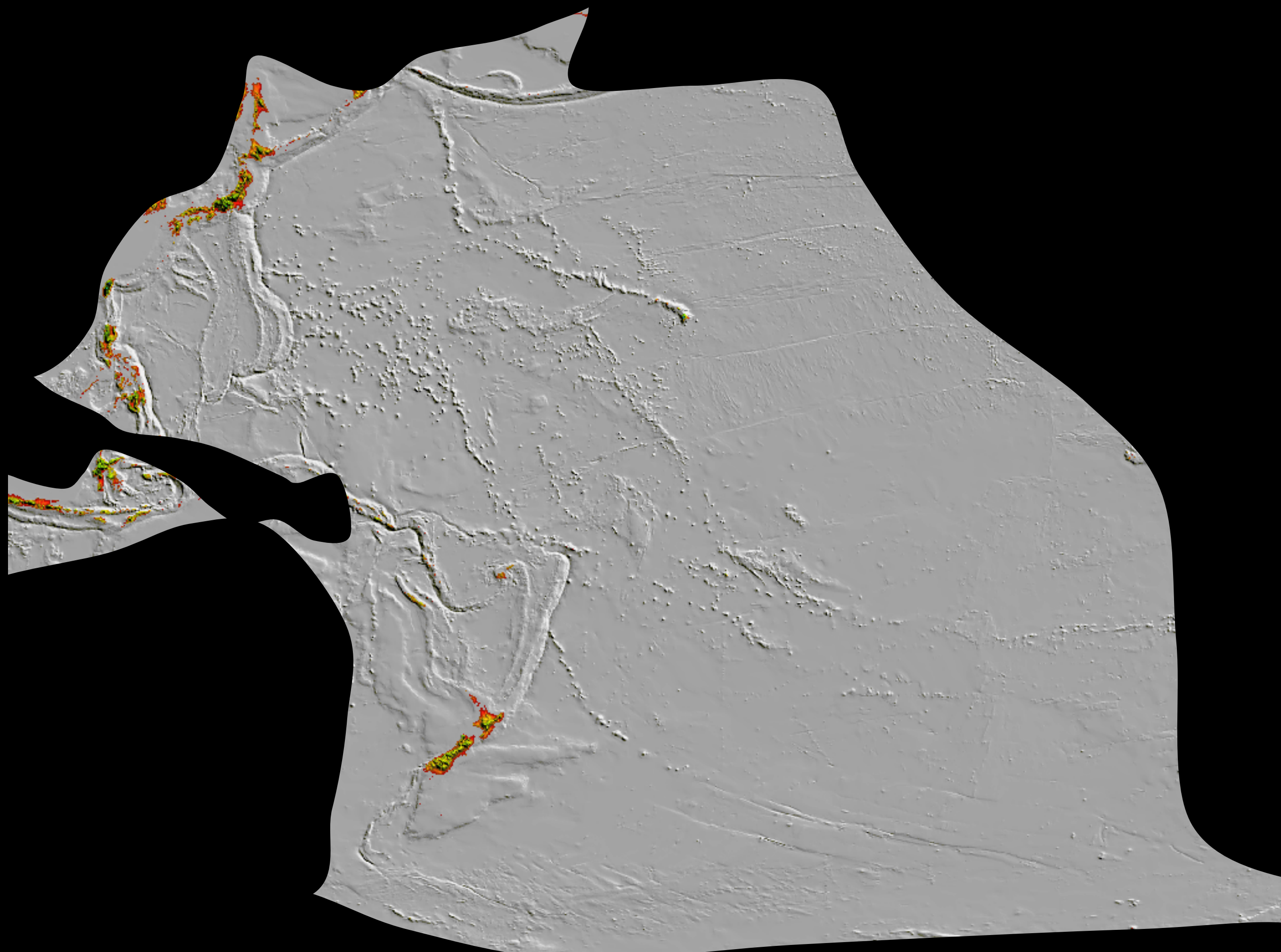


. . . that evolve into microcontinents

By igneous fractionation processes we already understand.



But, this early Earth had no continental land areas, perhaps not even large islands.



Archaean Geology

So they probably looked like this modern volcanic island just breeching the surface of the sea.

http://www.noaanews.noaa.gov/stories/s438.htm

Archaean Geology

Or, this . . .

http://austral.chez.tiscali.fr/v3/accueil.php?nav=galleries&page=gallery2

Archaean Geology

Or, this . . . Barren of life with hot springs and geysers.

