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| ❂ |  | *A History* |
| *of* |
| *the Universe* |
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## Prefix: A Chart of Geologic Time

International Commission on Stratigraphy. “International Chronostratigraphic Chart.” *Stratigraphy*.*org*. Mar. 2020. 27 Feb. 2021. Web. <https://stratigraphy.org/ICSchart/ChronostratChart2020-03.jpg>. (Timespans are in millions of years.)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| supereon \* | eons | eras | periods | epoch |
|  |  |  | Quaternary 2.58-present | Holocene 0.0117-present |
|  | Phanerozoic 541-present | Cenozoic 66-present | Pleistocene 2.58-0.0117 |
| Neogene 23-2.58 | Pliocene 5.333-2.58 |
| Miocene 23.03-5.333 |
| Paleogene 66-23 | Oligocene 33.9-23.03 |
| Eocene 56-33.9 |
| Paleocene 66-56 |
| Mesozoic 251.9-66 | Cretaceous 145-66 | |
| Jurassic 201.3-145 | |
| Triassic 251.9-201.3 | |
| Paleozoic 541-251.9  (upper 358.9-251.9)  (middle 419.2-358.9)  (or lower 541-358.9)  (or lower 541-419.2) | Permian 298.9-251.9 | |
| Carboniferous 358.9-298.9 | |
| Devonian 419.2-358.9 | |
| Silurian 443.8-419.2 | |
| Ordovician 485.4-443.8 | |
| Cambrian 541-485.4 | |
| Precambrian  4600-541 | Proterozoic 2500-541 | Neoproterozoic 1000-541 | Ediacaran 635-541 | |
| Cryogenian 720-635 | |
| Tonian 1000-720 | |
| Mesoproterozoic 1600-1000 |  | |
| Paleoproterozoic 2500-1600 |  | |
| Archean 4000-2500 | Neoarchean 2800-2500 |  | |
| Mesoarchean 3200-2800 |  | |
| Paleoarchean 3600-3200 |  | |
| Eoarchean 4000-3600 |  | |
| Hadean 4600-4000 |  |  | |

\* An informal, nonscientific term.

## Introduction

outline-book basis

This outline book uses as its basis: Sutherland, Stuart. *A New History of Life*: *Course Guidebook*. Chantilly VA: The Great Courses, 2013.

introductory comments

The Earth is composed of interrelated and complex systems . . . We called this viewpoint Earth system science . . .” (Sutherland *New History* 1)

Rock “strata can be read with just a little understanding of geology and paleontology, tools you will gain through this series.” (Sutherland *New History* 1)

“The tools we need . . . include an understanding of how rocks are formed and laid down . . . [and] how fossils form . . . We also need . . . a grand unifying theory of the geosciences . . . called plate tectonics . . .” (Sutherland *New History* 2)

“. . . the Earth evolving from a cloud of dust and gas through to a ball of magma [had] profound implications for the evolution of life on Earth . . .” (Sutherland *New History* 2)

The Moon, “too, would have a vital role to play in nurturing and then protecting Earth’s biosphere.” (Sutherland *New History* 2)

Everywhere “the stuff of life is abundant and available . . .” (Sutherland *New History* 2)

“Earth’s earliest fossils are rare and precious . . . [showing] the dawning of Earth’s life forms . . .” (Sutherland *New History* 2)

“The evolution of microbes performing new and complicated [2] tricks would start to radically alter the Earth system and drive the planet into a frozen state; this could have been a terminal experience for the biosphere but instead would spur it forward to greater complexity.” (Sutherland *New History* 2-3)

“Following another pole-to-pole glaciation, creatures composed of multiple cells started to emerge. They would diversify suddenly and dramatically around 542 million years ago, creating a biosphere—no longer drifting passively in the oceans or forming mats in shallow water. Instead, life [was] crawling over the ocean floor, swimming above it, and digging into it.” (Sutherland *New History* 3)

“The biosphere would eventually conquer the land, first by plants and insects and then by our ancestors, the vertebrates. . . . We will follow . . . their great leap onto the land.” (Sutherland *New History* 3)

## Earth System Science

introduction

“. . . of all the sciences, paleontology and geology are the most narrative. They tell the story of our planet, written in the rocks. [Rock strata] are like the pages in a book; each of those rock strata contains information about an ancient Earth . . .” (Sutherland *New History* 5)

earth system science

“. . . Earth system science [is] a new paradigm . . .” (Sutherland *New History* 10)

“Earth system science considers the interconnectedness of all aspects of Earth, which is the theme of *A New History of Life*.” (Sutherland *New History* 5)

“Earth system science divides the Earth into a number of spheres, or systems, which are then arranged in hierarchies. An example of a system is a tree leaf. The leaf is composed of plant cells, and each plant cell is itself a system . . . [The leaf is attached] to a branch and, of course, to the larger tree. The tree is part of the forest; the forest is part of a wider ecosystem.” (Sutherland *New History* 5)

“What we’re trying to do is to understand things in a greater context. For example, it is not enough to understand what a fossil looks like and what its shape and form are; we need to understand what this creature did when it was alive. It is so much more than a long Latin name and an age. We need to read it in the context of the Earth system that it originally inhabited.” (Sutherland *New History* 5)

Earth’s four major systems

lithosphere (aka geosphere): “all the rocky material . . .” (Sutherland *New History* 6)

hydrosphere: all the water “in lakes, rivers, oceans, or groundwater.” (Sutherland *New History* 6)

The cryosphere is “all the frozen water on the planet.” (Sutherland *New History* 6)

atmosphere: “the thin layer of gases that surrounds the surface of our planet.” (Sutherland *New History* 6)

biosphere: all the life, on the surface, in the geosphere, and in the atmosphere. (Sutherland *New History* 6)

“All major Earth systems are open systems. [They receive] matter and energy from other systems . . .” (Sutherland *New History* 6)

example: “Rain can fall into the ocean,” and water can form clouds. (Sutherland *New History* 6)

example: “Oceans can heat up and get cold, as well; they can exchange energy.” (Sutherland *New History* 6)

“The entire Earth, however, is a closed system . . .” (Sutherland *New History* 6)

But “there is some leakage of matter out of the atmosphere.” (Sutherland *New History* 6)

And there is energy exchange: “sunlight coming into the Earth [and heat] radiating . . . to space.” (Sutherland *New History* 6)

hierarchy of systems

systems hierarchy in an organism

“. . . a molecule is part of larger molecules and macromolecules—for example, DNA.” (Sutherland *New History* 6)

“DNA itself is a component part of small systems of cells that we call organelles—for example, mitochondria, which are the powerhouses of the cells. Mitochondria are like micro-machines within a cell system.” (Sutherland *New History* 6)

“A cell system forms tissue systems composed [6] of many cells.” (Sutherland *New History* 6-7)

“Tissues make up organs.” (Sutherland *New History* 7)

“Organs themselves are part of a wider system; for example, the stomach is part of the digestive system.” (Sutherland *New History* 7)

“The digestive system is one of many systems [that] form the highest level of this system, which is the human organism.” (Sutherland *New History* 7)

systems hierarchy in evolution

“Systems hierarchy . . . mirrors the evolution of systems from simple (molecules) to complex (organism).” (Sutherland *New History* 7)

Simple molecules were “the state of the Earth very early in its history.” (Sutherland *New History* 7)

“Once the Earth had cooled, there were pools of water full of organic molecules.” (Sutherland *New History* 7)

Organic molecules formed “macromolecules and, ultimately, the first cells, about 4 billion years ago.” (Sutherland *New History* 7)

“Then, associations of cells formed the first simple algae.” (Sutherland *New History* 7)

“Ultimately, about 600 million years ago, complex organisms formed.” (Sutherland *New History* 7)

feedback loops

Systems relate through feedback loops. (Sutherland *New History* 7)

“Feedback drives systems into or out of stability. There are two kinds of feedback: negative and positive.” (Sutherland *New History* 7)

“. . . negative feedback stabilizes conditions in systems . . .” (Sutherland *New History* 7)

“Early in its history, Venus may have had liquid water oceans, but as the Sun became brighter and the surface of the planet became warmer, the oceans on Venus evaporated into its atmosphere.” (Sutherland *New History* 7)

The greenhouse effect is a negative feedback system. (Sutherland *New History* 7)

“Carbon dioxide allows (as does the rest of the atmosphere) solar radiation, or short-wave radiation, to [7] penetrate to the surface. This radiation heats up the surface of the planet, and the planet then radiates long-wave radiation back into space. Some of that long-wave radiation, however, is absorbed by carbon dioxide molecules; in this way, the carbon dioxide acts like a blanket. It keeps the planet warm. The greenhouse effect, which has gotten some bad press, is not always such a bad thing. In fact, we need the greenhouse effect to keep our planet warm. It has been keeping our planet warm for billions of years.” (Sutherland *New History* 7-8)

“Positive feedback tends to drive systems into states of instability.” (Sutherland *New History* 8)

“Ice has what we call high albedo, or reflective power: It is white. It reflects a lot of solar radiation. That reflected solar radiation goes into space, which keeps our planet cool; thus, the less ice we have, the less reflection and, therefore, the more heat absorbed.” (Sutherland *New History* 8)

“As our planet warms, the cryosphere—the icy part of the atmosphere—starts to shrink. . . . once the ice is removed, surfaces are exposed—land and oceans . . . Dark surfaces absorb heat.” (Sutherland *New History* 8)

the Gaia hypothesis

James Lovelock “viewed the Earth as a very large, self-regulating organism. He called this the Gaia hypothesis. Gaia is a Greek goddess who personified the Earth. Lovelock maintained that the Earth’s homeostatic state is really just the result of many complex feedback mechanisms operating together.” (Sutherland *New History* 8)

“To demonstrate how Gaia could self-regulate just using simple feedback, Lovelock created a thought experiment. Imagine a planet that has two kinds of daisies: dark daisies and light daisies. The light daisies, with high albedo, reflect heat . . .” The dark daisies absorb heat. (Sutherland *New History* 9)

“This daisy world orbits a sun like ours that initially was not as bright. Like our Sun, it was 30 percent less luminous. And, at those times early in the history of this world, the daisies can inhabit equatorial regions only because those areas receive maximum sunlight and are the warmest. After the first generation, dark daisies will have selective advantage. They are dark and can absorb more heat; the planet starts to heat up, and the dark daisies, as a result, spread, absorbing more heat—which allows for the spread of more daisies. We are into a positive feedback loop here. The result at the end of this first stage is that the planet will be warmer than expected if life had not be present.” (Sutherland *New History* 9)

“Time moves on, the sun gets brighter, and the temperature increases. Now, it becomes too hot for dark daisies at the equator, and the white daisies have the selective advantage because they can reflect the sunlight back and keep those equatorial regions cooler. This is a negative feedback loop that has been initiated. Planet temperatures are starting to be regulated. We are moving into a homeostatic state. The sun eventually reaches a mature state, and some sort of equilibrium is reached.” (Sutherland *New History* 9)

Earth’s homeostasis

“Whether you buy into Lovelock’s idea of a self-regulating Earth system is not the point, however. What is important is an appreciation that the Earth is composed of many systems—the major ones being the hydrosphere, atmosphere, geosphere, and biosphere. Changes in one or the components of one will have domino effects on all the others.” (Sutherland *New History* 9)

“To understand how Earth systems have evolved over time, we need an appreciation of an incredibly important concept in the geosciences—one that is relatively recent. It is the concept of deep [9] geological time, which allows some incredible events to happen in the history of the planet. We will examine those in the next lecture.” (Sutherland *New History* 9-10)

suggested reading (Sutherland *New History* 10)

Lovelock, *The Ages of Gaia*.

Lovelock, Personal website.

Skinner, Porter, and Botkin, *The Blue Planet*.

## Calculating Geological Time

“Uniformitarianism.” *Wikipedia*. 31 Dec. 2020. 21 Feb. 2021. Web.

introduction

“. . . we can tell the story of the Earth by looking at rock layers.” (Sutherland *New History* 11)

“. . . this lecture will give you the tools you need to understand and read that narrative in the rocks.” (Sutherland *New History* 11)

calculating the age of Earth

“Archbishop James Ussher was one of the first people to try to calculate the age of the Earth. Using the Bible, he added up all the dates that were recorded to provide a timeline and came up with a date for the first day of creation, October 22, 4004 B.C., making the Earth just a little more than 6000 years old.” (Sutherland *New History* 11)

Nicolas Steno (1638-86): principles of stratigraphy

Stratigraphy is “the science of how rock layers are laid down and how they are arranged in various combinations. Stratigraphy is the basis of our understanding of geological time.” (Sutherland *New History* 11)

“. . . Danish anatomist and geologist Nicolas Steno . . . developed the principles of stratigraphy . . .” (Sutherland *New History* 11)

“Steno’s first principle of stratigraphy is that of superposition. . . . the layers at the bottom of a section are the oldest, and the layers at the top are the youngest.” (Sutherland *New History* 11)

“You may have seen rock layers that are tilted or folded into complex shapes. Steno’s principle of original horizontality states that rocks that were originally sediments laid down in oceans, lakes, or lava flows would not have been deposited at an angle; they would have been deposited flat and would have been tilted after they had turned into rock. Again, this implies a history to the rock layer . . .” (Sutherland *New History* 12)

James Hutton (1726-97)

Hutton built on Steno. (Sutherland *New History* 11)

cross-cuts

Hutton created the concept “of cross-cutting relationships.” (Sutherland *New History* 12)

“Think of the rock layers you see that are horizontal in nature, but running diagonally across them are darker rocks that cross-cut those horizontal strata. That darker area, the diagonal stratum, is called an igneous dike, and originally, it was hot magma that forced its way through those sedimentary rocks. It later cooled to form the rock that we see today. From that, we can make a rather simple but very profound deduction: The igneous dike must be younger than the sediments that it cross-cuts.” (Sutherland *New History* 12)

a long time

“An important moment for Hutton occurred in Siccar Point in Scotland—like the Grand Canyon, a holy place for geologists.” (Sutherland *New History* 12)

You see “vertical strata, or strata that have been turned up on their end. . . . they were deposited in a deep ocean during the Silurian period, about 425 million years ago.” (Sutherland *New History* 12)

“Other rocks [were deposited] in a desert during a period called the Devonian, about 345 million years ago.” (Sutherland *New History* 12)

“That hiatus, a period of non-deposition, is called an unconformity.” (Sutherland *New History* 12)

To explain an ocean and a desert in one spot, you needed a lot of time. (Sutherland *New History* 12)

Charles Lyell (1797-1875) and deep time

Lyell was a “uniformitarian.” (Sutherland *New History* 13)

Uniformitarianism assumes that present-day natural laws have always operated the same everywhere in the universe. (“Uniformitarianism”)

E.g.: “the constancy of cause and effect throughout space-time . . .” (“Uniformitarianism”)

It is “an unprovable postulate . . .” (“Uniformitarianism”)

Today “we use the term “actualism.” Uniformitarianism implies that the Earth processes are extremely [13] slow, such as the erosion of mountains by streams. Although actualism acknowledges the slowness of processes, it notes that occasionally, there are also sudden, dramatic, and catastrophic events, such as the eruption of a volcano or the impact of a meteorite from outer space. Geologically speaking, these are instantaneous events.” (Sutherland *New History* 13-14)

In fossiliferous (fossil-rich) limestone “around Mt. Etna in Sicily, he noticed that [its species] were not really all that different from species that could be found around the Italian coastline in the present day; thus, this rock could not really be all that ancient.” (Sutherland *New History* 12-13)

But he saw that the limestone “passed underneath Mt. Etna. . . . Using the principle of cross-cutting relationships, that must mean that Mt. Etna is younger than the limestone; therefore, the fossils must be millions of years old, too. If fossils millions of years old are the same as living species, then the rate of appearance of new species must be incredibly slow.” (Sutherland *New History* 13)

