A WALK THROUGH TIME

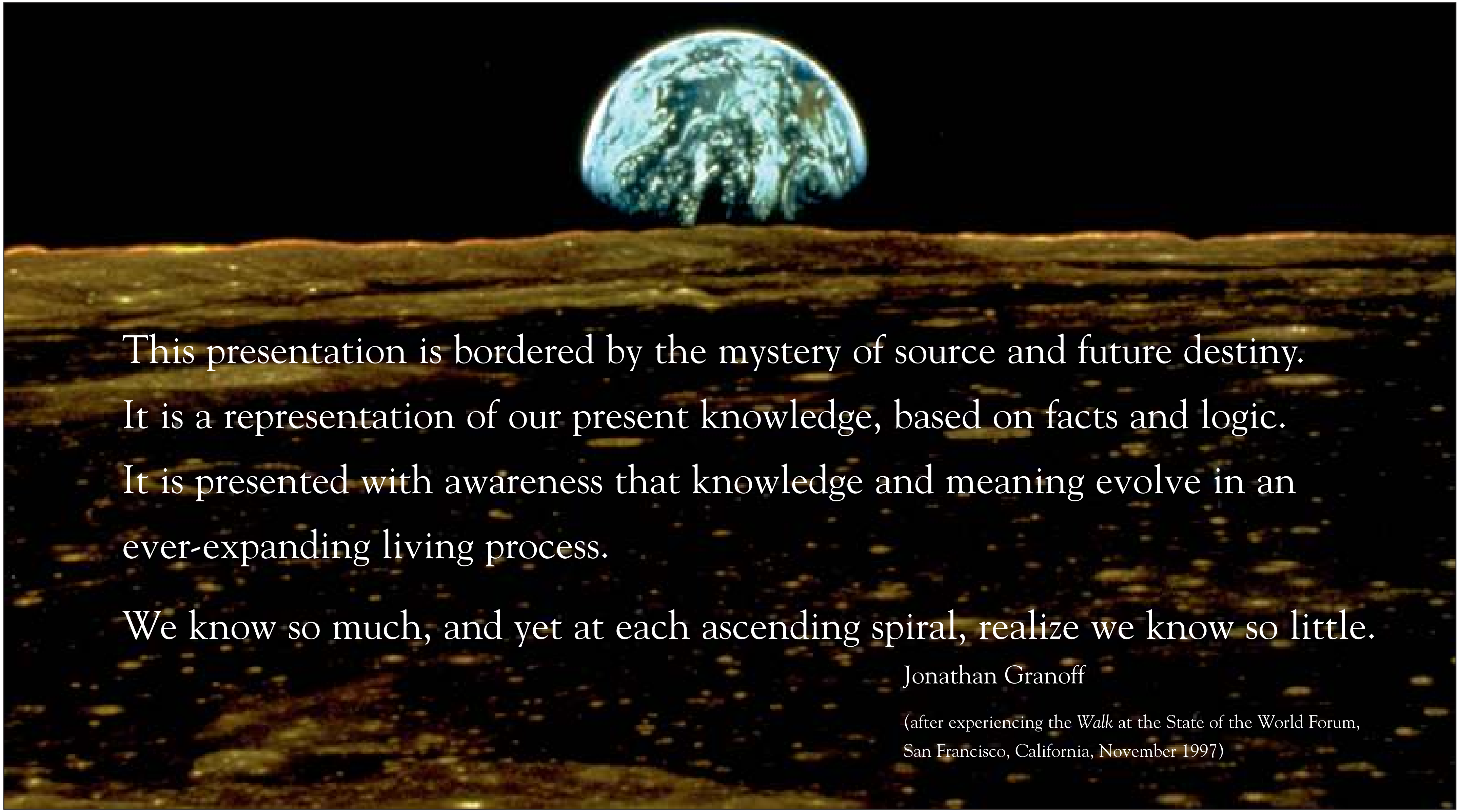
… FROM STARDUST TO US

The one-mile-long *Walk Through Time* you are about to take unfolds a scientific understanding of the five-billion year evolution of life on Earth. The *Walk* progresses from the formation of the solar system to the present. The *Walk* offers a rich context for exploring fundamental issues regarding humanity and the future of all life on Earth.

Scale – Each foot of the *Walk* represents one million years. At this scale …

1 foot	=	typical time for continents to move and earthquake faults to slip 20 miles
0.1 inch	=	time span back to the end of the last Ice Age
0.001 inch	=	human lifetime

We know so much ... and yet we know so little



This presentation is bordered by the mystery of source and future destiny.

It is a representation of our present knowledge, based on facts and logic.

It is presented with awareness that knowledge and meaning evolve in an ever-expanding living process.

We know so much, and yet at each ascending spiral, realize we know so little.

Jonathan Granoff

(after experiencing the *Walk* at the State of the World Forum, San Francisco, California, November 1997)

We felt the life of Earth when we first saw it from space.
photo, courtesy NASA

Deep-Time Terrain

What to Take With You
What to Leave Behind

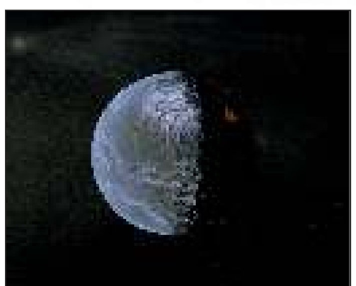
The fossil record offers a narrow window through which we try to glimpse vast vistas. Beings with hard parts have favored histories. Dates of evolutionary events are known to varying degrees of accuracy.

Life is a story of permanence and change. Exuberant and innovative, it is also deeply conservative. Traditions and relationships of life today provide clues to the past. DNA is a tangled repository of ancient history; its sequences reveal the presence of the past. Like evolutionary wax tablets, they reveal layers of time and change.

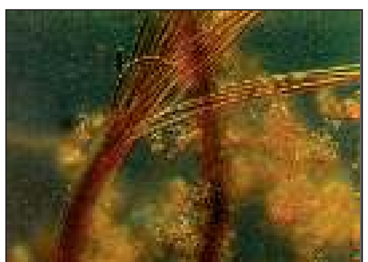
Evolution connotes "change" over time, not "progress." How recently an organism evolved does not define its "worth." While some organisms may be more specialized or complex, all share an equally long evolutionary history.

Evolution is not linear. Organisms and species do not just evolve or become extinct – they also anastomose (fuse together). In profoundly moving ways, life often grows in on itself, bringing previously-evolved beings together into new partnerships.

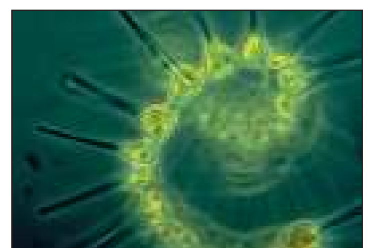
Origin of the Solar System



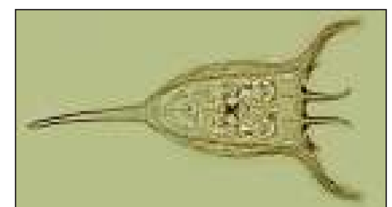
Bacterial Life Takes Hold



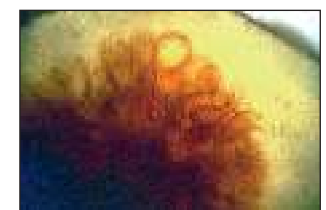
First Protists. Eukaryotic Cells (cells with nuclei and organelles) evolve through symbiosis



First Animals (marine)



First Plants, First Fungi



5,000 mya | 4,000 mya | 3,000 mya | 2,000 mya | 1,000 mya | Present

mya = million years ago

4600
MYA
MILLION YEARS AGO

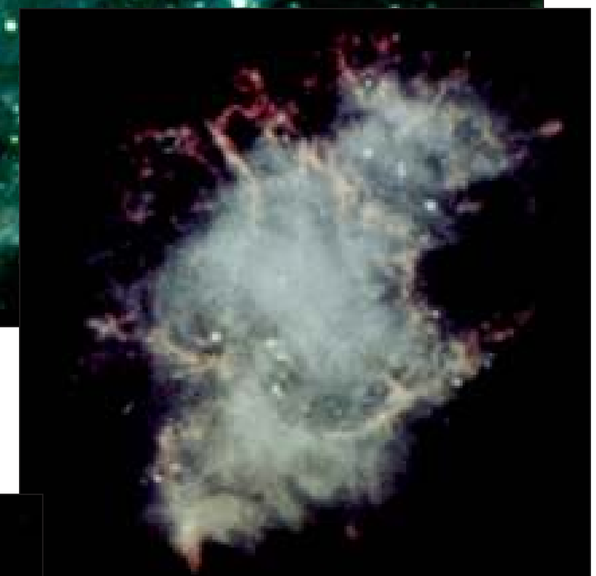
Pulse of the Spheres

We begin our *Walk Through Time* with the formation of Sun and Earth, two-thirds of the way through the history of the Universe and 4,600 million years before human beings appear.

About 15,000 million years before humans evolve (two miles behind you, at one million years to the foot), the Universe exploded out of the void in a "Big Bang." Early stars cycled through life and death. Supernova explosions spewed stellar elements into space, creating dense clouds of molecules and dust.

New stars and planets form as nebulae contract and condense under the force of their own gravity. In a galaxy we call the "Milky Way," the massive center of one such nebula contracts to form our Sun. Orbiting gas and dust accrete (grow by being added to) into planetesimals which then collide to build the planets of our solar system.

Deep-Space
photo, courtesy NASA



In 1054, an earthling in China records the explosion of a massive supernova 6,300 light years away. The explosion creates the Crab Nebula, which is still expanding 50 million miles per day.
photo, courtesy NASA

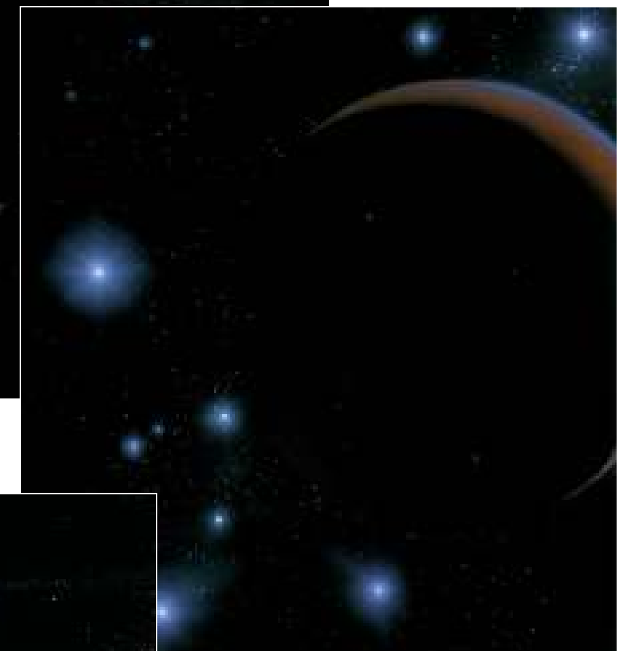
Crashing planetesimals begin to build Earth.
painting, William K. Hartmann, from the book "The History of the Earth," by William K. Hartmann and Ron Miller, ©1991

4500
MYA
MILLION YEARS AGO

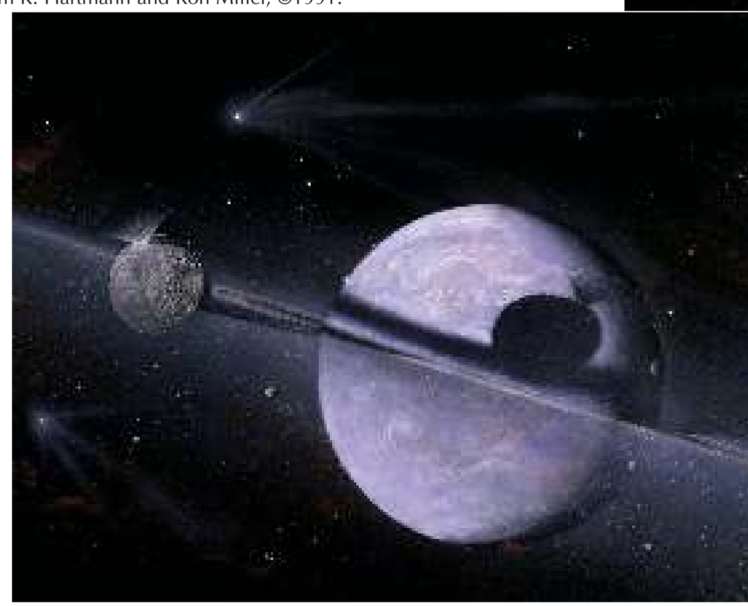
Star Stuff of Life

The early planets consist mostly of compounds of heavier elements. As the planets grow in size, their gravitational fields increase, drawing in nebular dust, planetesimals and carbon-rich meteorites. Ultimately, Earth is massive enough and cool enough to retain lighter gaseous compounds of carbon, nitrogen, oxygen and hydrogen, the star stuff from which life will spring.

Planetesimals continue to bombard the growing, half-sized Earth.
painting, William K. Hartmann, from the book "The History of the Earth," by William K. Hartmann and Ron Miller, ©1991.



A thick atmosphere shrouds the full-sized Earth. Meteorites from this period are the planet's oldest rocks.
painting, Ron Miller, from the book "The History of the Earth," by William K. Hartmann and Ron Miller, ©1991



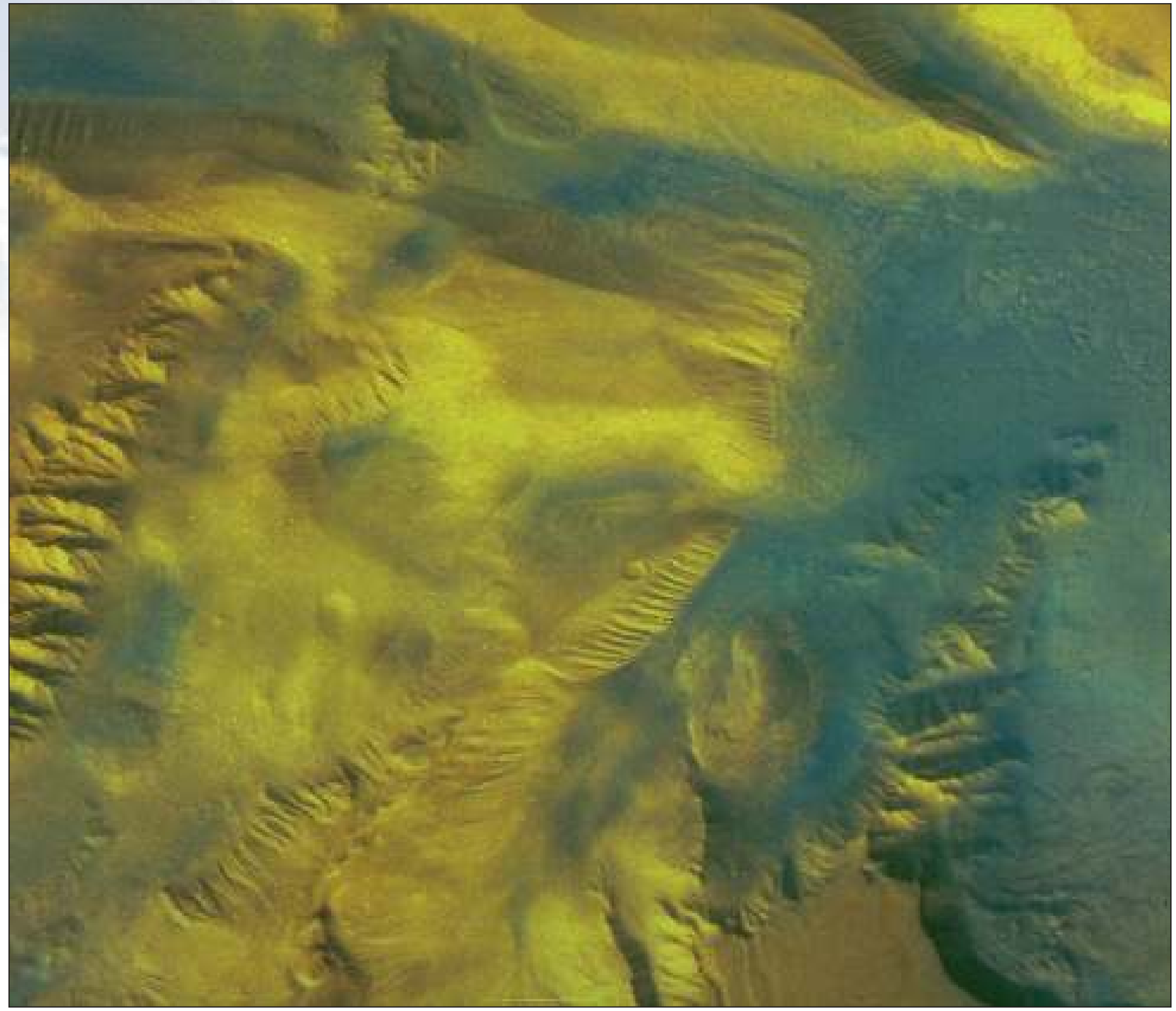
The early Moon, still quite close to Earth, casts a stunning shadow.
painting, William K. Hartmann, from the book "The History of the Earth," by William K. Hartmann and Ron Miller, ©1991

4400
MYA
MILLION YEARS AGO

Settling In

Radioactive elements inside Earth decay and planetesimals bombard Earth and her sister planets, causing tremendous heating. Heavy metals sink to form cores, while volcanoes spew lighter elements into the atmospheres. This "outgassing" transforms the early atmospheres.

The sister planets of the inner solar system – Mercury, Venus, Earth, Mars – reach their current configurations during this phase.



Mars-scape. We journey into Deep-Time when we journey into space. As we study planetary evolution, we better understand the environmental evolution of Earth and the central role life plays in shaping our home planet.
photo, courtesy NASA

4300
MYA
MILLION YEARS AGO

Rock
Not Always a Hard Place

Earth processes cycle so powerfully that little evidence remains of early planetary faces and flows. Critical and intriguing clues lie in the formulation of Earth rocks and minerals when compared to those on the Moon and other planets.

The oldest mineral crystals on Earth, zircons from western Australia, date back 4,300 million years. The oldest Moon rock brought back by Apollo astronauts is 4,200 million years old. Granite rocks found near Canada's Great Slave Lake go back 3,960 million years. Scientists believe these evolved from even older crustal material, melted and remelted by the restless Earth.

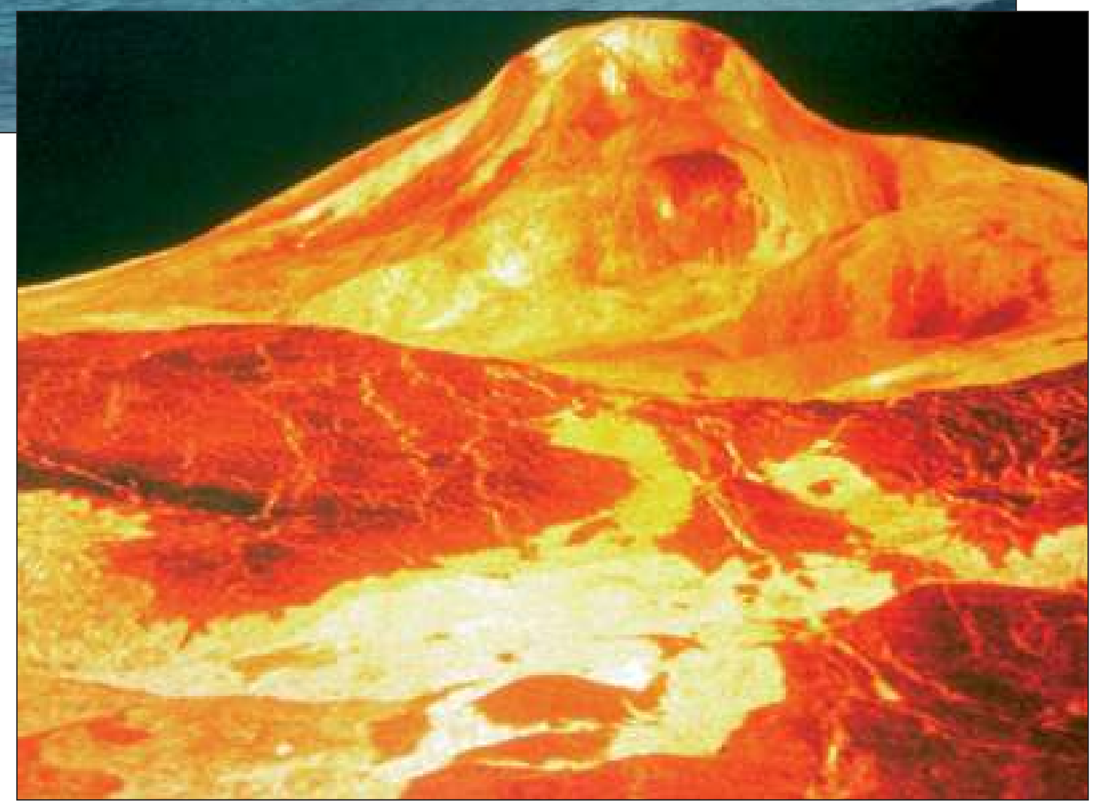
Explorers have not found the rocks that held the early zircons. Perhaps they metamorphosed (changed in form) in the continual cycling of Earth's mantle and crust. Rocks seem like such a "hard-place" from our human-time perspective. As inflexible as they appear, even rocks change form with heat, pressure and time. Continual transformation in the geological cycle foreshadows the patterns of life.
photo, Lois Brynes

4200
MYA
MILLION YEARS AGO

The Rains Reign

As Earth cools, water in the atmosphere condenses: torrential rains fall on, and on, and on. Great seas form. Exuberant volcanoes expel hotly agitated deep earth to the surface.

The hot, early atmosphere dances with an abundance of carbon dioxide, nitrogen, and water, and lesser amounts of methane and ammonia. Intense energy sources available on the primitive Earth form biologically important molecules from these gases. Candidate sources include solar UV-radiation (there is as yet no UV-protective ozone shield), radioactivity, and hot oceanic vents.



photos, courtesy National Center for Atmospheric Research

Nature and art are too sublime to aim at purpose, nor need they, for relationships are everywhere present, and relationships are life.

– Goethe

Gaia

The Gaia hypothesis, developed by British atmospheric chemist James Lovelock and U.S. biologist Lynn Margulis, proposes that planetary processes are neither simply geological and chemical, nor just geochemical; they are geophysiological. Variables such as the mean global temperature, the gaseous composition of the atmosphere, and the salinity and alkalinity of the oceans are sensitive to biological activity.

Earth's geology and biota are a single, tightly-coupled evolutionary system. Rocks carry tales as traces of bygone biospheres.
photo, Lois Brynes

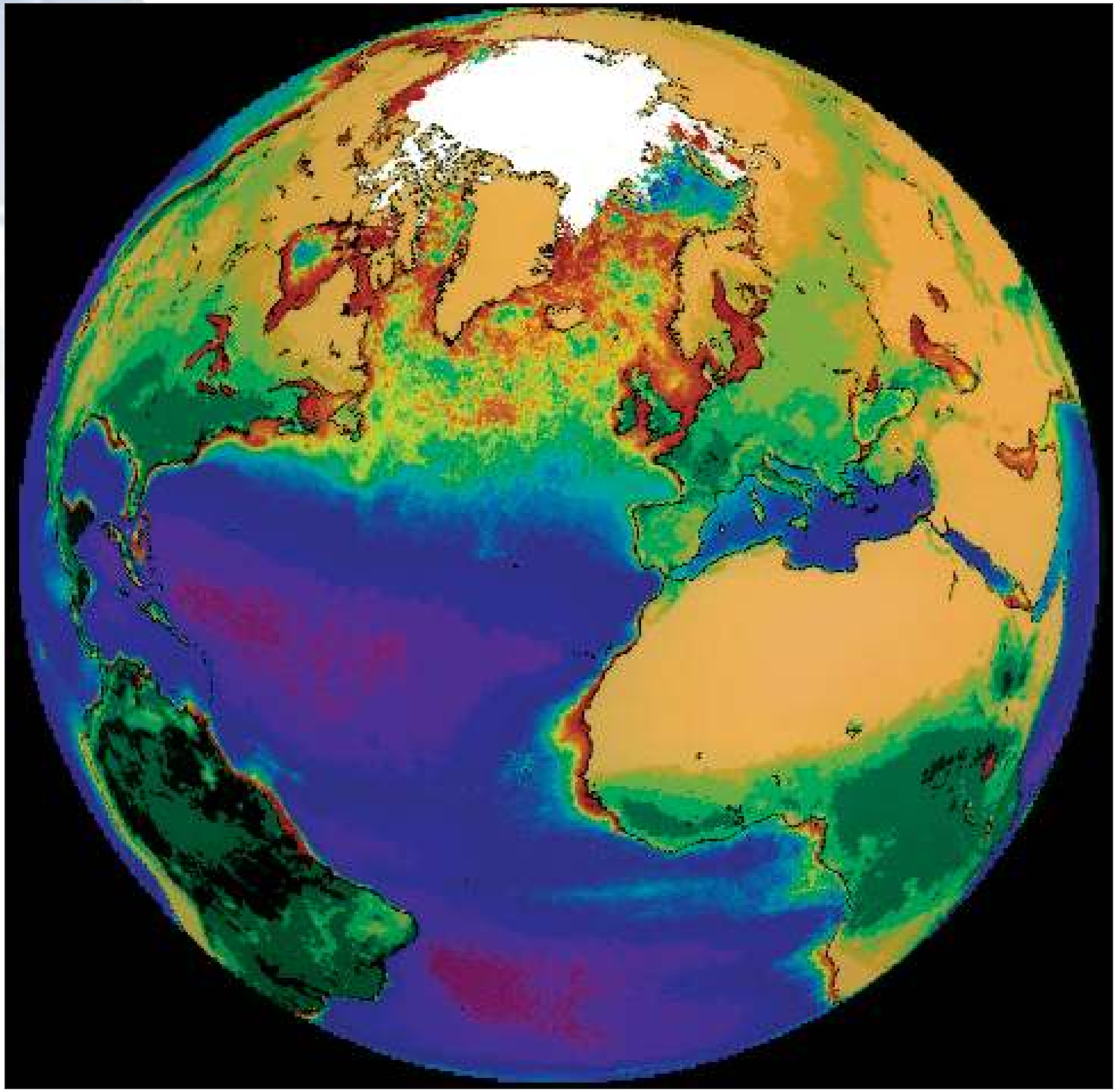
4100
MYA
MILLION YEARS AGO

PRIMORDIAL SOUP

The stage is set for life, but how does the play open?

Seeking to answer this question, some scientists investigate liquid and atmospheric chemical combinations that, when sparked, spontaneously generate the components of all life. Others investigate RNA and DNA, key information molecules that make up genes. Yet others explore the potential for life to begin at deep-sea vents, or in "bubbles," meaning greasy, bubble-like, pre-life droplets which might have provided hospitable enclosures. The surfaces of these droplets permit communication and exchange between inside and outside.

Absorbing solar energy, as well as organic matter from Earth, comets, and asteroids, these pre-life forms become increasingly complex. Growing, maintaining, and self-regulating, they transform subtly, amazingly into living cells.



Did life start at a hydrothermal vent? Billions of bytes of satellite information allow us to view life today as a planetary phenomenon.
satellite image, courtesy NASA

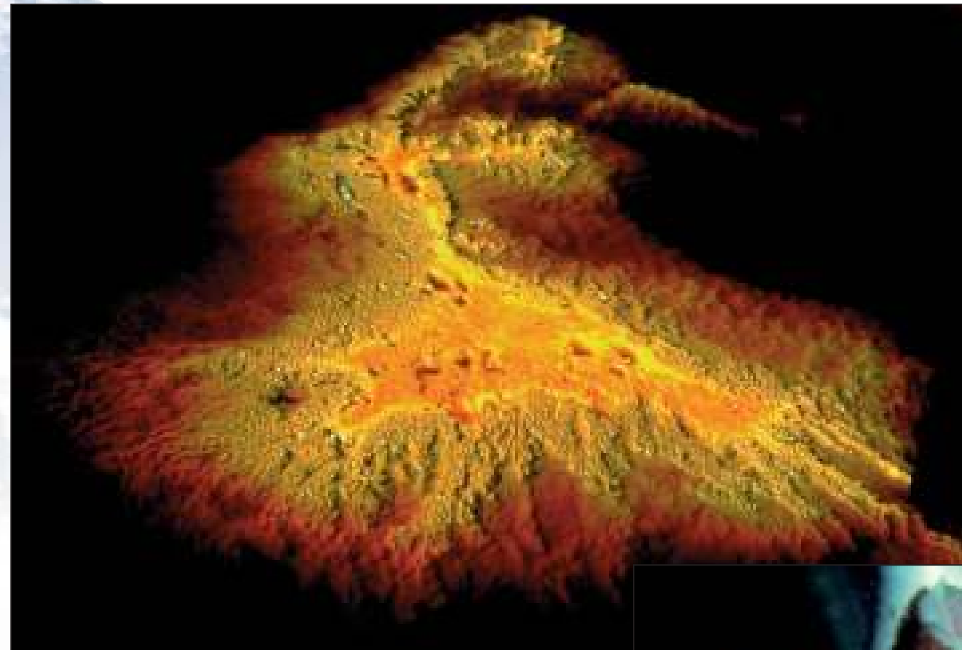
4000
MYA
MILLION YEARS AGO

The Extremists

Bacteria are Earth's first life forms. They continue to dominate environmental evolution in the twentieth century. Ancient bacteria (archae) thrive in extreme environments typical of Archean (early) Earth.

Heat- and acid-loving microbes flourish in boiling muds, hot springs, deep-sea vents and ash-ejecting volcanoes. They loll in waters as hot as 110 degrees C [230 degrees F], and freeze at temperatures below 55 degrees C [131 degrees F]. Some of these bacteria find an abode in pools of concentrated sulfuric acid.

Twentieth century microbial methane makers thrive in oxygen-free sediments inside animals, and in sewage. Producing all the methane in Earth's atmosphere, these bacteria prevent oxygen levels from reaching an explosive concentration.



Extremists bask in this sulfuric-acid-rich river, Rio Tinto, Huelva, Spain.
photo, Anabel Lopez

Extremist microbes inside tube worms form the cornerstone of this 20th century deep-sea hydrothermal vent ecosystem.
photo, courtesy Jason Foundation for Education

3900
MYA
MILLION YEARS AGO

LIFE TAKES TENACIOUS HOLD

The chronometer marking life's origin continues to march backward as we develop new tools for observation and analysis. Recent discoveries suggest that life on Earth may originate as early as 3,850 mya, even as the planet sustains heavy bombardment from meteorites and other incoming bodies.

Archean Earthscape
mural, Peter Sawyer courtesy Smithsonian Institution

Celebrating Diversity

Fast and Loose

Fast bacteria divide, cloning themselves every 20 minutes. In a million divisions, one bacterium may be a mutant. While most mutants die, successful ones quickly clone themselves across the environment.

Bacteria aren't just fast; they're also loose. Gene traders and swappers, they do not just create the next generation – they can become the next generation. "Horizontal" evolution yields brand-new kinds of beings.

What would happen if human beings could swap ideas as readily as these bacteria swap genes?