Boiling Mud Pot near Lake Myvatn, Iceland (a painting by William K Hartmann). This region reminded us of primordial Earth, before plants took over the landscape. Myvatn is a geothermal area that is the "Yellowstone" park of Iceland.

http://www.psi.edu/hartmann/volcano.html

~ 4.0 Ga

~ 4.0 Ga

~ 4.0 Ga

All beginning with tiny volcanic islands.

http://www.lpi.usra.edu/education/timeline/gallery/slide_18.html

~ 3.6 Ga

~ 3.6 Ga

~ 3.6 Ga

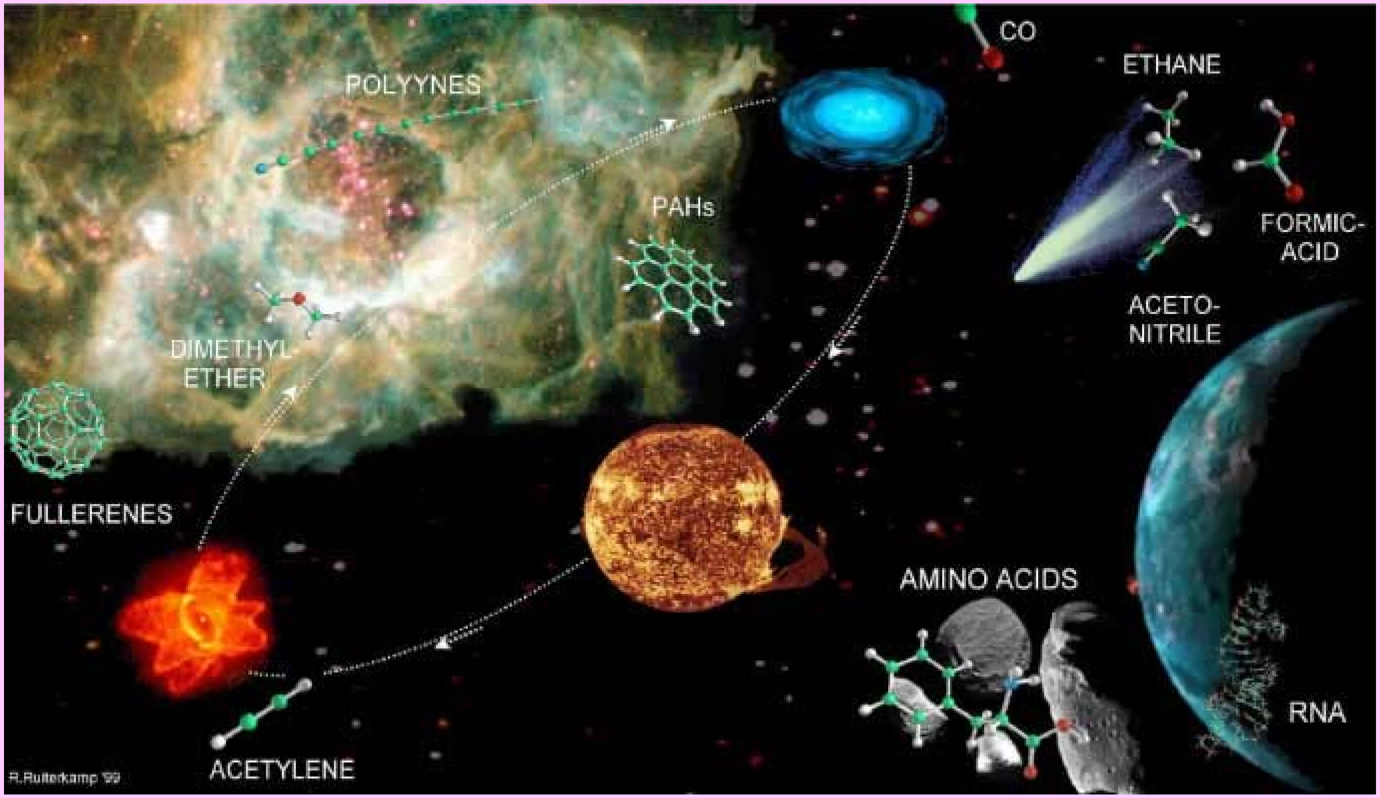
All beginning with tiny volcanic islands.