“From his observations of parasitic cones on Mt. Etna—that is, smaller volcanoes that develop on the back of a larger volcano—Charles Lyell concluded that Etna itself must be millions of years old.” (Sutherland *New History* 13)

relative dating

Relative dating “works out the relative order of events . . . what is older or younger than something else.” (Sutherland *New History* 14)

example: “trilobites are always [found below] ammonites.” (Sutherland *New History* 14)

You might determine that mudstone (mud sediment) accumulates in an ocean “about 10 feet per million years . . . [But this assumes] the accumulation rate of sediment is constant. [And it] provides only a very rough estimate of geological time.” (Sutherland *New History* 14)

absolute dating

Radiometric (radioactive) dating provides absolute dating. (Sutherland *New History* 14)

Some “elements exist in different forms, called isotopes.” (Sutherland *New History* 14)

Some isotopes change form regularly (radioactive decay). (Sutherland *New History* 14)

carbon-14

“Carbon has three naturally occurring isotopes: carbon-12, carbon-13, and carbon-14. Carbon-14 is an unstable isotope, which means it decays. . . . it gives off radiation and forms a more stable compound—in this case, nitrogen-14. This rate of [14] decay can be determined experimentally; therefore, the ratio of the unstable parent isotope to the stable daughter element can be used to determine the amount of time a certain substance has been decaying.” (Sutherland *New History* 14-15)

uranium-238

“Although carbon-14 is useful for archaeological studies, it cannot be used geologically because it decays too quickly. But fortunately for the geologists, there are many other isotopes in rocks that we can use. A good example is uranium-238, which decays into lead-206. This decay is much slower, taking place over billions of years.” (Sutherland *New History* 15)

“It is not difficult to test the age of rocks using absolute radiometric dating. . . . we measure a ratio between the unstable parent element and stable daughter material.” (Sutherland *New History* )

the age of the Earth

“. . . the further you go back in geological time, the less evidence you find [because] our planet is highly active. The very earliest parts of Earth history have been recycled or eroded.” (Sutherland *New History* 15)

“. . . the earliest parts of [Earth’s] story are lost to us.” (Sutherland *New History* 15)

But “there is still some of the debris left over from the early formation of the solar system. For example, if we do a radiometric date of a meteorite, we come up with an astounding age of about 4.54 billion years old . . .” (Sutherland *New History* 15)

Condense 4.54 billion years into one year. (Sutherland *New History* 15)

January 1: the Earth forms. (Sutherland *New History* 15)

February 1: “the oldest rock we have preserved today on the surface of our planet.” (Sutherland *New History* 15)

July 25: atmospheric oxygen (Sutherland *New History* 15)

November 15: animals with “skeletons or shells.” (Sutherland *New History* 16)

December 15: dinosaurs (Sutherland *New History* 16)

December 26: dinosaurs disappear. (Sutherland *New History* 16)

December 31 at 11:59:18: “end of the last glacial period” (Sutherland *New History* 16)

December 31 at 11:59:46: birth of Christ (Sutherland *New History* 16)

suggested reading

Denby, “Northern Lights.”

Levin, *The Earth through Time*.

## How Evolution Works

two theories of evolution

“There are two main theories of evolution, and their differences also have consequences for how we interpret the fossil record.” (Sutherland *New History* 137)

phyletic gradualism

Phyletic gradualism “speculates that life changes very slowly in small steps over millions of years . . .” (Sutherland *New History* 137)

When species appear suddenly in the fossil record, this is due to “incompleteness in the fossil record.” (Sutherland *New History* 138)

punctuated equilibrium

“In punctuated equilibrium, species populations do not change much. If environmental changes favor a particular feature, however, a population will change very rapidly indeed.” (Sutherland *New History* 138)

example: the peppered moth

The peppered moth is “a white speckled moth.” (Sutherland *New History* 138)

“Because coal smoke turned tree bark black during the industrial revolution, the peppered moth was suddenly visible to predators. . . . the darker forms then had the selective advantage. Over 50 years, they became the dominant type.” (Sutherland *New History* 138)

“. . . later environmental legislation reduced air pollution in the area, and the trees started to return to their natural colors. Now the selection advantage flipped in favor of the lighter speckled moths.” (Sutherland *New History* 138)

“Although this example does not demonstrate evolution of a new species, it does show how natural selection can rapidly change the favored genes in any population.” (Sutherland *New History* 138)

“Under the punctuated equilibrium model, transitional forms are difficult to find” because new species appear rapidly. Since “the geological record is full of gaps . . ., we might miss some of these sudden changes.” (Sutherland *New History* 138)

“Charles Darwin is often cited as a gradualist, but he had noted in his writings that there are sometimes periods of little change followed by sudden rapid change.” (Sutherland *New History* 138)

transitional forms

“Another term for evolutionary transitional form is “missing link.”” (Sutherland *New History* 137)

“. . . there is no direct link between a chimpanzee and a human being. We are not, in any way, descended from chimps. Instead, evolutionary biologists believe we share a common ancestor.” (Sutherland *New History* 137)

7m: “The common ancestor for chimps and humans . . .” (Sutherland *New History* 137)

“Our common ancestor was the branching point from which the creatures that would become chimps and the creatures that would become humans diverged via numerous transitional forms.” (Sutherland *New History* 137)

“. . . transitional forms show us that evolution happens.” (Sutherland *New History* 137)

“In general, the scientific community leans toward punctuated equilibrium. It is accepted that gradualism does occur in some species—certain microfossils, for example. And with punctuated equilibrium, we still find transitional models.” (Sutherland *New History* 139)

*Archaeopteryx*, “perhaps the most famous fossil of all time,” is a transitional form. “*Archaeopteryx* was a bird—but one that possessed a bony tail and a beak full of teeth. It also had odd reptile claws in the center of its wings. [It is a] transition between a ground-dwelling reptile and a bird [of] today.” (Sutherland *New History* 139)

unconformity features

An unconformity feature is “a break in the sedimentary geologic record.” (Sutherland *New History* 138)

example: in the UK are some yellow rocks “called Inferior Oolite; they are marine rocks [deposited 170m]. The rocks below [138] are gray carboniferous limestone and probably date to around 350 million years ago.” (Sutherland *New History* 138-39)

“The sediment below was at one time transformed into a rock and then tilted. Those tilted rocks were uplifted and exposed and eroded to an irregular surface. When sea levels rose, the ocean returned, and the upper layer was deposited.” (Sutherland *New History* 139)

“The eroded area created the unconformity between the two rock units. The unconformity in this case represents a potential gap—missing information, or lack of strata—of about 180 million years.” (Sutherland *New History* 139)

## Taxonomy

introduction

Taxonomy: “Organizing life in . . . logical hierarchical schemes” (Sutherland *New History* 159)

Linnaeus’s classification

1700s: Carl Linnaeus’s Latin “binomen system”: noun (genus) + adjective (species). (Sutherland *New History* 158)

species names

They “come from a variety of sources.” (Sutherland *New History* 159)

Scientists may honor someone.

*Angochitina milleri* “honors a micropaleontologist, Giles Miller, who helped collect the material that ultimately yielded this species.”

The name may refer to an area, “often where the specimen was collected . . .”

*Ancyrochitina gogginensis* “was collected from Goggin Road . . .”

It may be “some feature of the species that particularly designates its form.”

*Ancyrochitina narcissa* “was named because the top of the creature resembles a narcissus . . .”

“All these forms are then Latinized.” (Sutherland *New History* 159)

International bodies regulate definitions of new species. (Sutherland *New History* 159)

e.g., the International Code of Botanical Nomenclature

e.g., the International Code of Zoological Nomenclature

example: humans (Sutherland *New History* 158)

superkingdom Eukaryota

Eukaryotes have cell nuclei “where the genetic material sits [and] organelles in the cytoplasm.” (Sutherland *New History* 158)

kingdom Animalia

phylum Chordata (“anything with a notochord”)

subphylum Vertebrata (chordates with backbones)

class Mammalia (warm-blooded creatures that lactate)

order Primata

family Hominidae (including *Australopithecus* and *Zinjanthopus*)

genus *Homo* (including Neanderthals and *Homo sapiens*)

problems

“The Linnaean system . . . can fall short” because it is based on morphology, “how each individual creature looks superficially.” (Sutherland *New History* 159)

example: the class Pisces

This “includes fish, such as the cod and lungfish. . . . both live in the water; they both have fins.” (Sutherland *New History* 159)

But “the lungfish is [closer] to the frog than to the cod.” (Sutherland *New History* 159)

example: dolphins

The dolphin looks like a fish but is a mammal. (Sutherland *New History* 160)

cladistics

“Cladistics groups creatures on the basis of shared characteristics,” not looks. (Sutherland *New History* 159)

A cladogram is “an evolutionary tree of life. The ancestor of all the species is at the bottom of the diagram, and the descendants of that original creature branch at various points to form new species.” (Sutherland *New History* 160)

“Any grouping of organisms must . . . contain all its descendants.” (Sutherland *New History* 160)

“Valid groupings include all descendants; [they are] monophyletic.”

Invalid groupings “do not contain all the descendants; [they are] paraphyletic.”

In cladistics “there is no such thing as a reptile.” (Sutherland *New History* 160)

The grouping reptile is paraphyletic. It does not “contain all descendants, including the birds and the mammals.” (Sutherland *New History* 160)

Reptiles are included in a wider group called the amniotes—that is, all the tetrapods that have a terrestrially adapted egg.” (Sutherland *New History* 160)

## Fossil Clocks

American Geosciences Institute. “What Are Metamorphic Rocks?” *AmericanGeosciences*.*org*. 2021. 22 Feb. 2021. Web.

introduction

“We need to know if the story of geological time is the same in Canada as in China. We need a correlation tool to tie the two areas together in time. For that, we are going to need fossils . . .” (Sutherland *New History* 16)

Fossils “act as timepieces and can help solve the problem of correlation.” (Sutherland *New History* 17)

igneous and sedimentary rocks

With “absolute radiometric dating . . . to get the best results, we need an isolated, enclosed system.” (Sutherland *New History* 17)

“Fortunately, we have what is close to an isolated system naturally in igneous rocks—rocks that are crystallized from cooling magma. As those crystals grew when the magma was cooling, they trapped small amounts of radioactive parent material within their crystal structure—effectively isolating that material from the rest of the igneous rock. Within that isolated crystal system, the radioactive parent material can then decay into the daughter material.” (Sutherland *New History* 17)

[“Metamorphic rocks are [sedimentary or igneous rocks] changed by intense heat or pressure . . . inside the Earth’s crust . . . One way to tell if a rock sample is metamorphic is to see if the crystals within it are arranged in bands. . . . soft clay objects [heated in] a kiln . . . change from being squashy to rock hard. They cannot be changed back . . .” Marble is limestone made metamorphic. (American Geosciences Institute)]

“The problem here is that more than 75 percent of the rocks on the surface of our planet aren’t igneous rocks but sedimentary.” (Sutherland *New History* 17)

“Sedimentary sandstone is composed of rock that has been eroded from a preexisting rock, transported, and then deposited elsewhere. We do not see fine crystals; we see fragmented crystals or [17] fragmented parts of other rocks. Even if we were to find a complete crystal that had not been cracked open and contaminated, it really would not do us any good. If we were to date that crystal accurately, all it would tell us was the time of formation of the rock from which this sediment was derived. It wouldn’t tell us when the sediment was deposited.” (Sutherland *New History* 17-18)

“Sedimentary rocks contain the majority of the environmental and fossil evidence that we interpret to tell Earth’s history. What we really need is to be able to date sedimentary rocks.” (Sutherland *New History* 17)

history of fossil theory

Herodotus (484-425) “considered fossils representatives of formerly living organisms—which is the modern view.” (Sutherland *New History* 18)

Leonardo da Vinci (1452-1519) “concluded that fossil clams are evidence of former life that is now preserved in stone through some sort of process. He also concluded that the reason fossil seashells are found on mountaintops is that those seabeds had been raised to the level of the mountains. That was a fairly profound thought for someone in da Vinci’s day.” (Sutherland *New History* 18)

“In 1666, a shark was caught near Livomo in Tuscany, and the head of that shark was sent to Nicolas Steno. Steno dissected it and realized that certain structures he had been studying that resembled stones were, in fact, fossil shark teeth. He realized that the ancient shark’s teeth had changed from formal organic living things into nonliving things by a process—a process that we now know as fossilization.” (Sutherland *New History* 18)

principle of faunal succession

William Smith (1769-1839): “While working as a mine engineer and canal builder, Smith noticed that certain rock strata seemed to be characterized by certain groups of fossils. He realized that there was a regular order in the succession of these fossils, and that certain fossils always occurred stratigraphically above other fossils.” (Sutherland *New History* 18)

This is “the principle of faunal succession. . . . the same groups of fossils, even if they are separated by great distances, . . . are of the same relative age. We have correlation.” (Sutherland *New History* 19)

fossil range

“The science of biostratigraphy uses the range of life that has existed over geological time to help us correlate between vastly separated areas on the planet. Today, paleontologists use what is called a fossil range, which is the basis of how we correlate using fossils.” (Sutherland *New History* 19)

“If we are going to correlate using a fossil, it would help if that fossil had a very short range—in other words, if it came into existence, existed for a short period, and then went into extinction. It also helps if that fossil is not restricted to one particular area or one particular environment. We want it to be widespread if at all possible. It would also help if the fossils are relatively common and easy to identify.” (Sutherland *New History* 19)

correlating fossils

“As we can see, the ideal fossil is not very easy to come by. Sometimes, we have to make compromises.

Graptolites

“Graptolites were planktonic creatures that were very delicate. They floated around out in the ocean and existed in vast numbers. They evolved very rapidly, producing many short-range forms, and died and fell to the ocean floor, preserving many fossils. We use these for global correlation purposes.” (Sutherland *New History* 19)

“The problem is that when we get to sediments in shallower water, we do not find that many graptolites; they are too delicate. They tend to be smashed up. How do we correlate” deepwater sediments to shallow-water sediments? (Sutherland *New History* 19)

trilobites

So “we use trilobites.” (Sutherland *New History* 20)



“We find an area where the trilobites range geographically in the graptolites’ range . . . we can move around the globe, correlating from one group of creatures to the other.” (Sutherland *New History* 20)

ammonites

“Other useful fossils for correlation are ammonites, which swam in the ocean and, therefore, existed in or above many different environments. Ammonites are particularly useful in subdividing the Mesozoic period, the time when dinosaurs were common.” (Sutherland *New History* 20)

“Less useful are bivalves, or clams, and gastropods, or snails. These are fascinating fossils, but they tend to be tied to the substrate in which they exist. They tend to live on the ocean floor, which means that they are not as widely distributed and not quite as useful for correlation.” (Sutherland *New History* 20)

“They are, though, good for identifying specific [20] environmental conditions; a particular gastropod will have a particular affinity for a particular environment and sediment.” (Sutherland *New History* 20-21)

biostratigraphy today

“Geological time today is policed, if you will, by the International Union of Geological Sciences (IUGS). This body determines how the geological timescale is split up and when a time division actually will occur.” (Sutherland *New History* 21)

type sections

“Time boundaries are also defined in space, through type sections. These are international reference sections where scientists can compare their particular rocks and fossils to a section that has been set up for correlation purposes. For example, the base of the geological period that we call the Silurian occurs at 443.7 million years ago, and the international reference section is at a place called Dob’s Linn in Scotland.” (Sutherland *New History* 21)

example of a time division

“The Silurian period, as is the case with many geological periods, is defined by the first occurrence of a very distinctive fossil. In this case, it is the distinctive occurrence of a particular graptolite species, *Parakidograptus acuminatus*. As soon as we find *Parakidograptus acuminatus*, we have left the previous geological period, the Ordovician, and are in an entirely different geological period, the Silurian.” (Sutherland *New History* 21)

dating correlations

Biostratigraphy “uses fossils for correlation. How do we add accurate dates . . .?” (Sutherland *New History* 21)

relative dating

“For example, in the Grand Canyon, where there is an igneous dike cross-cutting the sediments, we can date that igneous rock. The oldest sediments that the dike is cross-cutting must be older than the date we get from the igneous dike.” (Sutherland *New History* 21)

absolute dating

“Radiometric dating can help us.” (Sutherland *New History* 21)

volcanoes

“. . . when a volcano erupts, it sends ash into the atmosphere. This ash can travel all around the world . . .” (Sutherland *New History* 21)

“Ash also contains some of those important igneous crystals.” (Sutherland *New History* 22)

(Within the crystals are isotopes that can be radiometrically dated.—Hahn)

“We can find ash layers [in] a sedimentary sequence. We call them bentonites, and they are a creamy color. Dating those ash layers gives us a date within that sedimentary pile.” (Sutherland *New History* 22)

“When we find successive volcanic eruptions, we can bracket sediments between them.” (Sutherland *New History* 22)

“Further, because volcanoes erupt very regularly (geologically speaking), we can produce lots of dates in these sedimentary sequences that we could not necessarily produce using radiometric dating.” (Sutherland *New History* 22)

suggested reading

Wicander and Monroe, *Historical Geology*.