In Baja California, billions of phototrophic bacteria clone themselves and swap their genes in the warmth of a sun-lit salt marsh puddle. With adequate food, water and space (and no predators!), a single bacterium could generate 2^{144} individuals in two days (vastly more than the total number of human beings who have ever lived) and, in four days, 2^{288} individuals (greater than the number of atoms physicists estimate exist in the universe).
photo, Lynn Margulis

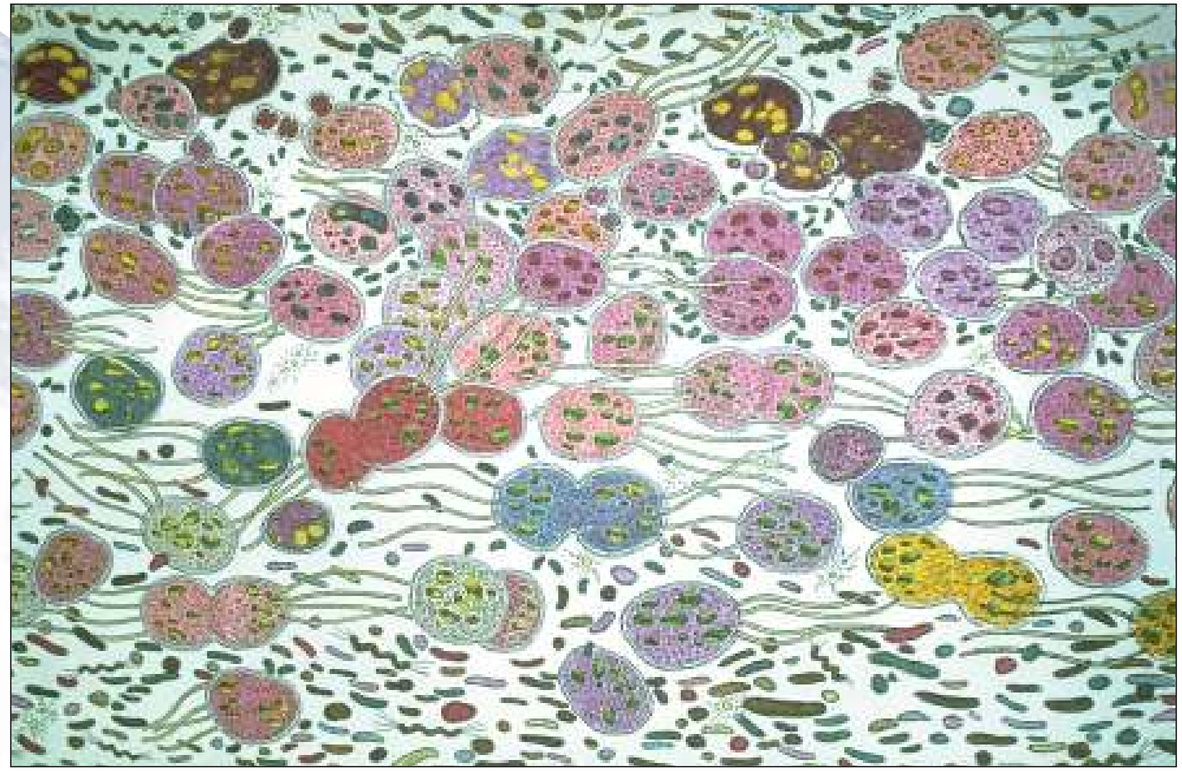
3700
MYA
MILLION YEARS AGO

LIFE'S FORTUNATE FERMENTERS

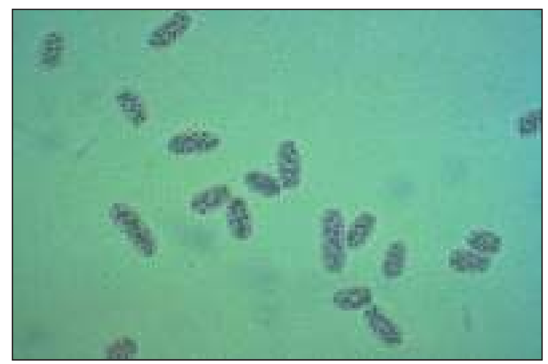
Life is easy for the biosphere's first beings, fermenting a pantry filled with free organic compounds formed in the atmosphere. These anaerobic (living in the absence of oxygen) freeloaders create life's first food crisis: rapidly reproducing, they consume food faster than the atmosphere renews it.

Certain descendants of these fortunate fermenters show notable problem-solving skills: they overcome the food shortage by learning to make their own food. These planetary "primary producers" use light or chemicals to generate energy, fabricating food directly from carbon-dioxide.

Green and purple microbes evolve Earth's most important metabolic innovation: photosynthesis. These early prodigies practice specialized photosynthesis, which gives off sulfur rather than oxygen "waste." Using solar power, the microbes take hydrogen from hydrogen-sulfide gas that is spewed out of deep-sea vents and volcanoes and combine it with carbon dioxide to make their bodies.



This lake community shows contemporary relatives of Earth's earliest photosynthesizers. Green Chlorobium, the first solar-powered sulfide munchers of the planet, reside here with pink and purple populations of other early non-oxygen photosynthesizers. About 3,700 Mya, the Archean landscape glistened bright green, red, purple and orange as hydrogen-hungry microbes colonized wet volcanic terrain, pumice and black sands.
drawing, Christie Lyons



Chromatium swim toward light and their favorite food, hydrogen-sulfide gas, and swim away at the slightest whiff of oxygen. Like most bacteria in the wild, they live in interdependent communities of large and varied populations.
photo, Norbert Pfennig

Pollution—NOT! Virtually all lakes harbor descendants of ancient microbes which photosynthesize but which cannot tolerate oxygen and thus usually remain in murky depths. Here, at Lake Cisó in Spain, abundant hydrogen sulfide and trees protect the waters from aerating winds, and the healthy Chromatium turn the lake a comely pink.
photo, Ricardo Guerrero

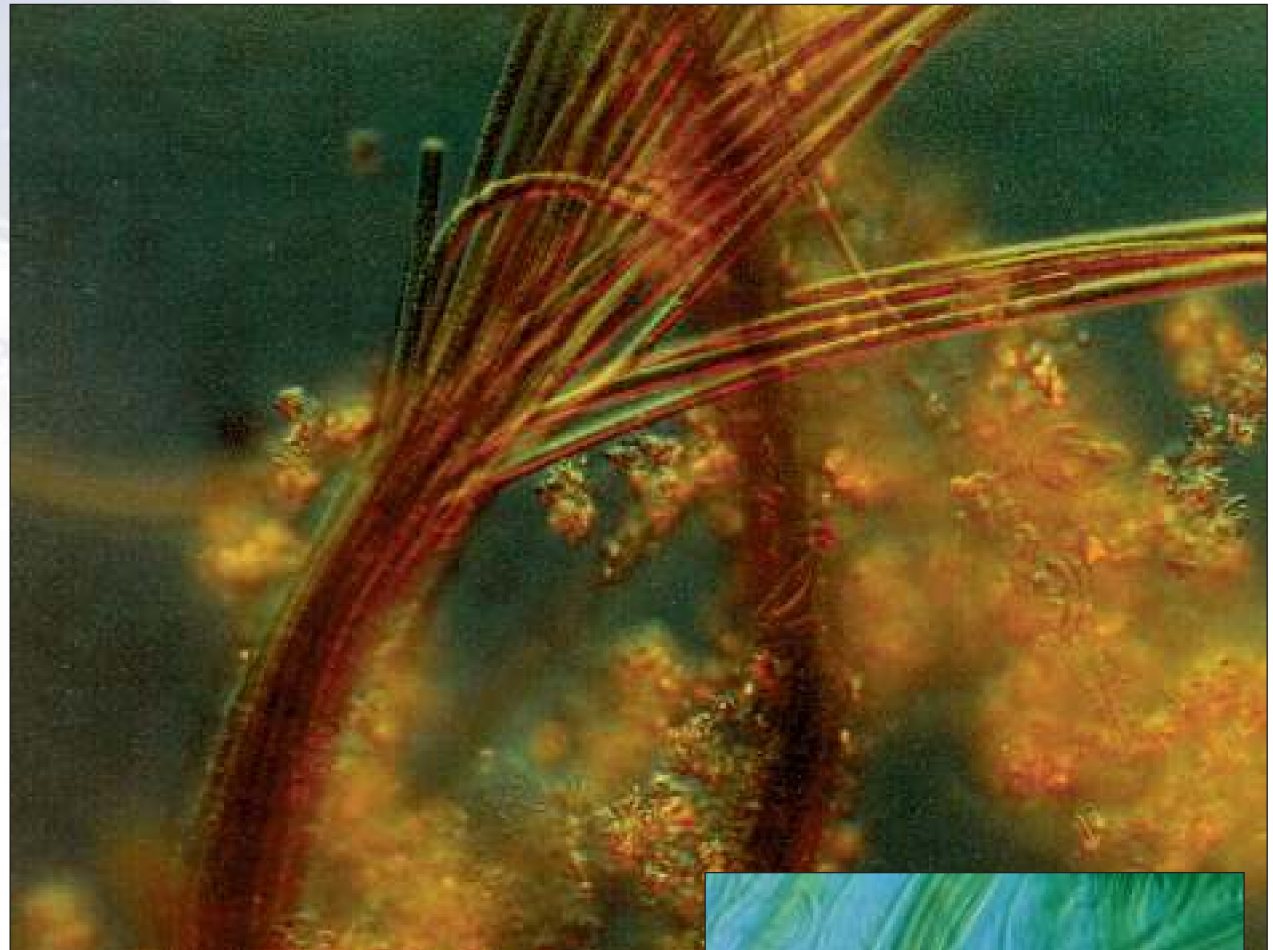
3600
MYA
MILLION YEARS AGO

Tripping the Light Fantastic

And the Waters Separated

As Earth calms, hydrogen becomes scarce. The cyanobacteria (the blue-greens, wiliest of the microbes), pioneer the intranet approach: inside themselves, they link together two photosystems. This gives cyanobacteria enough energy to split tightly knit water molecules and procure hydrogen.

Waste Not. Great innovations are often characterized by unexpected novelties and unimaginable results. This power-plant technique of harvesting hydrogen also produces highly toxic waste, oxygen, which poisons other anaerobic microbes while opening new and diverse paths for oxygen-breathing biota.



photo, Carmen Aguilar-Diaz

Microcoleus chthonoplastes bacteria, soaking in sunlight, employ protective sheaths to screen out ultraviolet radiation. We still do not understand how these gliding mat builders move.

photo, John Stoltz

3500
MYA
MILLION YEARS AGO

Stromatolites
Community Living

The benefits of community life impress microbes early on. One microbe's waste is another's lunch. Eating, reproducing and making waste are consistent features in the continual development of life. Microbial mats form richly layered ecosystems and, under the right conditions, these become stromatolite bacterial skyscrapers.

The blue-greens live in the top layers, slipping in and out of UV-light-shielding sheaths to gather solar energy. Cyanobacteria produce prodigious amounts of food. "Consumer" bacteria, immune to oxygen, quickly join the cyanobacteria. Beneath them live mixed populations of consumers and producers, each possessing unique diets, tolerances for oxygen, light and sulfides.

photo, J. William Schopf

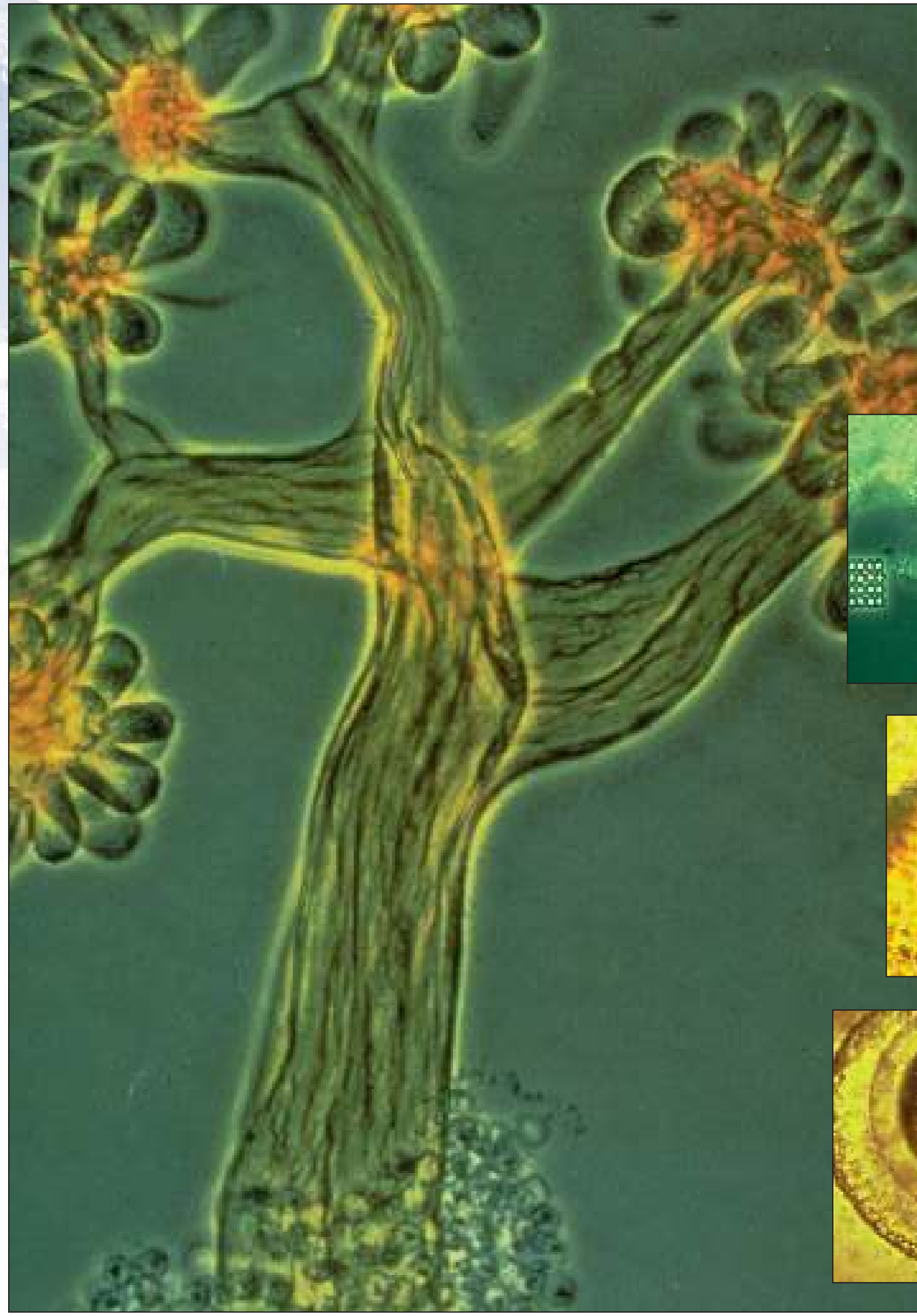
This fossil stromatolite (top) sings of the benefits of bustling, layered microbial community life in Warrawoona, northwest Australia, 3,500 Mya. The living microbial mat (bottom) is from Matanzas, Cuba.
photo, Peter Westbroek

3400
MYA
MILLION YEARS AGO

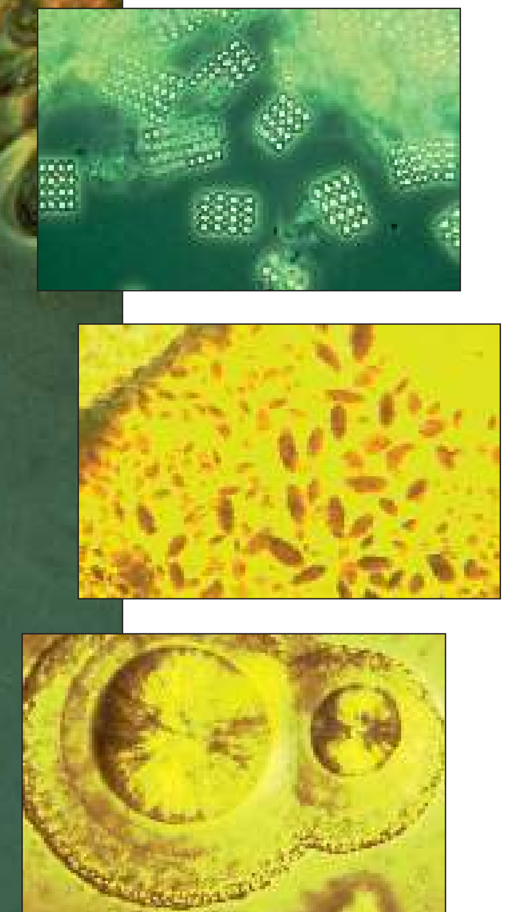
LIFE STYLES OF THE LITTLE

As the thickest and oldest parts of the continents form, microbes experiment with various life styles. Those who take up swimming explore habitats, moving with grace from meal to meal. Many microbes pursue colonial life styles, huge populations mixing with one another for food and flexible gene exchange.

Microbes also experiment with multicellular lifestyles, some forming complexes eerily like trees and other organisms of our familiar landscapes.



This myxobacterium practices the aggregate "tree"-habit as a way to hang out and hang on through nutrient and water scarcities. When resources rebound, this fancy microbe drops "melon"-like pseudo fruits, releasing thousands of bacteria to procreate and recreate.
photo, Hans Reichenbach



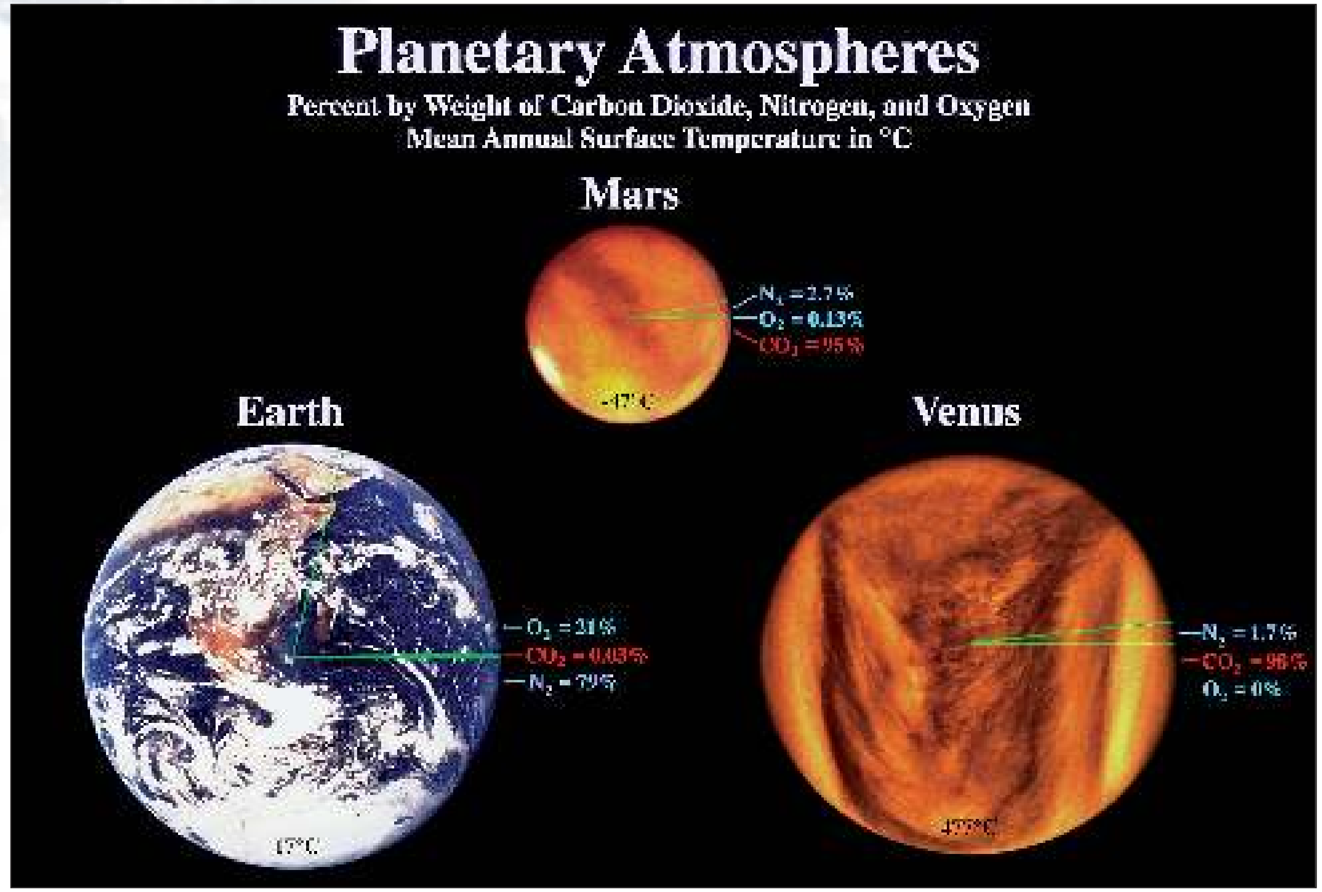
Bacteria practice many colony styles.
photo, Lynn Margulis

3300
MYA
MILLION YEARS AGO

GOLDILOCKS AND THE THREE ATMOSPHERES

Atmospheric differences among the inner planets are influenced jointly by their proximity to the Sun and individual aspects of their evolution. Earth is our solar system's "Goldilocks:" Venus is too hot; Mars is too cold; Earth is just right. One of the big questions: Why are the inner planets, so similar in origin and relative composition of elements, so different? What accounts for the strange nature of Earth's atmosphere?

Life makes the difference. Carbon-dioxide-consuming and producing beings of the biosphere, tightly coupled with geological processes, have influenced Earth's faces and flows for thousands of millions of years.



Global temperature, gaseous atmospheric composition, and oceanic salinity and alkalinity fall under active biological modulation. Chemical, geological and geophysiological forces influence our environment. The biosphere forms a living body, an aggregate of interactive Earth.
graphic, Jesse Anderson courtesy New England Science Center

3200
MYA
MILLION YEARS AGO

We've Come a Long Way

Not until 1950 do paleontologists begin to find signs of life earlier than the large-sized fossils dated 600 mya. Suspecting that microbial life evolved before animals and plants, thoughtful researchers commence a search.

In South Africa, explorers find the Fig Tree Formation. A rare series of sediments and rock many tens of thousands of feet thick, the Formation contains some units of dense rock called chert, a smooth form of quartz. Although the chert appears barren, a microscopic search reveals signs of the kind of life that helped make stromatolites. Fossilized bacteria, including cyanobacteria, lie peacefully arranged in smooth layers within the rock. Some of the minute microfossils within this Formation constitute precious evidence of early life.

Laminated chert from the Fig Tree Formation
photo, Lynn Margulis

3100
MYA
MILLION YEARS AGO

EARTH MOVES ON

Several huge, moving and shifting crustal plates carry Earth's small continents about. These plates, of which the continents are the raised portions, are part of Earth's lithosphere, which includes Earth's crust and the top rigid layer of its mantle. The lithosphere overlays a deeper "plastic" layer of inner Earth, where high temperature and pressure prevent rocks from solidifying.

Plate movement continually generates fresh lithosphere as molten rock erupts at mid-ocean ridges. Oceanic plate margins are drawn into the mantle and melt at continental edges. As these processes cycle, continents move together and pull apart, oceans shrink and expand, plates collide and form mountain ranges, and island chains appear and vanish.

When a plate moves across a "hot spot" it leaves a volcanic trail.
photo, courtesy National Center for Atmospheric Research

3000 MYA
MILLION YEARS AGO

Metabolic Modes

Earth life forms require energy and carbon for growth and reproduction. They satisfy these requirements through a variety of processes. Some skilled individuals produce their own food; many rely on others to make it for them.

By this time, microbes have evolved every metabolic mode known to 20th century scientists. Tiny gas-eating microbes, without using light, refine methods of making food and energy from sulfide, methane, ammonia, oxygen and carbon dioxide. Cyanobacteria and their kin, using sunlight as a source of energy create food from atmospheric carbon dioxide. Dependent on these primary producers, many microbes mix and match modes.

Stromatolite reefs, monuments of bacterial life, continue expanding across the planet.

This tall Canadian has stepped back 1800 million years, in the Canadian Northwest Territories, to show us just how grand bacterial building can be.
photo, Fred Campbell

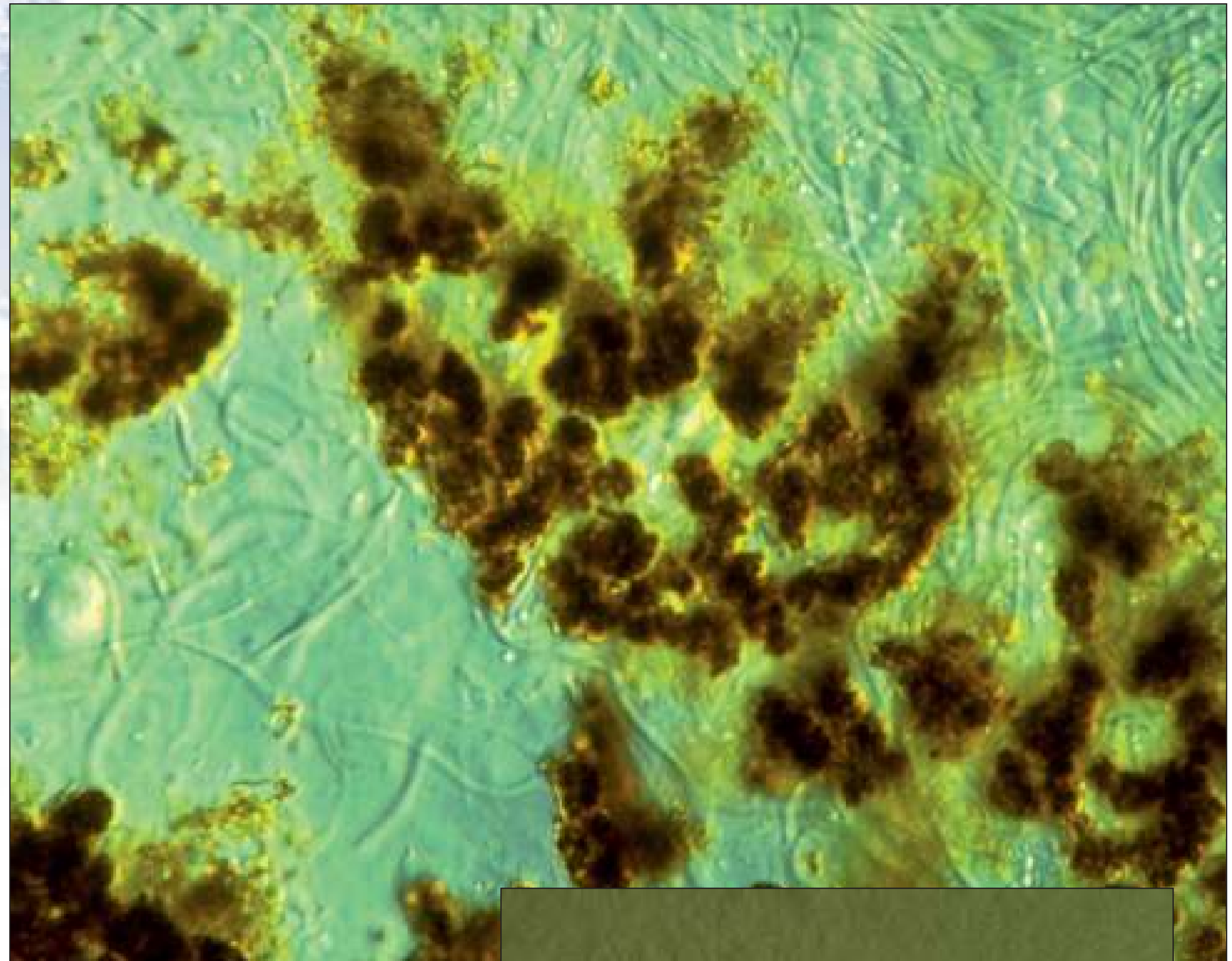
This awesome blue-green bacterium is a great adapter, a switch hitter. Usually, it grabs hydrogen atoms from water, releasing oxygen. Under high hydrogen sulfide conditions, it pops out gobs of yellow sulfur instead.
photo, Lynn Margulis

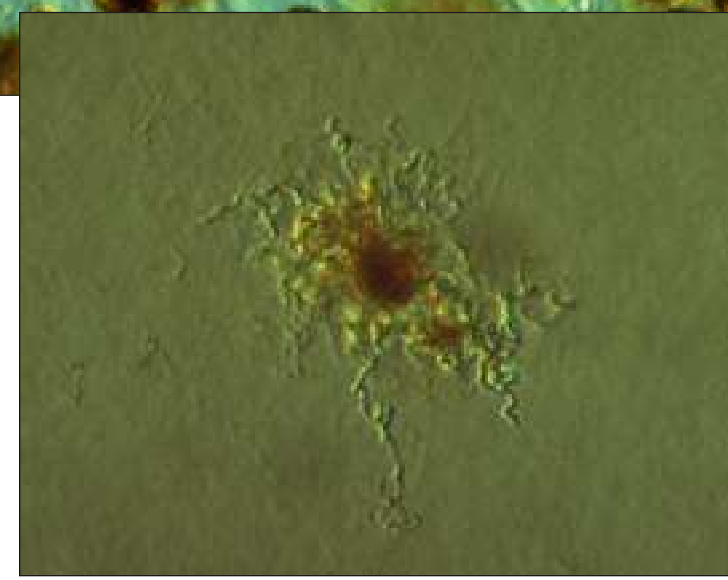
2900 MYA
MILLION YEARS AGO

MICROBIAL MINING AND MANUFACTURING

Bacteria modify the global mineral cycle in two important ways: they induce nearby minerals to precipitate (settle out of solution), and they internally manufacture minerals. Bacteria swimming in a river help precipitate the great gold deposits of South Africa. Today, these wee wonders head for the mines in Russia. Miners pump microbes and water into thin or hard-to-reach veins.

Initial research indicates that microbes biologically induce over 27 kinds of minerals. Which minerals these versatile fellows form depends upon their environment and their own genetic capabilities.