http://www.dailygalaxy.com/my_weblog/2007/08/earths-oldest-o.html

Organic Pollution

ASTROCHEMISTRY

Organic Molecules in Space

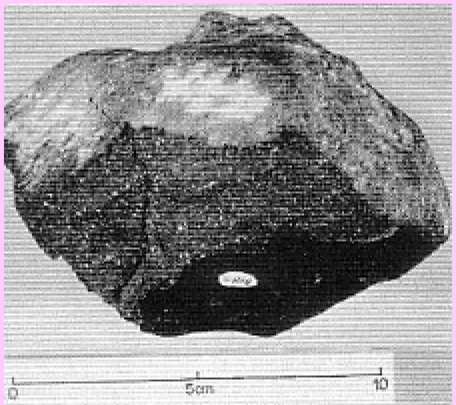


Pre-biotic chemistry results in a cornucopia of organic molecules in the harsh, low-density environment of space, all recognized by their electromagnetic fingerprint.

http://www.strw.leidenuniv.nl/~pascale/astrochemistry.html

http://www.ottawa.rasc.ca/articles/scott_al/specstroscopy/index.html

ORGANICS IN SPACE – MURCHISON METEORITE



On September 28th 1969 fragments of a meteorite fell in and around the small town of Murchison, Victoria. This meteorite has transformed our ideas about organic material in the Universe. The meteorite was found to contain a wide variety of organic compounds, including many of biological relevance such as amino acids. This showed that many organic molecules can be formed in space, and raised the possibility that such extraterrestrial material might have a role in the Origin of Life.

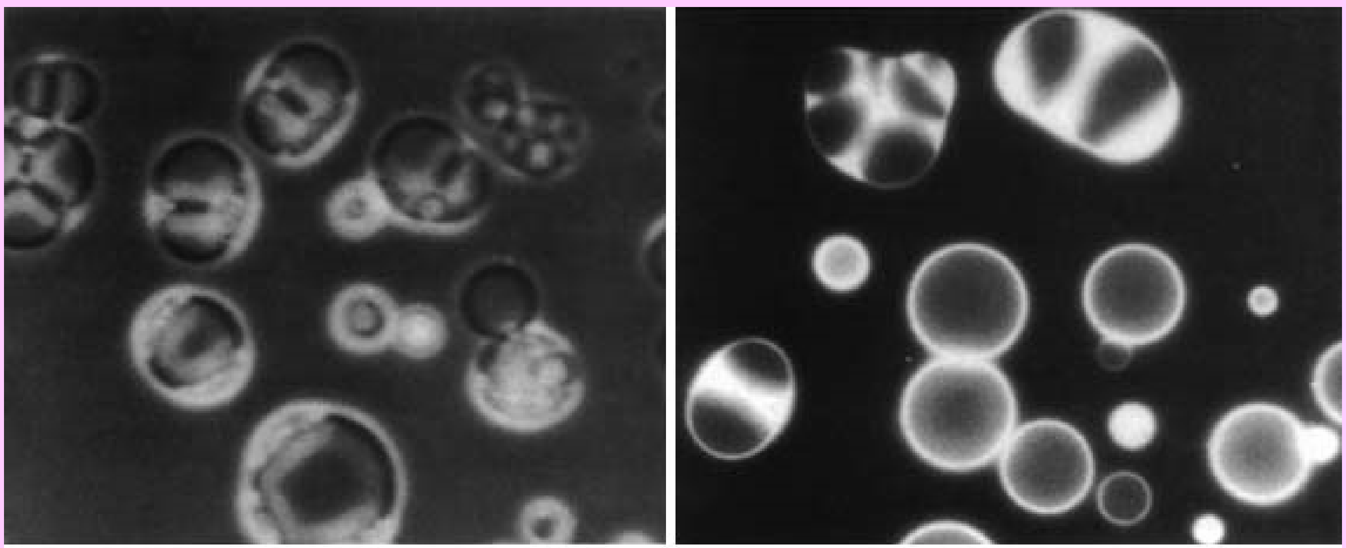
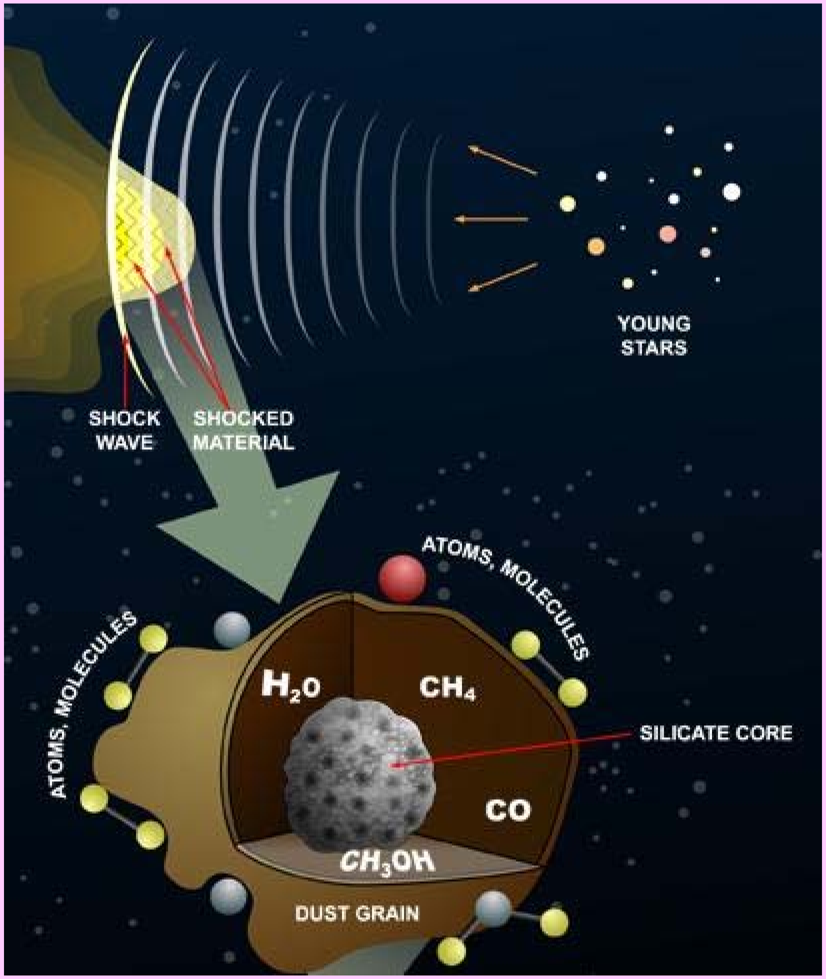