Winchester, *The Map That Changed the World*.

## Paleontologists as Detectives

introduction

“A fossil is anything that reveals evidence of past life.” (Sutherland *New History* 26)

“The paleontologist has very little evidence to go on . . . [often] fragments of creatures or a geological record that is missing through erosion.” (Sutherland *New History* 23)

“This lecture deals with”: (Sutherland *New History* 23)

“how the paleontologist builds a picture of a fossil from fragmentary evidence”

“what defines a fossil species”

“how ancient creatures interacted”

“how to identify bias in our interpretation of the fossil record”

how fossils are preserved

impressions

“Fossils can be preserved [as] simple impressions . . .” (Sutherland *New History* 26)

example: “an impression of a shell that has been made into the sediment.” (Sutherland *New History* 26)

mineralization

Mineralization is “the replacement of the original organic material by other minerals.” (Sutherland *New History* 26)

example: “the original shell material of a brachiopod has been replaced atom for atom by another mineralizing media: iron pyrite, or fool’s gold.” (Sutherland *New History* 26)

Other replacement minerals are “calcite, various iron minerals, and silica, as well.” (Sutherland *New History* 27)

freezing

example: “a baby woolly mammoth, about 40,000 years old, was recently identified. We can tell by looking at the lung content that it asphyxiated on mud. It was probably trying to cross some slightly swampy land; maybe permafrost had started to melt a little bit, and it got trapped and sank. The preservation is so good that we can actually open the gut and study this creature’s last meal.” (Sutherland *New History* 27)

paleontologists’ subdisciplines as tools

paleobiology: ancient creatures’ “form and function, how they moved, and so on.” (Sutherland *New History* 23)

modeling: “Paleobiology is all about making models and refining the hypotheses that we might form in the light of new discoveries and new evidence.” (Sutherland *New History* 24)

example: “In one reconstruction [of *Hallucigenia*], it has odd [23] spines as legs and tubes running down its back. Later discoveries of clearer specimens [turned it] upside down: It is now walking on those tube feet and has protective spines on its back.” (Sutherland *New History* 23-24)

paleoecology: how ancient creatures interacted with their own species, other species, and their environment. (Sutherland *New History* 23)

taphonomy: “everything that happens to a creature” from death to fossilization. (Sutherland *New History* 23)

comparative anatomy

We can compare “the leg of the dinosaur to one of a living creature and generally work out how it functioned. We can look at the articulation of the bones. We can look at muscle scars and see how big the muscles were and how powerfully they contracted to get a good idea of how this dinosaur moved.” (Sutherland *New History* 23)

“what defines a fossil species” (Sutherland *New History* 23)

Paleontologists “use the morphological species concept.” (Sutherland *New History* 24)

problems

Similar fossils may be one species or many. (Sutherland *New History* 24)

“. . . the same species can look very different depending on a number of factors, such as developmental factors, environment, and gender.” (Sutherland *New History* 24)

developmental factors

“Developmental factors include differences in size and proportion.” (Sutherland *New History* 24)

“Also, in some species, the young do not have skulls that are fully formed; the skull of a youth may be composed of more than one bone and may not be fused.” (Sutherland *New History* 24)

environmental factors

“Environmental factors can cause variations in the same species.” (Sutherland *New History* 24)

“For example, consider the Inuit and the Masai. The Inuit live in cold conditions, so they have an adaptation for cold—to be more short and stocky to retain heat. Masai, however, live in hot climates, so there is an advantageous selection trait to be taller and thinner in order to lose heat more easily.” (Sutherland *New History* 24)

gender

“In the case of gender differences, males tend to be larger and have more robust bones because of their greater muscle mass. Females tend to be more gracile; also, the female’s pelvis is adapted to allow for childbirth.” (Sutherland *New History* 24)

“A recent example of species confusion [is] *Triceratops*.” (Sutherland *New History* 25)

“John Scannella and Jack Homer at the Museum of the Rockies recently suggested that in fact *Triceratops* did not really exist. What it represented was a juvenile form of another dinosaur, *Torosaurus*.” (Sutherland *New History* 25) Torosaurus:



paleoecology (“how ancient creatures interacted,” Sutherland *New History* 23)

“What can we tell from the fossil evidence about ancient creatures and how they interacted with one another? Types of interactions include mutualistic arrangements, commensalism, parasitism, and predation.” (Sutherland *New History* 25)

mutualistic arrangements

Both sides benefit.

example: “often, we find *Platyceras* [a sea snail] right over the anal tube of the crinoid [“like a starfish on a long stalk”].” Perhaps “the snail is getting a free meal”; perhaps the crinoid “gets a cleaned-up environment in which to continue feeding.” (Sutherland *New History* 25)

commensalism

One side benefits, and there is “neither a positive nor a negative result for the other.” (Sutherland *New History* 26)

example: on the back of the echinoid (sea urchin) “are fossil tubes, probably from a worm . . . These tubes are not large enough to cause the echinoid any problems, but the worm is certainly getting benefits by having a hard substrate on which to live.” (Sutherland *New History* 26)

parasitism

“A good example of parasitism in the fossil record is Sue, one of the largest and most complete *Tyrannosaurus rex* skeletons in the world. Sue has odd holes in the jaw-holes that were initially thought to be evidence of predation, but they did not seem to match any predation patterns. In fact, what they look most similar to are holes that we find in the feet and the mandibles of birds caused by a protozoan called *Trichomonas gallinae*. We believe that Sue got protozoans in her jaw, and they caused an infection, ulceration, and damage [to] the bone, possibly fatally.” (Sutherland *New History* 26)

predation

“Examples of predation include holes bored into a fossil shell—probably some sort of snail boring into a clam to get to the meal inside. Some holes in specimens have been interpreted as puncture marks. For example, some marks have been identified as those of the mosasaur, which was an apex predator, a terror of the [Cretaceous] oceans . . .” (Sutherland *New History* 26)

biases in reading the fossil record

“Not every creature has an equal chance of becoming a fossil; therefore, there are biases in the fossil record in terms of the potential for something to become a fossil.” (Sutherland *New History* 27)

“The science of taphonomy—studying the process of the death of a creature, to its complete decay, to the time when it becomes a fossil—can help ameliorate any potential biases.” (Sutherland *New History* 27)

environmental bias

“Certain environments are more favorable to fossilization than others.” (Sutherland *New History* 27)

Terrestrial environments, or land environments, are very poor. Creatures that live on land tend to lie on the open ground, and they are subject to scavengers. They will rot very readily and be eroded.” (Sutherland *New History* 27)

In water “creatures can be covered by sediment once they die. Because the oceans are so large, there is a definite bias toward marine fossils.” (Sutherland *New History* 27)

biological bias

example: “the preservation potential for a soft-bodied creature is not as good as . . . for something that has a more robust shell or skeleton.” (Sutherland *New History* 27)

About 60% “of marine organisms in today’s oceans are actually soft-bodied.” (Sutherland *New History* 27)

cultural bias

example: “the *Iguanodon*, whose fossil was unveiled in 1854 at the Crystal Palace in London.” (Sutherland *New History* 27)

An “early reconstruction looks strange compared to our modern understanding of *Iguanodon*: There’s a spike on its nose, while we now know that the spike on *Iguanodon* goes on the thumb.” (Sutherland *New History* 28)

“The Victorians thought reptiles were lesser creatures, not as good as mammals. Reptiles were sluggish, stupid, primitive, lumbering creatures and were depicted as such. Today, there is a much different view of these dinosaurs as active and dynamic creatures.” (Sutherland *New History* 28)

In the literature on fossils, “The emphasis is on the vertebrates—creatures with a backbone. Another bias is in favor of the land creatures over fish. Plants also get short shrift . . .” (Sutherland *New History* 96)

suggested reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Foote and Miller, *Principles of Paleontology*.

## Mass Extinctions

“Extinction Event.” *Wikipedia*. 15 Nov. 2020. 17 Nov. 2020. Web.

introduction

“Species go extinct all the time. More than 99 percent of the species that once existed on Earth are now extinct.” (Sutherland *New History* 102)

But “biodiversity has stayed fairly even, with extinctions matched by the evolution of new forms.” (Sutherland *New History* 102)

background extinctions vs. mass extinctions

background extinction: “certain creatures go into extinction for various reasons . . .” (Sutherland *New History* 102)

mass extinctions: “the sudden destruction of vast numbers of species.” (Sutherland *New History* 102)

Mass extinctions are “extreme turnovers in species.” (Sutherland *New History* 103)

subdividing geological time

“The health of the biosphere is generally measured [by] number of species . . . Thus, it is important to examine how biodiversity changes over geological time.” (Sutherland *New History* 102)

“Broad changes in biodiversity help us subdivide geological time . . .” (Sutherland *New History* 102)

Geological periods “represent characteristic biospheres.” (Sutherland *New History* 102)

continental fragmentation and biodiversity

“In the 1970s, it occurred to two scientists—I.W. Valentine of Berkeley and E.M. Moores of the University of California in Davis—that the new theory of plate tectonics could explain changes in diversity over time. Continents drifting around the surface of the planet would affect the climate and food supply of creatures, would bring species into direct competition, and would isolate some species.” (Sutherland *New History* 103)

“Graphically plotting global biodiversity against the relative fragmentation of the continents, we see the greatest biodiversity during times of greatest continental fragmentation. This makes sense: Times of the greatest fragmentation will see the greatest climatic variation and the greatest possibility of evolution in isolation.” (Sutherland *New History* 103)

“Marsupials in Australia illustrate the idea of evolution in isolation that might be caused by fragmentation of the continents.” (Sutherland *New History* 103)

cycles of biodiversity

750m: Rodinia fragmented. (Sutherland *New History* 104)

“Fairly soon after the fragmentation of Rodinia, the remarkable Ediacaran fauna arose.” (Sutherland *New History* 104)

541m-419.2m: lower Paleozoic

“Fragmentation continued through the Lower Paleozoic, when a series of new continents emerged, with shallow tropical seas around their margins. The deep oceans between the continents acted as a barrier for many marine forms, as well as a climatic barrier. As a result, independent evolution and biodiversity escalated at this time.” (Sutherland *New History* 104)

358.9m-251.9m: upper Paleozoic

“. . . amalgamation of the continents began.” Diversity fell. (Sutherland *New History* 104)

There were also “a few small extinction pulses.” (Sutherland *New History* 104)

298.9m-251.9m: Permian Period

The supercontinent Pangaea consolidates, and “there was a massive drop in global biodiversity.” (Sutherland *New History* 104)

“In effect, everything was in direct competition.” (Sutherland *New History* 104)

251.9m-66m: Mesozoic

“As Pangaea fragmented through the Mesozoic, diversity increased.” (Sutherland *New History* 104)

“Today, the continents are as dispersed as they have ever been, and we have unique ecosystems existing on the many fragmented continental areas; thus, biodiversity is considered to be high.” (Sutherland *New History* 104)

defining mass extinctions

“The diversity changes associated with continental drift are slow. Earth’s history, however, has seen rapid and sudden drops in diversity: mass extinction events. . . . For mass extinction events, we have to look for other factors.” (Sutherland *New History* 104)

criterion for mass extinction: severity (Sutherland *New History* 105)

minor mass extinction: 20-30% of species go extinct

intermediate mass extinction: 50% of species go extinct

major mass extinction: 80-95% of species go extinct

criterion for mass extinction: extent

“A mass extinction extends across a wide range of ecologies—not just in coral reefs, not just in tropical rain forests, . . . from the tops of mountains to the bottom of the oceans.” It must be global. (Sutherland *New History* 105)

criterion for mass extinction: timing

“A mass extinction is short and sudden—less than a million years.” (Sutherland *New History* 105)

These criteria give us five mass extinctions: (“Extinction Event”)

|  |  |  |
| --- | --- | --- |
| 445.2m-443.8m | End Ordovician (Ordovician-Silurian, O-S)  glaciation | 85% of species |
| 375-360m | End Devonian (Devonian-Carboniferous)  glaciation | 70% of species |
| 253m | End Permian (Permian-Triassic, P-Tr)  volcanoes | 90%-96% of species |
| 233m | Carnian Pluvial Episode (CPE)  volcanoes in Canadian Rockies, then at equator | 33% of marine species |
| 201.3m | End Triassic (Triassic-Jurassic, Tr-J) | 70%-75% of species |
| 66m | Cretaceous-Paleogene (the K-P event)  asteroid | 75% of species |

10,000 bce: 6th mass extinction?

“. . . today we are losing species at an unprecedented rate—about 140,000 species every year . . . [It started] with the disappearance of the megafauna: mammoths and saber-toothed tigers.” (Sutherland *New History* 105)

causes of mass extinction

“Biological causes have been proposed . . . For example, an extinction may have been caused by competition between creatures occupying the same ecological niche. Perhaps they were brought together by continental drift, they competed for resources, and only the most adaptable survived. In other words, there were winners and losers.” (Sutherland *New History* 105)

Perhaps “continents moving around affected weather patterns and generated volcanic activity. Changing the configuration of the oceans altered ocean circulation patterns and the productivity of the oceans. These Earth processes had major global warming and cooling effects.” (Sutherland *New History* 106)

extraterrestrial impact (Sutherland *New History* 106)

“The most reasonable explanation . . . [is] many factors that all went wrong at the same time . . .” (Sutherland *New History* 106)

mass-extinction periodicity

“. . . in 1984, David Raup and Jack Sepkoski of the University of Chicago . . . [concluded:] Every 26 million years or so, biodiversity took a serious downfall.” (Sutherland *New History* 106)

“They looked at whether there were any plate tectonic features or climatological effects that had a 26-million-year periodicity but found none.” (Sutherland *New History* 106)

the Oort Cloud

“Raup and Sepkoski then suggested that the 26-million-year periodicity might be related to the Oort cloud, a cloud of comets in the outer reaches of our solar system, almost a light-year away from our Sun. The Oort cloud consists of the material left over after the development of our solar system. The scientists speculated that comets emerged from here and fell into the inner solar system. [106] Some of those comets crossed the orbit of Earth, causing extinctions or downturns in the biosphere every 26 million years.” (Sutherland *New History* 106-07)

“It was speculated that, every 26 million years, something happens to the Oort cloud—probably some sort of gravitational effect—that causes comets to fall out of that weak orbit around the Sun and start to careen toward the center of the solar system. The question is: What causes that gravitational effect?” (Sutherland *New History* 107)

“Raup and Sepkoski suggested that perhaps our Sun has a companion sun called Nemesis. Dual star systems are not uncommon in our galaxy.” (Sutherland *New History* 107)

“Another possibility is that a black hole created a singularity.” (Sutherland *New History* 107)

“A third possibility is that a massive planet exists just inside the Oort cloud; every 26 million years, its orbit brings it close to the Oort cloud, causing gravitational effects.” (Sutherland *New History* 107)

the Milky Way theory

Raup and Sepkoski considered the Milky Way. (Sutherland *New History* 107)

The galaxy rotates every 225 million years. (Sutherland *New History* 107)

“. . . there is an invisible line running through the galaxy that we call the galactic plane.” (Sutherland *New History* 107)

Our solar system swings around in the galaxy but also “moves up and down through the galactic plane. Every 26 million years, it’s right in the middle of the galactic arm of the spiral—where we have the greatest concentration of material and, therefore, the greatest potential for gravitational effects. It would appear that every 26 million years, we get a hammering.” (Sutherland *New History* 107)

We were “last in the middle of the galactic arm . . . a million years ago.” (Sutherland *New History* 107)

“This proposed cycle is still very much a matter of debate.” (Sutherland *New History* 107)

suggested reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Foote and Miller, *Principles of Paleontology*.