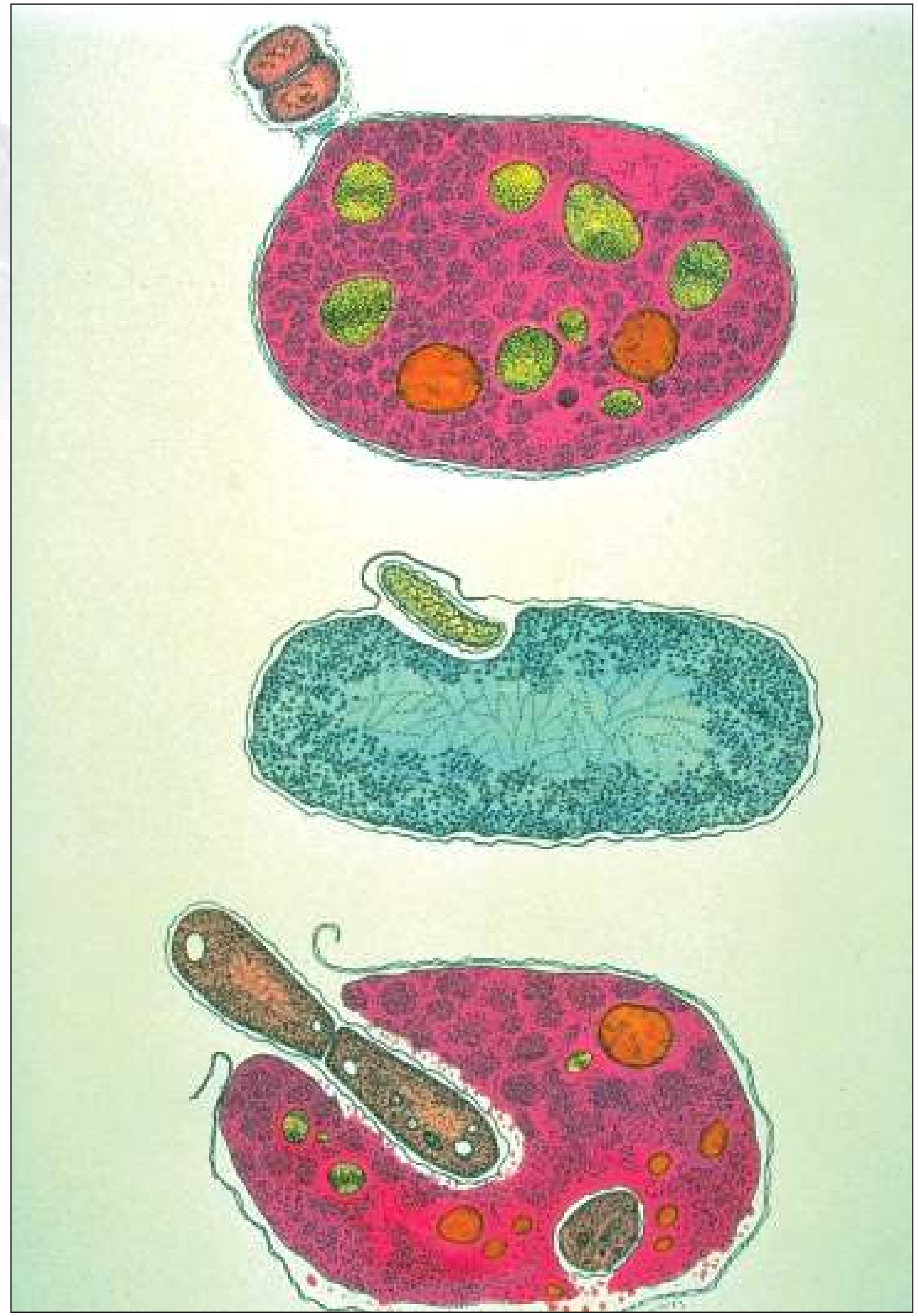
Metal makers do their thing. These bacteria have precipitated manganese dioxide minerals out of solution.
photos, Lynn Margulis

Horde Havoc

Community living offers great benefits. One drawback is overcrowding, which leads to unneighborly behavior. Confusing friend with food, predators appear within the playfully swimming bacterial cooperatives.

The "Vampire-berry" (*Vampirococcus*) attaches to and eats away the larger prey cells. Other microcosmic predators like *Bdellovibrio* slip just inside the surface of an unsuspecting neighbor, close the membrane and start digesting. A common predator lives and feeds by itself until resources diminish. When nearly overcome by crowding, it moves inside its intended victim and starts to divide.

It is speculated, in one of nature's luscious ironies, that the outcome of invasion, followed by truce, produces a grand blossoming in the history of life.



Vampirococcus, Bdellovibrio, and Daptobacter (top to bottom) practice new nutritional modes.
drawing, Christie Lyons

Symbiogenesis

Presence of the Past

Symbiosis is the prolonged physical association of two or more different kinds of organisms. *Endosymbiosis* involves one life-form actually living inside another, often in a long-lasting merger. *Symbiogenesis*, the source of true evolutionary novelty, occurs when the mergers of independent organisms actually form composites. A totally new kind of being may then evolve.

All life forms—with the exception of bacteria from which they evolved—are consortia. Our cells are the result of millions of years of mergers, the outcome of once free-living bacteria that came together in permanent relationships.

We are all chimera, composites of many life-forms and many mergers. Identity is less an object than a process. We all envelop traces of bygone beings.

> *"The trading by bacteria of genetic information provides the basis for understanding new concepts of evolution. Evolution is no linear family tree, but change in the single multidimensional being that has grown now to cover the entire surface of Earth."*
>
> – Lynn Margulis and Dorion Sagan

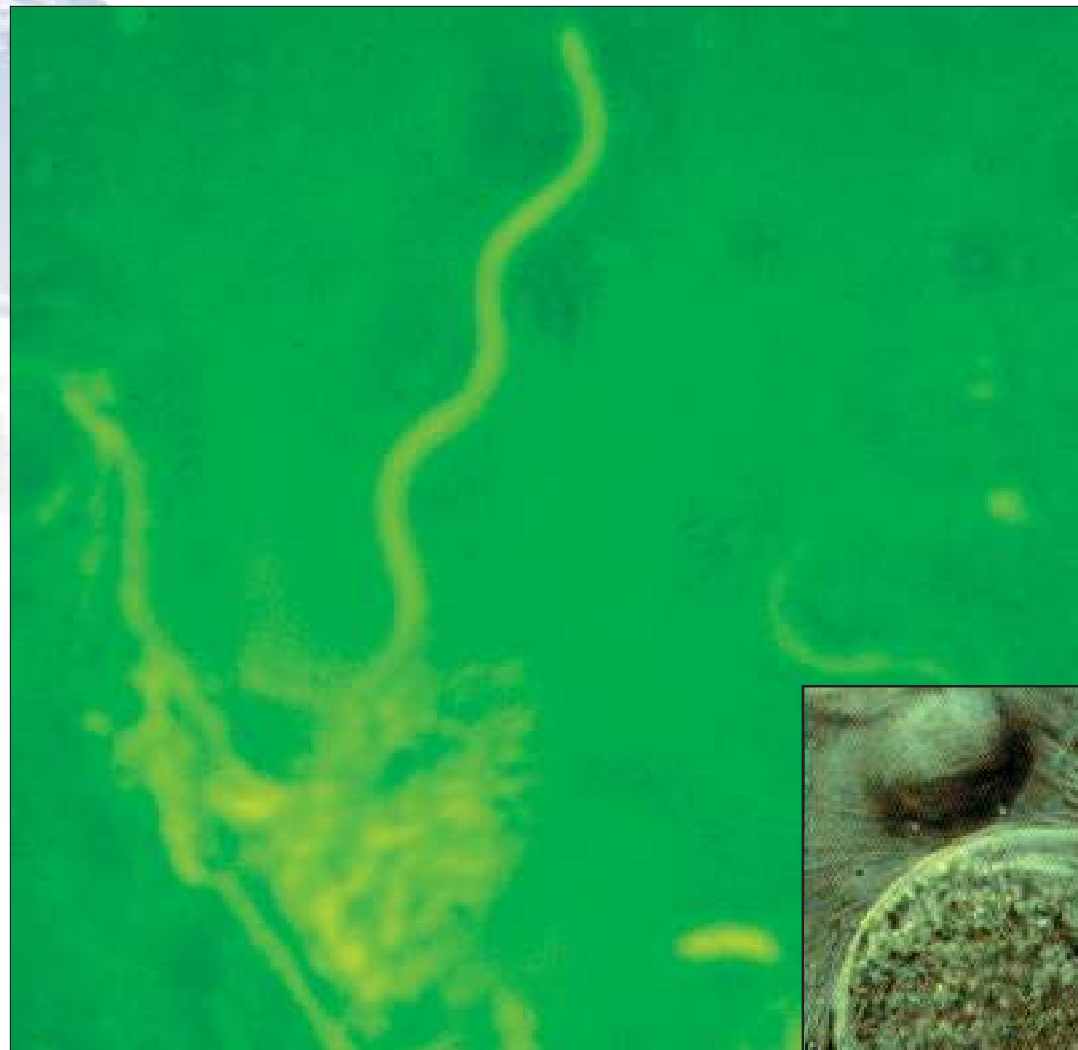
Images of Earth from the Moon vibrantly convey the life of the planet.
photo, courtesy NASA

Joint Ventures

Special joint ventures occur in communities of mixed populations. A sluggish, ancient fermenting bacterium and a small, swimming, spirochete-like bacterium may have formed a particularly brilliant partnership.

Spirochetes, speedsters of the microbial world, arrive quickly at food sources. Their corkscrew bodies move perfectly through seaside muds, the viscous insides of animals, and all around our gums. Spirochetes have neither head nor tail until they attach to something. Seeping a sticky substance, individuals and often groups easily tack directly onto a larger microbe.

The adhered spirochetes enjoy the microbe's byproducts in exchange for providing their partner with fast and easy transport toward food.



Spirochetes are masters of movement, corkscrewing about with neither head nor tail.
photo, Lynn Margulis

This contemporary protist, Trichonympha, is pushed through its viscous termite hindgut habitat by thousands of symbiotic spirochete bacteria attaching at the rear.
photo, David Chase

2600
MYA
MILLION YEARS AGO

SURFACING

Larger, thicker, stronger continents emerge as Earth cools, closing the period of major crust-formation. The continents grow and stabilize. Shallow, wide continental shelves provide ideal habitats for the growth and preservation of stromatolites. These cosmopolitan communities grow abundantly and luxuriantly along the continental margins.

photo, Paul Strother

photo, Lynn Margulis

photo, Elso Barghoorn

Miniature versions of deep-time scapes are preserved in Shark Bay, Australia and off the coast of Lee Stocking Island in the Bahamas.

2500
MYA
MILLION YEARS AGO

BIOLOGIC AND GEOLOGIC SYSTEMS WED

Modern geological processes begin. Coupling tightens between geologic and biologic systems. Mineral-forming organisms modify the chemical and physical nature of the biosphere. Bacteria induce minerals to precipitate huge carbonate platforms, giant barrier reefs, fringing reefs, and mounds.

Mat, stromatolite and reef-building communities are highly varied. These tiny architects build huge and diverse rock-solid parts of the planet.
photo, Stjepko Golubic

2400
MYA
MILLION YEARS AGO

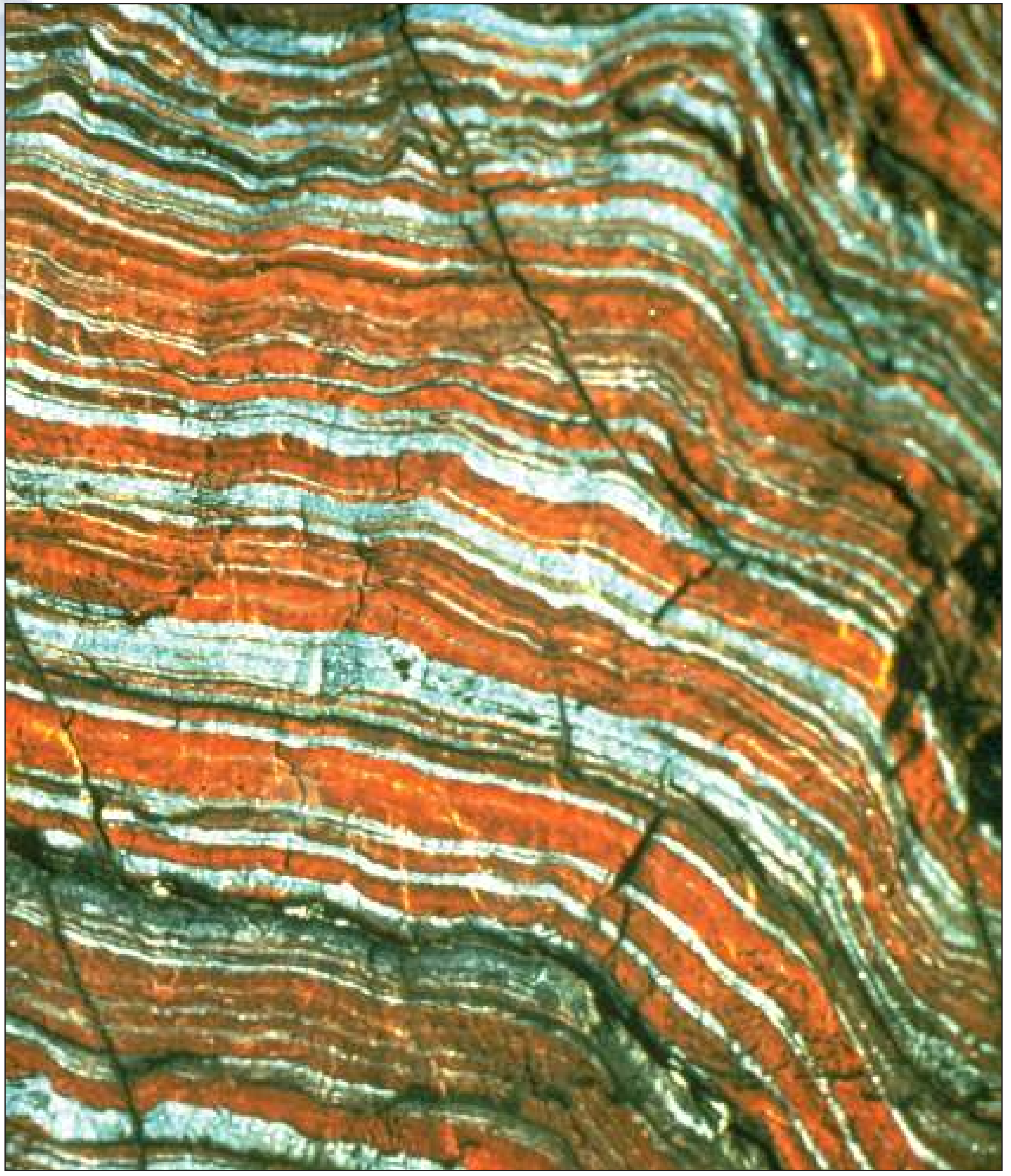
ORE-IGINALS

Although global cyanobacteria release massive amounts of oxygen "waste," no surplus builds up in Earth's atmosphere. Oxygen gas reacts immediately with hydrogen, carbon and iron to form oxides such as water, calcium carbonate (limestone) and iron ore (hematite and magnetite).

For 600 million years, sediments of alternately higher and lower concentrations of iron oxide settle out on the ocean floors. Some of these sediments metamorphose into massive banded-iron formations, or BIFs, which are the principal source of iron mined by humans two thousand million years in the future.

Scientists theorize that fluctuations in these iron oxide deposits were caused by some combination of seasonal upwelling of iron-rich waters from the depths of the ocean, seasonal variations in photosynthetic activity, periodic volcanic eruptions, and seasonal variations in the oxygen production of cyanobacteria.

One interpretation is that the layers may be read as growth rings, indicating increases in oxygen "exhaust" by cyanobacteria in warmer seasons and lower exhaust in cooler seasons.



Jaspilite-hematite BIF Michigan, USA
The "World Wide Age of BIFs" extends from 2400 MYA through 1800 MYA. BIFs cover vast stretches of the planet, hundreds of kilometers across, and contain 90 percent of Earth's minable iron. Next time you drive your car, you might want to thank the Earth and its greatest bacteria, the bluegreens, for their contribution.
photo, Preston Cloud

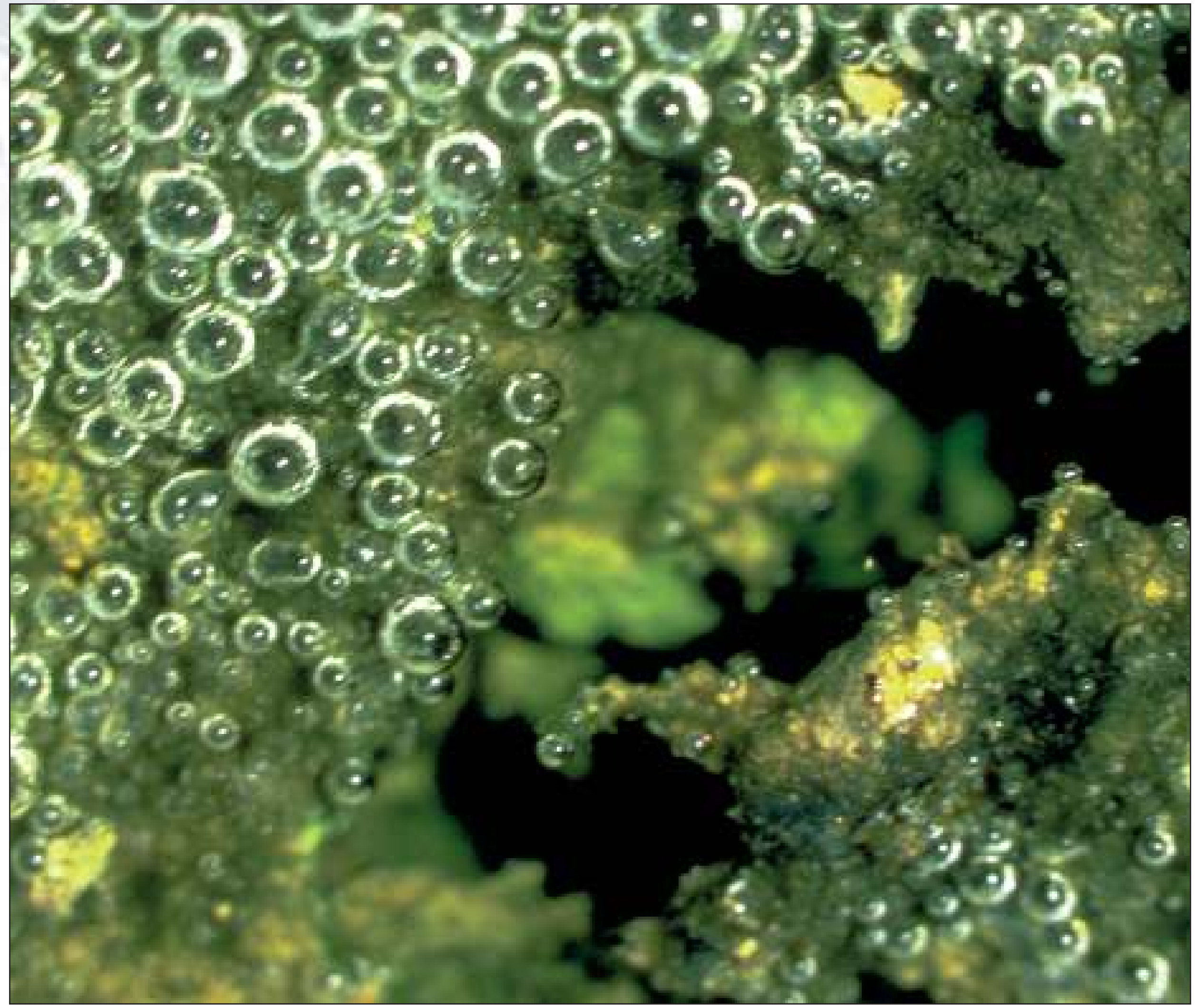
2300
MYA
MILLION YEARS AGO

Energized

Able to swap and repair genes, some microbes evolve ways to tolerate oxygen by forming protective enzymes. These enzymes react with dangerous radicals produced by oxygen, converting them to innocuous compounds.

Other microbes develop a radical approach to oxygen, which both protects them and provides a powerful new means of energy transformation. They consume the oxygen produced by photosynthesis. Aerobic respiration commences: controlled combustion breaks down organic molecules for energy and gives off energy-poor carbon dioxide and water.

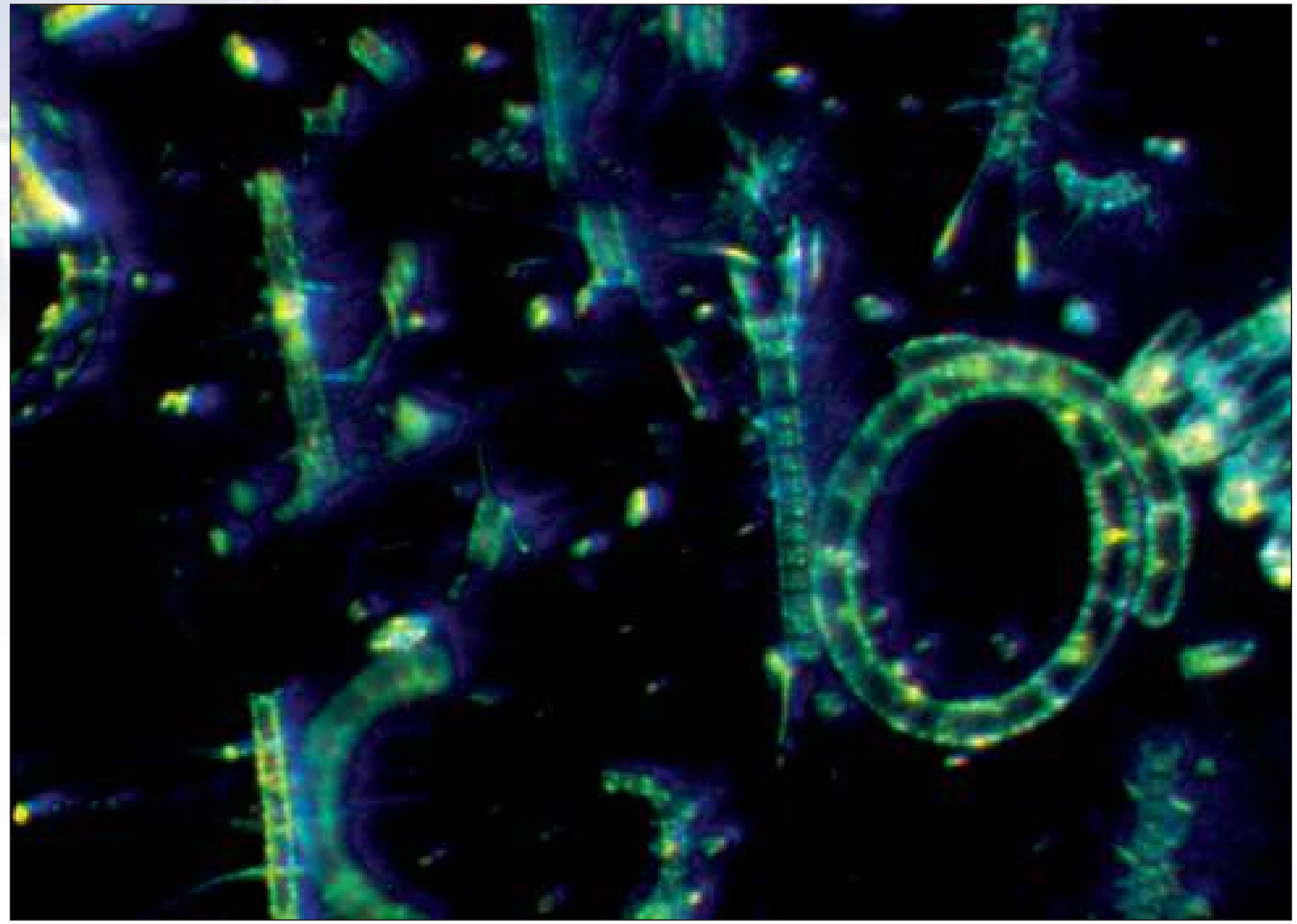
This innovation energizes life. Fermenting a single sugar molecule produces two molecules of ATP, the primary energy carrier for cell metabolism and motility. Processing the same sugar molecule through respiration yields as many as 36 energizing ATP molecules.


photo, Richard Ettinger

2200
MYA
MILLION YEARS AGO

Off to Sea

Expanding reefs are a springboard for life in the oceans. Some bacterioplankton and algae, floating in the upper layers of Earth's oceans, become primary producers (photosynthesizers that make their own food) for expanding life. As they did in the shallows of early Earth, these microbes evolve a myriad of independent and interacting life styles.



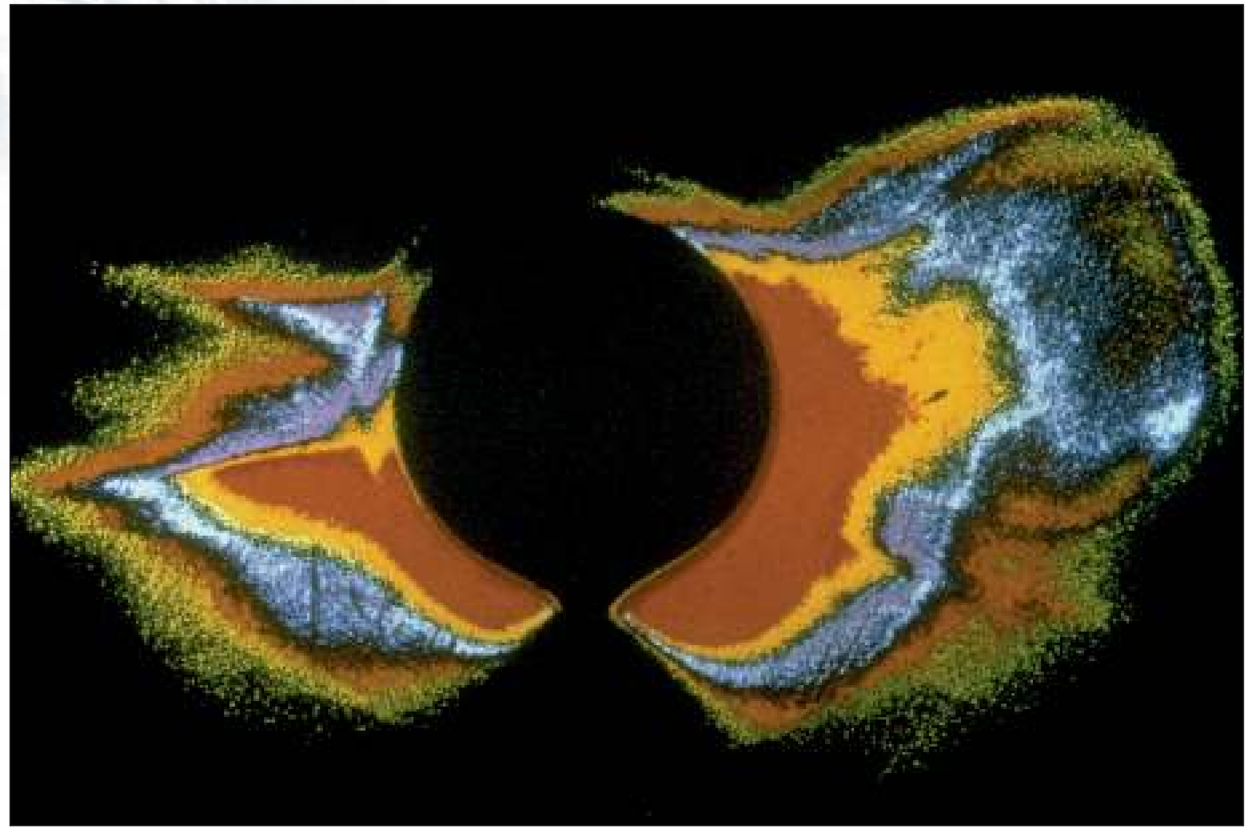
Current photoplankton photo opportunity
photo, M. Despezio courtesy Marine Biological Laboratory, Woods Hole

2100
MYA
MILLION YEARS AGO

Putting the O's into Ozone

As cyanobacteria-generated oxygen continues to accumulate in the atmosphere, a protective ozone layer begins to form. In another remarkable twist in the evolutionary story of life, oxygen, once a fatal form of air pollution, becomes a shield for future life against the sun’s destructive ultraviolet (UV) rays.

Long before the Earth's ozone layer formed, bacteria had developed mechanisms to cope with UV light: making sheaths, submerging themselves, digging in. They evolved the ability to repair genes damaged by UV light. Had no UV-absorbing ozone layer formed, life on Earth might have remained the exclusive realm of the microbes.



The solar corona, a halo of light around the darkened Sun, visible during a total eclipse.
image, courtesy National Center for Atmospheric Research

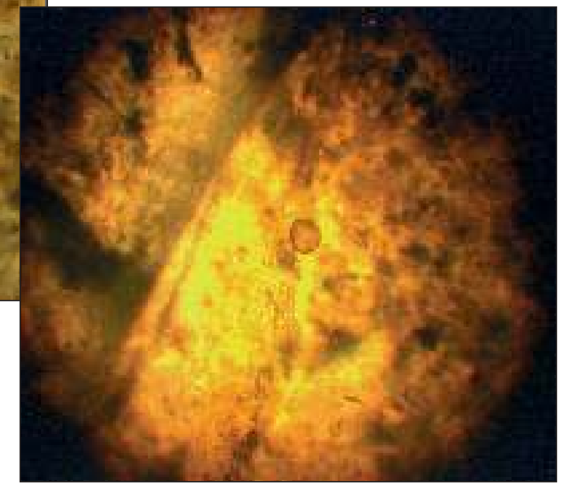
2000
MYA
MILLION YEARS AGO

Abundant Life

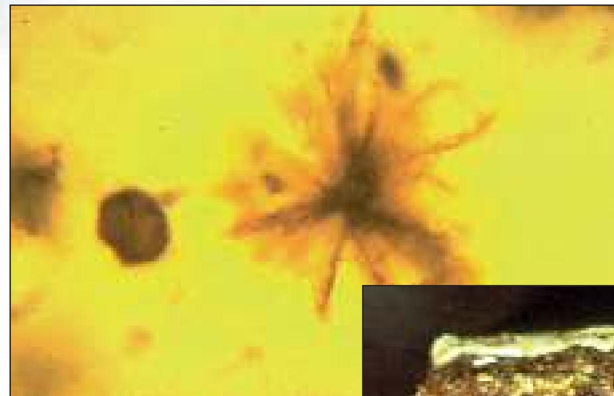
Fossil records reflect the abundance of life. Total anaerobes bury themselves as deeply as they can in their communities. Strains of cyanobacteria, poisoned by their own oxygen waste, team up with populations of respiring bacteria which immediately slurp up the oxygen so toxic to their cousins.

Off and running in waves of innovation, aerobes' new-found energies allow them to experiment. They forge new niches, specialize and try new sorts of life styles. Some bud motile off-spring who, although clones, look nothing like the parent. These baby bacteria swim to a favorable location, attach to a solid surface and "metamorphose" back into parental form.

photo, Gonzalo Vidal



photo, Stanley Awramik



The fine chert of the Gunflint Iron Formation sports a profusion of stellate (star-shaped) and ovoid microorganism fossils. A complicated assemblage of living and growing bacterial communities have lain preserved, locked in the rocks of the formations for 2000 million years.
photo, Lynn Margulis

Year after year, layers of photosynthesizers and their followers pile up. This hand-sample of a contemporary mat community reflects over 100 years of stable community growth.
photo, Stanley Awramik

1900
MYA
MILLION YEARS AGO

Great Mortalities for the Immortals

Bacteria have no specified life-span; they suffer no "programmed" death. When environmental factors are right, bacteria are immortal. These tiny organisms can be killed, of course, by predators, through starvation, and by encounters with kitchen-counter sprays, chlorinated water and terrorist-like antibiotics.

The light-eating cyanobacteria start an oxygen revolution.
Due to their waste, the concentration of oxygen in the atmosphere jumps from virtually nothing to one part in five. For those masses of fermenters with no protective hideaway, an oxygen catastrophe results. A guess is that up to 90 percent of anaerobes die in the revolution.