Figure 3. Self-assembled vesicular structures are produced by organic compounds extracted from the Murchison carbonaceous meteorite when they interact with water. The vesicles are 10-50 micrometers in diameter, and are bounded by bilayer membranes that can act as a diffusion barrier to ionic flux. Such relatively impermeable boundary structures are essential to the membranes that define all cellular life today. Left: phase micrograph. Right: light micrograph showing the natural fluorescence of the vesicles. The fluorescence is caused by polycyclic aromatic hydrocarbons that are abundant in carbonaceous meteorites. Original magnification: 400 X.

http://evolution.berkeley.edu/evosite/resources/images/deamerfig3.jpg

Sugar in Space



Astronomers using the National Science Foundation's giant Robert C. Byrd Green Bank Telescope (GBT) have discovered a frigid reservoir of simple sugar molecules in a cloud of gas and dust some 26,000 light-years away, near the center of our Milky Way Galaxy. The discovery suggests how the molecular building blocks necessary for the creation of life could first form in interstellar space.

http://www.nrao.edu/pr/2004/coldsugar/

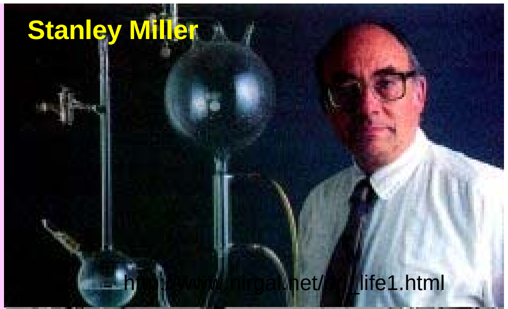
Methane

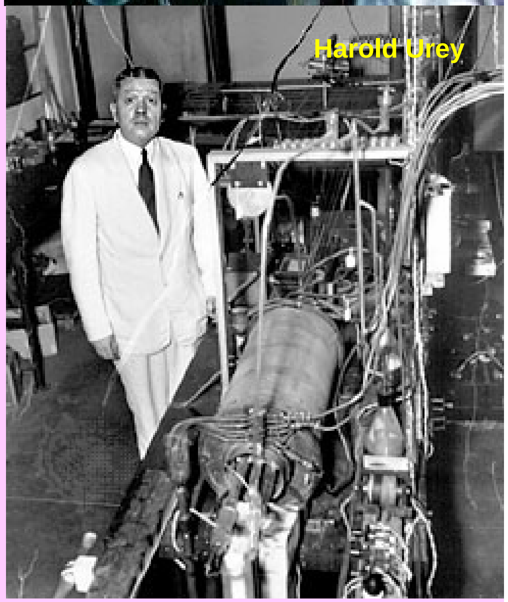
Artist's impression of the extrasolar planet HD 189733b, now known to have methane and water. Astronomers used the Hubble Space Telescope to detect methane -- the first organic molecule found on an extrasolar planet.

http://www.nrao.edu/pr/2004/coldsugar/

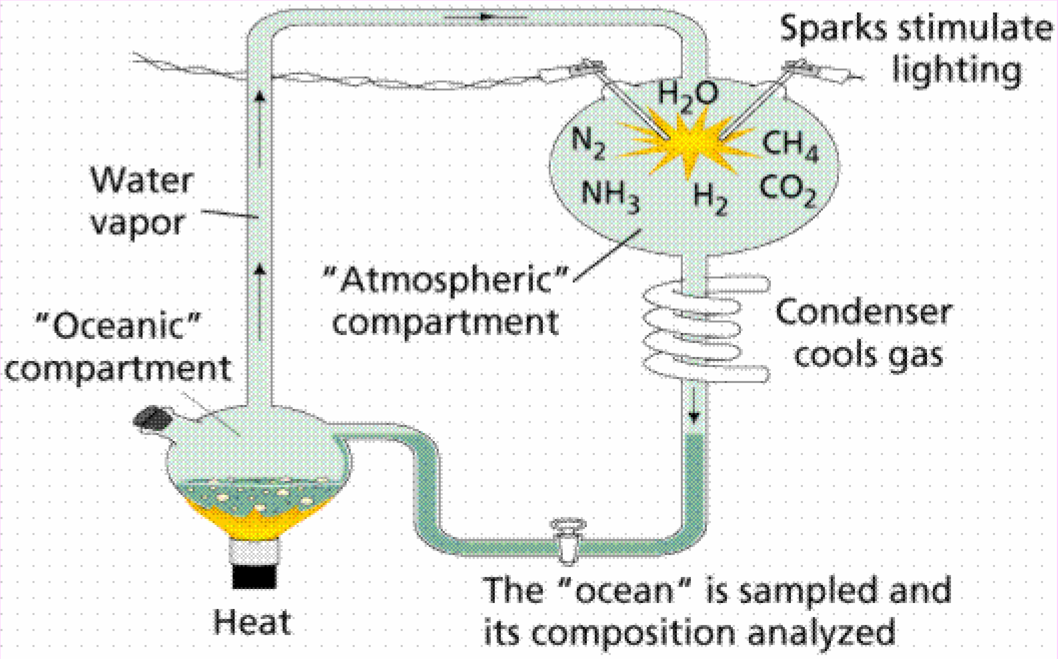
Abiotic Synthesis of Organic Molecules and The Origin of Life:

Stanley Miller, Harold Urey, and one of the most famous experiments ever.