Hallam, *Catastrophes and Lesser Calamities*.

## 4.54-3.8b: Planet Formation

DiVenere, V.J. “The Life of A Star: Stellar Evolution.” *Introduction to Earth Sciences I*. N.d. 3 Mar. 2021. Web. <columbia.edu/%7evjd1/origins.htm>.

Fort Worth Astronomical Society. “Mars will be as BIG as the Moon.” *FortWorthAstro*.*com*. 7 Aug. 2015. 24 Feb. 2021. Web.

“Granite.” *Wikipedia*. 22 Feb. 2021. 23 Feb. 2021. Web.

“Nebular Hypothesis.” *Wikipedia*. 24 Feb. 2021. 24 Feb. 2021. Web.

introduction

“This lecture explores”: (Sutherland *New History* 36)

how the solar system formed

the Hadean period

“how the formation of the solar system influenced the evolution and development of life on Earth”

the Hadean period

These period from “4.54 to 3.8 billion years ago [is] called the Hadean period.” (Sutherland *New History* 38)

“We have very little record of it . . .” (Sutherland *New History* 38)

“. . . even without atmospheric oxygen, our planet had a very erodible surface.” (Sutherland *New History* 38)

“Plate tectonics also recycled parts of the crust . . .” (Sutherland *New History* 38)

“. . . impacts affected the record of Earth’s early history.” (Sutherland *New History* 38)

how the solar system formed

1755: Immanuel Kant first proposed the nebular theory. (“Nebular Hypothesis”)

“The widely accepted modern variant of the nebular theory is the solar nebular disk model (SNDM) or solar nebular model.” (“Nebular Hypothesis”)

The solar system “began as a massive cloud of interstellar hydrogen and dust. That cloud then started to collapse in on itself. As it contracted, it started to spiral down into a central mass. We think that about 90 percent of the mass of that cloud would have been the elements in the center.” (Sutherland *New History* 36)

“We imagine that the Eagle Nebula resembles the original nebula that formed our solar system; the pillars are concentrations of dust and gas, probably where young stars are forming.” (Sutherland *New History* 36)



“About 100,000 years after that initial collapse, a flattened, rotating disk called the accretion disk formed, which was about 200 astronomical units across.” (1 AU = 93 million miles, from the Sun to the Earth.) Grains of dust knocked together and clumped; their gravity attracted other clumps. (Sutherland *New History* 37)

“. . . temperature and pressure increased as more material was added to the center. This was the embryonic period of the Sun [and] the T Tauri protosun phase of solar system formation.” (Sutherland *New History* 37)

T Tauri stars are protostars on the verge of becoming main-sequence stars.

In the T-Tauri phase, “The young star . . . gives off a very active “solar” wind of protons and neutrons that clears out most of the remaining gas, dust, and fragments smaller than about 1 m from the inner nebula.” (diVenere)

A star becomes a main-sequence star when the energy from fusion equals the energy radiating from the surface. (https://quizlet.com/161360325/chapter-19-flash-cards/)

After another 50 million years, “Positively charged hydrogen nuclei started to fuse together.” (Sutherland *New History* 37)

“Because hydrogen nuclei have positive charges, they really want to repel; they do not want to combine.” (Sutherland *New History* 37)

“But the pressure and temperature were so high in the central mass of that cloud that the repulsion was overcome and the hydrogen atoms were fused together, forming helium and a tremendous amount of energy. Then, the Sun switched on.” (Sutherland *New History* 37)

“Close to the Sun, the inner planets continued to go through massive collisions. This is called the merger phase.” (Sutherland *New History* 37)

“. . . the Earth and Venus probably formed by the collision of embryo planets.” (Sutherland *New History* 37)

“After about a billion years, the planets reached their current size.” (Sutherland *New History* 37)

how the Earth formed

The Earth has “layers with different densities. Structurally, it has a light crust surrounding increasingly denser material, with the densest material being right in the center.” (Sutherland *New History* 37)

The cool accretion hypothesis “suggests that the Earth originally [37] accreted cold. In the accretion disk, we had lumps of dust and rock clumping together, . . . eventually forming . . . a large rock pile in space.” (Sutherland *New History* 37-38)

Then the rock pile “heated up by two processes.” (Sutherland *New History* 38)

“First, as the planet got larger, collisions between rocks got more catastrophic and released more energy . . .” (Sutherland *New History* 38)

Some of the concentrating material was radioactive. “When radioactive material decays, it gives off energy. That also helped the rock pile to melt.” (Sutherland *New History* 38)

“As the rock pile heated up, the heavy material under gravity, mostly iron and nickel, sank to the center of the Earth, forming the core. The much lighter materials, such as carbon, silicon, and aluminum, remained concentrated on the surface.” (Sutherland *New History* 38)

“The result was a layered Earth with abundant carbon-based materials on the surface and a metallic core . . .” (Sutherland *New History* 38)

The varying densities may be what started plate tectonics. (Sutherland *New History* 38)

oldest rock

“One remnant of the Hadean period is the oldest rock found to date. It is called gneiss, which means it’s a fairly high grade of metamorphic rock. Metamorphic rocks are those that have been heated and pressurized. This particular rock exhibits bands of different minerals.” (Sutherland *New History* 38)

“Analysis of it suggests that it was originally a granite from about 4 billion years ago.” (Sutherland *New History* 38)

“Granite is a coarse-grained igneous rock composed mostly of quartz, alkali feldspar, and plagioclase. It forms from magma with a high content of silica and alkali metal oxides that slowly solidifies underground. It is common in the Earth's continental crust, where it is found in various kinds of igneous intrusions. These range in size from dikes only a few inches across to batholiths exposed over hundreds of square kilometers.” (“Granite”)

formation of the Moon

4.5b (“30 to 50 million years after the origin of the solar system”): “a Mars-sized planet” hit the Earth. (Sutherland *New History* 40)

Such an impact explains Earth’s tilt. (Sutherland *New History* 40)

It also may explain the Earth’s “relatively fast spin.” (Sutherland *New History* 40)

The Earth “has been slowing down, about 2 seconds every 100,000 years.” (Sutherland *New History* 40)

Corals “secrete a calcium carbonate, known as calcite, in their skeletons. They lay down a layer of calcite every day. [Through analysis] we can get an idea of the length of a year. . . . during the Devonian [360 Mya], a year had 400 days.” (Sutherland *New History* 40)

The impactor and “parts of the Earth” became the Moon. (Sutherland *New History* 40)

But “Mars is roughly twice the size of the Moon” (2160 miles in diameter to 4,213). (Fort Worth Astronomical Society)

In the early Precambrian, soon after the Moon formed, the Moon “dominated the sky. It was about 200,000 miles closer than it is today.” (Sutherland *New History* 40)

significance of the Moon

“Three important features of the Moon were crucial to the formation of the biosphere on our planet.” (Sutherland *New History* 39)

The Earth’s axis is “tilted to the plane of ecliptic at about 23.5 degrees. This tilt, or obliquity, changed slowly over about 41,000 years, and it appears that the variation in the degree of tilt is possibly linked to climatological cycles. It might explain, in some way, the periodicity and frequency of glacial episodes, for example.” (Sutherland *New History* 39)

The Moon’s gravity has stabilized the wobble. Otherwise, “the Earth would have experienced many more severe and dramatic climatic shifts.” (Sutherland *New History* 39)

A more stable climate “means we have the potential to develop a more stable biosphere with greater complexity.” (Sutherland *New History* 39)

“Second, the Moon is unusually large compared to the planet it orbits . . .” The Moon has taken some of the impacts that would have hit Earth. That has allowed for “a more stable biosphere and more complex life forms.” (Sutherland *New History* 39)

“The third important feature of the Moon is the impact of tides.” (Sutherland *New History* 39)

In the early Precambrian, a closer Moon meant more severe gravity: the tides “were more like mega-tsunamis. Those tsunamis would have scoured the early continent, washing minerals and nutrients into the oceans and thoroughly mixing the oceans up. In this way, it’s thought that the Moon was the spoon that mixed the brew of life from which the biosphere developed.” (Sutherland *New History* 40)

suggested reading

Faure and Mensing, *Introduction to Planetary Science*.

Varricchio, *Inconstant Moon*.

questions to consider

Solar systems seem common, but are Earth-Moon systems likely? (Sutherland *New History* 41)

## Origins of Land, Ocean, and Air

“Gabbro: Igneous Rock—Pictures, Definition and More.” *Geology*.*com*. 2021. 24 Feb. 2021. Web.

“Oceanic Crust.” *Wikipedia*. 24 Feb. 2021. 24 Feb. 2021. Web.

introduction

“Before we move on to describe the formation of the Earth’s biosphere, we’ll consider where the other major systems come from . . . because it is in these spheres of the Earth’s system that the biosphere would evolve.” (Sutherland *New History* 41)

“We’ll explore”: (Sutherland *New History* 41)

“the origin of the lithosphere (all the rock)”

“the atmosphere (the gassy envelope that surrounds our planet)”

“the hydrosphere (all the water)”

“We’ll also answer three important questions about the events following the formation of the solar system, the Earth, and the Moon: Where did all the land come from, what is the nature of the early Earth’s atmosphere, and what created the oceans? These are critical questions because it is in this earliest iteration of Earth systems that life would evolve.” (Sutherland *New History* 42)

Earth’s crust

“Initially, the Earth was a huge magma sea hanging in space. As that magma cooled, a skin formed on its surface. Today, that skin, or the crust, represents less than 1 percent of the Earth’s total volume . . .” (Sutherland *New History* 42)

There are two types of crust: oceanic and continental. (Sutherland *New History* 42)

oceanic crust

“Oceanic crust is generated in oceanic ridge systems. Magma is injected in these ridges, moving the old material to the side, and eventually, that material is removed and subducted at the plate margins.” (Sutherland *New History* 42)

“Ocean crust is about 4.3 to 6.2 miles thick . . .” (Sutherland *New History* 42)

structure

“. . . material below the crust [is] very dense . . ., like mantle rocks.” (Sutherland *New History* 42)

“Above that is a material called gabbro, a dark rock that represents a magma chamber at a spreading ridge.” (Sutherland *New History* 42)

“Above that magma chamber, feeder pipes take the magma to the surface of the ocean, where it erupts as lava called pillow lava.” (Sutherland *New History* 42)

“Above the pillow lava is usually a thin cover of ocean sediments.” (Sutherland *New History* 42)

“Fragments of ocean crust exposed above sea level are called ophiolites.” (Sutherland *New History* 42)

Ophiolites are “sections of oceanic crust that are thrust onto and preserved on the continents . . .” (“Oceanic Crust”)

chemical composition

“Overall, the crystal composition of the ocean crust is basalt.” (Sutherland *New History* 43)

Basalt has the same composition as gabbro. The difference “is their grain size. Basalts are extrusive igneous rocks that cool quickly and have fine-grained crystals. Gabbros are intrusive igneous rocks that cool slowly and have coarse-grained crystals.” (“Gabbro”)

“mafic”

Basalt is minerals rich in magnesium and iron, “which explains why these rocks are fairly dense and dark in color.” (Sutherland *New History* 43)

The oceanic crust’s chemical composition is mafic. (*Ma-* is for magnesium; *-f-* is for iron, Latin *ferrum*.) (Sutherland *New History* 43)

continental crust

“Continental crust is about 15.5 to 43.4 miles thick.” (Sutherland *New History* 43)

chemical composition

“Overall, the composition is similar to granite, composed of lighter-colored elements, such as aluminum and silicon. Silicate minerals are far less dense than gabbro.” (Sutherland *New History* 43)

The continental crust’s chemical composition is felsic. (*Fel-* is for feldspar; *-sic* is for silica.) (Sutherland *New History* 43)

“Today, the Earth’s crust consists of a thin oceanic crust [c. 5 mi thick] and a thick but lighter continental crust [c. 30 mi thick] riding above it . . .” (Sutherland *New History* 43)

age

Ocean crust is recycled. “No ocean crust is older than 180 million years old.” (Sutherland *New History* 43)

Continental crust is lighter and less dense. It is rarely “subducted into the denser mantle below the crust.” (Sutherland *New History* 43)

Hence, “the oldest rocks [are] on the continents.” (Sutherland *New History* 43)

how the continents formed

“Earth’s first crust was probably all basaltic, like oceanic crust.” (Sutherland *New History* 43)

“Continental crust was produced from the thin skin of basalt by recycling that skin at subduction zones.” (Sutherland *New History* 43)

“If two oceanic plates come together, the older plate subducts because it is cooler and denser.” (Sutherland *New History* 43)

“As the subducting plate descends, it heats up, and water gets driven up the plate. The release of that water into the mantle above the descending slab causes melting in the mantle.” (Sutherland *New History* 43)

“Mantle rock—for example, peridotite—is composed of different minerals, each of which has a different melting point. When the mantle rock melts, only some of those minerals melt, however—this is called a partial melt. Magma will be generated with a different composition than the mantle rocks that are being partially melted. [43] The magma that is produced is not going to be like peridotite or mantle rocks.” (Sutherland *New History* 43-44)

“The mantle rock produced is called ultramafic. These rocks are very high in iron minerals and very dense. The magma produced by partially melting an ultramafic rock is a mafic rock. It will be less dense than the surrounding rocks from which it is produced, and it will be extremely hot, so it rises. The magma rises and gets erupted through the overriding plate to form small basaltic islands.” (Sutherland *New History* 44)

“These islands are the first seeds of continents. Imagine an Earth with lots of little volcanic islands dotted all over it, but with no large continental land masses. Over time, those islands moved around on the plates and collided and amalgamated, making larger and larger land areas. These are mafic basaltic islands.” (Sutherland *New History* 44)

“As the continents grew, they became thicker . . .” (Sutherland *New History* 44)

“Scientists believe that felsic [feldspar + silica] material was produced through subduction below those growing volcanic islands. As the magma generated by this subduction rose into these islands, a process called magmatic differentiation produced magmas of lighter composition. Once those felsic magmas cooled to form granites and similar rocks, they were far too light to be subducted. They simply accumulated over time.” (Sutherland *New History* 44)

Ur: the first continent

“We have evidence of Earth’s early crust from rocks that were derived from earlier progenitors—zircon crystals from Australia that were eroded from a very old rock. These crystals were incorporated in a sedimentary rock called a conglomerate. When these zircons were radiometrically dated, they were found to be 4.4 billion years old. That means there must have been some sort of solid surface back then in Earth’s history.” (Sutherland *New History* 44)

3b: Ur, “The first large continental land mass . . .” (Sutherland *New History* 44)

“We can still find fragments of Ur preserved in present-day Australia, Antarctica, India, and Madagascar.” (Sutherland *New History* 44)

“Seed continents continued to grow by continental collision and accretion over all of geological time. In fact, the process is still going on today. Many continents form fragments and recombine over time.” (Sutherland *New History* 45)

1.2b-650m: the supercontinent Rodinia. It fragmented 650m. (Sutherland *New History* 45)

“Rodinia”: from Russian родить, *rodit*, “beget, give birth,” or родина, *rodina*, “motherland, birthplace” (“Rodinia”)

It was a largely “Neoproterozoic supercontinent that assembled 1.1-0.9 billion years ago and broke up 750-633 million years ago.” (“Rodinia”)

200m: the supercontinent Pangaea, formed from the fragments of Rodinia (Sutherland *New History* 45)



Earth’s protective shield

“The Earth has a solid inner core, but around it is a layer of rotating liquid metal. Because that area is rotating, it sets up a dynamo effect that generates Earth’s protective magnetic field.” (Sutherland *New History* 46)

“After fusion had initiated in the Sun, there was a release of solar radiation, generating a strong solar wind. We can see some of those strong solar winds, called solar flares, today. When they erupt, they release energy—the equivalent of billions of hydrogen bombs in just one event.” (Sutherland *New History* 45)

The magnetosphere protects from solar flares. (Sutherland *New History* 45)

“. . . the aurora borealis in the northern hemisphere [and] the aurora australis in the southern hemisphere [are] charged energy particles from the solar wind interacting with the Earth’s magnetic field.”