A moment of silence, please
photo, Lois Brynes

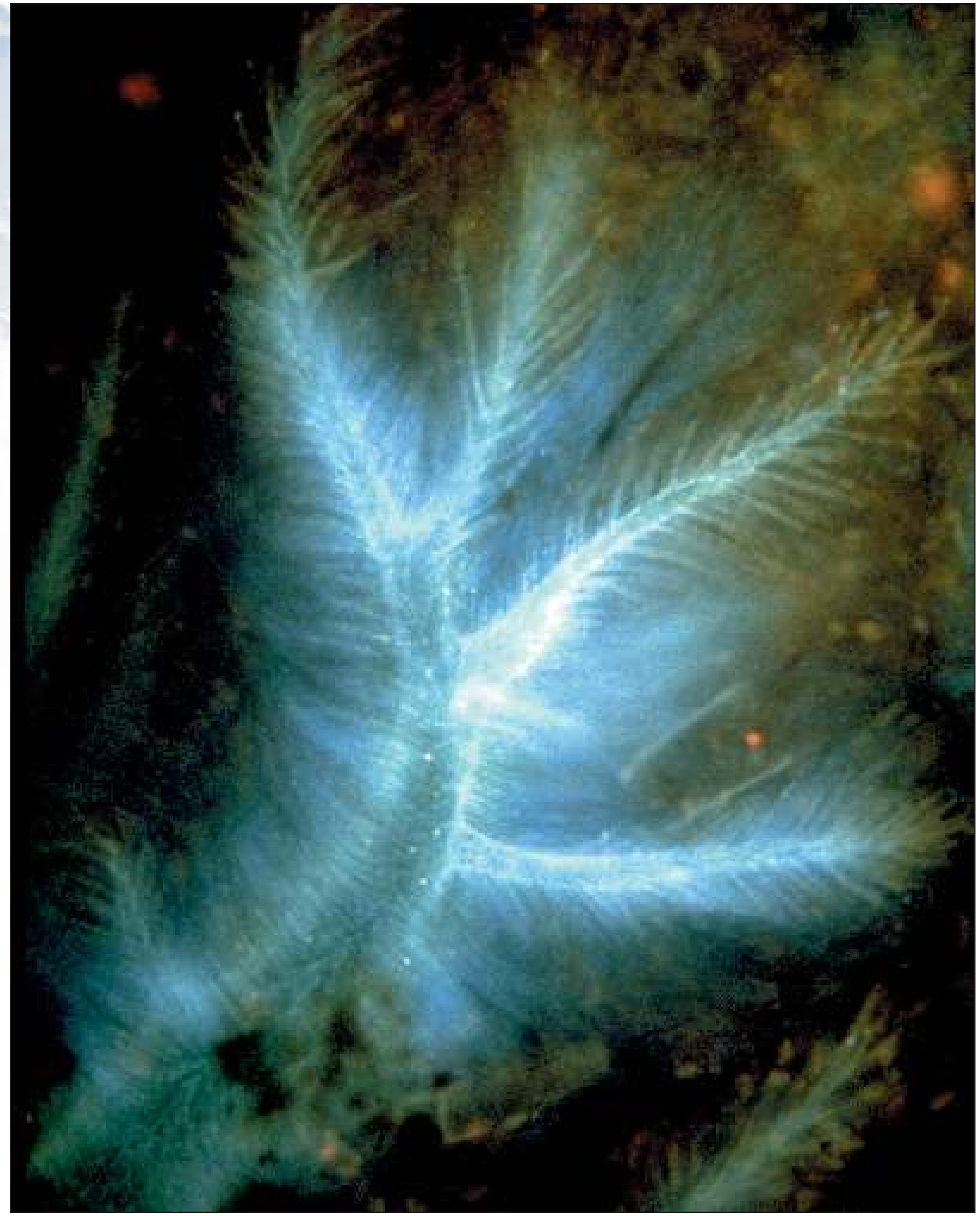
1800
MYA
MILLION YEARS AGO

THE EARTH RUSTS

Major atmospheric changes radically transform Earth's surface. "Red Beds," those huge, rusty piles of uniformly oxidized iron mineral, form everywhere on the planet. BIFs stop accumulating.

The lucky among the anaerobic bacteria find mud flats and airless niches in which to survive. These relics of the Archean atmosphere still thrive in the 20th century – at the sulfurous smelling edges of the sea, in swamps, inside insects and inside us.

In oxygen-tolerant and now, oxygen-loving bacteria, grand innovations continue. Their mode of respiration is about to lead to new life forms emerging from a dramatic symbiogenesis.



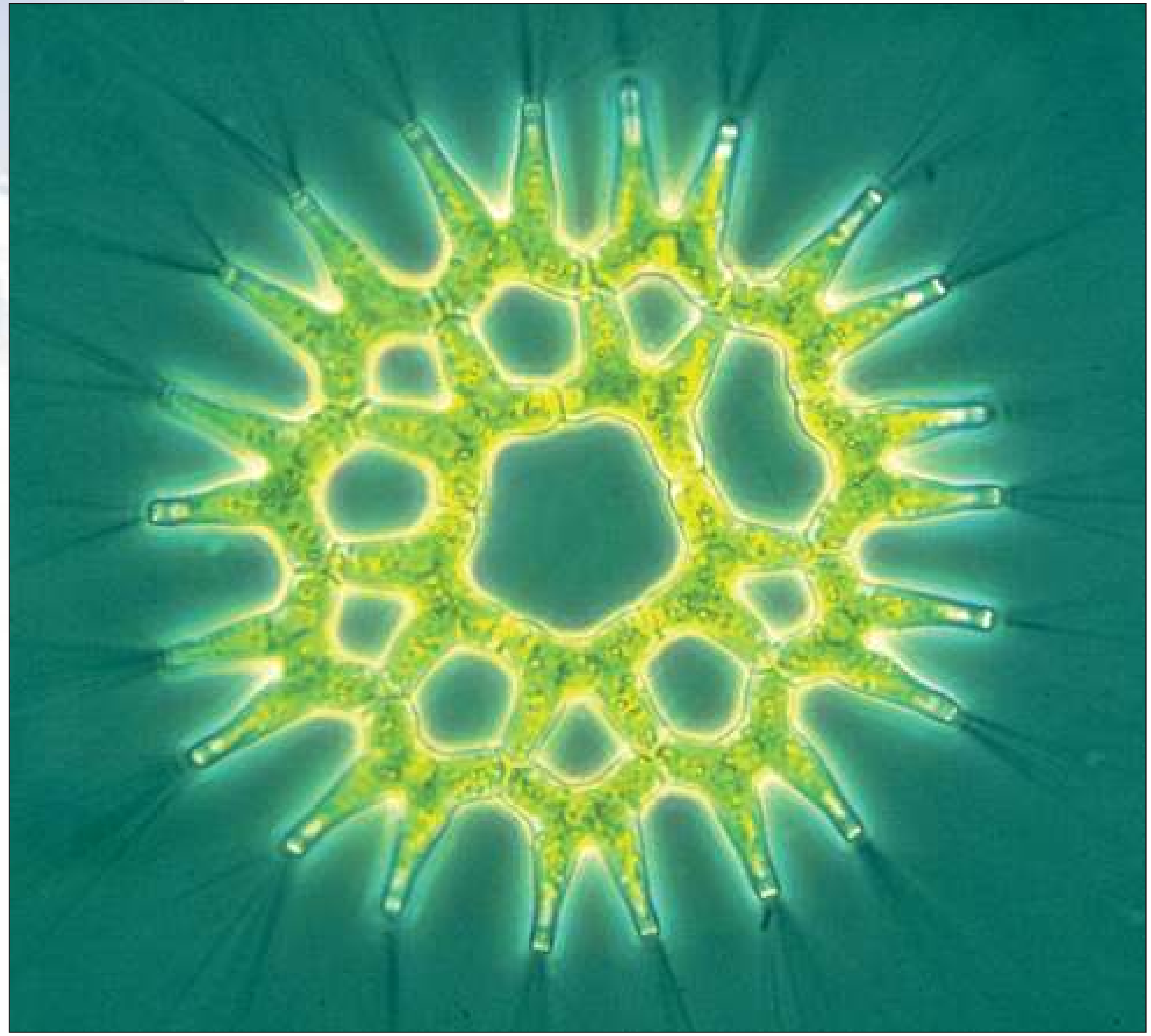
Over deep-time, anaerobic life forms not only find special niches, they make them. This beautiful feather is actually a specialized organ in the intestine of the beetle larva, symbiotically made by and for glowing methanogenic bacteria.
photo, Johannes H.P. Hackstein

1700
MYA
MILLION YEARS AGO

Metamorphic Mergers

In many places on Earth, complex new cells arise as microbes permanently merge. These community members form consortia in new ways: some eat but do not totally digest other microbes; others form peaceful alliances.

Protoctists, whose name means simply "first established beings," are like mythic chimera, assembled from distinctly different beings. Sudden symbiotic alliances, supplemented by gradual mutations, transform the face of life. The great Kingdom Protoctista is born, launching life toward increasing complexity, new perils and new potential.



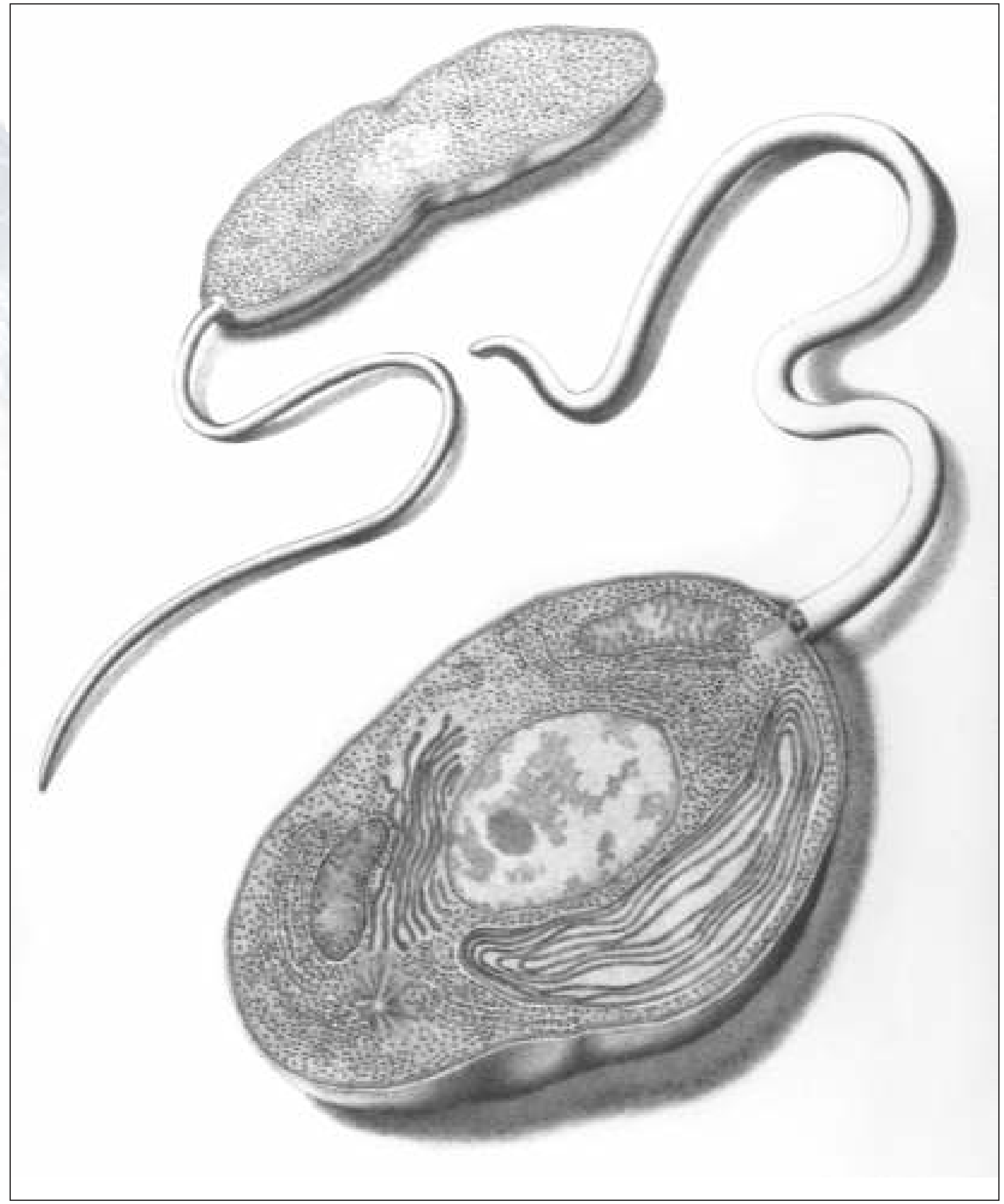
Alga happily photosynthesizing and leaking foodstuffs to other less fortunate beings in its surroundings.
photo, Ludwig Kies

What are Protoctists?

Protoctists (the smallest called protists) are all living beings other than plants, animals, fungi and bacteria. Ubiquitous in damp, wet, watery places, these amazingly diverse beings reside everywhere from ocean abysses to ephemeral dew drops, from moist plant tissues to dark deeps of animal bodies. Some 250,000 different species of protoctists are estimated to exist today!

The earlier joint venture of sluggish fermenting bacteria with microbial speedster spirochetes may have been a prime mover in the development of protoctists. Partners for some time, this hardy combination forms permanent attachments to a new larger cell and gets it moving. Some slide inside the cell and eventually become little organs of motility for that cell.

Some mergers also take oxygen-respiring bacteria as partners. These consortia set the stage for two more great Kingdoms of life: Animals and Fungi. Not about to be left out, cyanobacteria join the fray and convert many protists to photosynthesis. This distinguished clan, the algae, expands, eventually giving rise to the great Kingdom of Plants.



All Earth life consists of only two kinds of cells: the prokaryote (pronounced "pro-carry-oat") which has no nucleus, and the eukaryote (pronounced "you-carry-oat") which does. All protoctists, animals, plants and fungi are eukaryotes. The two cell classifications mark a great divide in all Earth life. Bacteria founded the eukaryotes through a symbiotic merger, creating the great chasm.
drawing, Christie Lyons

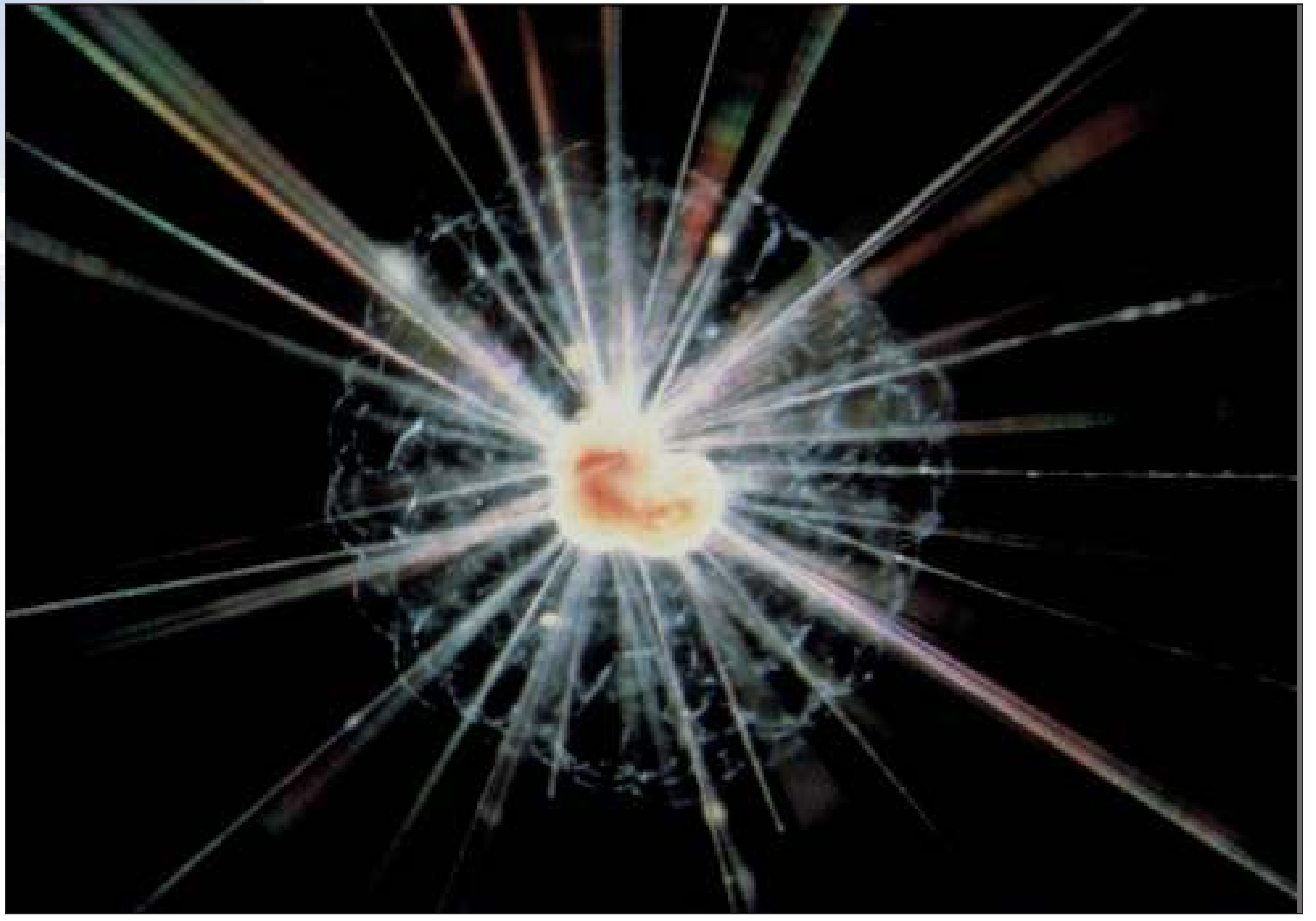
1600
MYA
MILLION YEARS AGO

Thriving in the Oxygen World

The Mighty Mitochondria

Mitochondria reside, sometimes by the hundreds, inside each of our cells. They respire the oxygen that keeps alive the cells of all animals, plants, fungi and most protoctists.

Mitochondria look like the free-living symbiotic bacteria from which they came. They do their own thing: they have their own private DNA and they grow and divide on their own inside each cell. Fortunately for all oxygen-breathing organisms, mitochondria cannot abandon us as they can no longer live outside of our cells.



Oxygen-energized protoctists wildly diversify life. Planktic (floating) and benthic (bottom-dwelling) beings thrive, thanks to their symbiotically acquired, air-breathing mitochondria.
photo, David Caron, Woods Hole Oceanographic Institution

Have you ever thought of yourself as akin to a mitochondria, living within the protective cell of our Earth? What part do we play in this symbiotic planet?

1500
MYA
MILLION YEARS AGO

Sex
A Survival Strategy

For most of our single-celled ancestors, reproduction and sex are entirely distinct. Reproduction involves making more individuals. Most Earth organisms reproduce in single-parent style: by fission, budding, or forming small internal offspring cells. Sex involves fusion of genetic material from at least two individuals. Sex evolves as a survival strategy. In times of extreme stress – colds of winter, drying summer heat – our protoctist ancestors resort to cannibalism to survive. Some do not totally digest their meal; they become doubled beings and, gobbling still others in order to survive, most bloat up and die.

When the environment rebounds, the survivors need to shed their doubleness and tripleness to avoid dying. These problem solvers evolve ways to regularly double every winter (or dry season) through sex, and relieve the doubling every spring.

Seasonal cycling is both a beauty and a constraint for life on Earth. Sex originated for survival, not for reproduction. The orange structure formed as a result of sexual doubling in this green alga.
photo, Ludwig Kies

Why Do Some Cells Die? – Shaping Up

Complex multicellular colonies of protoctists form. In many successful communities, cells become specialists. A different kind of dedication to one's community prevails as the "superorganism" (the new larger individual) evolves. Colonies elaborate on techniques developed for seasonal relief of doubling and invent organized "celli-cide" as the superorganism grows and increases in complexity. Eventually, exquisitely organized individuals, hundreds of millions of cells working together, emerge.

The hundred trillion cells in the human body shape themselves through differentiation and selective death. Programmed death of certain cells is required for differentiation. Think of a block of marble. Without Michelangelo chipping away just the right bits, no figure of David ever appears. Without death on cue, no embryo, brain or immune system develops. Scientists call such programmed death "apoptosis," a Greek word meaning "the falling away of petals from a flower."

How do we allow the fear of death to shape our lives?
photo, Lois Brynes

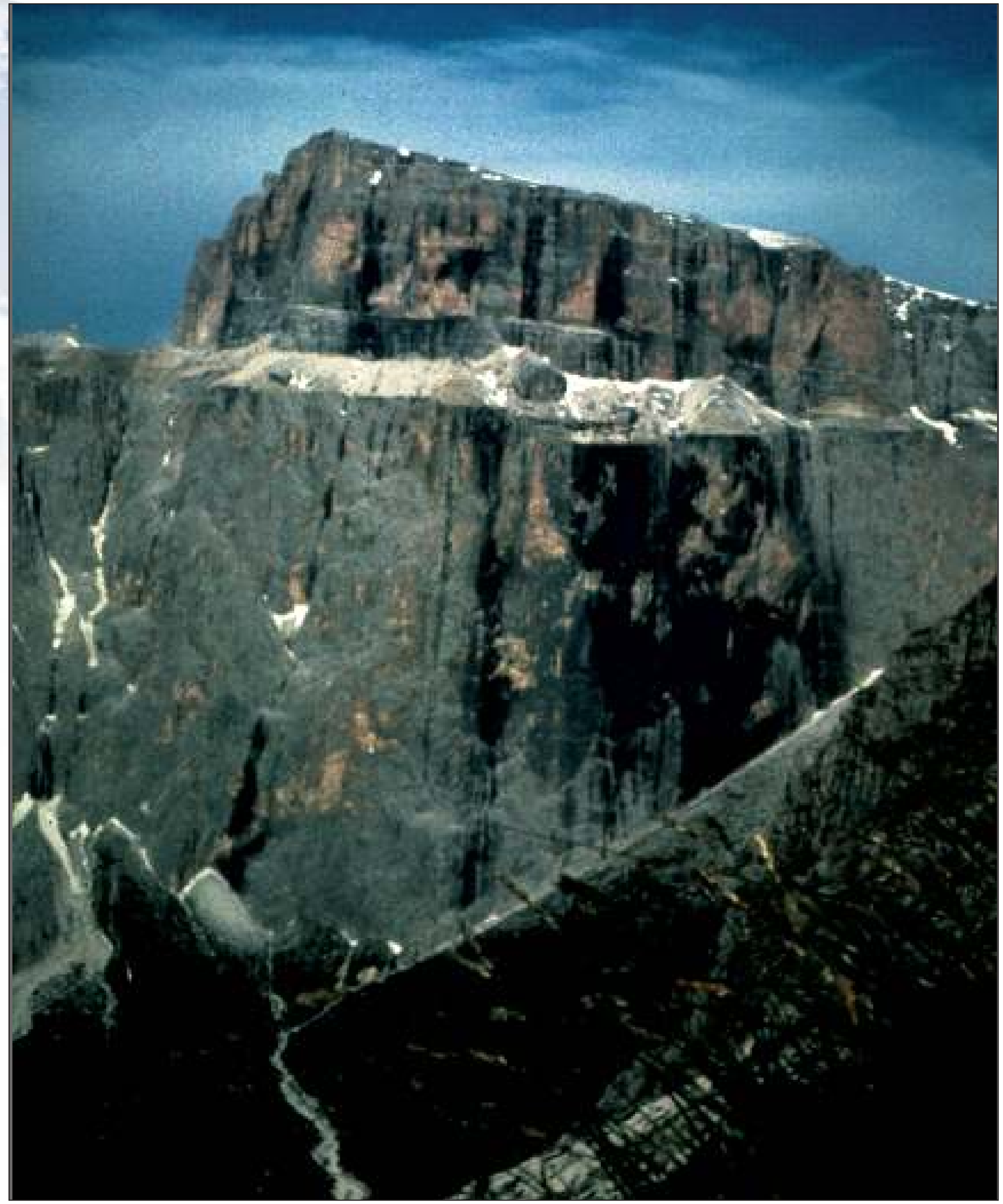
1400 MYA
MILLION YEARS AGO

Niche Masters
Land Ho!

Bacteria move inland, still testing their breathy expertise in new niches. They quickly settle into rivers, ponds and the soils which erosion processes are rapidly creating.

A few ambitious microbes advance to a rough frontier. Expanses of desert become crust-covered communities. Although rare today, these ancient communities still bind the grains of desert sands.

Just as their early bacterial ancestors loved hot springs and acid, some microbes spread in icy climes. The particularly rugged outdoor types take to bare rock and mountain heights, with a breadth of metabolic strategies to meet their needs.



These Norwegian cliffs teem with cyanobacteria that are virtually identical to their rugged fossilized ancestors.
photo, Susan Campbell

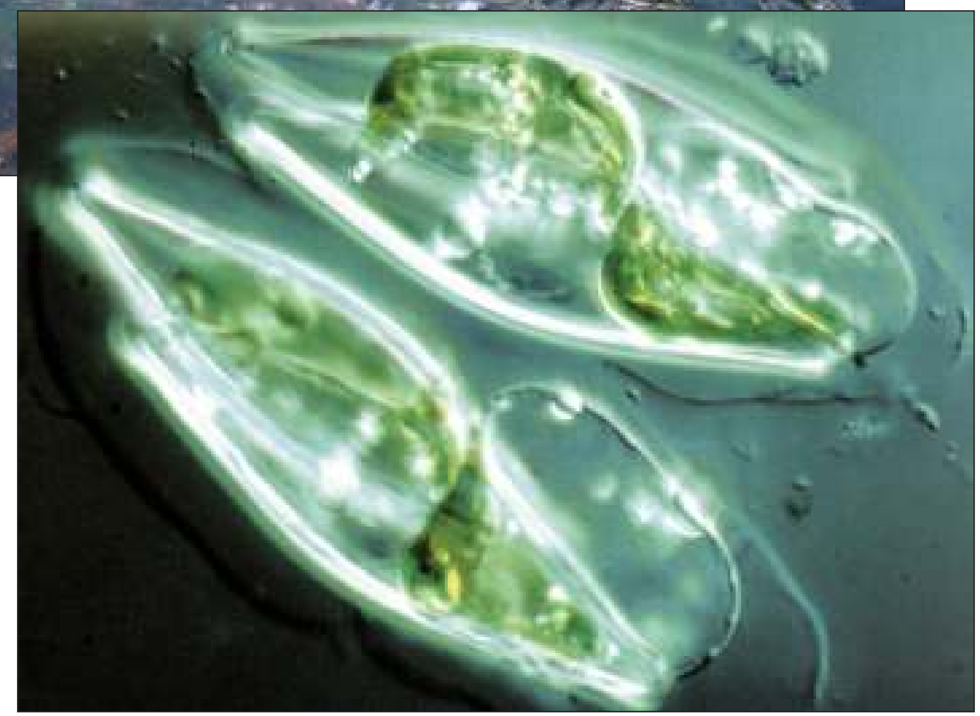
1300
MYA
MILLION YEARS AGO

Corporal Mergers

Protoctists have co-evolved with photosynthetic bacteria for some time. Swallowed up but not digested, some bacteria provide the protoctist with a constant supply of food, which makes them self-sufficient algae. The engulfed bacteria receive a safe, comfortable home and rapid transport to sunlight. With their endosymbiotic (living inside) bacteria, the protoctists, now algae, are virtual living greenhouses.

These cross-species associations celebrate success with permanent mergers. The bacteria transform into new organelles called plastids. Eventually, splashes of green and red seaweed will decorate Earth's coasts.

photo, Lois Brynes



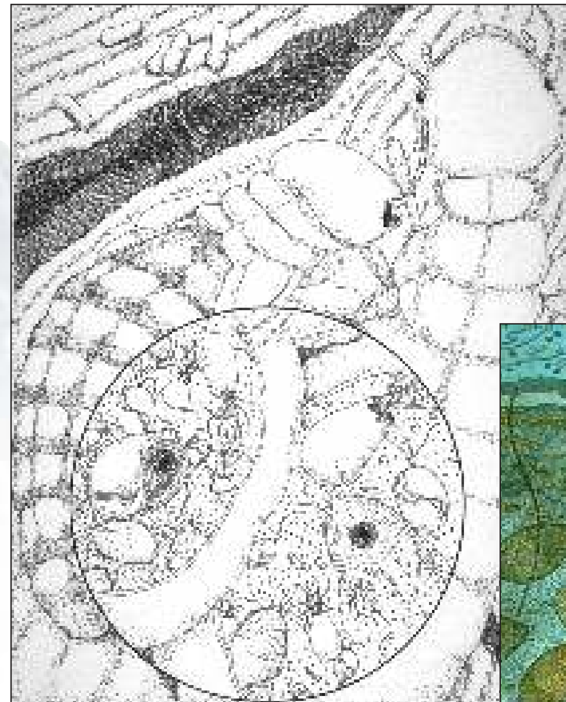
photo, Jeremy Pickett-Heaps

WHAT IS AN INDIVIDUAL?

Identity is a process, not an object. All Earth life is connected through a common ancestry. Each "individual" (each organism) — cow, beetle, daisy, human — is actually a consortium of transformed and still-living other beings.

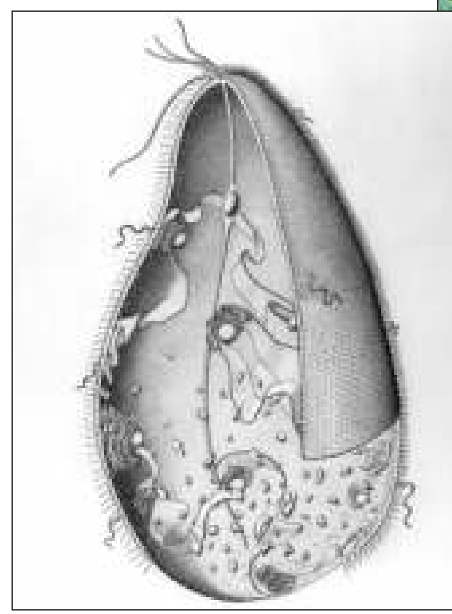
Mixotricha paradoxa ("paradoxically mixed-up hairs"), as seen in the termite community, may help to explain the fractal, nested-network nature of life. A termite nest functions as a superorganism: each nest is an "individual" made up of thousands of termites with specialized, integrated roles. Within an "individual" termite are wall-to-wall microorganisms numbering up to 10^{12} (a trillion) bacteria and 10^{7} (10 million) protists. A termite's hindgut microbial community (an anoxic habitat for successors of ancient microbes) helps digest the wood consumed by the chewing machine.

Within that hindgut microbial community lives a beautiful tiny protoctist called *Mixotricha*. It is actually a consortium of populations: one nucleated cell, two kinds of spirochete bacteria, a rod bacterium on the surface and internal (endosymbiotic) bacteria. *Mixotricha* is in the process of emerging a new "individual."



The microbial world inside a New England termite (Reticulitermes) is seen in this circle of microscopic light.
drawing, Kathryn Delisle

Hindgut wall of a wood-eating termite..
drawing, Christie Lyons



drawing, Christie Lyons

Bosch? Dali? No, it's Mixotricha paradoxa. From 250,000 to 500,000 tiny spirochetes move the "giant" Mixotricha through the viscous habitat.