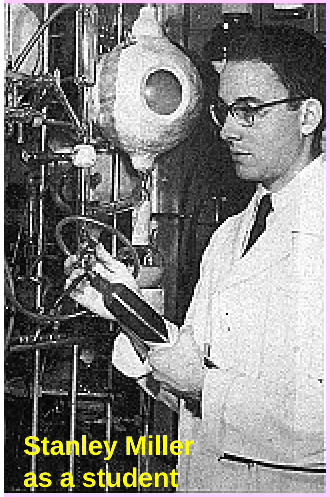




http://www.britannica.com/nobel/micro/614_56.htm

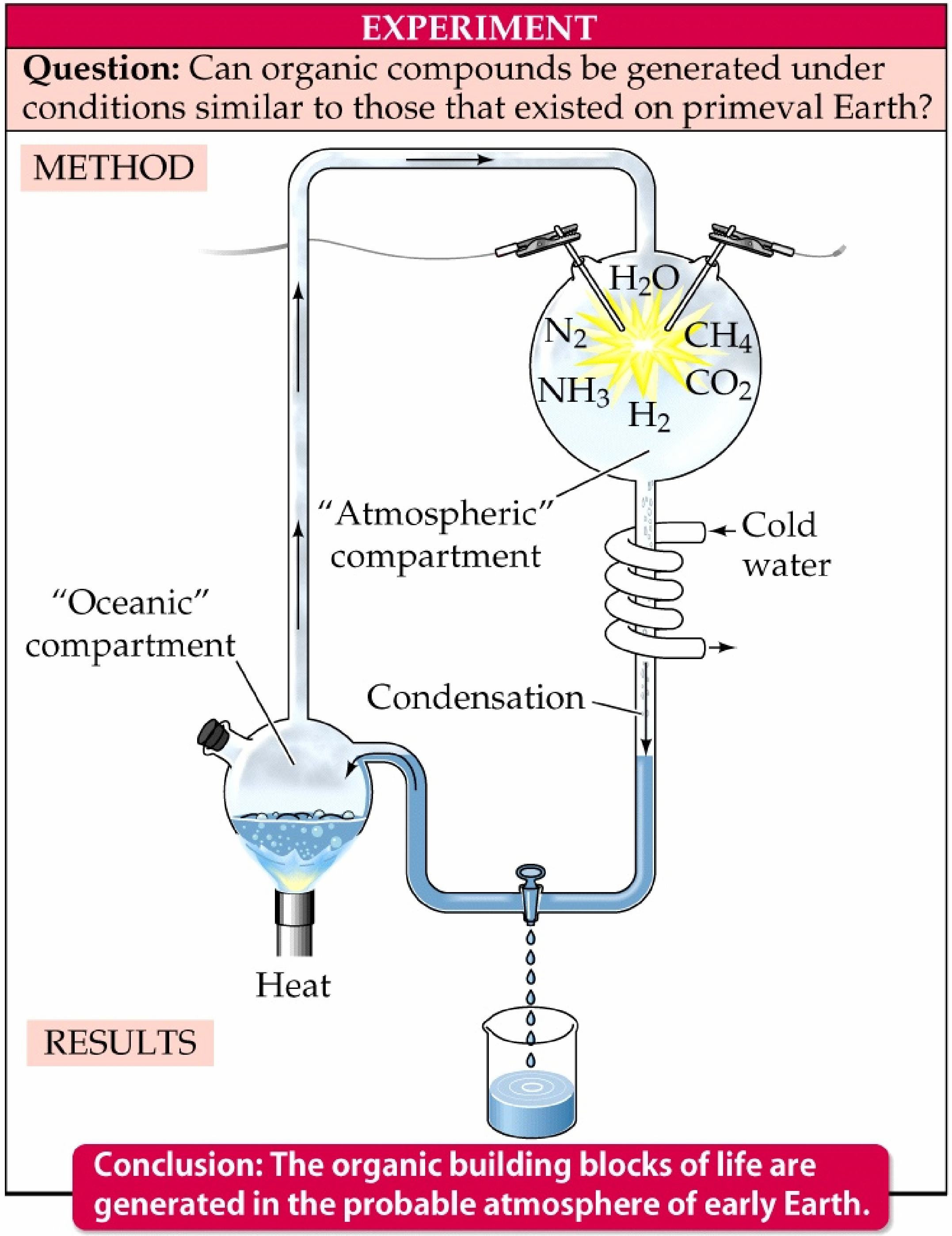


http://www.cbs.dtu.dk/staff/dave/roanoke/bio101ch19a.htm



http://www.astrosurf.com/lombry/bioastro-prebiotique.htm

Self Organizing Evolution by bottom-up processes



http://biology.arizona.edu/classes/182/Urey-Miller.HTM

The early Earth was bathed in a great diversity of organic molecules, some, by today's standards, being highly toxic