The magnetosphere has protected “the biosphere from solar storms for billions of years.” (Sutherland *New History* 45)

how the atmosphere formed

“Before the magnetosphere was in place, the first atmosphere of hydrogen and helium disappeared.” (Sutherland *New History* 46)

The second atmosphere came from volcanoes, which allow planetary degassing. (Sutherland *New History* 46)

“Our planet is continually trying to lose heat. The heat-loss process releases a great deal of gases. We think that the initial Earth atmosphere that developed after the formation of the magnetosphere would have been fairly similar to current volcanic emissions: lots of water, carbon dioxide, hydrogen, nitrogen, sulfur-based gases, and chlorine. The proportions of the gases may have varied, but there was probably a great deal of water and carbon dioxide in those gases. Today, the atmosphere is 78 percent nitrogen and 21 percent oxygen, with a variable amount of water vapor.” (Sutherland *New History* 46)

how the hydrosphere formed

water from space

“Initially, the Earth’s water was most likely also produced by volcanoes. That water vapor [stayed] in the atmosphere 0 because the Earth was initially too hot to allow for condensation . . .” (Sutherland *New History* 46)

“when the first raindrops started to fall . . . it probably rained for centuries.” (Sutherland *New History* 46)

But volcanic emissions don’t account “for all the water that we find on the surface of our planet today. There must be another source.” (Sutherland *New History* 46)

“The theory is the early solar system had a great deal of water in it, and many more comets impacted the Earth. Some of those comets delivered water.” (Sutherland *New History* 47)

“. . . comets account for a large proportion of Earth’s water . . .” (Sutherland *New History* 48)

“Comets range in size from a few hundreds of meters to tens of kilometers. They are generally composed of various ices and debris—they are like dirty snowballs in composition.” (Sutherland *New History* 46)

“In 2005, [46] NASA studied an impact of a comet that created a crater about 330 feet across. Within the large plume of material created by the impact was about 11 million pounds of water.” (Sutherland *New History* 46-47)

“Initially, Earth’s oceans would have been freshwater, but the erosion of rocks and the introduction of minerals at volcanic vents eventually turned the oceans salty.” (Sutherland *New History* 47)

“When do we have evidence of the first liquid water? The oldest sedimentary rocks that were deposited in water and the oldest features on some igneous rocks deposited or erupted in water come from Greenland and are about 3.8 billion years old.” (Sutherland *New History* 47)

“Earlier evidence is in the zircon crystals from Australia. Some of the oxygen isotopes found in those crystals suggest that the parent rock that formed them developed in an environment that had liquid water. If this is true, it pushes back liquid water as a reality on the surface of our planet to about 4.4 billion years ago. That means we have a potential cradle of evolution far back in geological time. With water, life processes can potentially start moving along. The stage is now set.” (Sutherland *New History* 47)

suggested reading

Lindsey, “Ancient Crystals Suggest Earlier Ocean.”

Wicander and Monroe, *Historical Geology*.

## Plate Tectonics

“Caledonian Orogeny.” *Wikipedia*. 19 Oct. 2020. 23 Feb. 2021. Web.

Lee, Howard. “Scientists Pin Down When Earth’s Crust Cracked, Then Came to Life.” *QuantaMagazine*.*org*. 25 Mar.2021. 27 Mar. 2021. Web.

introduction

“Plate tectonics is the grand unifying theory of geology.” (Sutherland *New History* 29)

“. . . plate tectonics completely altered the way we understand how the Earth worked in the late 1960s and early 1970s . . .” (Sutherland *New History* 35)

“Plate tectonics explains all the major geologic phenomena that we see today and helps paleontologists understand changes in the deep geological past.” (Sutherland *New History* 29)

“This lecture will explore”: (Sutherland *New History* 29)

“plate tectonics”

evidence for continental drift

“why continental drift was originally rejected”

how continental drift was ultimately vindicated



The “plates—15 main ones and dozens of smaller ones—spread apart at mid-ocean ridges, move with the mantle’s flow, scrape against each other at their edges, and plunge back into the mantle at “subduction zones.”” (Samuel Velasco/Quanta Magazine; source: USGS)

“. . . plate tectonics has helped Earth [maintain a habitable climate for billions of years](https://www.quantamagazine.org/how-earths-climate-changes-naturally-and-why-things-are-different-now-20200721/) despite a gradually brightening sun. Our Goldilocks climate largely results from chemical reactions between carbon dioxide in the air and silicate minerals, which slowly reduces the level of the greenhouse gas in the atmosphere by burying it in sediments. Most of that silicate-carbon dioxide reacting [happens on the slopes of mountains](https://pubs.geoscienceworld.org/gsa/geology/article-abstract/42/6/527/131586/The-contribution-of-mountains-to-global-denudation) made by colliding plates.” (Lee)

early theories of continental movement

“The theory of drifting continents is not a new idea. In the 1500s, Abraham Ortelius, a Flemish cartographer and geographer, published what is considered to be the first modern atlas. In studying the shape of the continents, he noticed the odd fit that one can make between South America and Africa. It is almost as if the two continents had been tom apart, he noted.” (Sutherland *New History* 29)

“Similar ideas were proposed by Antonio Snider-Pellegrini in 1858. He constructed a theory of a supercontinent that looks fairly similar to reconstructions made today. He based his reconstruction on the similarity of plant fossils 300 million years old that are found across the Atlantic Ocean.” (Sutherland *New History* 29)

“In the early 1900s, James Hall proposed the geosynclinal theory, which suggested that there are large troughs in the Earth, generally in oceanic areas, that receive sediment from the continents and then slowly subside. As they sink, they heat up and then start to fold in on themselves and create chains of mountains. The geosynclinal theory is a static model that involves vertical change, however; it is contrary to an idea of drifting continents, which implies lateral forces. Even so, the geosynclinal theory would remain firmly entrenched in the scientific literature until the 1970s.” (Sutherland *New History* 29)

“In 1910, a German meteorologist named Alfred Wegener wrote, “Doesn’t the east coast of South America fit exactly against the west coast of Africa, as if they had once been joined? This is an idea I’ll have to pursue.” In pursuing his idea, Wegener brought a great deal of evidence to the table.” (Sutherland *New History* 30)

evidence from matching mountains

“Throughout the world . . . [mountains] match up . . .” (Sutherland *New History* 30)

example: the Appalachian and Caledonian mountains were once one chain.

The Appalachian Mountains “pass up the east coast of North America, move into Newfoundland, and then seem to disappear into the Atlantic Ocean.” (Sutherland *New History* 30)

In “Britain and into Scandinavia, we find mountains that are the same age, composed of very similar rocks, and have a comparable deformation—they have been crunched and folded in a similar way. This is called the Caledonian mountain chain, which existed about 400 million years ago.” (Sutherland *New History* 30)

Here is the “Location of the different branches of the Caledonian/Acadian belts at the end of the Caledonian orogeny (Early Devonian [419.2-393.3 Mya]). Present-day coastlines are indicated in gray for reference. Later . . . the Atlantic Ocean opened and the different parts of the orogenic belt moved apart.” (“Caledonian Orogeny”)



evidence from matching stratigraphies, rocks, sediments, and deformations

“Throughout the world, it is not just mountains that match up; it is also stratigraphy, characteristic rocks, similar sediments, and comparable deformation histories.” (Sutherland *New History* 30)

example: “lava in Africa almost exactly matches the chemistry and age of lava found in South America.” (Sutherland *New History* 30)

evidence from matching glaciers

“Glaciation leaves characteristic features behind in the landscape and in till—a lumpy sediment created when a glacier rumbles across a rock surface and chews it up. Glaciers also have scratch rocks embedded in their undersurfaces; as they move across a rock surface, they gouge characteristic lines or striations into them.” (Sutherland *New History* 30)

Glacier evidence shows glaciers “moving from the ocean and up onto the continents. Glaciers do not do that. If, however, we reconfigure the continent to form a southern polar continent that we call Gondwanaland, we have a much more reasonable climatic model to understand a large glaciation in the southern polar hemisphere.” (Sutherland *New History* 30)

Wegener especially examined a glaciation that occurred 280-270 Mya. (Sutherland *New History* 30)

evidence from coal

Coal “is basically compressed plant material.” (Sutherland *New History* 31)

“Coal in the northern hemisphere generally comes from a period called the Carboniferous [359-299 Mya]. That coal was deposited in a hot and swampy environment.” (Sutherland *New History* 31)

“Yet the majority of the coal that we extract today comes from temperate regions—that fact doesn’t fit with current continental configuration.” (Sutherland *New History* 31)

evidence from corals

“Tropical corals are very specific to their environment: clear, shallow water at 77° to 86° Fahrenheit. Yet we find tropical coral fossils in the Arctic Circle.” (Sutherland *New History* 31)

evidence from fossils

example: “we find the same fossil, *Lystrosaurus*, from around 250 million years ago, in India, South America, and Antarctica.” (Sutherland *New History* 31)

example: “A tropical fossil flora that we call *Glossopteris* [299-251 Mya] is found in South America, Africa, India, Australia, and Antarctica. This is far too wide a distribution for a tropical flora. The distribution only makes sense when we reconfigure the continents to form an obvious climatic belt centered on the southern pole.” (Sutherland *New History* 31)

Wegener’s hypothesis of continental drift

“. . . in 1915, Wegener published his hypothesis of continental drift in *The Origin of Continents and Oceans*. By the third edition of this publication, he proposed a supercontinent called Pangaea [Greek for “all lands”] that existed more than” 200 Mya. (Sutherland *New History* 31)

Wegener “gathered enough evidence to suggest continental drift,” but scientists rejected his theory. (Sutherland *New History* 32)

He was questioning an established paradigm. (Sutherland *New History* 31)

“. . . the mechanism he proposed to explain why the continents moved was not acceptable. He suggested that centrifugal forces caused the continents to move. In addition, the gravity from the Sun and the Moon, he proposed, might also help shift the continents. . . . there is not nearly enough energy in those forces to cause the moving of continents through oceanic rocks.” (Sutherland *New History* 32)

Hess’s theory of seafloor spreading

“The theory of continental drift was vindicated by events during World War II. Harry Hess, a geologist, was also the captain of the U.S.S. *Cape Johnson*, a transport ship outfitted with a new technology, sonar, to detect German submarines. Hess left his sonar on while he was crossing the Pacific Ocean and, in doing so, started to create profiles of the ocean floor.” (Sutherland *New History* 32)

He discovered that “The ocean floor in that area—in fact, all over the world—was not flat. It was covered with ridges, commonly with sunken volcanoes along the edges of continents. There was a deep oceanic trench. These findings were bizarre, because if the oceans had existed for billions of years, they should be full of sediment and completely flat.” (Sutherland *New History* 32)

“Hess suggested that in these long ridges . . . magma was rising up continually, generating new ocean crust. As that new ocean crust was formed, it would displace the older crust to either side. This older crust would eventually descend and be recycled back into the ocean trenches. Hess called this process “seafloor spreading” and, in 1962, published his ideas in an article entitled “History of Ocean Basins.”“ (Sutherland *New History* 32)

“According to Hess, continents are the thickened parts of crustal plates, and the continents are carried on those plates. They move as oceanic crust spreads from the mid-oceanic ridge at its edge or [32] is subducted at another plate boundary.” (Sutherland *New History* 32-33)

Hess’s work forms the basis of the theory of plate tectonics.” (Sutherland *New History* 33)

plate tectonics

3.2b: Earth transitioned to plate tectonics. (Lee)

“Radioactive decay made early Earth’s interior much hotter than it is today, so its crust was flaccid. For decades, scientists have debated when the core cooled enough for the crust to harden into plates that began to move, break apart, collide and plunge.” (Lee)

Converging evidence has made 3.2b “the growing consensus . . .” (Lee)

“In plate tectonics, the majority of activity occurs at the plate boundaries.” (Sutherland *New History* 33)

divergent plate boundary

“. . . the ocean crust is continually being generated, oozing up.” (Sutherland *New History* 33)

“There is one area in the world where we can actually stand on a divergent plate boundary: Iceland. One part of Iceland is moving toward North America, and the other part is moving toward Europe.” (Sutherland *New History* 33)

convergent plate boundary

“Convergent plates undergo . . . subduction, where one plate is physically pushed below another into the Earth.” (Sutherland *New History* 33)

three types of subduction

When two ocean plates converge, “an oceanic volcanic island arc develops above the descending plate due to the heating caused.” (Sutherland *New History* 4)

The Aleutian Islands have “developed as the Pacific plate is pushed below” them. (Sutherland *New History* 34)

“If two oceanic plates come together, the older plate subducts because it is cooler and denser.” (Sutherland *New History* 43)

When an ocean plate and a continent plate converge, it “looks like a train wreck. Because continental rocks are not as dense as oceanic rocks, they cannot physically be subducted. The edge of the continent gets ripped up. These . . . collisions generate volcanic activity, such as the activity we see in the Pacific Northwest.” (Sutherland *New History* 34)

When two continental plates converge, they can only go up. (Sutherland *New History* 34)

example: the Himalayas are from “an ongoing collision between India and Asia.” (Sutherland *New History* 34)

transform plate boundary

“At a transform plate boundary, the plates just slide past one another.” (Sutherland *New History* 34)

In California, “the North American plate and the Pacific plate are moving past each other but not smoothly [the San Andreas Fault]. The plates can stick, build up pressure, and then suddenly give, generating earthquakes.” (Sutherland *New History* 34)

the concept of deep time

“Tectonic plates move very slowly. The Atlantic plate, for example, is spreading and opening at about the same rate that fingernails grow. This is why the concept of deep time is very important . . .” (Sutherland *New History* 34)

suggested reading

Kious and Tilling, *This Dynamic Earth*.

McCoy, *Ending in Ice*.

## The Origin of Life

introduction

“In this lecture, we will look at a number of possible scenarios for the origin of life on our planet. Did life emerge, as Charles Darwin supposed, from some warm little pool, or should we look to the deep ocean environment for life’s origins? Did life—or at least the building blocks of life—have a more exotic, perhaps extraterrestrial, origin? What were the first stirrings of life like?” (Sutherland *New History* 49)

early theories of the origin of life

There were the biblical accounts.