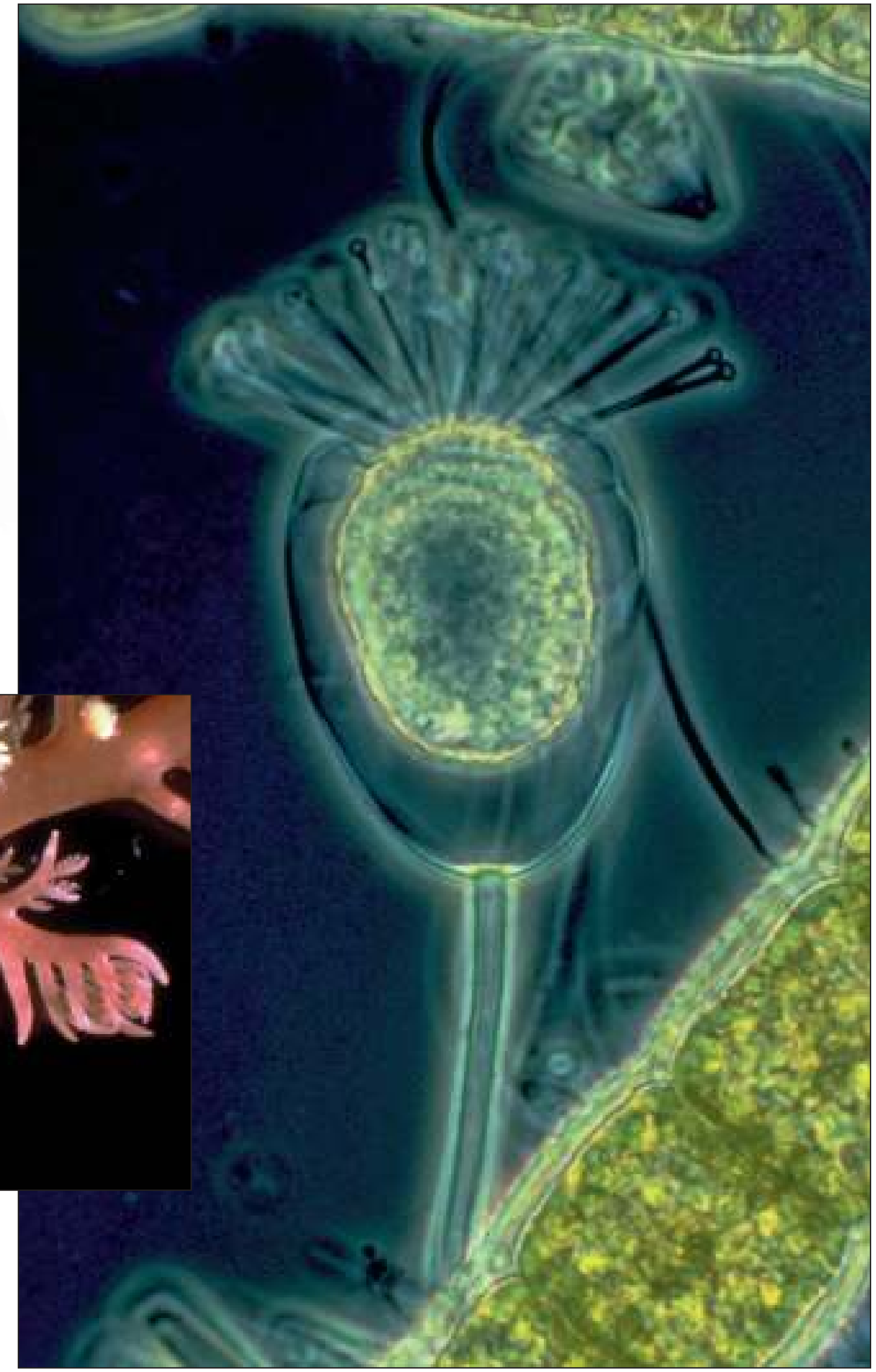
1200
MYA
MILLION YEARS AGO

The One and the Many

The explosive growth of the fossil record of algae and other organisms moves some paleobiologists to dub this the Big Bang period of eukaryotes, beings made of cells with nuclei. Over all Earth, protoctists form communities with bacteria as well as with other protoctists. Manic mixing and matching of populations occurs.

In "colonial" protoctists, a few cells break off from the individual body and regenerate the entire organism. This is not possible for most multicellular protoctists, whose cells, like ours, differentiate (specialize).

The white blobs are freeloading red algae living on photosynthesizing other red algae. The white blob actually sends its nuclei into the red photosynthesizer. It then directs the transfer of photosynthetic products back "home."
photo, Lynda Goff



A filamentous alga, coated with bacteria, supports the base of a tulip-like cilliate that grabs even tinier organisms out of the water through multiple feeding tubes.
photo, John Sieburth

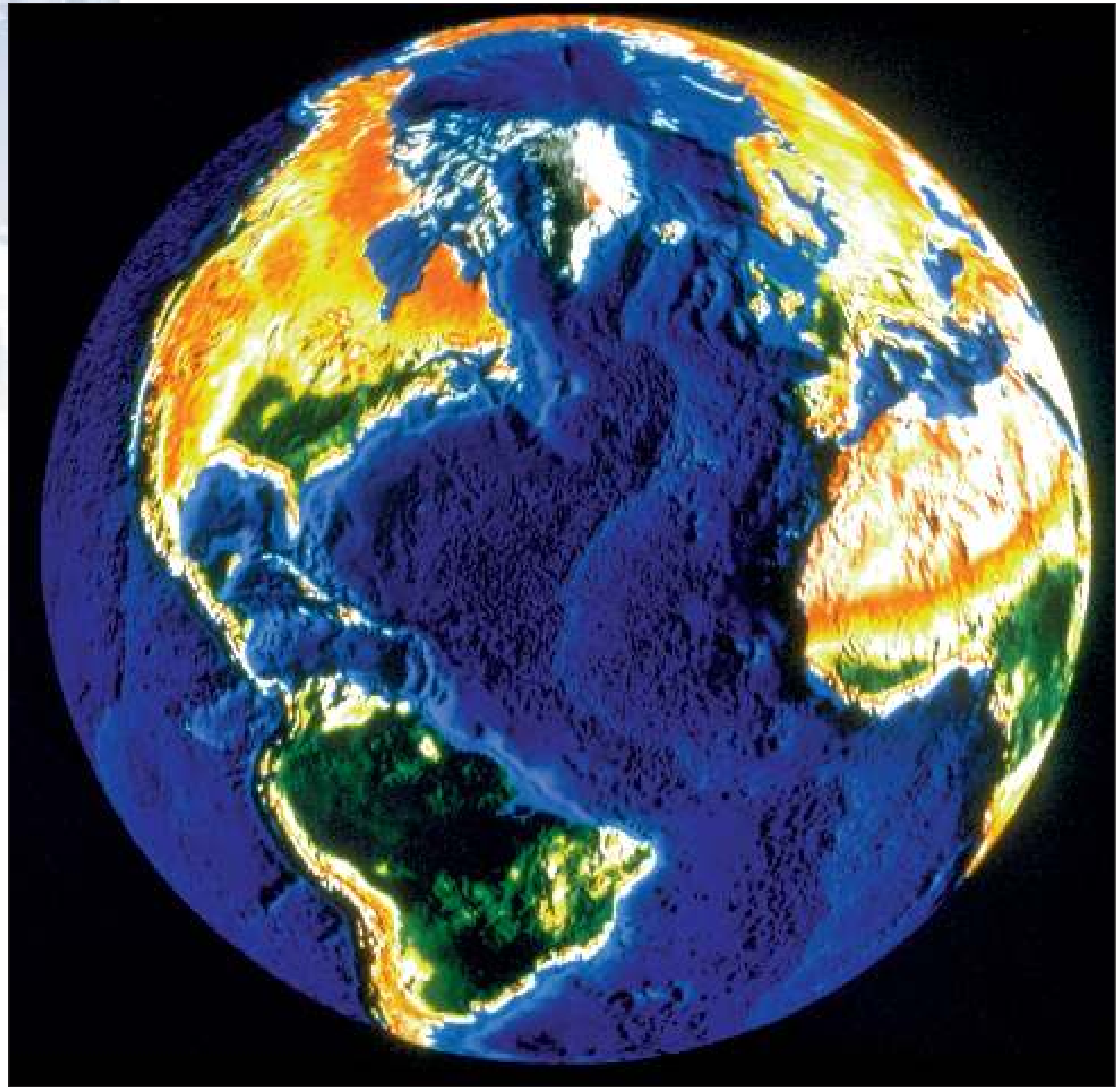
1100
MYA
MILLION YEARS AGO

Into the Breach

Due to the brevity of human life, we struggle to grasp the movement of continents and ocean crusts. From the perspective of Deep-Time, we can feel Earth move under our feet.

Earth is restless. Major global rifting occurs in a very short amount of geologic time. Great valleys open within the continental shield, rivers pour in and new oceans form. Plate collisions fold Earth, and huge mountain chains rise. Volumes of magma spew from the deep.

Continents are the raised portions of tectonic plates.



Topography is as mountainous and deeply gorged under the oceans as it is on land.

image, courtesy National Center for Atmospheric Research

1000 MYA
MILLION YEARS AGO

MINI-MINERAL MARVELS

As geological processes create and metamorphose Earth rocks and minerals, life radiates (multiple species diverge from common ancestors). New protoctist species evolve, each with their own special mineral interests. Some of these microbes produce their own minerals (biomineralization), using them in diverse and creative ways.

Bacteria learned long ago, for example, to make magnetite, which they use for compass orientation in muds and shallows. Although still in early development, the protoctists display manufactured minerals in a variety of styles unmatched by other kingdoms of life.

Scientists today recognize over 60 different inorganic minerals produced by life. A variety of organisms, ranging from bacteria to humans, participate in the production processes. This living protist is a foram. The foram makes its shell of calcium carbonate. Diatoms, smaller symbiotic protists living inside the foram, make their own silica shells.
photo, John Lee

Many contemporary anemones are symbionts with hermit crabs: the crab provides a free ride, the stinging anemone provides protection. Crabs move out and on when they grow too large for their borrowed shell homes, rather disruptive and discomforting for the anemone. This beautiful golden shell is actually a biomineralized overlay and addition created by an anemone for its crab partner. As a crab grows in size, its anemone partner can add to the shell to maintain a fit that is just right.
photo, Daphne Fautin

900
MYA
MILLION YEARS AGO

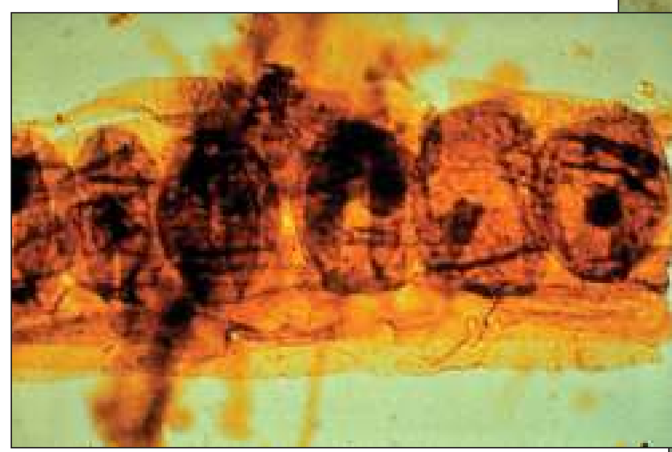
Category Questions

Abundant acritarch fossils, some giant-sized by microstandards, are thought to be fossil cysts or other life stages of algae. Although we cannot discern exactly "who" they are, they speak to us of life's diversity over millions of years.

Categories are maps, but maps are not the territory. In the game "20 Questions," the basic categories of animal, vegetable and mineral underestimate the richness of life forms. Similarly, basic categories such as "small," "large," "single-celled" and "multicellular" can confuse us.

This contemporary alga is an example of one of the largest protoctists.
photo, Lois Brynes

This thin rock section displays fossils 900 million years old
photo, Andrew Knoll



Ancient filamentous microfossils; the one above and to the right are fossil cyanobacteria.
photos above and right, Gonzalo Vidal

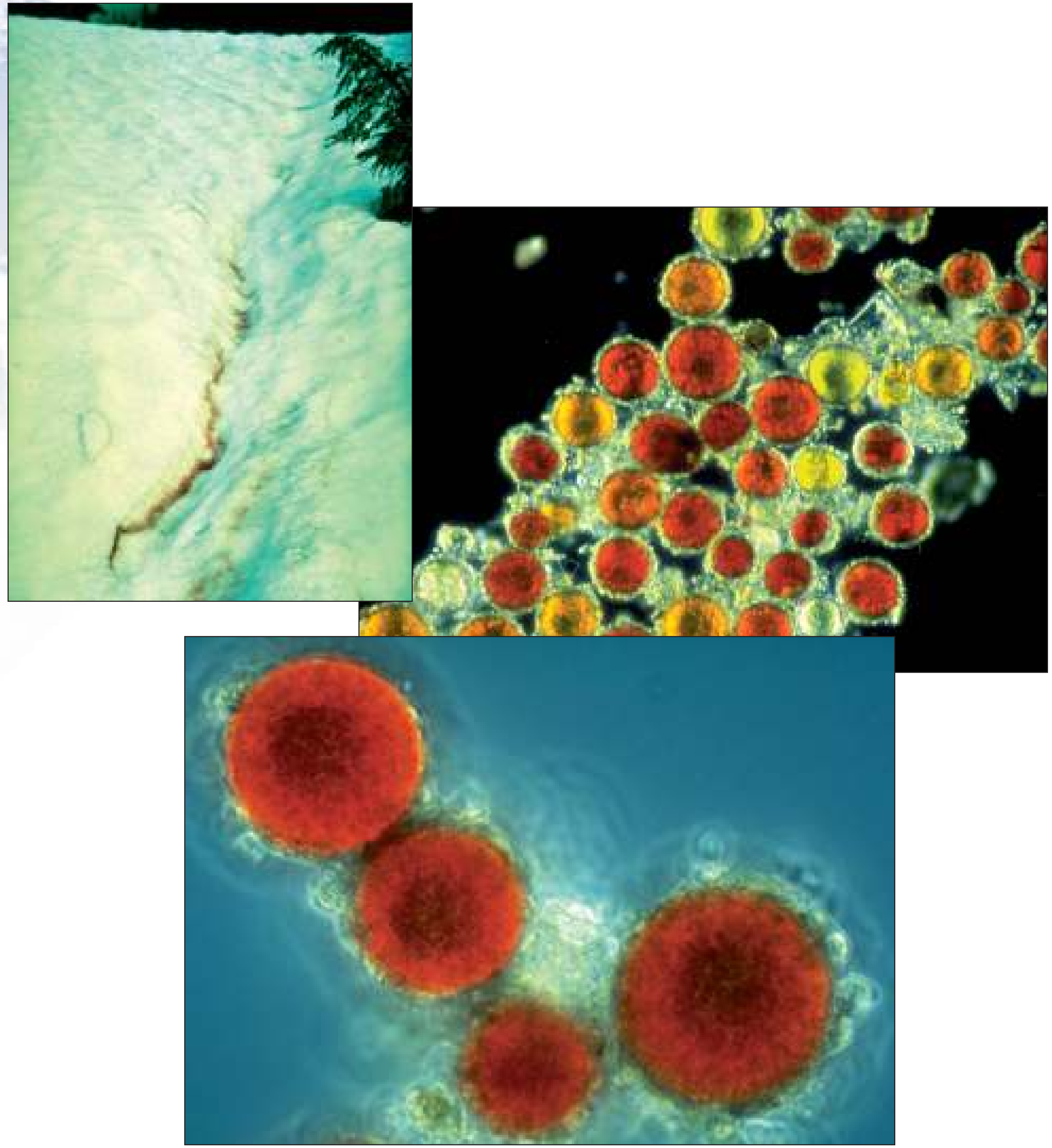
800
MYA
MILLION YEARS AGO

Some Like it Cool

One of a world-wide series of ice ages sets in. Thick ice sheets expand over vast areas of Earth. What causes these ice ages is not completely understood. One theory attributes the ice ages to fluctuations in Earth's orbit, which affect the delivery of solar radiation to Earth.

Temperature swings can be amplified by other factors. If solar radiation decreases, for example, Earth cools and glaciers expand. Since glaciers are reflective, the expansion reduces the amount of heat absorbed by Earth. Thus, temperatures spiral down.

The life system of Earth is closely coupled to climate change. Since the origin of life, microbes have played a major role in the carbon cycle. Ocean-floor and ice-core drilling shows precision synchrony between climate change and atmospheric carbon dioxide. This coupling affects the magnitude of climate change.



Diverse new planktic and benthic communities evolve from these ice ages, thanks to the rich nutrients found in colder waters. Some land protoctists, like these red snow algae, also like it cool.
photos, Brian Duval

700
MYA
MILLION YEARS AGO

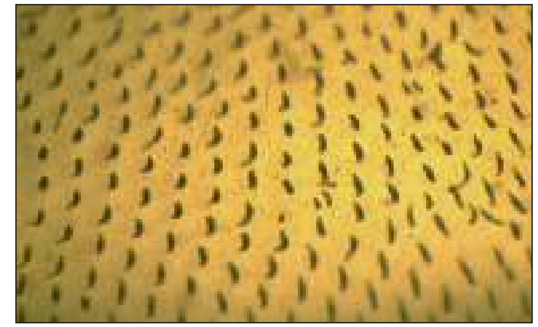
Supple Testimonies

Ediacaran organisms leave quite an impression, which is rare for soft-bodied biota. Beautifully bizarre, their shapes vary from leaf-like, to three-armed, to flat, to "quilted." In the shallow coastal seas of the "Garden of Ediacara," photosynthetic and chemosynthetic symbionts help some of these organisms grow large, while others graze on plentiful bacteria. These gelatinous creatures have no hard parts and no predators. Theirs was a pre-armored world.

Ediacaran fossils are found all over the world. Evolutionary biologists disagree about the nature of these enigmatic beings, since none of their relations survive to tell the tale. The delicate Ediacarans, an evolutionary experiment in life forms, go gently into that good night.

A mystery fossil with no known relatives, the species Pteridinium occurs abundantly on the surfaces of Precambrian sandstones in Namibia, southwest Africa, and some other parts of the world. Some scientists consider Pteridinium to represent the earliest known animal fossil; others are skeptical that the organism was related to animals at all.
photo, Mark A. McMenamin

(above) Green jelly ball colony



(above) Lots of zooids ("little eyebrows") in the jelly ball

(right) Zooids, up close and personal

Ophrydium versatile is a colonial ciliate in the process of becoming what we humans call an "individual." These "green jelly ball" colonies are microbial worlds within worlds, consortia of several hundred different kinds of microbes. Ophrydium may be the closest living analogue of the large photosynthetic and chemosynthetic protoctist colonies of the quilted soft-bodied wonders of Ediacara.
photos, Lynn Margulis and Brian Duval

WHAT ARE ANIMALS?

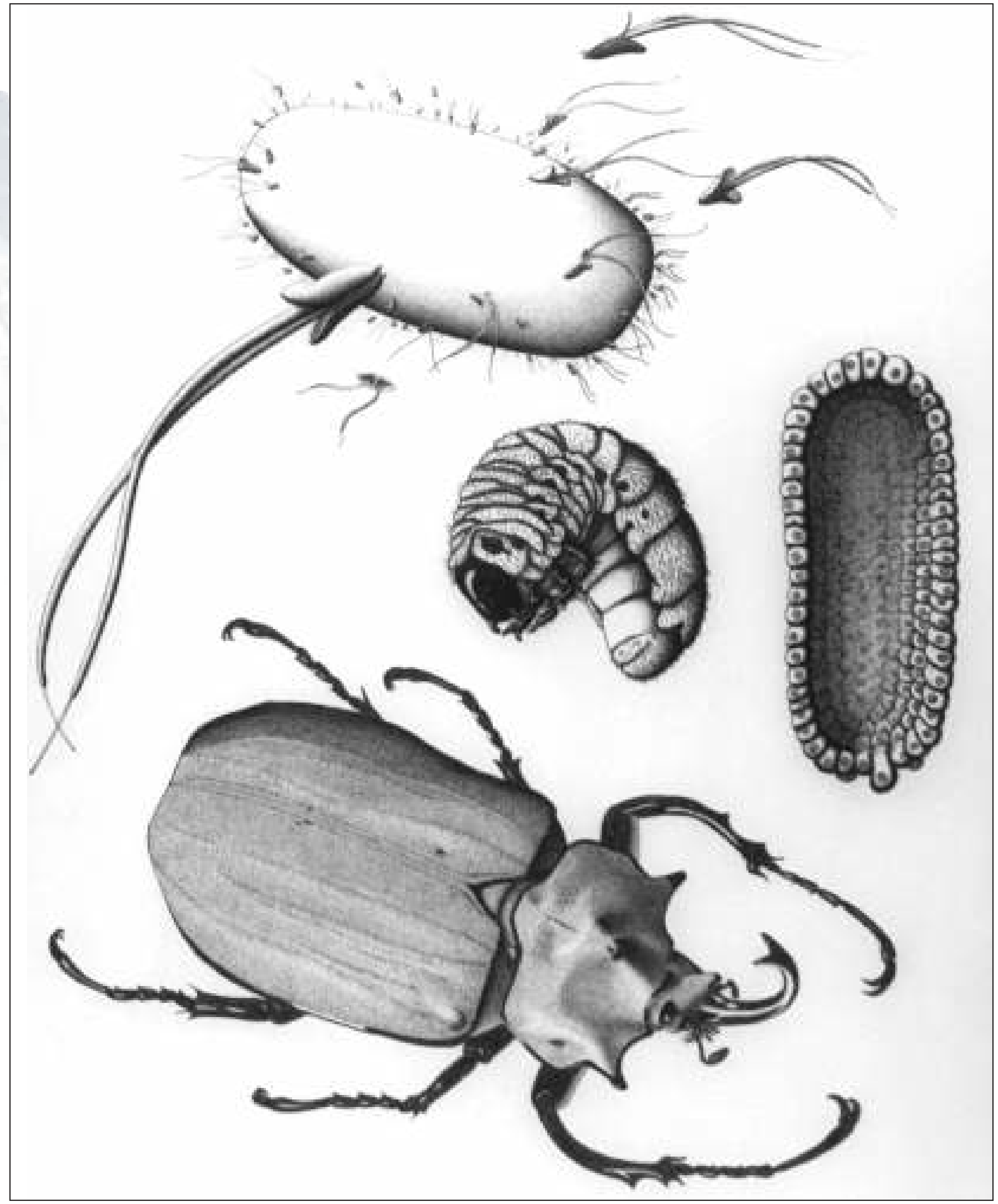
We usually think "mammal" when we hear the word “animal.” In fact, we and this Rhinoceros beetle are both animals.

In the Animal Kingdom, a small swimming sperm makes it to a large egg, spurred on by its undulating tail. The fertilized egg repeatedly divides to form, in the initial stage of embryo development, a hollow sphere of cells — the animal blastula. This blastula is the defining trait of animal-hood.

The bodies of animals are individualized with special cell-to-cell connections. As the embryo cells divide, some must form alliances, while most others die on a preprogrammed cue. If these cells do not commit cell-icide in the proper fashion, no animal body develops.

The following true, or untrue, bug story cites J.B.S. Haldane, hero of evolutionary biology. At a formal dinner, Haldane was seated next to his staunch foe, the Archbishop of Canterbury. There was, of course, "polite" British exchange:

Archbishop: *What do your studies tell you, Professor, about the nature of the Creator?*
Haldane: *He must have had an inordinate fondness for beetles.*

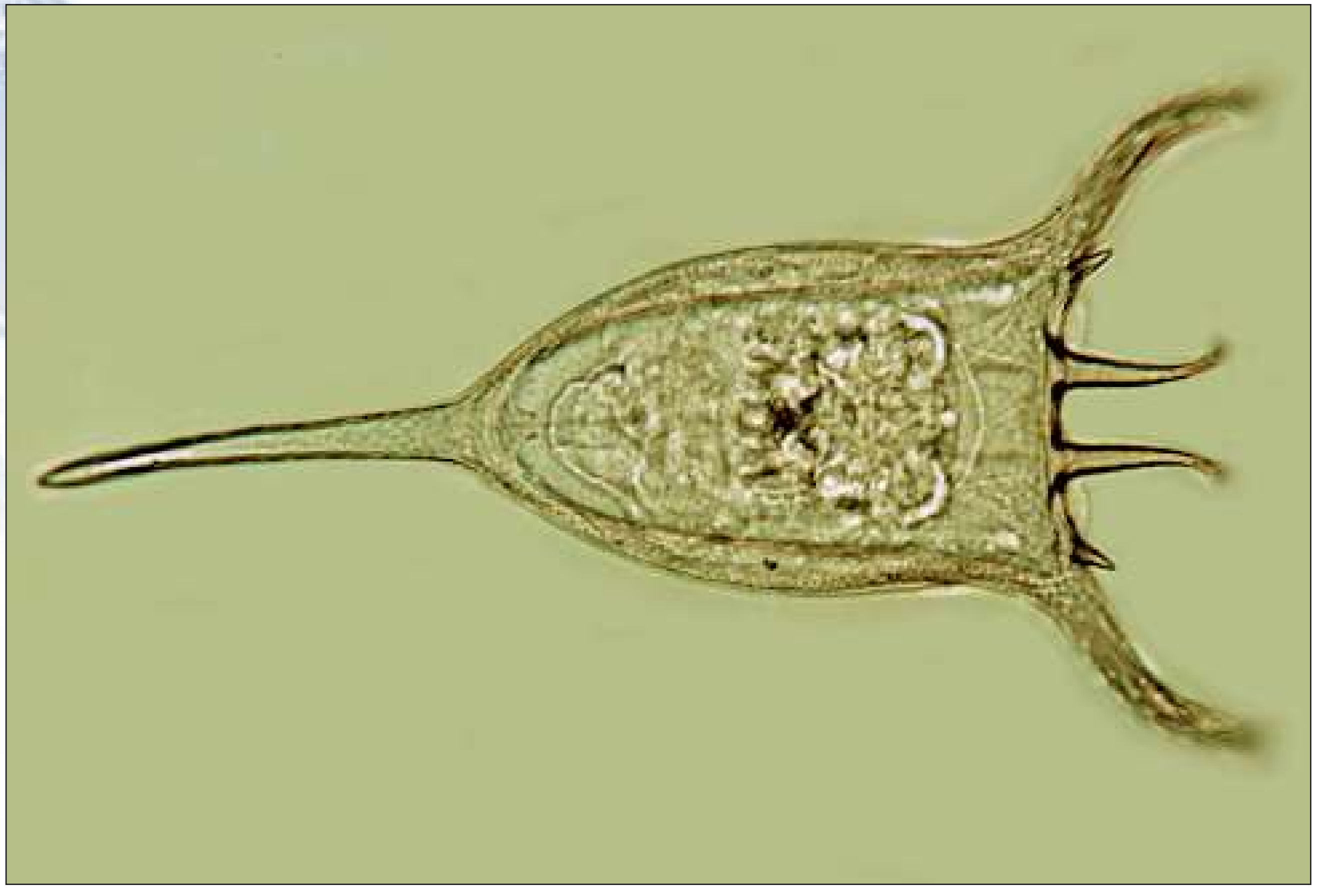


Insects innovate more successfully than do any other animals. Close to a million different species have been identified . . . and we're still counting. Above, beetle sperm penetrate egg (top), which divides to evolve sequentially into blastula (right), larva (center) and beetle (bottom).
drawing, Christie Lyons

600
MYA
MILLION YEARS AGO

Animals Arise

The first animals arise when marine protoctists curtail reproduction in favor of specialization. They are very small, with only soft-body parts, so they may swim with their protoctist cousins for millions of years before circumstances are favorable for their preservation in the fossil record.



This beautiful little creature, just two thousandths of an inch long, is one of the smallest animals in the world. It is called a "rotifer" because the cilia of its tiny retracted wheel-like head beat and flush food toward its mouth.
photo, Richard Stemberger

Blue buttons (cnidaria)
photo, Charles E. Cutress, Jr.

Tubeworms
photo, Norman Meinkoth

Colonial coral, Alcyonian, "dead men's fingers"
photo, courtesy Marine Biological Laboratory, Woods Hole

Comb jelly (ctenophore)
photo, courtesy Marine Biological Laboratory, Woods Hole

All of these lively relatives of some of the first soft-bodied animals are found in the fossil record.

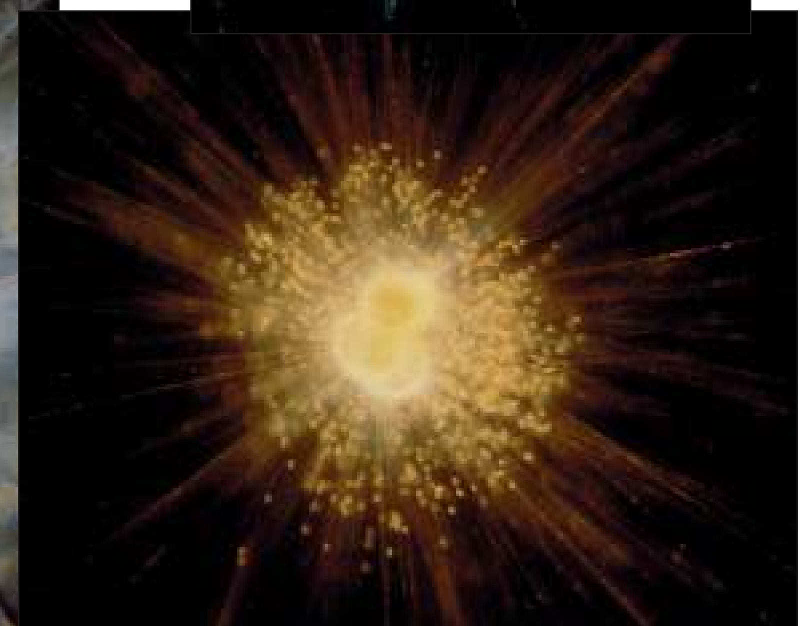
580
MYA
MILLION YEARS AGO

Fabulous Forams

Foraminifera ("forams" for short) are aquatic protoctists whose cells are enclosed in loose-fitting, hard, shell-like covers called tests. Found throughout the world's oceans, tests provide clues to the past. They are key biomarkers for oil companies looking for layers from the "right age" for drilling. Their presence in the desert means an ocean once covered the area. Different species of forams are very fussy in choosing their habitats; their fossils help us "read" the nature of paleoenvironments.

Foram individuals are small, but as a group they are a mighty force. The calcium carbonate of their abundant tests affects the global carbon cycle. Forams of the past unite; their tests make up the sedimentary rock of the great pyramids in Egypt and the White Cliffs of Dover.

photos above and right, Esmeralda Caus

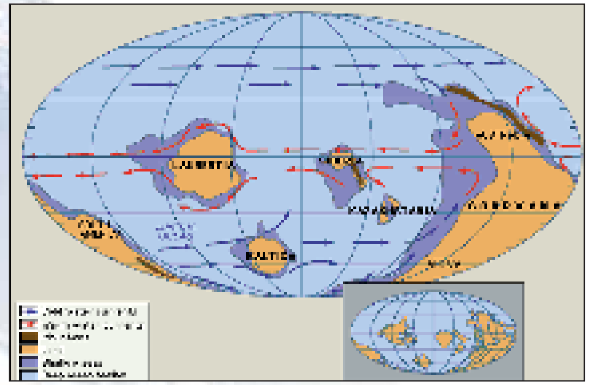


The "spots" on these living forams are their photosynthetic symbionts.
photos above, David Caron, Woods Hole Oceanographic Institution

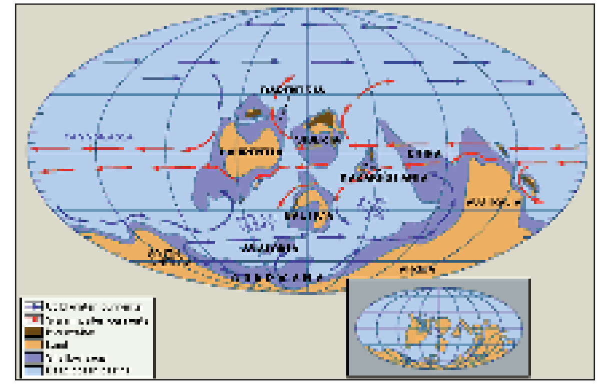
CONTINENTAL CAPERS

The Paleozoic Era runs from 541 to 245 million years ago, and geologists divide it into six major periods: Cambrian, Ordovician, Silurian, Devonian, Carboniferous and Permian. The "Cambrian Explosion" ushered forth a great burst of life and the appearance of the first shelled animals. The Paleozoic Era ends with the greatest known mass extinction of life in Earth's history.

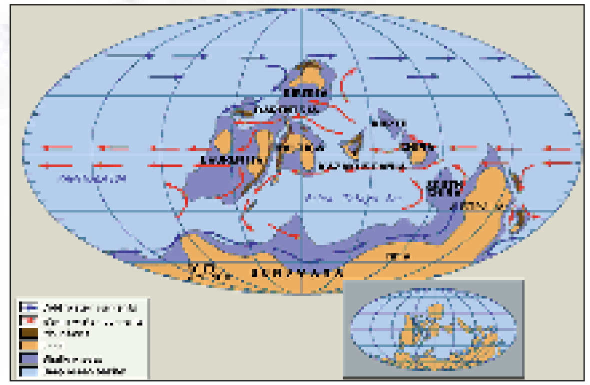
The Era opens dramatically: first, algae and then animals make a great and perilous leap from water to land (approximately 1000 mya after some bacteria colonized land). These new inhabitants devise ingenious ways to carry the ocean with them. The Plant and Fungi Kingdoms make an official debut in life's drama. Earth itself changes as continents astride their plates congregate, converge, break apart and recombine.