a–Αμινο–*ν*–βυτψριχ αχιδ	50	0.34
a–Αμινοισοβυτψριχ αχιδ	1	0.007
b–Αλανινε	150	0.76
Αχετιχ αχιδ	150	0.51
Αλανινε	340	1.7
Ασπαρτιχ αχιδ	4	0.024
Φορμιχ αχιδ	2330	4.0
Γλυταμιχ αχιδ	6	0.051
Γλψχινε	630	2.1
Γλψχολιχ αχιδ	560	1.9
Ιμινοδιαχετιχ αχιδ	55	0.37
Ιμινοδιαχετιχ–προπιονιχ αχιδ	15	0.13
Λαχτιχ αχιδ	310	1.6
Ν–Μετηψλαλανινε	10	0.07
Ν–Μετηψλ υρεα	15	0.051
Προπιονιχ αχιδ	130	0.66
Σαρχοσινε	50	0.25
Συχχινιχ αχιδ	40	0.27
Υρεα	20	0.034

http://bill.srnr.arizona.edu/classes/182/Urey-Miller.HTM

Earth's Earliest Environments

~ 4.05 Ga. Volcanic eruptions on the early Earth, showing the dark smoggy atmosphere and tremendous lightening displays that accompanied it. The atmosphere would have been filled with thick, choking, poisonous gasses. Land areas were small, while tides and ocean currents strong.

A Hell Broth

The Spark of Life: Darwin and the Primeval Soup
by Christopher Wills, and Jeffrey Bada

SUPPOSE THAT YOU ARE ABLE TO GO BACK IN TIME TO ABOUT four billion years ago and walk along an island beach of the early Earth. You will find it a breathtaking experience in more ways than one. First of all, you must wear a space suit, for there is no oxygen in the atmosphere. And the suit will have to be Teflon coated, because nasty gases present in the thick air, such as hydrogen sulfide and the vapors of sulfuric and hydrochloric acids, would certainly kill you very quickly by eating through any protective suit made of ordinary materials.

Can you see your surroundings? Not very well -- the atmosphere is so smoggy that little or no light can penetrate to the surface, even at high noon. But lightning flashes do give you brief, lurid glimpses of your immediate neighborhood. And you might be able to see the red glow of a nearby active volcano.

A vast ocean stretches away into the darkness and murk. During the brief lightning flashes, you can see that it is covered by lumps of oily material. The color of the water between the lumps is a muddy reddish brown, stained by large quantities of organic substances. Great waves crash on the shore, built up unimpeded to awesome size as they cross the vast stretches of ocean that girdle the planet. As they break, strong winds whip the sea up into a roiling mass of foam. Gusts of rain slash across the landscape.

Winds and tides together have produced the huge, sandy intertidal zone across which you are trudging. The sand is of many colors -- black, red, yellow. Even through your spacesuit you can hear a great hissing noise as the water withdraws after each wave. As you look more closely, you see that the rocks and sand are encrusted with glistening layers of organic material of many different colors that has been thrown up by the wind and tides. The layers hardly have time to dry out before the next tide sweeps back up the beach.

This ocean water of four billion years ago is salty, perhaps even more than today's oceans, but it also contains quantities of toxic compounds such as hydrogen cyanide and formaldehyde. Like a single breath of the atmosphere, a small amount would kill you.

You are not enjoying your stroll. The world is a noisy, dangerous, and utterly alien place. You can walk no further because, not far down the beach, a river of lava runs down to the sea, hissing and boiling and throwing up clouds of steam.

Captain FitzRoy of Darwin's ship the Beagle described his landfall on the Galapagos Islands as a shore fit for pandemonium. But he could not have imagined the truly hellish landscape of the early Earth.

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The Spark of Life: Darwin and the Primeval Soup
by Christopher Wills, and Jeffrey Bada

SUPPOSE THAT YOU ARE ABLE TO GO BACK IN TIME TO ABOUT four billion years ago and walk along an island beach of the early Earth. You will find it a breathtaking experience in more ways than one. First of all, you must wear a space suit, for there is no oxygen in the atmosphere. And the suit will have to be Teflon coated, because nasty gases present in the thick air, such as hydrogen sulfide and the vapors of sulfuric and hydrochloric acids, would certainly kill you very quickly by eating through any protective suit made of ordinary materials.

Can you see your surroundings? Not very well -- the atmosphere is so smoggy that little or no light can penetrate to the surface, even at high noon. But lightning flashes do give you brief, lurid glimpses of your immediate neighborhood. And you might be able to see the red glow of a nearby active volcano.