“. . . there was the theory of spontaneous generation. For example, if someone left putrid matter on the floor, it was thought that fleas spontaneously generated from that.” (Sutherland *New History* 50)

Darwin: life as part of the Earth system

Charles Darwin (1871 letter to botanist Joseph Hooker): “We could conceive in some warm little pond, with all sorts of ammonia and phosphoric acids, light, heat, electricity, present.” Darwin thought that this was the [49] brew from which proteins could form, and from proteins, we could move to the progenitor of all life.” (Sutherland *New History* 49)

“Charles Darwin believed that life originated in some sort of volcanic pool, and some scientists today are still in favor of this idea.” (Sutherland *New History* 49)



Darwin “suggested that life emerged inorganically—life being an emergent property of the evolution of a developing Earth system.” (Sutherland *New History* 50)

abiogenesis

Even after Darwin, “spontaneous generation still plays a part—right at the beginning.” (Sutherland *New History* 50)

But now “we call it abiogenesis—effectively, life from lifelessness.” (Sutherland *New History* 50)

life from the atmosphere

Alexander Oparin (1894-1980)

Oparin, a Russian biochemist, supported abiogenesis. (Sutherland *New History* 50)

“In studying the atmospheres of the Jovian planets, Oparin noted that while many of their gases were carbon-based gases, such as methane, there was water vapor, ammonia, and a great deal of hydrogen present. He surmised that these gaseous giant atmospheres could be analogous to Earth’s primitive atmosphere. Oparin also theorized that inorganic systems were arranged in hierarchies of increasing complexity. He suggested that life is just one extra level of chemical complexity of the system.” (Sutherland *New History* 50)

1952: the Miller-Urey experiment

Stanley Miller and Harold Urey at the University of Chicago “recreated the conditions on the early Earth. They took the gas giant atmosphere as an analog for the early Earth atmosphere, using water, ammonia, methane, and hydrogen.” (Sutherland *New History* 50)

“Miller and Urey created a closed system, using glass tubing.” (Sutherland *New History* 51)

“The bottom of the experimental assembly was full of liquid water, representing the early oceans. That water was heated, and as it heated, it evaporated and rose up into the vessels that simulated the atmosphere.” (Sutherland *New History* 51)

“Eventually, that atmosphere passed into an object at the top, where two prongs delivered electricity and created a spark. This simulated lightning, an energy source in the early Earth atmosphere.” (Sutherland *New History* 51)

“The atmosphere then moved around the system, cooled, and ultimately condensed and was returned to the ocean, where it was again heated and recycled through the system again and again.” (Sutherland *New History* 51)

“Miller and Urey left the experiment going for a week and then came back. What they found was that system no longer looked like an inorganic system; it was full of dirty, black muck [that contained] organic compounds, including amino acids.” (Sutherland *New History* 51)

“Amino acids are the building blocks of proteins. Proteins are important food sources for some creatures, but they also form important parts of DNA, DNA-related components, and cell membranes. It would appear that the early Earth atmosphere was conducive to forming life molecules.” (Sutherland *New History* 51)

“Interestingly, there is supporting evidence for this hypothesis that comes from the studies of what we call old genes. These are genes that are common to most life forms on the planet—in other words, they share a common ancestor. These old genes are rich in the type of amino acids produced by the Miller-Urey experiment.” (Sutherland *New History* 51)

But wouldn’t life from the ocean (see next), or from outer space (see after next) be equally supported by the old-genes evidence?—Hahn

life from the ocean

“Another possible scenario for the origin of life lies in the deep ocean. Along ocean ridges, where there are plate margins, new oceanic [51] crust is created. Pillow lavas are generated in this environment, and the rock close to the ocean ridge remains hot for a long time. Ocean water seeps into this crust through cracks, and as it descends into these hot crustal areas, it heats up.” (Sutherland *New History* 51-52)

“As the ocean water heats up, it starts to circulate through the crust, dissolving minerals as it goes. Then, eventually, it is returned to the surface in geyser-like structures called black smokers. Its chemical composition contains metals, sulfides, and very hot water. When this brew comes into contact with ocean water that is charged in carbon dioxide, it catalyzes reactions that, again, form many biologically useful organic molecules.” (Sutherland *New History* 52)

life from outer space

1969: “A meteorite was found in Murchison in Victoria, Australia, that is part of a class of meteorite called a carbonaceous chondrite; as the name suggests, it is very rich in carbon. But this carbon is not just the usual carbon or graphite. It contains amino acids—the building blocks of proteins. It also contains alcohols, phosphonic acids, and nucleobases, some of the basic components of molecules like DNA.” (Sutherland *New History* 52)

“Earth was bombarded with comets and meteorites early on in its history. It is likely that organics were frequently deposited from space. But it is also quite likely that we were generating organics on the Earth, as well—a from the atmosphere and in the ocean. Creating those live chemicals is no problem; however, they are still not life.” (Sutherland *New History* 52)

What is life?

“We can think of life as having four essential components.” (Sutherland *New History* 52)

“First, life must demonstrate some sort of organization or structure.” (Sutherland *New History* 52)

“Second, it must be separated from its external environment—most likely through some kind of membrane.” (Sutherland *New History* 52)

“Third, it must generate energy; it has to be able to metabolize in some way.” (Sutherland *New History* 53)

“Fourth and probably most important, it needs to be able to replicate itself. It needs to be able to preserve its kind and pass copies of itself into the future.” (Sutherland *New History* 53)

Whether from the atmosphere, the oceans, or outer space, organic molecules are not life.

“. . . we can create simple important life molecules—sugars, amino acids, and so on—but that is not life. We need to get these organic molecules together. We need to polymerize them into more complex organic molecules, strings of molecules.” (Sutherland *New History* 53)

What is still missing is “deep geological time.” (Sutherland *New History* 53)

possible catalysts of life

A catalyst can “independently help these molecules get together and generate longer-chain molecules.” (Sutherland *New History* 53)

polyphosphates

“A common way to catalyze is to use polyphosphates. In fact, one of the most common catalyzing agents, or energy generators, is adenosine triphosphate (ATP).” (Sutherland *New History* 53)

clay

“Clay is a fine-grain sedimentary particle. When it is found in the oceans, however, it takes on positive and negative electrical charges. Those charges attract organic molecules to its surface, which can then align along the surface of the clay.” (Sutherland *New History* 53)

radioactivity

“It is thought that the early Earth had more phosphoric radioactive minerals than today. These minerals would tend to be concentrated on beaches. It’s possible that some . . . were concentrated by ocean waves, and the phosphorus and radioactive activity helped catalyze reactions.” (Sutherland *New History* 53)

self-replicating molecules

“For life to prevail, ordinary long-chain molecules are not enough; we need . . . a self-replicating molecule. We need something that will pass copies of itself down through time.” (Sutherland *New History* 54)

“. . . the most prominent self-replicating molecule is DNA. But we have a problem: DNA needs a hand in replicating itself.” (Sutherland *New History* 54)

“Fortunately, there is . . . ribonucleic acid (RNA). There are many different forms of RNA.” (Sutherland *New History* 54)

“Messenger RNA (mRNA) goes into the nucleus of cells where recombinant DNA is stored and makes copies of the coded messages on the DNA. It then takes copies of those messages out into the cell to help code for proteins in the cell’s cytoplasm.” (Sutherland *New History* 54)

“Transfer RNA (tRNA) brings specific amino acids to these assembly points to help build proteins.” (Sutherland *New History* 54)

“Ribosomal RNA (rRNA) is the one of greatest interest to us because this RNA helps catalyze the formation of proteins. Possibly even more significant, rRNA can also self-replicate.” (Sutherland *New History* 54)

early self-replicating molecules

“In 1996, Walter Gilbert of Harvard University proposed the existence of an RNA world, an early planet dominated by self-replicating naked genes of RNA before the emergence of life that was based on DNA. In the RNA world, RNA molecules competed for component molecules, for the nucleotides that made themselves up.” (Sutherland *New History* 54)

“These forms that could catalyze their own development would have a selective advantage. In this scenario, evolution by natural selection had been initiated, potentially, even before life really got going at all.” (Sutherland *New History* 54)

the biosphere among Earth systems

“The biosphere does not exist in isolation. The evolution of life affects every Earth system—the hydrosphere, lithosphere, and [54] atmosphere.” (Sutherland *New History* 54-55)

suggested reading

Knoll, *Life on a Young Planet*.

Ricardo and Szostak, “The Origin of Life on Earth.” In Schopf, ed., *Life*’*s Origin*.

Wicander and Monroe, *Historical Geology*.

## First Life Forms

“Cyanobacteria.” *Wikipedia*. 25 Feb. 2021. 26 Feb. 2021. Web.

introduction

“This lecture examines the evidence of early life on our planet.” (Sutherland *New History* 56)

“We will explore”: (Sutherland *New History* 56)

“whether life began on Earth or . . . arrived from another place”

“Earth’s oldest fossils and consider how life survived in . . . a very crowded solar system”

“the possibility that life evolved more than once, or whether it simply hid away when the planet was bombarded from outer space”

Panspermia

“The idea that life was seeded from elsewhere [than Earth] is called panspermia . . .” (Sutherland *New History* 58)

“. . . it is regarded by many as a fringe science.” (Sutherland *New History* 58)

But Mars “is much smaller than Earth . . .” Mars diameter: 4212.3 mi; Earth diameter: 7917.5 mi. (Sutherland *New History* 57)

So “it would have cooled much faster and developed liquid oceans before Earth did.” (Sutherland *New History* 57)

So life may have “evolved on Mars before it did on Earth.” (Sutherland *New History* 57)

“Mars at this time was still receiving many impacts from space, and because Mars has less gravity than Earth, it is easier to launch rocks off its surface—and any microbes on those rocks.” (Sutherland *New History* 57)

Microbes could have survived the vacuum from Mars to Earth. (Sutherland *New History* 58)

“. . . bacteria have been found to survive three years of exposure to vacuum, radiation, and extremes of cold and heat with no available sources of nutrition and water.” (Sutherland *New History* 58)

Allan Hills meteorite (ALH 84001)

Dec. 1984: a meteorite was found by a U.S. team in the Allan Hills area of Antarctica.” (Sutherland *New History* 56)

“Scientists look for such specimens in Antarctica because dark meteorites show up against the white background of the snowy landscape . . .” (Sutherland *New History* 56)

Also, “meteorites tend to get locked in ice, which removes them from the highly oxidizing atmosphere.” (Sutherland *New History* 56)

“. . . gas analysis and other techniques” showed that the meteorite came from Mars. (Sutherland *New History* 56)

1996: the Allan Hills meteorite “hit the headlines [because] It was claimed that fossils were found within this meteorite—fossils from Mars.” (Sutherland *New History* 56)

“Scientists believe this Martian rock was originally a magma that crystallized to form an igneous rock around about 4.1 billion years ago. Around 4 to 3.9 billion years ago, it was fractured in a meteorite impact and lay exposed on the surface of the planet. At that particular time, Mars was warmer and wetter and probably had areas of open water. The speculation is that the rock later became encrusted or invaded with microbes, and eventually, those microbes became fossilized.” (Sutherland *New History* 56)

evidence the meteorite has fossils

The meteorite contains “polycyclic aromatic hydrocarbons (PAHs), common decay products of bacteria.” (Sutherland *New History* 57)

“The meteorite also contains rosette-like structures that have cores of manganese surrounded by rings of iron carbonate and iron sulfides. These bear a strong resemblance to mineral features that are produced by terrestrial bacteria today.” (Sutherland *New History* 57)

“. . . the meteorite contains magnetite crystals; magnetite is also found in certain bacteria, such as magnetotactic bacteria.” (Sutherland *New History* 57)

All this “seems to be strong evidence of fossil life on Mars brought to Earth in a meteorite . . .” (Sutherland *New History* 57)

evidence the meteorite has pseudofossils

“. . . certain inorganic processes, such as mineral deposits, can replicate fossils . . .” (Sutherland *New History* 57)

“Some of the structures found in the rock are 20 to 30 nanometers in length . . .” (Sutherland *New History* 57)

That is “smaller than the smallest bacteria discovered on our planet. Some scientists have questioned if it is even possible for biochemistry to work on this small scale.” (Sutherland *New History* 57)

“All the evidence described here can be explained by some sort of inorganic process.” (Sutherland *New History* 57)

“If we assume that these are real fossils, however, we get an interesting alternative to the evolution of life.” (Sutherland *New History* 57)

“. . . we might be Martians . . .” (Sutherland *New History* 61)

With our explorations of space, we [may] have become agents of panspermia . . .” (Sutherland *New History* 61)

oldest fossils: cyanobacteria

3.5b: oldest fossils (from the Apex Chert, western Australia) (Sutherland *New History* 58)

“Chert is a fine-grain silica deposit that closely resembles . . . cyanobacteria.” (Sutherland *New History* 58)

Cyanobacteria are aquatic bacteria whose “common name is pond scum.” (Sutherland *New History* 58)

They are also called “blue-green algae.” But “modern botanists restrict the term algae to eukaryotes [all algae are eukaryotes] and don’t apply it to cyanobacteria, which are prokaryotes.” (“Cyanobacteria”)

(The two types of prokaryote are archaea and bacteria. Cyanobacteria are bacteria.)

Cyanobacteria developed “an incredibly complex process: photosynthesis.” (Sutherland *New History* 58)

Photosynthesis uses sunlight “to convert carbon dioxide [and water] into organic compounds and oxygen.” (Sutherland *New History* 58)

evidence of water and carbon

evidence of water

3.8-3.7b: the Isua Greenstone Belt (Greenland) has hints of life. (Sutherland *New History* 58)

Isua “has the oldest structures that we can positively identify as being formed in water: pillow lavas.” (Sutherland *New History* 58)

“Pillow lavas, basaltic in composition, are lavas that erupted underneath water . . .” (Sutherland *New History* 58)

So “Isua provides the first direct evidence that we had open water on the surface of the planet.” (Sutherland *New History* 58)

evidence of carbon

“In Isua are also found sedimentary rocks with dark bands that contain particles of carbon. It has been speculated that these particles of carbons were produced by microorganisms.” (Sutherland *New History* 59)

“There are three isotopes of carbon: carbon-14 [used for dating] and the two stable isotopes, carbon-12 and carbon-13.” (Sutherland *New History* 59)

“Photosynthesizing life has a preference for organic carbon dioxide, which is carbon-12. Organisms tend to be enriched in carbon-12, and a high concentration of carbon-12 could indicate that photosynthesis was occurring.” (Sutherland *New History* 59)

“The carbon-12 signature was found within those carbon blobs at Isua.” (Sutherland *New History* 59)

“If it indeed indicates the presence of photosynthetic life, it means that life existed more than 3.7 billion years ago.” (Sutherland *New History* 59)

4.1-3.8b: the late heavy bombardment period

4.1-3.8b is the Late Heavy Bombardment (LHB) period. (Sutherland *New History* 59)

It was “a very crowded solar system . . .” (Sutherland *New History* 59)

“Mercury, Mars, and our Moon show evidence of intense battering . . .” (Sutherland *New History* 59)

Earth in the LBH

“. . . most likely, Earth also suffered . . . extremely large impact events.” (Sutherland *New History* 59)

But plate tectonics and erosion have removed most evidence of the LHB. (Sutherland *New History* 59)

“These catastrophic impacts would have formed craters thousands of miles in diameter, spewing rock vapor high up into the atmosphere. The impacts would have superheated the atmosphere to such an extent that the oceans would have boiled and evaporated away into the atmosphere.” (Sutherland *New History* 60)

“The Earth’s crust may have started to melt.” (Sutherland *New History* 60)

Earth’s surface “would have been, in effect, sterilized.” (Sutherland *New History* 60)

Life existed before the end of the LHB period. (Sutherland *New History* 60)

“. . . life was already becoming complex 3.8 billion years ago . . .” (Sutherland *New History* 60)

“Genetic evidence suggests that the origin of life is before the LHB period . . .” (Sutherland *New History* 60)

How did it survive the LHB?

archaea: the ultimate survivors

“Could life have evolved more than once? Genetic evidence suggests . . . a single train of life to the present.” (Sutherland *New History* 60)

“The answer may be found in hot, hydrothermal vent systems found around mid-ocean ridges. The water in these systems is full of toxic heavy metals. It is close to boiling and is subject to tremendous pressures. But we also find life there.” (Sutherland *New History* 60)

Archaea are “simpler than bacteria . . .” (Sutherland *New History* 60)

Archaea are extremophiles.