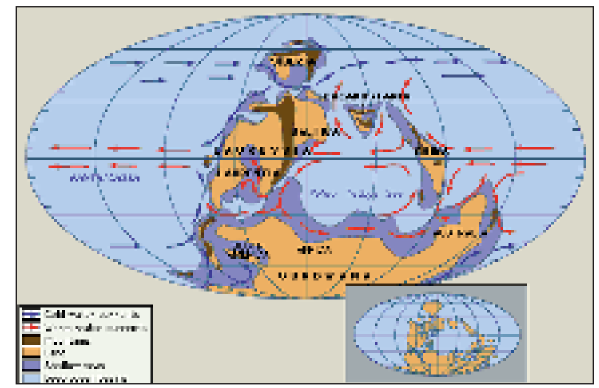
Cambrian 500 Mya



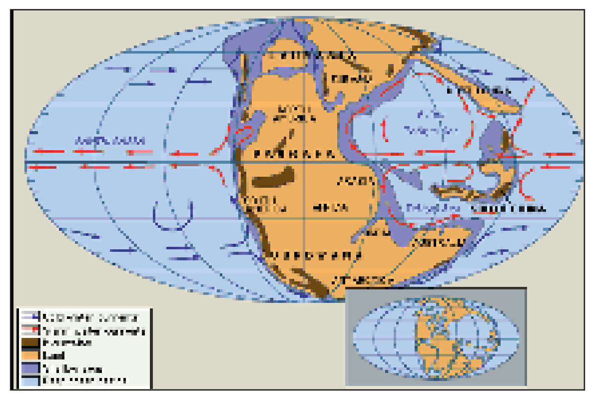
Mid to Late Ordovician 460 Mya



Early Silurian 435 Mya



Early Devonian 405 Mya



Early Triassic 240 Mya

"California moves at about a centimeter or two each year, producing earthquakes as the Pacific plate slides past the North American Plate. 'Baja' California will move up opposite to the interior of 'Alta' California. Eventually, Los Angeles will be pushed opposite Berkeley, with results we cannot predict."

Raymond Siever

maps, reproduced with permission from *Britannica CD 97* © 1997 by Encyclopaedia Britannica, Inc. – Adapted from C.R. Scotese, University of Texas, Arlington

540
MYA
MILLION YEARS AGO

Cambrian Explosion

For years, we knew very little about the microcosmos. Bacteria and protoctists, abundant for over 2000 million years, remained soft-bodied. The great discoveries of Cambrian fossils suggest an explosion of life from virtually nowhere.

A tremendous burst of animal evolution springs from protoctist and animal biomineralization. Life rapidly radiates. All of today's animal phyla (great groups) originate in the Cambrian Period. Magnificent fossil traces (furrows and burrows) record our own distinguished, flexible ancestors — the worms.

painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

510
MYA
MILLION YEARS AGO

The Burgess Shale

The Burgess Shale, in the Burgess Pass of the Canadian Rockies, is an impressive fossil-find dating some 30 million years into the Cambrian Period. Its impressions are especially precious because such preservation of soft-bodied marine animals is rare in the fossil record. This discovery provides a unique glimpse into the true range and diversity of early animal forms and their ecosystem.

Opabinia, a fantasy-like predator of the Burgess Shale, measures three inches long. It has five eyes, gills all along its segmented body and an efficient nozzle which vacuums prey for transfer to its mouth.
painting, © Jan Sovak

This velvet worm is very similar to fossils found in the Burgess Shale. These animals are thought to be the link between two extensive and important phyla, the arthropods (which include all insects and seagoing crustaceans) and the annelids (which are segmented worms). Scientists use these fossils, widespread before the breakup of Gondwanaland (precursor to our present Southern Hemisphere), to reconstruct the history of drifting continents.
photo, Donald Zinn

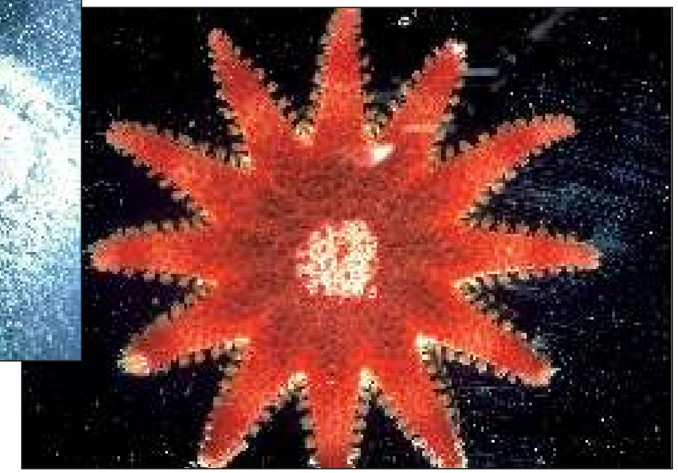
505
MYA
MILLION YEARS AGO

REVERBERATING CHORDS

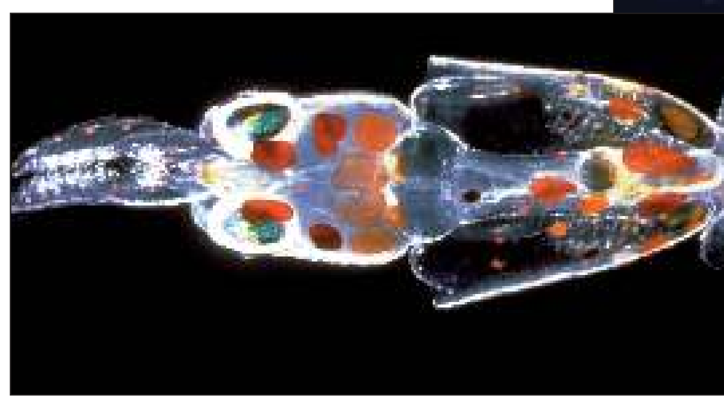
Human beings belong to the phylum Chordata, all members of which have notochords, cartilage rods down the middle of the back, at some time during their life history. Chordata include all vertebrates (mammals, birds, amphibians, reptiles and fish) along with several groups of lesser know marine animals. Details of the evolutionary path of notochords from sea-squirts to jawless fish to bony fish remain obscure.

Whatever the precise path, the backbone that enables us to stand before this exhibit panel speaks to the wonder of evolution. Branches, truncations, mergers — as evolutionary continuity — span nearly 4000 million years.

Sand shark
photo, courtesy Royal British Columbia Museum



Sea star
photo, courtesy Marine Biological laboratory, Woods Hole



photo, J. Lecomte

photo, courtesy Marine Biological laboratory, Woods Hole

Squid have nervous systems very similar to our own.

500
MYA
MILLION YEARS AGO

HAPPY LANDINGS

Green algae (ancestors to plants) living in sunlit shallows and tide pools, start a “green” revolution. They invent ways to stay wet on the inside while drying up on the outside. Algae become plants by carrying the ocean inside themselves as they move ashore.

Why go to all that effort when they could just lounge at the sea's edge? Some algal colonies take to the land in response to a disturbing increase in marine predators. Once ashore, the spirit of life drives them to expand across this huge new frontier. The insects, which are both predators and pals to algae, follow with dispatch.

These green and brown algal protoctists are thready chains of cells full of plastids.
photo, Lois Brynes

The amazing arthropods, which constitute over 80 percent of the species in the Animal Kingdom, are the first to follow algae inland. No doubt, their hard-shelled, lobster-like legs helped.
photo, courtesy Jason Foundation for Education

What are Fungi?

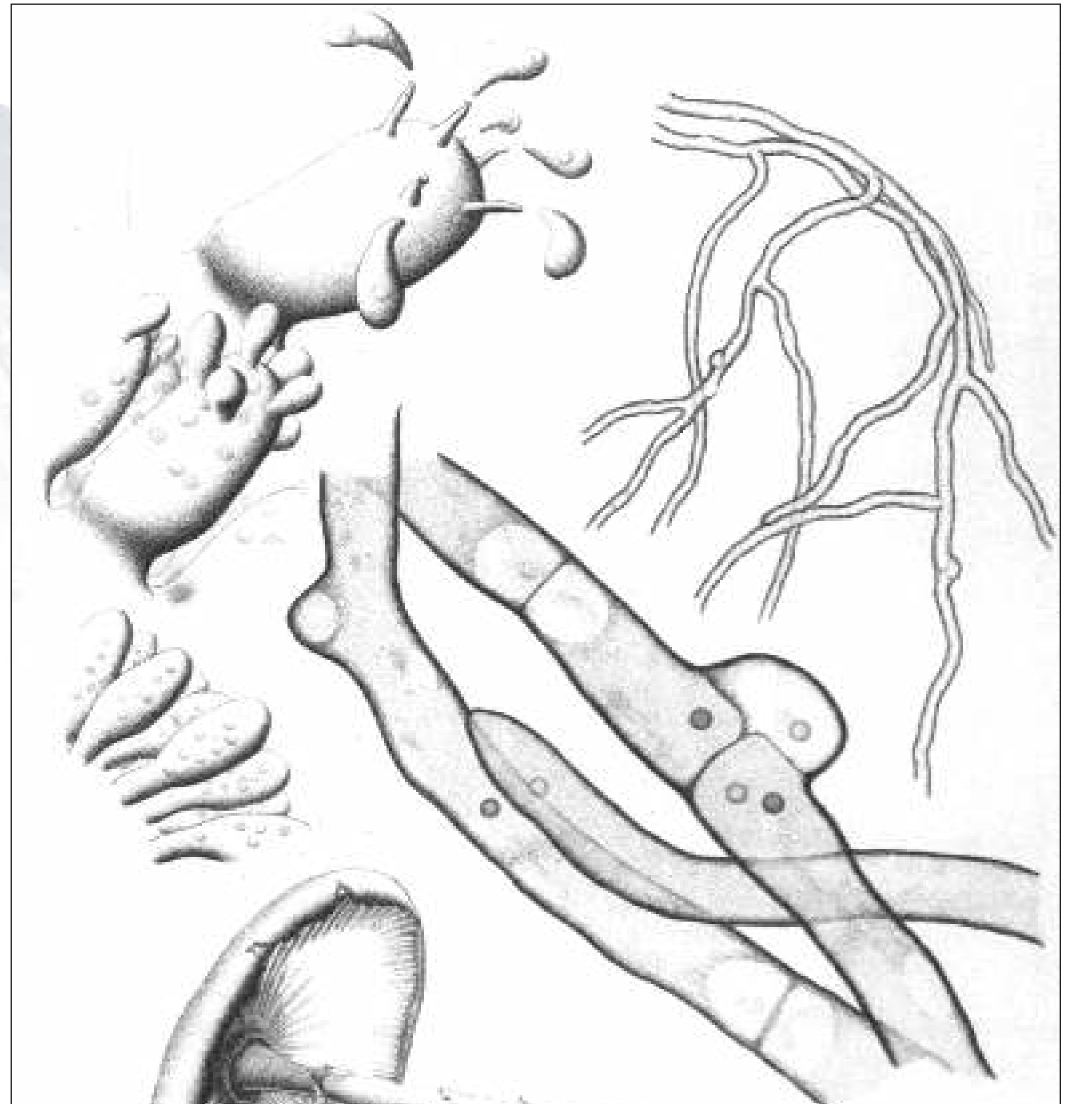
"And fungi are fungi; they're like nobody else on Earth."

-Jun Takami

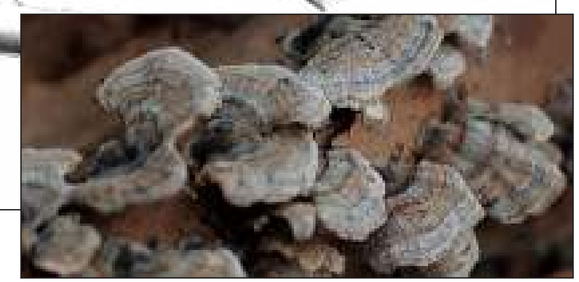
Fungi have an unbounded love of life and death. Converting waste and corpses into resources, they are crucial to global metabolism. Inverting our habit of consumption, fungi digest their food before they eat it. They excrete enzymes onto organic materials and then absorb the soluble, pre-digested meals.

What we see in the wild is only the tip of the fungi; they spread gregariously underground. A famed Michigan fungus — one individual fungus with identical genes throughout — has been expanding for over 1500 years. It spans 37 acres and weighs over 11 tons!

Unlike animals and plants which form embryos, fungi form propagules — dormant or reproductive environmentally-resistant spores. The propagules can be blown about for thousands of years before moisture startles them into fungi-hood. They are maestros of reproduction. Their bodies are composed of threads, and during a sexual phase, many types of fungi fuse "complementary" threads. At other stages, they just clone-out and pinch off spores.



Stages in the life history of Amanita
drawing, Christie Lyons



Crucial to global metabolism, fungi transform waste and dead bodies into life-sustaining resources.
photo, Lois Brynes

455
MYA
MILLION YEARS AGO

Fungal Fusion

Plant-It Earth

The Plant and Fungi Kingdoms evolve on land so closely together in time that we are unclear which of the two came first. The Fungal Fusion hypothesis opts for neither, suggesting a joint venture. It proposes that fungi and landward photosynthetic algal symbionts joined together to evolve the capability to survive dryness. Was it just a joint venture or did it go further?

Perhaps land plants arose through both a somatic (body) and a permanent fusion of fungi with algae. This symbiogenesis is much like the "horizontal" gene transfer which bacteria practice.

Life on land poses far different demands than did life in the sea. Life forms develop "hypersea"— the movement of sea water onto land, but inside organisms.

photo, courtesy Jason Foundation for Education

How many ecosystems are within this ecosystem?

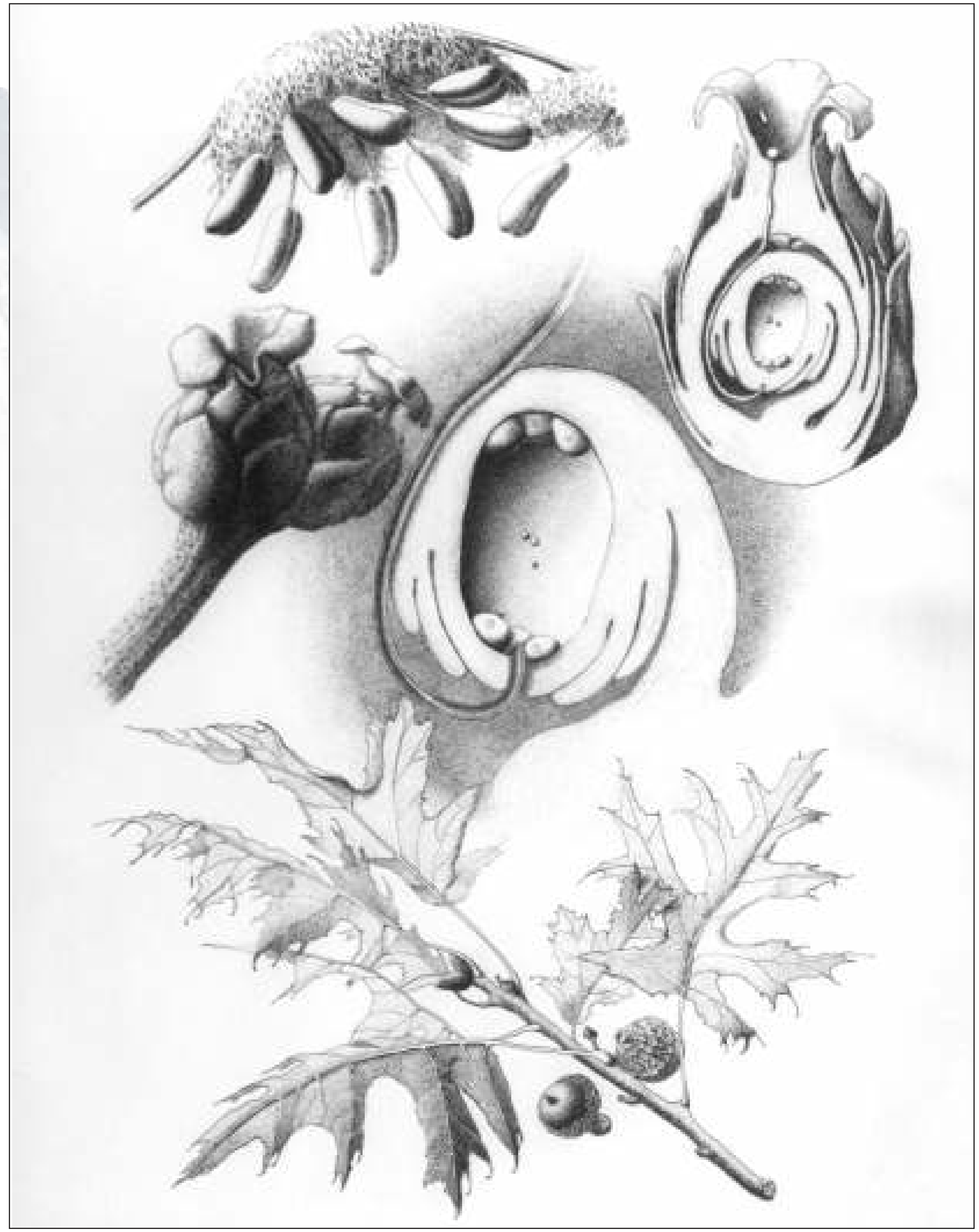
"Redwood trees, wasps and other organisms visible to the unaided eye are habitats for rich ecosystems of much smaller organisms that cover their surfaces, probe their interstices, take up residence in body cavities, and invade (sometimes peacefully, sometimes not) even the inner sanctum of their cells."

Mark A. McMenamin, *Hypersea*

What are Plants?

Plants are more complex than animals and fungi: in addition to nuclei and mitochondria, plant cells contain plastids (organelles for tapping the Sun's energy). Plants evolved from protoctist algae that had already incorporated cyanobacteria that became chloroplasts.

Significant challenges face the earliest plants as they confront the demands of surviving on dry land. Accustomed to an aquatic life style, early plants lay on the surface, unable to support their weight against gravity. Watery conjugation is no longer a viable survival strategy. The most crucial innovation for the first true plant is the ability to develop a fertile egg into an embryo, a multicellular young plant, within moist protective maternal tissue.



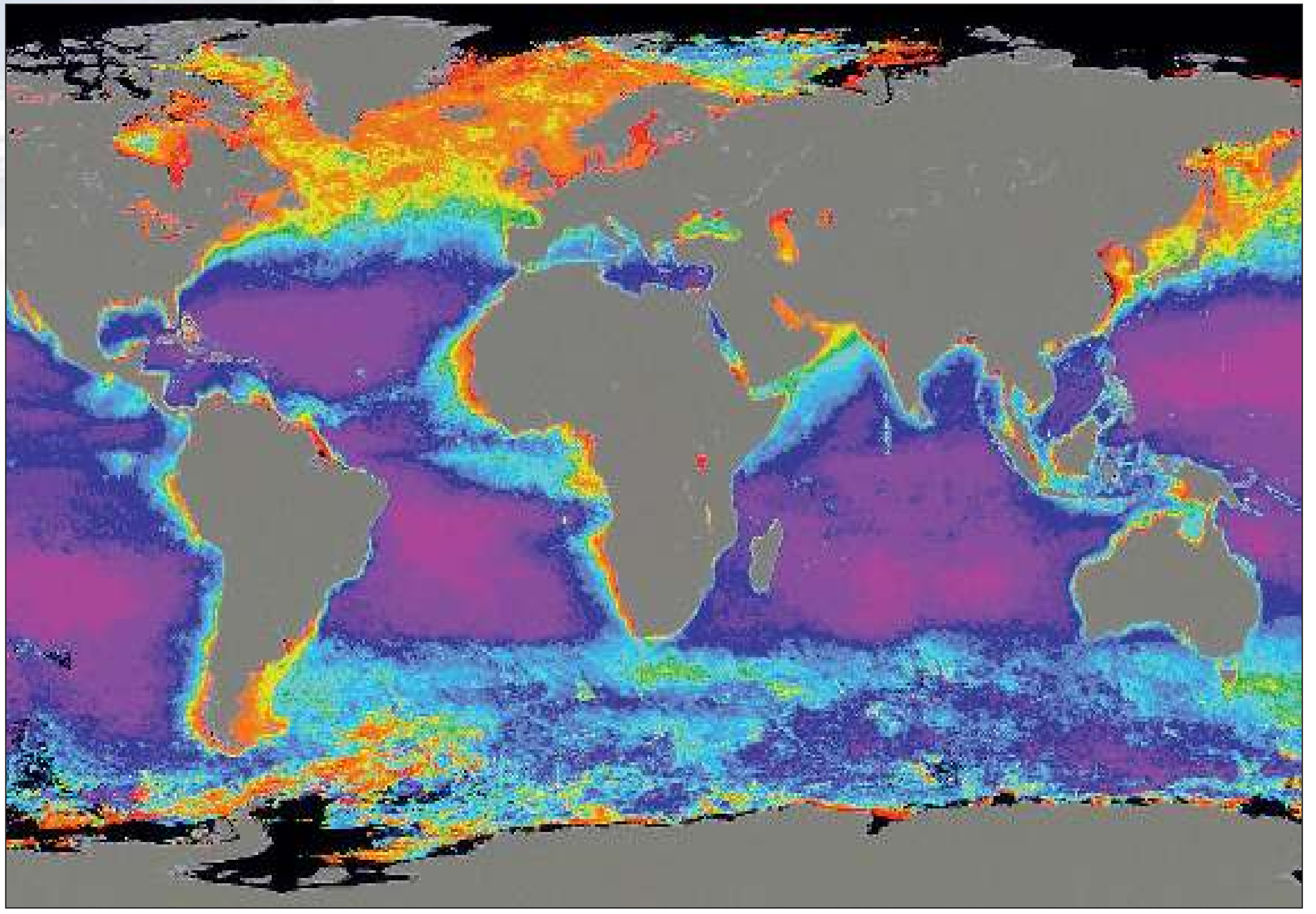
Life history of an oak tree. Great oaks from little acorns grow. Sexual coupling of the female and male flower (left) results in the embryo.
drawing, Christie Lyons

440
MYA
MILLION YEARS AGO

FORTUNE'S WHEEL

Global environmental change and continental glaciation induce a mass extinction which impacts all marine animals. As the Ordovician Period closes, over 50 percent of species world-wide decline and then vanish. The mass deaths open new niches for benthic (bottom-dwelling) and planktic (free-floating) marine life. New species and new groups of organisms which depend on these primary producers evolve. Researchers estimate biodiversity did not fully recover from this extinction for 25 million years.

Phytoplankton (photosynthesizing protoctists) bloom in colder resource-rich waters. They, in turn, enrich the food web. It is a period of plenty in the seas: plenty of room and plenty to eat.



Computer and satellite technologies make visible the ubiquity and power of ocean phytoplankton. This composite, highlighting chlorophyll, shows ocean productivity. Note the blooms of life in colder waters.
photo, courtesy NASA

435
MYA
MILLION YEARS AGO

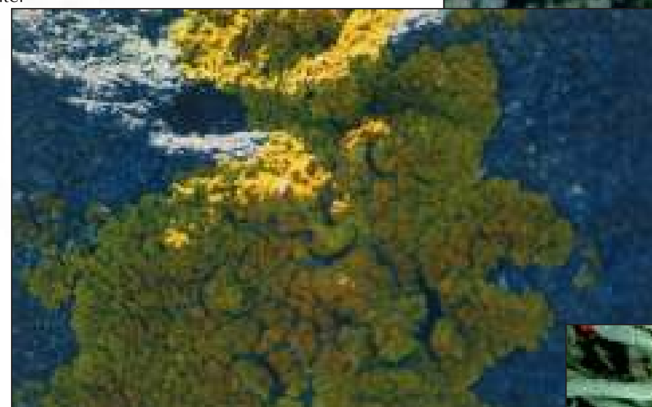
THE LICHEN CONSOLIDATION

Lichen land pioneers spread. Hardy and long-lived (some reach 9000 years of age), these low-lying photosynthesizers are an arresting example of symbiosis.

Just as bacteria and protoctist mergers led to algae, lichens represent a merger of fungi with photosynthesizers (algae and/or cyanobacteria). An entirely new life form, lichens enjoy the algae's ability to use solar power to make food and the fungi's ability to store water and protect themselves from the elements.

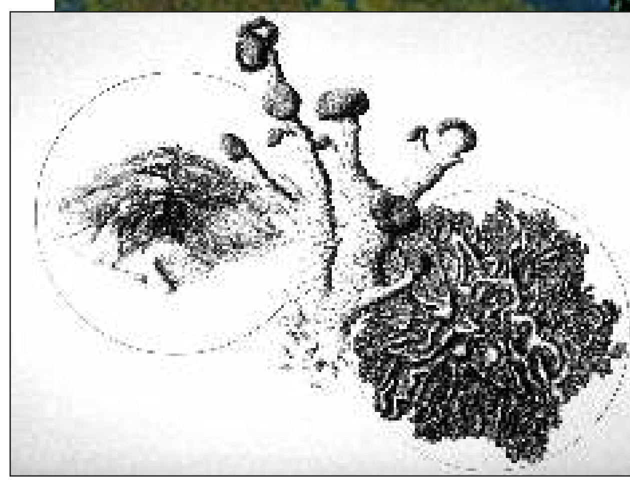
Through rock weathering, lichens play a significant role in the geological cycle. Crustose lichens produce acids which chemically decompose rocky substrates; lichens manufacture a variety of acids depending upon the nature of the rock. Lichens also produce a glory of pigments. We still do not understand how or why.

photo, Roger Leo courtesy New England Science Center



Over 25,000 fungal species consort with photosynthetic companions, producing eminent varieties of lichens.
photos above and left, Lois Brynes

photo, Stephen and Sylvia Sharnoff



On the left is a healthy fungus; on the right, a healthy alga. Their merger produced the British Soldier Lichen (in the center). Taking everything we know about algae and fungi, we still never would have predicted the outcome of their synergy.
drawing, Christie Lyons

400
MYA
MILLION YEARS AGO

INTIMATE ALLIANCES

Intimate ecological interactions occur among plants, fungi and bacteria. Mycorrhizal fungi live within special root compartments co-created with plant partners and they are symbionts with over 90 percent of living plants today. Fungi help make many valuable nutrients available to plants. The plants provide sugars to the fungi.

Symbiosis generates the high diversity and vast biomass of terrestrial life. All organisms consist primarily of water, and interact easily in fluid habitats. The evolution in land biota of the intimate association of networks of cells (through which fluids and solids are transported) are already well established in the Devonian Period.

A mycorrhizal root fungus from the Rhynie Chert of Scotland, one of the world's most important fossil deposits.
photo, Lynn Margulis, of specimen discovered by Mark A. McMenamin

This synergistic mycorrhiza of an alfalfa plant is a symbiotic protuberance produced by fungus and plant root.
photo, Lucien Bordeleau

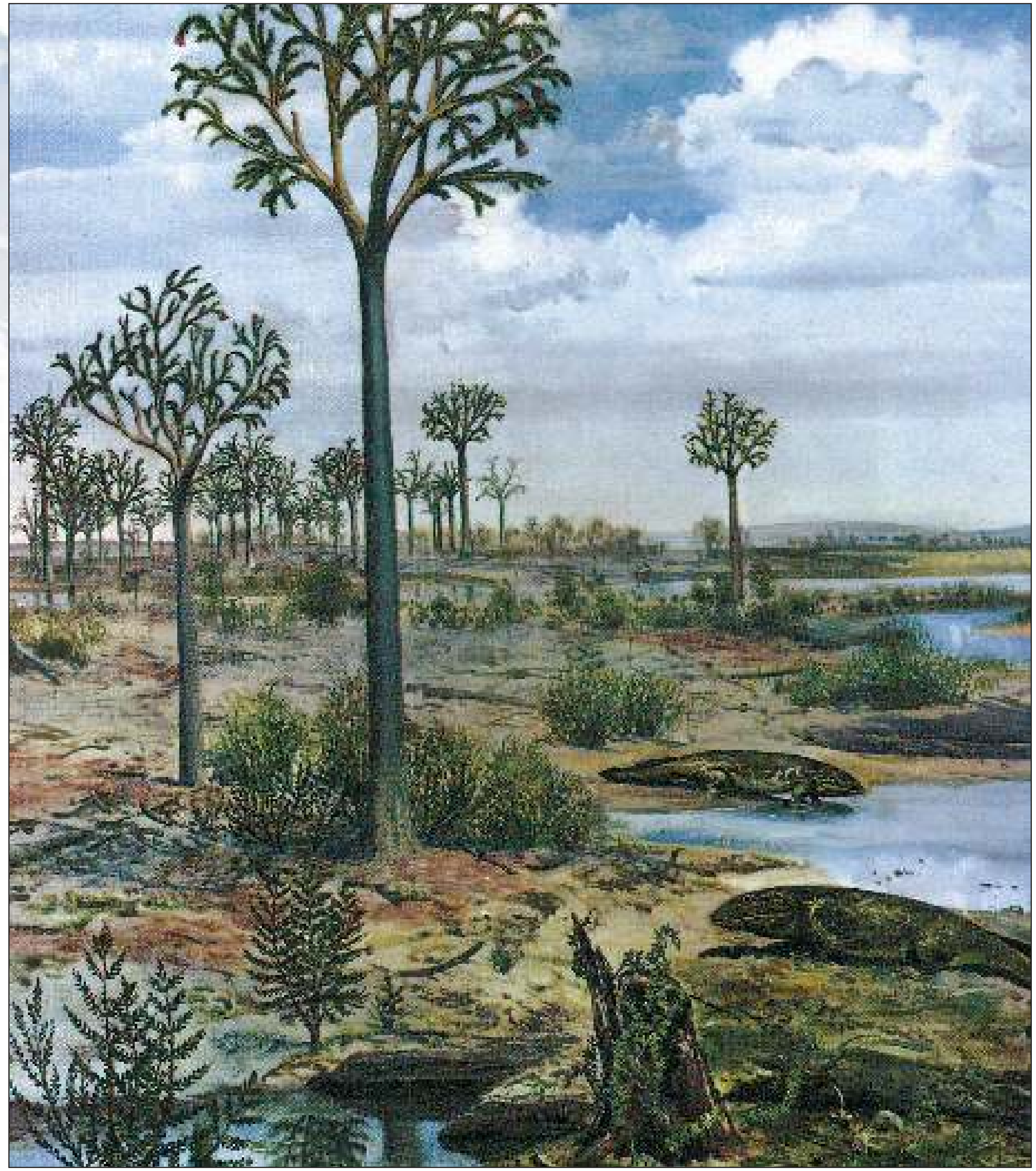
395
MYA
MILLION YEARS AGO

AMPHIBIANS
LURED TO LAND

Air breathing, four-footed, ambling amphibians leave many marks by the late Devonian Period. Their ancestors — the lobe-fin fishes — were most likely lured out of the oceans by a profusion of insects.

Evolving to breathe in air was not the only challenge faced by lobe-finned fish in their move to land. They also had to support their weight against gravity. The bony skeletons of amphibian precursors (who lobbed about on already-muscular fins) give clear clues to the transition some animals made from dragging in drying mud-pools to true walking movements.

Amphibians do not make a complete land transition: they must return home to lay eggs, where their tadpole progeny keep one evolutionary foot in the water.