A vast ocean stretches away into the darkness and murk. During the brief lightning flashes, you can see that it is covered by lumps of oily material. The color of the water between the lumps is a muddy reddish brown, stained by large quantities of organic substances. Great waves crash on the shore, built up unimpeded to awesome size as they cross the vast stretches of ocean that girdle the planet. As they break, strong winds whip the sea up into a roiling mass of foam. Gusts of rain slash across the landscape.

A Hell Broth

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Winds and tides together have produced the huge, sandy intertidal zone across which you are trudging. The sand is of many colors -- black, red, yellow. Even through your spacesuit you can hear a great hissing noise as the water withdraws after each wave. As you look more closely, you see that the rocks and sand are encrusted with glistening layers of organic material of many different colors that has been thrown up by the wind and tides. The layers hardly have time to dry out before the next tide sweeps back up the beach.

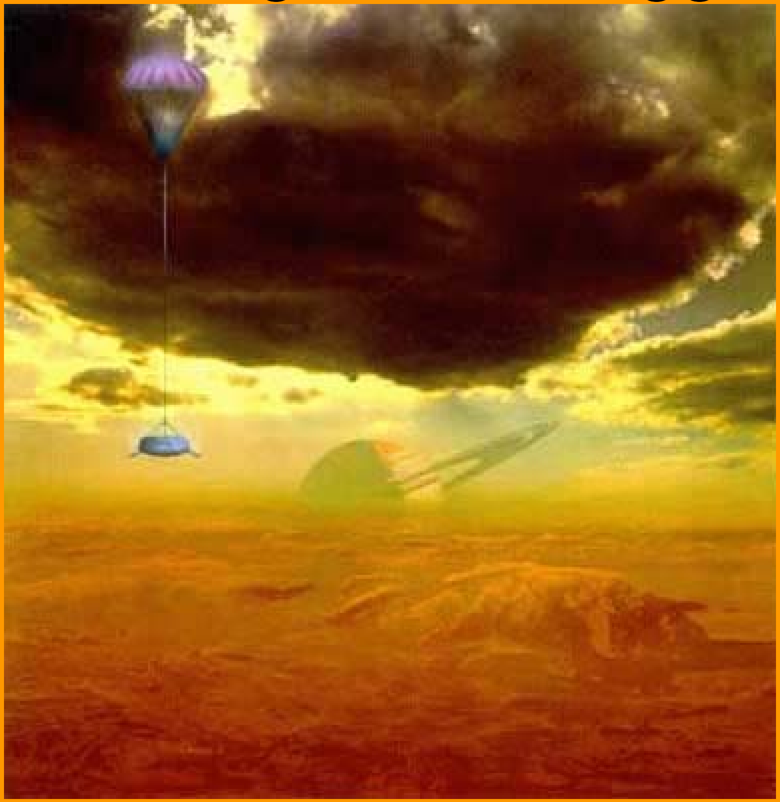
This ocean water of four billion years ago is salty, perhaps even more than today's oceans, but it also contains quantities of toxic compounds such as hydrogen cyanide and formaldehyde. Like a single breath of the atmosphere, a small amount would kill you.

You are not enjoying your stroll. The world is a noisy, dangerous, and utterly alien place. You can walk no further because, not far down the beach, a river of lava runs down to the sea, hissing and boiling and throwing up clouds of steam.

Captain FitzRoy of Darwin's ship the Beagle described his landfall on the Galapagos Islands as a shore fit for pandemonium. But he could not have imagined the truly hellish landscape of the early Earth.

Archaean Environments

Only we have to remember, Archaean Earth, like Titan, is orange and smoggy, not blue.



Huygens probe as it descends through Titan's murky, brownish-orange atmosphere of nitrogen and carbon-based molecules, beaming its findings to the distant Cassini orbiter. Titan's sky may well be darker and smoggier than this painting suggests and Saturn never actually rises above the horizon at the probe's landing site.

http://en.wikipedia.org/wiki/Image:Huygensprobe.jpg

Ozone Smog

Titan Revealed

It is not known what lies beneath Titan's obscuring haze. but Titan's atmosphere is one-and-a-half times as dense as the Earth's. Its is roughly 90% nitrogen and 10% other complex molecules such as methane. The thick haze would make it unlikely that a visitor to Titan's surface could look up and see Saturn itself.

http://www.arcadiastreet.com/cgvistas/saturn_017.htm