Archaea “are found in many environments with extremes of temperature and pH.” (Sutherland *New History* 60)

“The species *Archaeoglobus fulgidus* is found in hot sediments near submarine hydrothermal vent systems. It exists in temperatures around 181° Fahrenheit.” (Sutherland *New History* 60)

“Some live in salty brines . . .” (Sutherland *New History* 60)

“Archaea have been found 2 miles under the ground, where the water inside the rock is about 140° Fahrenheit. There’s no oxygen or light, but life is pervasive at these great depths in the planet.” (Sutherland *New History* 61)

Archaea are “the answer to the LHB paradox . . .” (Sutherland *New History* 61)

“. . . the heat pulse from the impacts on the Earth [melted rocks] but would have never reached deep enough to sterilize all” the archaea. (Sutherland *New History* 61)

“They could survive there until temperatures on the surface of the planet cooled, the oceans condensed, and water rained on the surface. Then, life could migrate back to the surface of the planet and start again.” (Sutherland *New History* 61)

“Perhaps life’s earliest ancestor was not from Darwin’s warm little pool; perhaps it is the archaea living in near-boiling water deep within the crust of our planet.” (Sutherland *New History* 61)

suggested reading

Gould, ed., *The Book of Life*.

Knoll, *Life on a Young Planet*.

Lane, *Life Ascending*.

## Life Transformed the Early Earth

“Eukaryote.” *Wikipedia*. 24 Feb. 2021. 26 Feb. 2021. Web.

Ravilious, Kate. “Earth Was a Frozen Snowball When Animals First Evolved.” *BBC*.*com*. 12 Jan. 2015. 27 Feb. 2021. Web.

introduction

After the LHB, the Earth was warm and “rich in methanogenic archaea.” (Sutherland *New History* 62)

The sky was pink, “owing to high levels of methane in the atmosphere.” (Sutherland *New History* 62)

2.5b-541m: Proterozoic eon: oxygen to complex life (*proteros*, “former, earlier”)

Paleoproterozoic (2500-1600): atmospheric oxygen

Mesoproterozoic (1600-1000): major events: (“Mesoproterozoic”)

“breakup of the Columbia supercontinent [and] formation of the Rodinia supercontinent”

first mountains (the Grenville Orogeny, Labrador to Mexico)

“high point of the Stromatolites before they declined in the Neoproterozoic”

start of multicellular organisms and communal living

Neoproterozoic (1000-541): major events:

three Snowball Earths (Hoffman)

earliest fossils of multicellular organisms (the Ediacaran biota) (“Neoproterozoic”)

This lecture discusses”: (Sutherland *New History* 62)

the beginnings of our atmosphere

“why the planet was warm, not frozen”

how life almost ended, “encased in ice”

methane atmosphere

4.49b: the Sun ignites. It was only 70% as luminous as today. (Sutherland *New History* 62)

Since the Earth received les heat, “The oceans should have been frozen.” (Sutherland *New History* 62)

“Yet we have found evidence of liquid water and life where there should have been ice and no life at all. This is known as the faint young Sun paradox. In fact, we think that life may actually hold the answer to this paradox.” (Sutherland *New History* 62)

“Many archaea are methanogens, [producing] methane as a waste gas.” (Sutherland *New History* 62)

“This is not unlike the process by which cyanobacteria produce oxygen as a waste product of photosynthesis.” (Sutherland *New History* 62)

Methane is a 20-times stronger greenhouse gas than carbon dioxide. (Sutherland *New History* 62)

2.4-2.1b: the Huronian Glaciation (Sutherland *New History* 65)

Ice from the poles “met at the tropics, creating [a] Snowball Earth.” (Sutherland *New History* 65)

The Huronian Glaciation deposited rocks called tillites, and some “were deposited close to the equator.” (Sutherland *New History* 65)

“Around 2.2 billion years ago, the methane blanket covering the Earth was gradually reduced through the action of oxygen produced by cyanobacteria. Because we had a faint young Sun [30% less luminosity than now], the carbon dioxide presence in the atmosphere was not sufficient to keep the planet warm, creating the first Snowball Earth.” (Sutherland *New History* 70)

accumulation of oxygen

Today the atmosphere is 21% oxygen.

The early atmosphere hardly had any. Good: oxygen “tends to break down organic compounds.” (Sutherland *New History* 63)

Oxygen accumulated from photosynthesis.

3.5b: oldest fossils (from the Apex Chert in Australia): cyanobacteria, which photosynthetize (Sutherland *New History* 58)

stromatolites

Cyanobacteria lay down sediments that become stromatolites. (Sutherland *New History* 63)

Stromatolites “give us a picture of the landscape of the early Earth.” (Sutherland *New History* 63) Stromatolites in Shark Bay, Australia:



“The stromatolites consisted only of loose associations of cyanobacteria; each bacterium was an independent unit.” (Sutherland *New History* 66)

Stromatolites “are evidence that [63] cyanobacteria were spread across the planet.” (Sutherland *New History* 63-64)

The “Precambrian stromatolites were some of the largest life structures. They reached a peak of diversity about 1.25 billion years ago.” (Sutherland *New History* 96)

“In the Cambrian, the stromatolites became restricted to areas of low oxygen, high salinity, and the intertidal zone. They were grazed away by the new Cambrian” forms. (Sutherland *New History* 96)

“Today, the stromatolites are generally found only in extreme environments.” (Sutherland *New History* 96)

2.4-2b: the Great Oxygenation Event

3.5b: banded iron formations

Iron eroded from continent rocks and moved to the ocean floor. (Sutherland *New History* 64)

“. . . iron existed in the oceans in a reduced ferrous state referred to as Fe2+.” (Sutherland *New History* 64)

When oxygen appeared, it combined with Fe2+, converting it to Fe3+, ferric iron, “creating banded iron formations.” (Sutherland *New History* 64)

“Banded iron formations consist of iron minerals—in particular, two iron oxides, the minerals hematite and magnetite.” (Sutherland *New History* 64)

Banded iron formations “are extensive and represent vast areas of deposition of iron-based minerals.” (Sutherland *New History* 64)

2.5b: banded iron formations peaked, then declined. (Sutherland *New History* 64)

1.8b: banded iron formations became rare. (Sutherland *New History* 64)

Banded iron formations are proof of “the emergence of oxygen . . . called the Great Oxygenation Event . . .” (Sutherland *New History* 64)

“. . . the iron [in any object] may have precipitated out of oceans by the activity of photosynthetic organisms billions of years ago.” (Sutherland *New History* 68)

“Eventually, more oxygen was produced than could be used up by the iron, and that oxygen started to escape from the ocean and travel into the atmosphere.” (Sutherland *New History* 64)

effects of oxygen

“Oxygen was highly toxic to” archaea. (Sutherland *New History* 64)

Maybe the Great Oxygenation Event “caused Earth’s first mass extinction . . .” (Sutherland *New History* 64)

Oxygen “oxidizes the methane and produces carbon dioxide and water. As the methane disappeared”: (Sutherland *New History* 65)

the “sky turned from pink to blue”

“global temperatures plummeted”

Complex cells (eukaryotes) and multicellular creatures “most likely required elevated levels of oxygen.” (See below.) (Sutherland *New History* 66)

“Elevated levels of oxygen would allow creatures to grow larger because, if creatures are multicellular, oxygen can penetrate through all the cells in the body and allow them to grow to a larger size.” (Sutherland *New History* 66)

eukaryotes (complex cells)

“Life up until this time had been prokaryotic slime.” (Sutherland *New History* 65)

“Severe climatological disturbances stirred the brew again, greatly mixing up the oceans. This caused a massive rise in oxygen levels, to about 1 percent of the levels we see today.” (Sutherland *New History* 65)

“After the ice retreated, there was “a leap in the complexity of the biosphere.” (Sutherland *New History* 65)

“Oxygen is an energetic molecule. An environment with oxygen and creatures that can actually use that energetic molecule opens the possibility of developing more complex creatures.” (Sutherland *New History* 65)

Prokaryotes are simple and “show few internal modifications within the cell.” (Sutherland *New History* 65)

“Within a prokaryote, genetic material is randomly distributed through the cytoplasm.” (Sutherland *New History* 65)

“Bacteria are prokaryotes.” (Sutherland *New History* 65)

Eukaryotes are much more complex.

They “have complex structures . . . called organelles.” (Sutherland *New History* 65)

DNA is “tidied [65] away in a discrete nucleus.” (Sutherland *New History* 65)

2.1-1.6b: earliest eukaryotes, probably “flagellated phagotrophs.” (“Eukaryote”)

“How did life progress” from prokaryotes to eukaryotes? (Sutherland *New History* 65-66)

endosymbiotc hypothesis

In an ocean, one prokaryote attempts to eat another. But the engulfed prokaryote “isn’t destroyed; instead, a symbiotic relation is set up . . ., resulting in eukaryotes.” (Sutherland *New History* 66)

multicellular creatures

Multicellular creatures differentiate cell functions. Cells are adapted to perform specific functions. (Sutherland *New History* 66)

“. . . cellular differentiation [means] cells with specific roles like liver, muscle and blood.” (Ravilious)

1.2b: a red alga (the fossil *Bangiomorpha pubescens*) is “Possibly the earliest example of multicellularity . . .” (Sutherland *New History* 66)

“The cells at the base of these algae are clearly differentiated into holdfasts, the cells used to cement the organisms to rocks.” (Sutherland *New History* 66)

“It has also been suggested that . . . certain cells have been adapted to perform specific sexual functions.” (Sutherland *New History* 66)

1.2b: first animal eukaryote (choanoflagellate)

“The first animal eukaryote was probably the choanoflagellate, a free-living, single-celled organism.” (Sutherland *New History* 66)

Choanoflagellates closely resemble “some of the component cells found in sponges.” (Sutherland *New History* 66)

Probably “associations of eukaryotes, such as choanoflagellates, eventually gave rise to sponges . . .” (Sutherland *New History* 67)

Sponges are among “the most primitive multicellular animals . . . today.” (Sutherland *New History* 67)

“Diversification of the eukaryotes and the first truly multicellular creatures occurred with 1 percent of oxygen in the atmosphere . . .” (Sutherland *New History* 67)

1.2b-630m: evolution stalled

Perhaps the oxygen levels were “too low to permit diversification in the production of more complex creatures.” (Sutherland *New History* 67)

Perhaps “the addition of oxygen [led] to a sulfidic ocean.” (Sutherland *New History* 67)

Atmospheric oxygen reacts with the mineral pyrite (FeS2). Pyrite oxidizes, “producing sulfate, SO4. These sulfates are then washed into the oceans, where sulfate-reducing bacteria use it in their metabolism. As they do, they convert the sulfate into hydrogen sulfide, H2S.” (Sutherland *New History* 67)

“. . . dissolved hydrogen sulfide in the oceans . . . reduced the solubility and availability of certain key metals, such as molybdenum and copper. These metals play vital roles in the enzymatic pathways of many organisms.” (Sutherland *New History* 67)

So perhaps “the biological innovation of photosynthesis may have ultimately held back evolution.” (Sutherland *New History* 67)

630m: first truly complex creatures (Sutherland *New History* 67)

all Earth’s systems are related

“. . . Earth’s systems—biosphere, atmosphere, geosphere, hydrosphere—are related.” (Sutherland *New History* 67)

“Changes in the biosphere [affected the] atmosphere: Cyanobacteria released oxygen into the atmosphere to at least 1 percent.” (Sutherland *New History* 68)

“This changed how minerals weathered in the geosphere: Pyrite oxidized to produce sulfate.” (Sutherland *New History* 68)

“Sulfate [altered] the hydrosphere by . . . sulfate-reducing bacteria producing hydrogen sulfate.” (Sutherland *New History* 68)

Hydrogen sulfate had “consequences in the biosphere by putting the brakes on evolution.” (Sutherland *New History* 68)

suggested reading

Biello, “The Origin of Oxygen in Earth’s Atmosphere.”

Lane, *Oxygen*: *The Molecule That Made the World*.

University of California-Riverside, “Oxygen-Free Early Oceans Likely Delayed Rise of Life on Planet.”

## 720-635m: Cryogenian Period

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introduction

“Among the major sources of evidence [for past climates] are sediment cores from the ocean bottom. They preserve the fossils of tiny organisms called foraminifera. By measuring oxygen in the skeletons of these organisms, scientists can calculate fluctuations in temperature and moisture over millions of years.” (“Frequently”)

“In this lecture, we’ll ask:” (Sutherland *New History* 69)

“How could ice get all the way to the equator?”

“How could such a mega-glaciation be stopped once it started?”

“. . . how could life survive below ice—possibly miles thick—for millions of years?”

Snowball Earth hypothesis

glacial striations

“As ice moves out across the land, it picks up debris and rock and freezes these into its undersurface. Some of the rocks make scour marks, creating glacial striations.” (Sutherland *New History* 69)

glacial dropstones

“The evidence for a Snowball Earth first emerged in the early 1990s. Unexpectedly, geologists discovered evidence of glaciers—such as stones that had clearly been carried on ice rafts and then dropped—in the tropics.” (Ravilious)

“If those rocks and ice move out across open water, the rocks can fall into sediments, producing the phenomenon of a glacial dropstone—a large boulder that does not belong in finer-grain sediment.” (Sutherland *New History* 69)

“In the 1940s, a geologist named W. Brian Harland found glacial dropstones dating to 600 million years ago on virtually every continent, including in the tropics. [Harland proposed] a global glaciation: a Snowball Earth.” (Sutherland *New History* 69)

The scientific community rejected the hypothesis, explaining away the data as “caused by continental drift.” (Sutherland *New History* 69)

“Russian chemist and climatologist Mikhail Budyko “theorized that the cloud of ash and dust created by a catastrophic nuclear exchange would block out the Sun and create what is known as a nuclear winter.” (Sutherland *New History* 69)

“As the Earth became dark and cold, we would get into a positive feedback loop in which more solar radiation than the Earth could absorb would be reflected back to space. Ice would advance very rapidly to the equator and totally cover the planet. . . . The ice would continue to reflect the sunlight back into space, and Earth would never be free of ice again.” (Sutherland *New History* 70)

Joseph Kirschvink of Princeton tested “the Snowball Earth hypothesis using magnets.” (Sutherland *New History* 70)

“. . . the Earth’s magnetic field has lines of flux that are vertical at the magnetic poles and more parallel to the ground closer to the equator. The inclination of those lines of flux with respect to the Earth’s surface can provide information on latitude and position.” (Sutherland *New History* 70)

“Because rocks contain iron minerals, when sedimentary rocks are deposited or basalt lava cools, those magnetic minerals align themselves to Earth’s magnetic field. Their alignment preserves the inclination of the magnetic field at the time that the rock was actually formed, identifying the latitude and position of the rock.” (Sutherland *New History* 70)

“Kirschvink’s magnetometer readings of magnetic inclination indicated that some glacial dropstones had indeed formed at the equator . . . a Snowball Earth had occurred.” (Sutherland *New History* 70)

717m-660m: second Snowball Earth (Sturtian Glaciation) (Hoffman)

2.2b: the first Snowball Earth, because oxygen weakened the methane greenhouse effect. (See lecture10, “How Life Transformed the Early Earth.”) (Sutherland *New History* 65)

The second Snowball Earth was the severest. (Ravilious)