Fish, evolving into amphibians, were the first vertebrates (the group of animals with backbones, to which human beings belong) to make it to land.
painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

365
MYA
MILLION YEARS AGO

RHYTHMS OF LIFE AND LOSS

The Devonian Period closes with another decline and mass extinction. Again, 50 percent of species vanish world-wide, the major losses taken this time by ocean life. Basic biota body blueprints remain conservative.

Note the "bottom-heavy" trend in evolution: new lineages generate remarkable diversity when they first appear, but settle to a limited number of body plans in what paleontologist Stephen Gould calls, "early experimentation and later standardization."

It takes 30 million years for biodiversity to recover fully from this mass extinction.

Exemplary of the way new life fills evolutionary niches, life grows in a tide pool. Climate and changes in the nature and distribution of habitats appear to drive most of the recent mass extinctions and extensive speciations which follow. Species capable of filling newly emptied niches do so rapidly.
photo, Lois Brynes

360 MYA
MILLION YEARS AGO

Carboniferous Period
The Coal Forests

Continental movement folds the lands. Extensive forests of mosses, horsetails and tree ferns rise in massive basins during the sultry, swampy Carboniferous Period. These plants practice "giant-ism." Some of their descendants, today's club mosses, will follow an alternate evolutionary strategy: when things get tough, get smaller.

Dead vegetation does not completely decay in these swamps. The dead organic matter accumulates in huge "carbon sinks." The burning of fossil fuel (coal, oil and gas) during the 19th and 20th centuries has already consumed a substantial fraction of the fossil fuel laid down during the 70 million years of the Carboniferous Period. This combustion has significantly raised the carbon dioxide content of the atmosphere, risking green-house warming of Earth.

The discovery in the Antarctic of coal, which forms only in warm, wet subtropical settings, initially startled and confused scientists. Ultimately, however, it was one of many observations that may be best explained by a most important earth system theory: continental drift and plate tectonics.

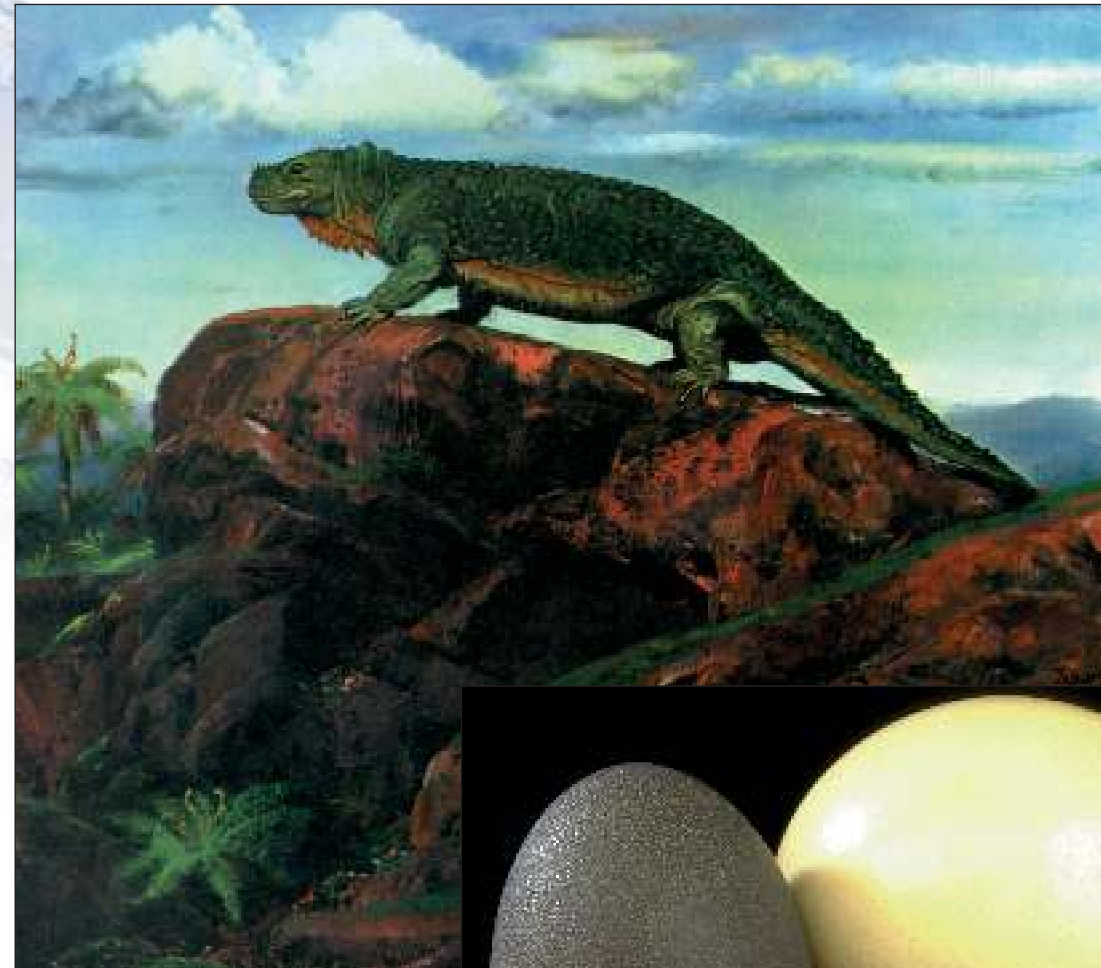
painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

340
MYA
MILLION YEARS AGO

Enveloping Eggs

Amphibians transform into reptiles with a grand innovation: internal fertilization, which results in the "closed" egg. A new class of vertebrates spins off, generating the Great Age of the Reptiles. The reptiles' new reproductive strategy allows them to move inland to drier territories where they rapidly expand the vertebrate presence on land.

Egg architecture evolves. A biomineralized shell prevents fluids from evaporating and protects the growing embryo. Separate compartments for pantry and for waste are easily accessed by the embryo.



This herbivorous reptile, just under two meters in length, represents the transition from amphibian to reptile.
painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

Reptile relations – lizards, snakes, crocodiles, pterosaurs and birds – later take advantage of the egg innovation. Communication systems emerge that become critical to chicks' survival. Unhatched chicks hear one another chirping and clicking, which somehow enables the baby birds to hatch at the same time. While still in the incubating egg, they recognize parental alarm calls in such a way that they hush-up until they receive a parental all-clear.
photo, Patrick O'Connor courtesy New England Science Center

280
MYA
MILLION YEARS AGO

Sowing and Reaping

Profound changes in climate, glaciation and finally widespread desertification are linked to the tectonic assembly of the supercontinent Pangaea. Conifers, gingkos and cycads — naked-seed, "cone-bearing" trees — and dry-tolerant spore ferns replace the dying lush Carboniferous forests. Wind carries pollen from tree to tree, a common pollination method before some animals begin to provide the service.

Cycads grow well in soils extremely low in nitrogen. Cyanobacteria, living in the roots where they induce a special layer of tissue, convert nitrogen from the air to a form usable by the cycad.

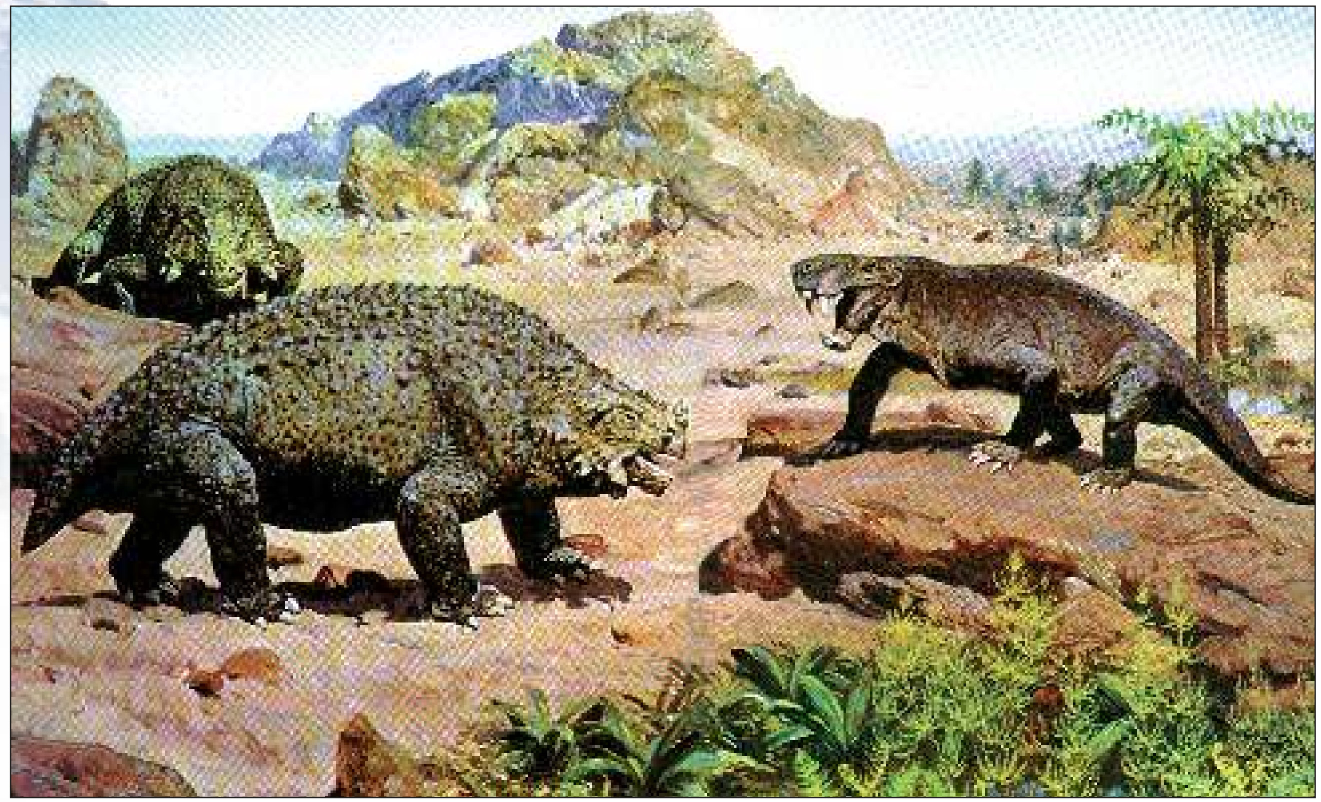
The giant ferns did not make it through the climate change; smaller close relatives did.
Spring fern in serpent disguise
photo, Lois Brynes

265
MYA
MILLION YEARS AGO

RADIANT REPTILES

Reptiles evolve many new species. Reptile fossils are abundant: aquatic reptiles, "stem reptiles," early ancestors of snakes and lizards, ancestors of turtles, and archosaurs are the first in line of the great ruling reptiles to come. The first mammal-like reptiles also appear.

Most paleontological excursions through time focus on large land animals. Ocean water, however, which is Earth's largest habitat, also bustles with life. As tectonic plates move and collide, altered land-masses, with their nutrient enriched coastal habitats, appear and disappear.



Mammal-like reptiles are part of the bushy speciation of reptiles.
painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

Variations on the theme of mollusk: nudibranch (left) and "ole blue eyes," a scallop (right)
left photo, Alan Kuzirian,
courtesy Marine Biological Laboratory, Woods Hole
right photo, courtesy Marine Biological Laboratory, Woods Hole

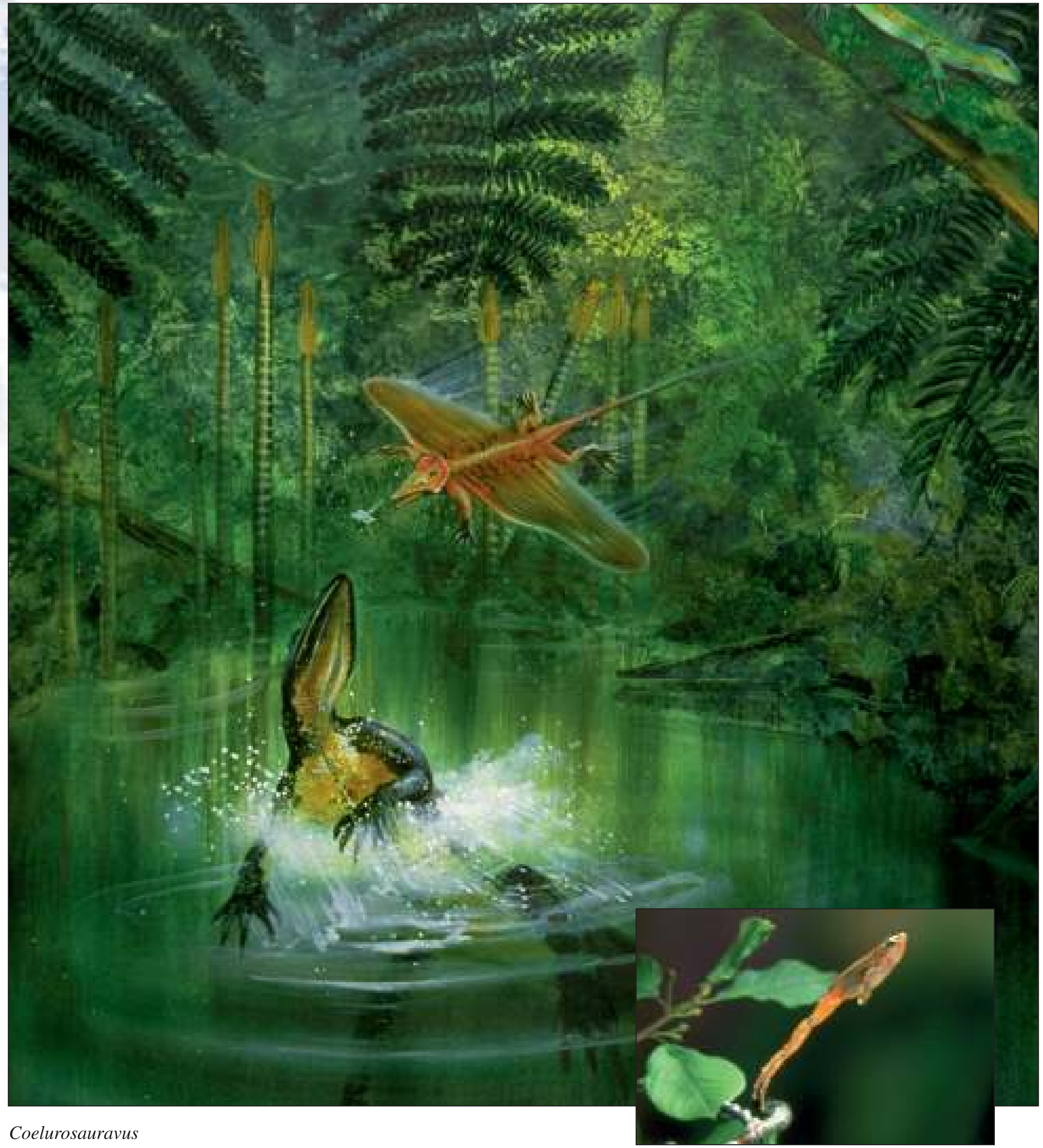
250
MYA
MILLION YEARS AGO

I do not know which to prefer,
The beauty of inflections
Or the beauty of innuendos,
The blackbird whistling
Or just after.
– Wallace Stevens

LEAPING LIZARDS

New forms of life launch into the air, occupying previously untapped habitats. Although birds, bats, and insects are aeronautical experts, no Earth organism is known to spend its entire life in the air.

Coelurosauravus jaekeli, one of the first known reptiles to take to the air, has a "totally bizarre" wing design. With membranes connected to hollow-rod skin structures, the fossil lizard's wings more resemble hang-gliding gear than the transformed forearms with which birds and bats keep themselves aloft. Based on a 1997 find, paleontologists suspect that the hang-gliding habit allowed the lizard to sail following a running or falling start.



Coelurosauravus
painting, © Jan Sovak

Ponder this amphibian's future.
photo, Nic Bishop courtesy New England Science Center

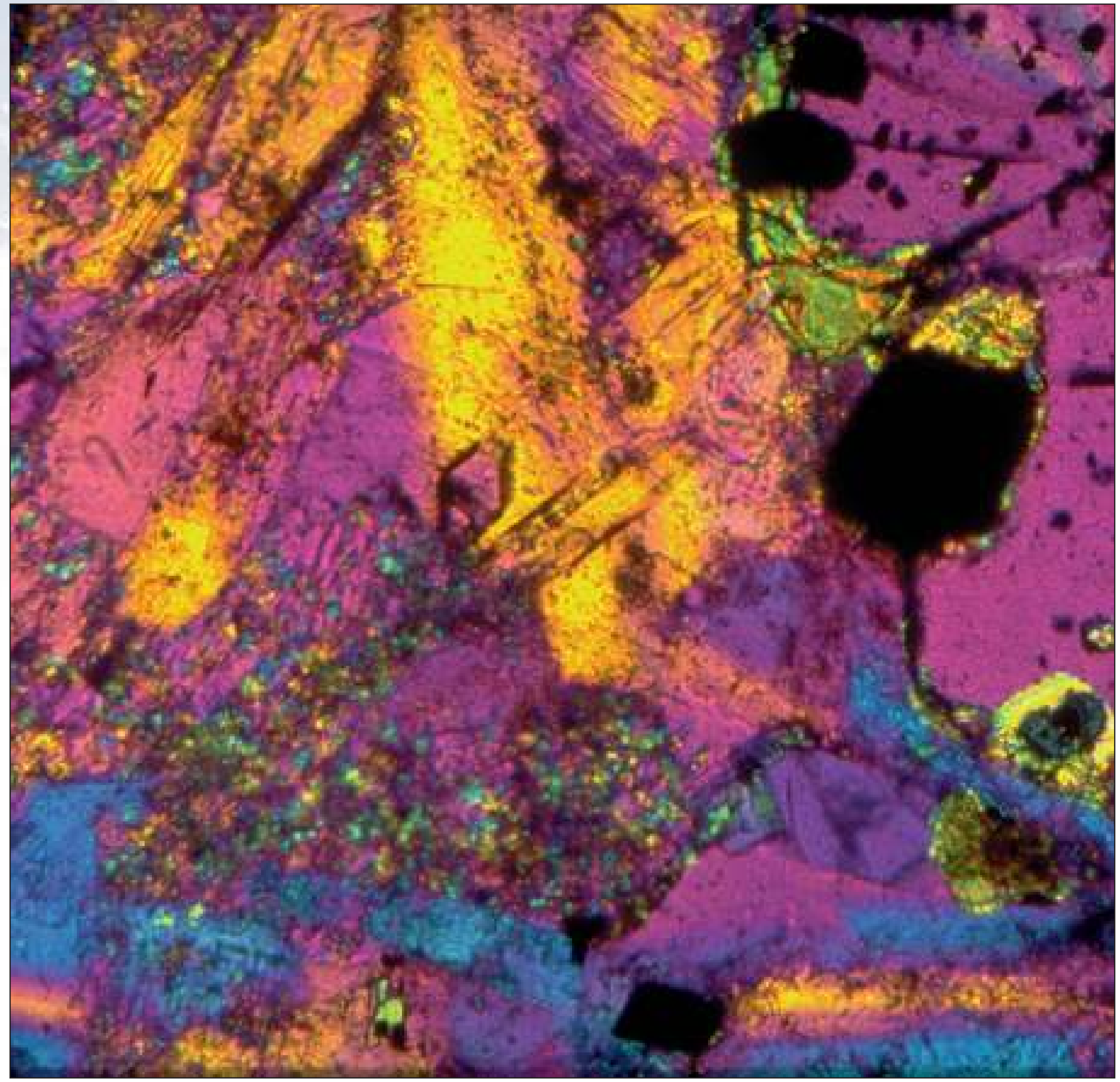
245
MYA
MILLION YEARS AGO

Permo-Triassic Extinction

The Permian Period ends with by far the greatest of the five mass extinctions occurring between 440 mya and the 20th century. Over 95 percent of species and 50 percent of families disappear, roughly twice as many as in any of the other four: the Ordovician (438 mya), Devonian (367 mya), Triassic-Jurassic (208 mya) and Cretaceous-Tertiary (65 mya). Profound waves of life expansion and species diversification follow each mass extinction.

The first four mass extinctions involved dramatic declines, for which scientists have found no obvious cause, whereas the Cretaceous-Tertiary extinction likely resulted from a cataclysmic asteroid impact.

Full biodiversity recovery time following past mass extinction ranges from 10 to 100 million years. If irreversible species loss, precipitated by the impact of human population, continues at its current rate through the 21st century, Earth risks losing as many as one third of all now-living species world-wide by the year 2100. Will we allow this to happen?



Ocean drilling, ice core drilling and computer modeling technologies enable us to move confidently onto the terrain of paleoenvironments. Global climate alteration figures in many mass extinctions. As sea levels change, both cooling and warming modify land and ocean habitats.
photo, courtesy Ocean Drilling Program

230
MYA
MILLION YEARS AGO

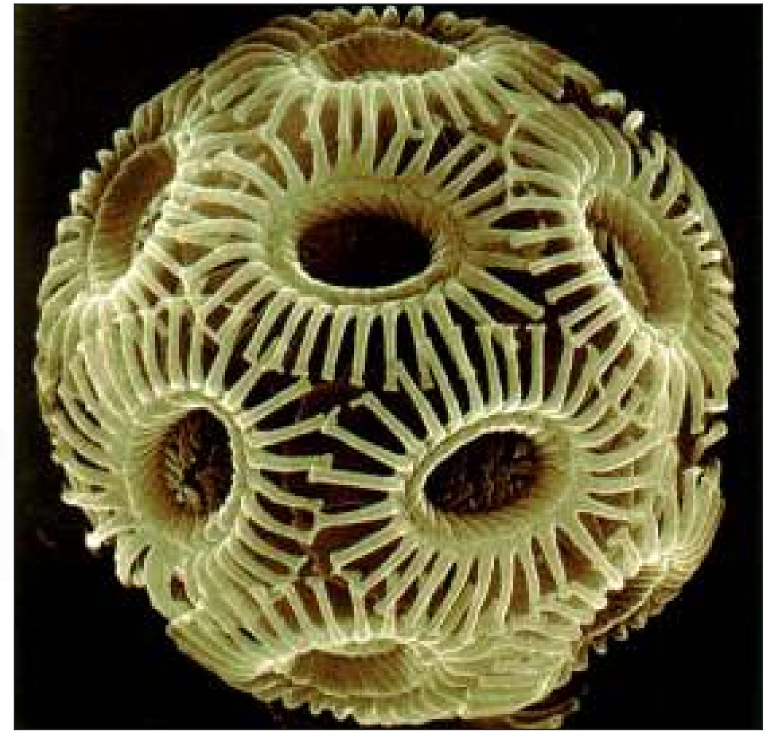
EMILIANIA HUXLEYI

BELLE OF THE BALL

"Emily" is a planktic protoctist; this photosynthesizing alga spends time freely floating in the upper layers of the ocean, gathering solar energy. Though only a half a thousandth of an inch in diameter, *Emiliania huxleyi* plays an expanding role in Earth's climate through both coccolith formation and gas emission.

A major geological force, proliferating populations ("blooms")of this alga extract carbon dioxide from the atmosphere to form calcium carbonate shells that ultimately settle to carpet the sea floor, covering areas larger than all the continents.

In "bloom," Emily's gas emissions are equally potent. As their sulfur-containing gas wafts into the atmosphere, solar radiation transforms it to sulfuric acid. The droplets of acid serve as nucleation sites for water condensation and the formation of ocean cloud cover.



This SEM (scanning-electron micrograph) shows off Emily's almost Baroque "coccoliths" (buttons). This environmental activist designs and bio-manufactures one plate every two hours, sending each to its proper place on the outside of the cell.
photo, Annelies Kleÿne

The microbial 50 kilometer-wide bloom extends 200 kilometers along the coast of Scotland. When satellites first picked up these images, boats immediately went out to explore, but the shell coccoliths of Emily's body were invisible to the unaided eye. Under a laboratory microscope, Emily and cohorts appeared aplenty.
photo, Patrick Hooligan

225
MYA
MILLION YEARS AGO

Night Journeys
First Mammals

Small and nocturnal, the first mammals jump, climb, swing and swim through the dinosaur world. Obliged to inhabit small niches in a world of giants, mammals will discover that their diminutive size opens a proverbial window of opportunity.

In the first waves of mammal diversification, some rodent-sized insect-eaters evolve lactation, enabling mothers to spend more time in the nest keeping their young both fed and warm. Some mammal species evolve even smaller bodies.

These insect-eating mammals, among the oldest known, grew to about 4 inches (10 cm) in length.
painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

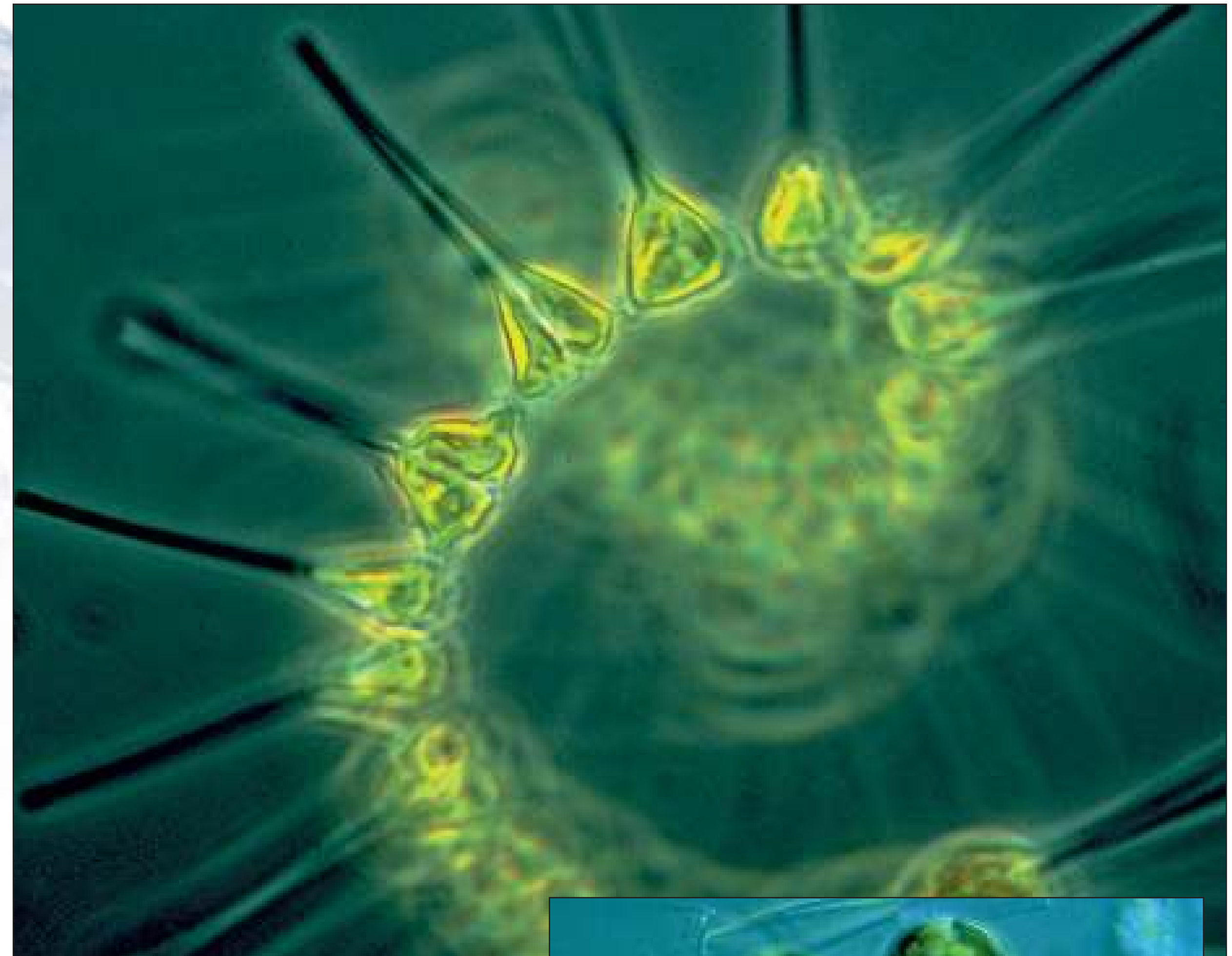
208
MYA
MILLION YEARS AGO

Silicon Symmetry
Triassic-Jurassic Mass Extinction

Just 37 million years after the Permo-Triassic mass extinction, the Triassic Period comes to an end with another mass extinction. It will require 100 million years for biodiversity levels to recover from the combination of these two neighboring devastations of life.

New species evolve. Diatoms with magnificent silica microshells appear and spread quickly throughout the seas. These micro mineral-magicians extract and cycle silica and other elements from the oceans.

Before these creatures evolved, the oceans were supersaturated with soluble silica. As each silica-forming group arose, silica concentrations decreased. Major accumulations of biogenic opal begin to cover the ocean floors of the world.



Each spine in this colonial diatom comes from an individual diatom cell. At one end of the colony, one cell operates as a steady grip, while all of the other cells float in the current and collect nutrients to share.
photo, R. George Rowland courtesy Marine Biological Laboratory

These diatoms are mating. The gametes (reproductive cells), having left their silicious tests (the flying-saucer-shaped shells in the backgound) are about to fuse.
photo, Jeremy Pickett-Heaps

Who is being served?

"... The dimensions of bacterial biotransfer processes have considerably increased with the development of animals and plants; they, in turn, serve as energy sources and more fractal space for bacteria."

Wolfgang Krumbein

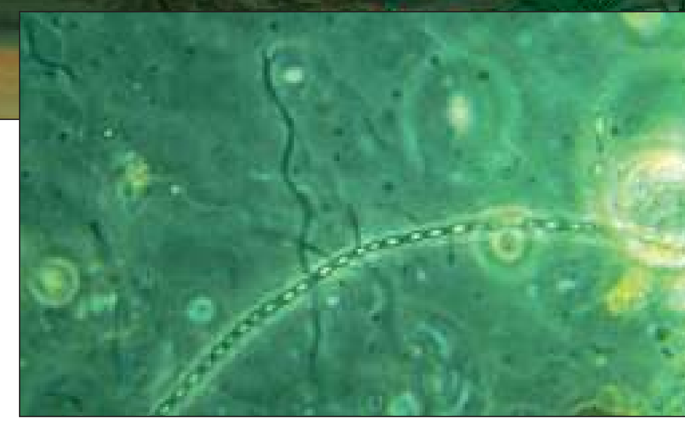
DINOS

DINING OUT AND DINING IN

Modern American movies depict dinosaurs as dauntingly ferocious carnivores. In fact, most mega-massive dinos, regardless of their fearsome horns, spikes and claws, eat plants. They feed on tough cycad leaves, twigs, seeds and fruits of trees common in shrublands and woodlands. Fossilized dino dung (coprolite) shows that while some herbivores mingled tastes, others were fussy eaters.

Thousands of millions of cellulose-fermenting bacteria enable herbivorous dinos to digest the daily tonnage of cellulose (a process similar to that in 20th century cows, elephants and termites). In exchange for their food-processing services, the microbes receive a large tract of habitat.

The paleontologists' menu features high-tech explorations into dino dietary preferences. Research on fossil bones and teeth adds considerable information about the dino taste in food.
painting, © Jan Sovak



This spore-forming filamentous bacterium (Arthromites) lives in the anoxic world within termites and cockroaches. Its chain of cells attach to the gut wall. Unattached gut microbes constantly swim upstream to avoid being defecated.
photo, Lynn Margulis

175
MYA
MILLION YEARS AGO

All Creatures Great and Small

Huge dinosaurs rove mid-Jurassic Earth. Bigger is not necessarily better: larger life forms require more space and food, and have fewer offspring and fewer survival options in times of change. Microscopic "water bears," which survive today, appeared 200 million years before the huge dinosaurs. The Californian water bear loves to cling to moss and lichens with its tiny claws.

The dinosaur and the water bear are archetypes of animal mega-micro waverings. Getting smaller is not uncommon in evolution. The fossil record suggests that beings which "miniaturize" are those most likely to survive mass extinction crises.

Sauropods, reaching 120 feet in length, are representative of the giant dinosaurs of the Jurassic Period.
painting, © Jan Sovak

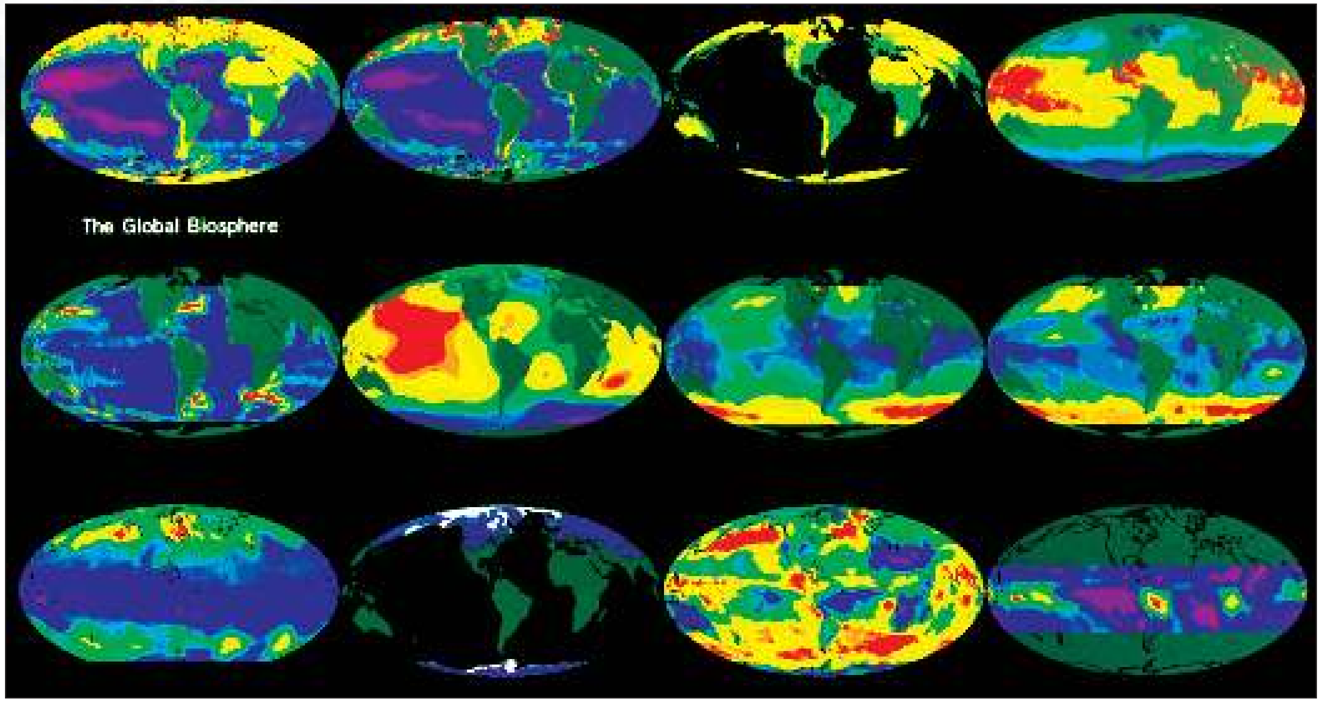
Tardigrades ("slow-step") or water bears, tolerate extremes. Water bears can survive almost total desiccation: rolling up into their tuns (mini-wine-cask shapes), they can hold out as long as 100 years awaiting water. They tolerate temperature ranges from 151 degrees C to -270 degrees C (almost absolute zero). They tolerate X-radiation: the lethal dose of X-rays for human beings is about 500 roentgens; for water bears, 570,000, making the bears of interest to scientists working on future space travel. They are tough, and many species can reproduce partheno-genetically (females hatching females on their own).
photo, Jerome Paulin

150
MYA
MILLION YEARS AGO

Thermoregulation
Warm-blooded Dinos?

Fossil evidence suggests that mammal-like reptiles and some dinosaurs could internally regulate their temperatures. Most contemporary reptiles, amphibians and most fish (except the talented tuna) cannot do this. Birds, most mammals, skunk cabbages and lotus flowers do regulate the temperatures of their bodies. Snakes in colder regions hibernate, lowering their metabolism to such a slow rate that even experts cannot tell if they are dead or alive. How did this regulation evolve?

Many mammals which can thermoregulate still hibernate — no sense hanging about if there's nothing to do in the heat o' the sun or the furious winter's rages. Is falling into deep unconsciousness, as we do at night, a pre-adaptation?



The biosphere is one, biota and environment inseparable. Life evolves in concert with seasonal and deep-time change. Gaian cycling is a harmony of interchange and modulation.
image, courtesy NASA

145
MYA
MILLION YEARS AGO

Descent into the Air

Flight evolves in *Archaeopteryx*; it leaps through treetops in search of insects. Birds are the only dinosaurs which will survive the coming Cretaceous-Tertiary mass extinction. Flight gives birds a leg up: they evolve long-distance seasonal migration, which permits them to respond to Earth's hard times.

Like all migrating animals, birds have a series of preferred and back-up migration systems. They read the stars for orientation; they read the landscape through sounds of water flow and low-frequency sound waves around mountain peaks and passes; they track magnetic fields by use of internal compasses.

The first known bird suggests its dinosaur lineage.
painting, © Jan Sovak

110
MYA
MILLION YEARS AGO

Descent with Co-modification

Earth is much more than a passive 3-D diorama or backdrop to which life forms either adapt or go extinct. Locally, regionally, and at a global planetary level, life modifies Earth environments as much as environments shape life.

Few changes have so touched vista, ecosystem and global cycling as has the evolution of the angiosperms (plants with flowers). In the lush Cretaceous forests of fern and cycad, new colors and scents arise. Intricately woven visual and chemical communication systems set the stage for myriads of flowering plants and their animal pollinators.

photo, Lois Brynes

65
MYA
MILLION YEARS AGO

MEGAFAUNA MEGA-EXTINCTION

The Cretaceous Period ends with a mass extinction. An asteroid six miles in diameter is believed to have hit the Yucatan Peninsula. Shock waves reverberate around Earth. Debris flying high above the atmosphere rains down with incinerating heat. Later, dust and aerosols block sunlight, and temperatures plunge. Photosynthesis stalls. All animals over 55 pounds disappear, including the beloved dinos. Many plant species disappear, and the diversity of plankton and sponges falls sharply. Approximately 85 percent of ocean-dwelling protoctists and marine animal species are lost. It requires 20 million years for new life forms with high levels of diversity to reappear.

paintings from the book "The History of Earth," © 1991 William K. Hartmann and Ron Miller

55
MYA
MILLION YEARS AGO

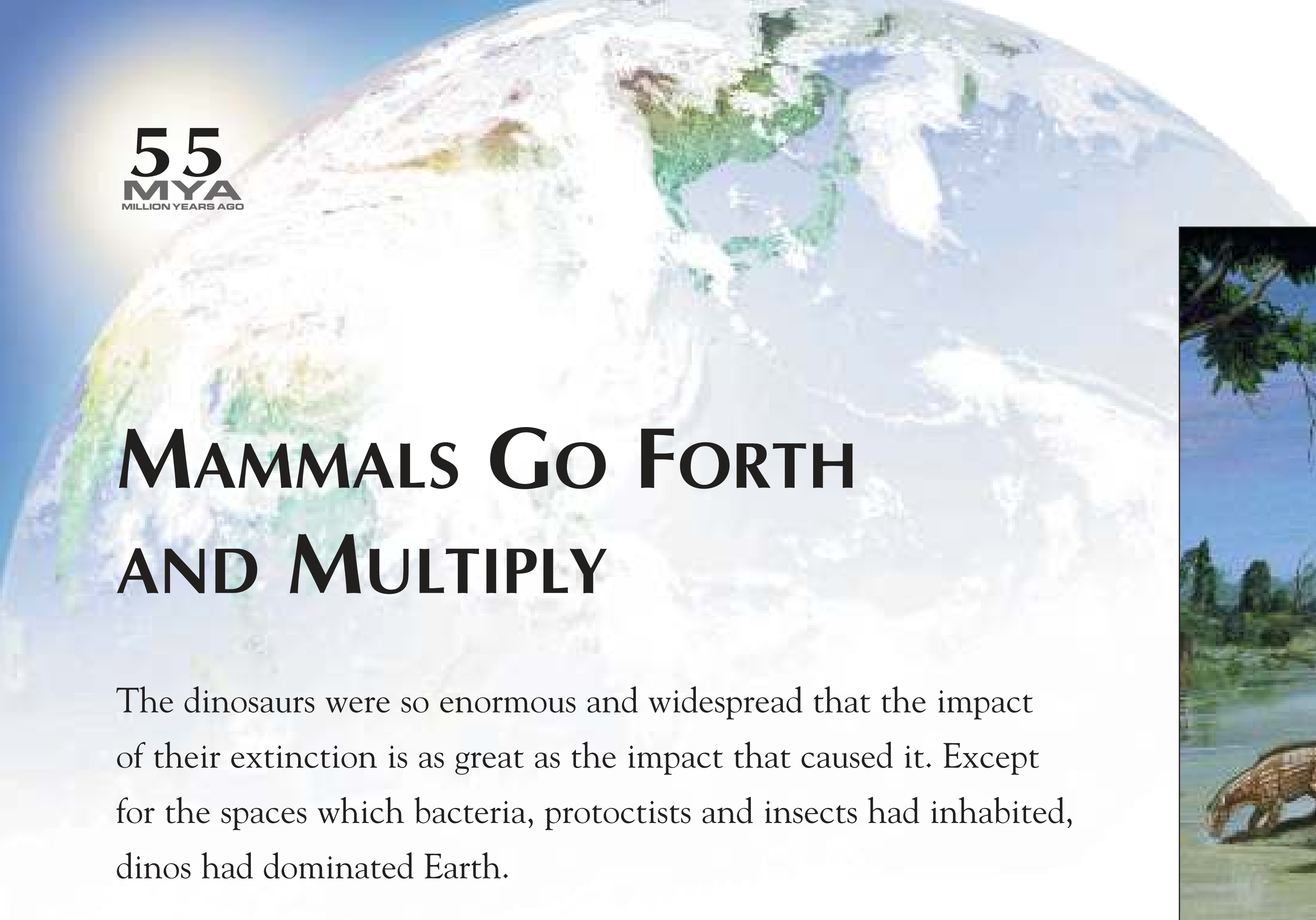
Mammals Go Forth and Multiply

The dinosaurs were so enormous and widespread that the impact of their extinction is as great as the impact that caused it. Except for the spaces which bacteria, protoctists and insects had inhabited, dinos had dominated Earth.

Now that dinos are extinct, the once dark and sheltered mammals stride into daylight. They move quickly to occupy available ecological niches. Among these are primates, which had evolved 30 million years earlier as forest-dwelling creatures. Primates possess several or all of the following characteristics: the ability to hold things with their hands and, sometimes, their feet; thumbs that oppose the forefinger; flattened nails in place of claws; unique teeth, skulls and other bones; a prolonged gestation period; large brains; and acute vision with binocular capability.

Early primates romp on a log.
painting, © Jan Sovak

Prior evolution and radiation of flowering plants — grasses, fruits and leguminous plants — provide an Eden-like world in which newly evolving mammals go forth and multiply.



40
MYA
MILLION YEARS AGO

You Can Go Home Again

Shifts in ocean currents and the development of Antarctic bottom waters drop ocean temperatures by as much as five degrees centigrade. Life thrives and expands in these nippy, nutrient-rich ocean waters.

Perhaps some combination of increased ocean productivity, shifting sea margins, the complexities of megafaunal movement on land, and a nostalgia and logic we've yet to understand — inspires a change. The whales' land-roving mammalian ancestors, after thoughtful ambling on the edge, return to the sea. They do go home again.

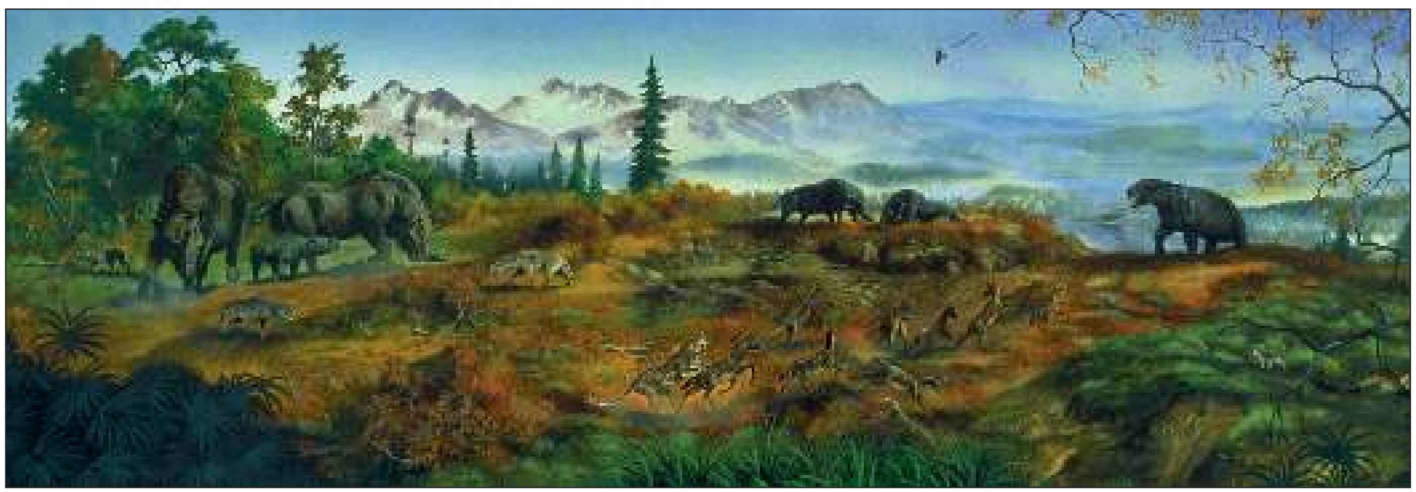
photo, courtesy Royal British Columbia Museum

30
MYA
MILLION YEARS AGO

Fruits of the Earth

Grasslands and trees with fruits spread. Mammals help pollinate and fertilize as they graze and swallow delicious fruits.

Earth grows cooler and more seasonal. Although extinction overtakes those animals requiring steamy tropical climates, this is largely a period of relative stability – a moment of evolutionary rest.



Nitrogen, an element crucial for DNA, RNA and protein syntheses, is critical for all life-forms. Grasslands and grazers spread, unmindful of their dependence upon the microcosm in Gaian cycling of nitrogen.
painting, © Jan Sovak

Bacterial metabolic mastery is shown once more in this cyano's facility for fixing nitrogen. Although abundant in Earth's atmosphere, paired nitrogen atoms are loath to separate. Breaking the bond for transformation into useable form is accomplished only by lightning and bacteria.
photo, Stjepko Golubic

20 MYA
MILLION YEARS AGO

Pressures Mount

Tectonic pressures mount and mountain ranges form — the Cordilleras, the Andes, the great Himalayan range. As inland seas shrink, the climate wavers through extremes of hot and cold. Ocean currents change and nutrients well up from the deep, supporting enormous growth of phytoplankton, allowing species higher in the food web to prosper as well. Seals and sea lions flourish. Species of diving birds diversify. With falling sea levels, land bridges connect Siberia to North America and England to the continent. Grand parades of intercontinental migrations take place.

Most mammals appear essentially modern in form. Fossils from the state of Nebraska include camels, deer-like animals, bear dogs, foxes, peccaries, small beavers, ground squirrels and horses. Horse evolution occurs primarily in North America. Early elephant-like creatures spread from Africa to the Eurasian continent.

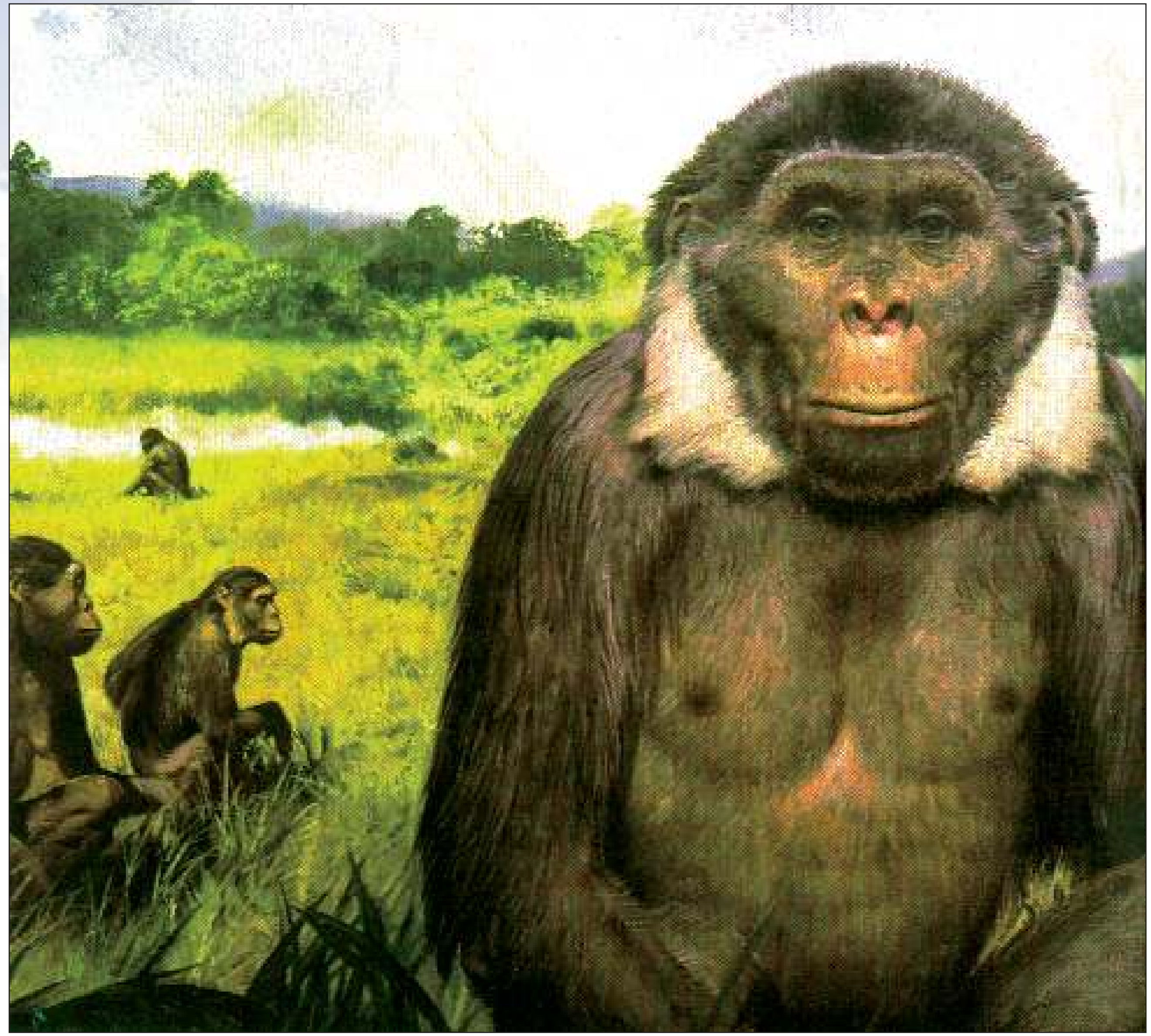
Cormorants are among the most ancient of living diving birds. With special retractable lenses, their underwater vision is unsurpassed.
photo, Lois Brynes

The ancestry of modern great apes is not well known. Proconsul, *an early member of the hominid lineage, may have been too primitive in a number of respects to represent a link in the evolutionary chain to modern forms.*
painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

10
MYA
MILLION YEARS AGO

Getting Familiar

Breakthroughs in molecular biology are revolutionizing our understanding of the history and relationships of hominid primates. Orangutans depart from the combined African great ape and human line about 13 mya. The great ape (or gorilla) lineage splits from the combined chimpanzee and human lineage some eight mya. We share over 99 percent of expressed DNA with chimpanzees. This does not mean that we are "descended" from chimpanzees, but rather, that we last shared a common ancestor eight mya.



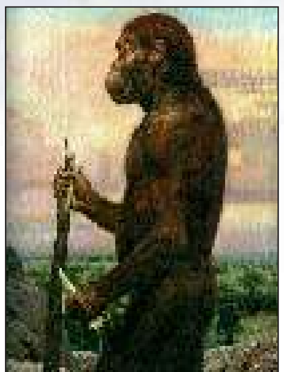
The Indian species Ramopithecus punjabicus, an ape speculatively reconstructed here from fossil evidence, belongs to the family Hominidae.
painting, Zdeněk Burian © Jiri Hochman and Martin Hochman

5 to 0 MYA

MILLION YEARS AGO

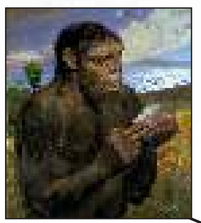
UP TO US

Chimpanzee and human lines split 5 Mya. Humans and chimps share close to 99.9 percent of expressed genes.



Astralopithecus demonstrates hominid bipedalism.

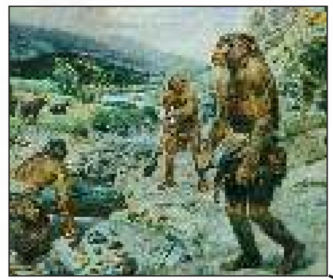
Stone tools appear, possibly associated with *Homo habilis.*



Homo erectus emerges from Africa.

Archaic sapiens is one of the oldest fossil humans found in Europe.

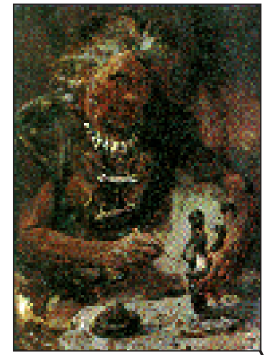
Humans build shelters and use increasingly refined tools, weapons, fireplaces, grease lamps and sewn pelts.



Neanderthal man co-exists with Cro-Magnon man in Western Europe.

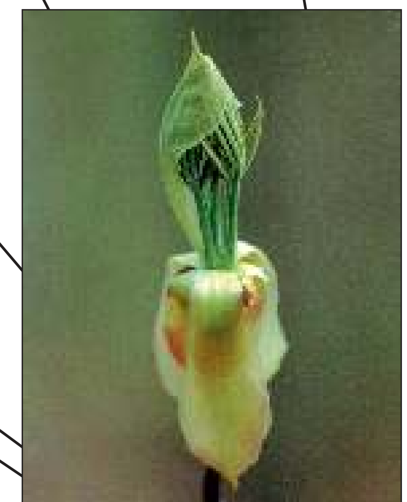
Cro-Magnon man returns from a hunt in the Dordogne region of France.

Early European Homo sapiens sapiens kill a mammoth. Three different species of humans coexist: Neanderthal man (Homo sapiens neanderthalensis) in Asia and eastern Europe, Homo erectus in Asia, and the relentlessly spreading Homo sapiens sapiens.



A late stone age European artist crafts a figurine. Homo sapiens sapiens spread over the world, entering North America over the Bering land bridge.

Many large North American animals, such as this woolly rhino, become extinct, perhaps due to overhunting by humans.



And, for a moment, we are a part of the beauty.
photo, Lois Brynes

Human Population (billions): 0, 1, 2, 3, 4, 5, 6

4 mya | 3 mya | 2 mya | 1 mya | Present

mya = million years ago

paintings, Zdeněk Burian © Jiri Hochman and Martin Hochman

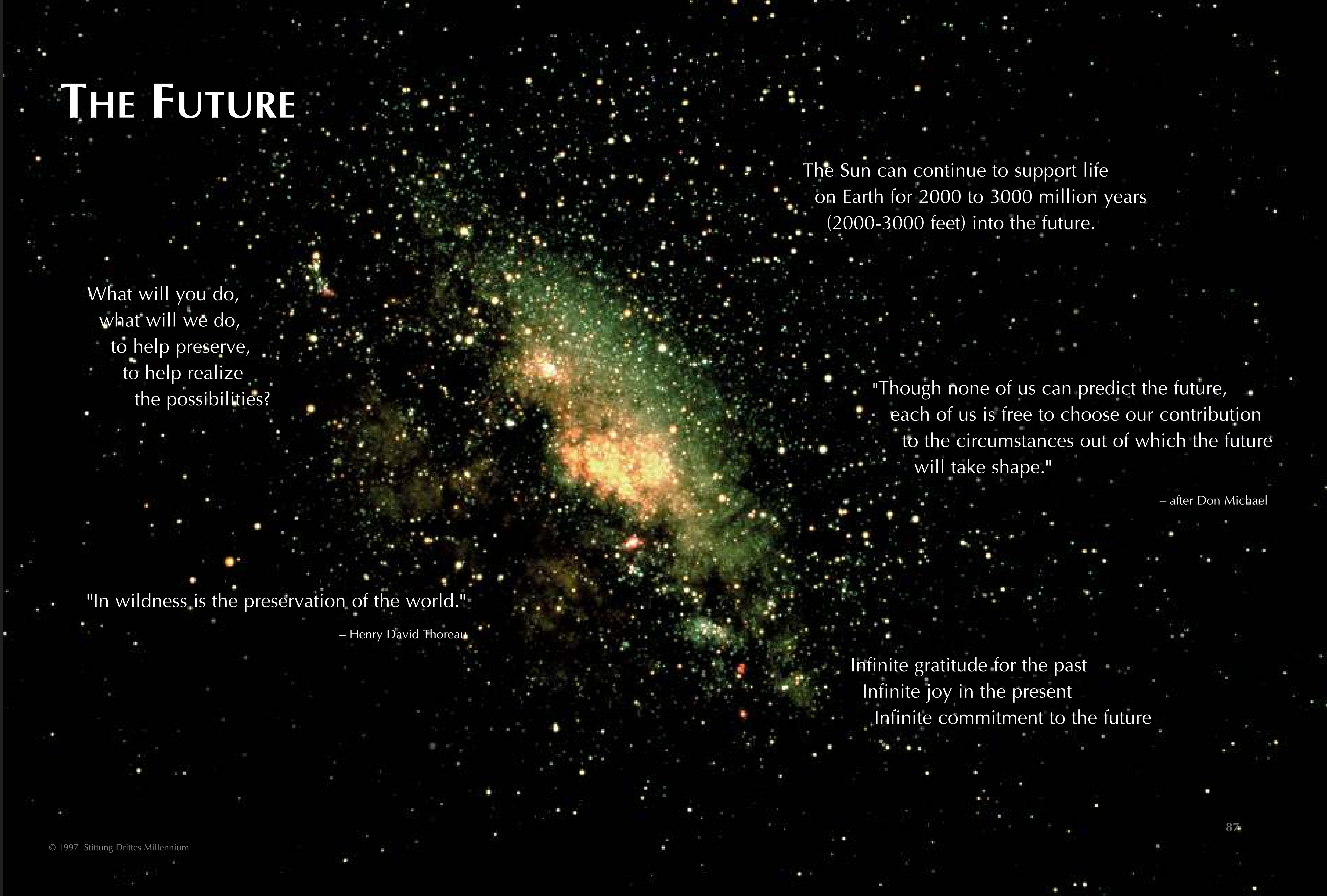
painting, Paul Gauguin, Tompkins Collection, courtesy Museum of Fine Arts, Boston

"D'où venons nous? Que sommes nous? Où allons nous?"

Where do we come from? What are we? Where are we going?

Our *Walk Through Time* is a celebration of creativity, of the diversity and continuity of life. We have walked through Deep-Time, our collective past, which includes 4000 million years of weaving, wandering life forms. As we "hold the mirror up to nature," Deep-Time calls up the presence of the past.

The deep-past lives in each of us, in all of us – each cell, each thought. Walking through the grand pageant of life on Earth can be humbling, sometimes overwhelming. It is also exhilarating.



THE FUTURE

The Sun can continue to support life
on Earth for 2000 to 3000 million years
(2000-3000 feet) into the future.

What will you do,
what will we do,
to help preserve,
to help realize
the possibilities?

"Though none of us can predict the future,
each of us is free to choose our contribution
to the circumstances out of which the future
will take shape."

– after Don Michael

"In wildness is the preservation of the world."

– Henry David Thoreau

Infinite gratitude for the past
Infinite joy in the present
Infinite commitment to the future

Acknowledgments

Origin of the Walk Through Time … from stardust to us

The original one-mile *Walk Through Time … from stardust to us* was created by the employees of the Hewlett-Packard Company under the Company's sponsorship. It was first presented as part of HP Laboratories' Celebration of Creativity on Earth Day, 22 April 1997, at the HP Laboratories sites in Palo Alto, California; Bristol, England; and Tokyo, Japan.

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EARTH CHARTER

We stand at a critical moment in Earth's history, a time when humanity must choose its future. As the world becomes increasingly interdependent and fragile, the future at once holds great peril and great promise. To move forward we must recognize that in the midst of a magnificent diversity of cultures and life forms we are one human family and one Earth community with a common destiny. We must join together to bring forth a sustainable global society founded on respect for nature, universal human rights, economic justice, and a culture of peace.

Towards this end, it is imperative that we, the peoples of Earth, declare our responsibility to one another, to the greater community of life, and to future generations.

We urgently need a shared vision of basic values to provide an ethical foundation for the emerging world community. Therefore, together in hope we affirm the following interdependent principles for a sustainable way of life as a common standard by which the conduct of all individuals, organizations, businesses, governments, and transnational institutions is to be guided and assessed.

PRINCIPLES

I. RESPECT AND CARE FOR THE COMMUNITY OF LIFE

1. Respect Earth and life in all its diversity.
2. Care for the community of life with understanding, compassion, and love.
3. Build democratic societies that are just, participatory, sustainable, and peaceful.
4. Secure Earth's bounty and beauty for present and future generations.

II. ECOLOGICAL INTEGRITY

5. Protect and restore the integrity of Earth's ecological systems, with special concern for biological diversity and the natural processes that sustain life.
6. Prevent harm as the best method of environmental protection and, when knowledge is limited, apply a precautionary approach.
7. Adopt patterns of production, consumption, and reproduction that safeguard Earth's regenerative capacities, human rights, and community well-being.
8. Advance the study of ecological sustainability and promote the open exchange and wide application of the knowledge acquired.

III. SOCIAL AND ECONOMIC JUSTICE

9. Eradicate poverty as an ethical, social, and environmental imperative.
10. Ensure that economic activities and institutions at all levels promote human development in an equitable and sustainable manner.
11. Affirm gender equality and equity as prerequisites to sustainable development and ensure universal access to education, health care, and economic opportunity.
12. Uphold the right of all, without discrimination, to a natural and social environment supportive of human dignity, bodily health, and spiritual well-being, with special attention to the rights of indigenous peoples and minorities.

IV. DEMOCRACY, NONVIOLENCE, AND PEACE

13. Strengthen democratic institutions at all levels, and provide transparency and accountability in governance, inclusive participation in decision-making, and access to justice.
14. Integrate into formal education and life-long learning the knowledge, values, and skills needed for a sustainable way of life.
15. Treat all living beings with respect and consideration.
16. Promote a culture of tolerance, nonviolence, and peace.

The above is an excerpt from the full text of the Earth Charter, released officially by the Earth Charter Commission in March 2000. For further information regarding the Earth Charter Initiative and opportunities to participate, visit www.earthcharter.org.