“The theory is that more recent Snowball Earths were created because carbon dioxide greenhouse protection was compromised.” CO2 was trapped in carbonic acid. (Sutherland *New History* 70)

“Even at the equator—the warmest place on Earth—the average temperature was a frigid –20°C, equivalent to modern-day Antarctica.” (Ravilious)

chemical weathering

Chemical weathering is “a process in which carbon dioxide breaks down rocks and then gets trapped in sediment . . . Scientists have generally thought that this process takes hundreds of thousands to millions of years . . . Rather than potentially millions of years, . . . researchers now suggest it can take several tens of thousands of years.” (Haughney)

cause 1: warm rain

“Around 830 million years ago, the supercontinent Rodinia was fragmenting. The result was a configuration of continents grouped [70] around the equator and separated by ocean. That continental configuration led to . . . intense evaporation and tropical rainfall along the continental areas.” (Sutherland *New History* 70-71)

silicate weathering

“Warm rain falling at the tropics [dissolved] carbon dioxide [which then] formed carbonic acid. . . . This process swept carbon dioxide from the atmosphere.” (Sutherland *New History* 71)

The carbonic acid “reacted with the rocks, producing bicarbonate ions that were washed into the oceans.” (Sutherland *New History* 71)

cause 2: lava

“About 723 million years ago, there was a massive outpouring of basalt lava. Given that basalt is particularly susceptible to chemical weathering, we have a further contributory factor to the massive drawdown of carbon dioxide from our global greenhouse blanket.” (Sutherland *New History* 71)

With less CO2 in the atmosphere, the Earth cooled, and ice advanced to the equator. (Sutherland *New History* 71)

“. . . More sunlight was reflected back into space than was being absorbed by the surface of the planet, and ice advanced rapidly into the tropics, sealing up the surface with a highly reflective white surface, possibly miles in thickness.” (Sutherland *New History* 72)

“. . . a positive feedback effect took hold as the ice reflected more sunlight back into space.” (Sutherland *New History* 71)

“There were two distinct pulses of extreme glaciation, interspersed with a 20-million-year warm period.” (Ravilious)

650-635m: third Snowball Earth (Marinoan Glaciation) (Hoffman)

ending Snowball Earth

“How and why did it cease?” (Sutherland *New History* 72)

Volcanoes are the answer, but not because “lava erupts and melts the ice . . .” (Sutherland *New History* 72)

660m: “volcanoes topped up the atmospheric carbon dioxide enough to haul the climate out of its frozen state.” (Ravilious)

“. . . volcanoes emit carbon dioxide. Because the Earth was completely encased in ice, there was nowhere for the carbon dioxide to go but up; thus, atmospheric levels of carbon dioxide started to increase.” (Sutherland *New History* 72)

“After about 10 million years, carbon dioxide was about 10 percent of the atmosphere. (Today, it is less than 1 percent.)” (Sutherland *New History* 72)

Temperatures rose “from -122° to +122° Fahrenheit. In those temperatures, ice, even if it’s miles thick, would melt in less than 2000 years.” (Sutherland *New History* 72)

evidence in limestone

“After the Snowball Earth event, the Earth still had very hot surface conditions; there were remnants of carbon dioxide in the atmosphere, causing a greenhouse effect.” (Sutherland *New History* 72)

Water vapor from ocean surfaces rose and produced clouds. (Sutherland *New History* 72)

“Formation of clouds released latent heat of condensation. That further warmed the air, which continued to rise and drew in more [72] moist air below it into” hurricanes. (Sutherland *New History* 72-73)

“At about 112° Fahrenheit, these [were] vast hyper-hurricanes.” (Sutherland *New History* 73)

“This rain washed the excess carbon dioxide out of the atmosphere, which combined with water to form carbonic acid. That started to erode rocks again. Erosion of calcium aluminum silicate rocks created calcium ions, which combined with bicarbonate, producing calcium carbonate: limestone.” (Sutherland *New History* 73)

“If this hypothesis is correct, one of the net effects of Snowball Earth would be limestone formation. In fact, limestones have been found on the tops of cold glacial sediments.” (Sutherland *New History* 73)

720-635m: Life in the Cryogenian Period

photosynthetic creatures survived

“. . . evolutionary evidence suggests that they [photosynthetic creatures] evolved only once.” (Sutherland *New History* 73)

“The science journalist Paul Hoffman has theorized that ice in the ocean and ice on land move in slightly different ways. Where ocean and land meet, tension cracks open up in the ice. It’s possible that these tension cracks created oases of light that filtered down to the ocean floor and allowed the continued existence of photosynthetic creatures.” (Sutherland *New History* 73)

Other theories hypothesize, not a Snowball Earth, but “a Slushball Earth. In other words, there were still areas of open ocean—areas where photosynthetic life could exist.” (Sutherland *New History* 73)

“. . . the creatures that did survive huddled in . . . just a few small pockets of open water where hot springs bubbled up.” (Ravilious)

Nick Butterfield (Cambridge palaeontologist): “most geologists don’t buy the idea of a hard Snowball Earth anymore . . .” “Butterfield argues that life probably retreated to the open waters of the tropics during Snowball times, but otherwise carried on as normal.” (Ravilious)

“. . . subglacial lakes could also explain how photosynthetic life survived. Lakes that exist under even vast [73] thicknesses of ice are not really quite as sterile as we think.” (Sutherland *New History* 73-74)

“Further, ice that cools slowly can be very pure and glass-like; it can allow sunlight to penetrate right to the bottom of the ocean or lake floor. Such areas can quite adequately support a photosynthetic bacterial population.” (Sutherland *New History* 74)

top taxons: these currently seem to be:

domain Archaea

domain Bacteria

domain Eukarya

Burki lists five eukaryote supergroups: Ophiskontha, Amoebozoa, Excavata, Archaeplastida and SAR. (Burki) (Vidyasagar “Algae”)

Cavalier-Smith (2002) introduced the supergroup Amorphea, and he combined Opisthokonta and Amoebozoa in Unikonta, an unranked taxon. (“Amorphea”)

supergroup Amorphea (“Amorphea”)

Unikonta—two clades: (“Unikonta”)

Amoebozoa (“Amorphea”)

Obazoa (from OBA, acronym for Opisthokonta, Breviatea, and Apusomonadida)

Opisthokonta (*opísthios* rear + *kontos* pole, i.e., flagellum)

choanoflagellates

fungi

animals

Breviatea

Apusomonadida

supergroup Excavata

supergroup Archaeplastida

supergroup SAR (from SAR, acronym for Stramenopiles, Alveolata, and Rhizaria)

Stramenopiles (“Stramenopile”)

(*stramen* straw + *pilus* hair: they have “an anterior flagellum with short hairlike extensions”) (“Stramenopiles”)

Stramenopiles with chloroplasts (Stramenochromes)

Stramenopiles without chloroplasts

Alveolata

Rhizaria

plants

“Plant-like protists are called algae. They include single-celled diatoms and multicellular seaweed. Like plants, algae contain chlorophyll and make food by photosynthesis. Types of algae include red and green algae, euglenids, and dinoflagellates.” (“Algae”)

800-635m: pre-Ediacaran metazoans

“Metazoan”: an animal with “the body composed of cells differentiated into tissues and organs and usually a digestive cavity lined with specialized cells.” (First use: 1879.) (“Metazoan.” *Merriam-Webster*)

800-750m: first metazoans (Erwin)

“Recent molecular clock studies date the origin of Metazoa to 750-800 million years ago, roughly [when] oxygen levels rose from less than 0.1% present atmospheric level (PAL) to perhaps 1-3% . . .” (Erwin)

800/750m-600m: there is “a missing 150-200 Myr . . . [that] includes two major glaciations, and complex marine geochemical changes . . .” (Erwin)

convergent nervous systems

Perhaps “animals of these still unknown Cryogenian and early Ediacaran ecosystems were relatively simple, with highly conserved developmental genes involved in cell-type specification and simple patterning. In this model, complex nervous systems are a convergent phenomenon in bilaterian clades which occurred close to the time that larger metazoans appeared in the fossil record [541m].” (Erwin)

colonial flagellate hypothesis

According to the colonial flagellate hypothesis, “metazoans descended from ancestors characterized by a hollow, spherical, colony of flagellated cells. Individual cells within the colony became differentiated for specific functional roles (reproductive cells, nerve cells, somatic cells, and so on), thus subordinating cellular independence to welfare of the colony as a whole.” (“Origin of Metazoa”)

“We now have phylogenetic evidence based on small-subunit ribosomal RNA sequences and on similarities in complex biochemical pathways. This evidence generally supports the colonial flagellate hypothesis that metazoans represent a monophyletic assemblage including choanoflagellates (“collared” flagellates such as *Codosiga*). The sister group of metazoans appears to be fungi.” (“Origin of Metazoa”)

suggested reading

Hoffman, *Snowball Earth* (website).

Walker, *Snowball Earth*.

## 635-541m: Ediacaran Period

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introduction

“Evolution does not happen without a purpose . . .” (Sutherland *New History* 76)

“In this lecture, we’ll look at”: (Sutherland *New History* 76)

“the evidence we have for multicellular creatures”

“why and how creatures increased in size”

“the nature of the first broad animal ecosystem”

what ended it

molecular clocks

hemoglobin

Hemoglobin is “the key molecule for transporting oxygen in the blood. Although the structure of hemoglobin is very similar in animals, subtle differences exist, and those differences increase the farther back in time we go . . .” (Sutherland *New History* 80)

Human and chimpanzee hemoglobin is the same. (Sutherland *New History* 80)

Human and fish hemoglobins are significantly different. (Sutherland *New History* 80)

“It’s estimated that differences in hemoglobin occur every few million years or so; that can be used as a rough calibration to estimate the timing of divergence between different animals.” (Sutherland *New History* 80)

DNA and RNA

“Today, we use DNA and RNA differences to do this . . .” (Sutherland *New History* 80)

“We can estimate times of divergence using molecular clocks and then go to the hard evidence: the fossil record.” (Sutherland *New History* 81)

Molecular clocks give “a range of time, depending on what is used to calibrate the clock.” (Sutherland *New History* 81)

why evolution resumes

“. . . the next advance of global ice over our planet broke this stalemate and allowed for the next major innovation and leap in life’s story.” (Sutherland *New History* 68)

The biosphere “had apparently stalled, perhaps as a result of the oxygen causing the erosion of pyrite and the development of the sulfidic ocean.” (Sutherland *New History* 69)

“Earth was a slime planet with some small multicellular algae.” (Sutherland *New History* 69)

635m: “another global glaciation” [69] was perhaps what “allowed for the next major innovation and leap in life’s story.” [68] (Sutherland *New History* 68-69)

“The theory is that [several] events released the deadlock on evolution . . .” (Sutherland *New History* 74)

phosphorus

“During the Snowball, the glaciers would have worn huge amounts of phosphorus-rich dust away from the underlying rocks. . . . at the end of the Snowball, rivers washed this dust into the oceans, where it fed the [cyanobacteria].” (Ravilious)

Noah Planavsky (Yale): “High phosphorus levels would have increased biological productivity and organic carbon burial in the ocean, leading to a build-up of atmospheric oxygen.” (Qtd. in Ravilious)

In 2010 Planavsky “identified a massive spike in phosphorus levels in sediments from around the world, just as Snowball Earth was ending.” (Ravilious)

oxygen

“Until 800 million years ago, atmospheric oxygen levels were just one-hundredth of today’s levels. Planavsky thinks that is far too low to support complex animal life.” (Ravilious)

But “Sponges, one of the oldest kinds of animal, need just 0.5% of modern oxygen levels. Sponges may have been the first complex animals.” (Ravilious)

635m: “Oxygen levels had risen . . . to about 10 percent of current levels by the end of the last Snowball Earth . . .” (Sutherland *New History* 76)

ozone (O3)

“This rising oxygen level was associated with the development of [ozone].” (Sutherland *New History* 77)

“Ozone blocks ultraviolet radiation . . ., [which is] conducive to larger associations of cells in shallower water, where there are many food resources.” (Sutherland *New History* 77)

“Another benefit of oxygen is that animals need relatively high levels of oxygen to form collagen. Collagen, a net of proteins, is the scaffolding that animals use to build bigger bodies.” (Sutherland *New History* 77)

photosynthesis

“After the Snowball Earth event, oxygen was freely available for the first time, increasing the potential for life forms to become bigger and more differentiated. The stage was set for multicellular life forms.” (Sutherland *New History* 76)

“After the snowball, photosynthetic algae were released into warm oceans.” (Sutherland *New History* 74)

“There was a massive rise in temperatures. The hyper-hurricanes mixed up the oceans and caused torrential tropical rains, which washed erosion products and nutrients from the continents into the oceans.” (Sutherland *New History* 74)

“After the release of nutrients . . ., there was a proliferation of cyanobacteria—pond scum—and because of that, a leap in oxygen. The oceans turned green.” (Sutherland *New History* 74)

“This burst of photosynthesis introduced even more oxygen into the Earth’s atmosphere and ocean systems.” (Sutherland *New History* 74)

no more sulfidic ocean

“Because these conditions are not favored by sulfate-reducing bacteria, their reign over much of the ocean was over, ending the sulfidic ocean. Because production of hydrogen sulfide was halted, key elements, such as molybdenum and copper, that are crucial for enzymatic pathways were suddenly available.” (Sutherland *New History* 74)

Evolution now produced “larger and more complex life forms.” (Sutherland *New History* 74)

“Up to this point, Earth had been a slime ball, teeming with pond scum. Now it was filled not with algae or small protozoans but with a vast array of diverse . . . creatures.” (Sutherland *New History* 74)

Why be big?

“The majority of the biosphere’s mass was still microscopic compared to creatures that lived on the surface of the planet.” (Sutherland *New History* 76)

“Why did animals evolve to larger forms? . . . There must be an advantage to growing larger.” (Sutherland *New History* 76)

“Larger size permits a creature to physically interact with its environment.” (Sutherland *New History* 76)

“. . . amoebas can move around a bit, but in general, they are at the mercy of water currents.” (Sutherland *New History* 76)

“Larger creatures are much more in control of their own destiny . . .” (Sutherland *New History* 76)

“A larger creature can also differentiate in specialized functions and perform more complex activities. These specialized functions increase the creature’s ability to exploit varied opportunities and enhance its chances of passing on its genes to the next generation.” (Sutherland *New History* 76)

“Finally, multicellular creatures can replace their damaged components. They are not reliant on just one unit.” (Sutherland *New History* 76)

635-541m (Precambrian): Ediacaran Period

history of discoveries

pre-1950: most thought Precambrian fossils were impossible: “all the rocks below the Cambrian were called Azoic, meaning “without life” . . .” (Sutherland *New History* 78)

1946: in the Ediacara Hills (S Australia), geologist Reg Sprigg saw “structures on the underside of sandstone beds. Because he was in Precambrian rocks, he was somewhat surprised to find a rich fauna full of strange disk-like creatures, some of which resembled jellyfish and others that were segmented, like worms.” (Sutherland *New History* 78)

“It would take discoveries in the United Kingdom to convince the scientific community that Precambrian fossils existed. In 1957, Roger Mason discovered such a fossil in Charnwood Forest [*Charnia masoni Charnia*]. [The rocks] were clearly Precambrian.” (Sutherland *New History* 78)

635-551m: Doushantuo Formation

The Doushantuo Formation in southwest China has “tiny fossils, less than 0.03 inches in diameter.” (Sutherland *New History* 77)

“The sediments in the Doushantuo formation were deposited in a series of lagoons that developed as sea levels rose following glaciation.” (Sutherland *New History* 77)

“The fossils have been preserved by a process called phosphatization—an atom-by-atom replacement of the original material by phosphate. The preservation is extraordinary; it goes down to the very cellular level.” (Sutherland *New History* 77)

The fossils include “algae, acritarchs, seaweeds, sponges, and primitive corals.” (Sutherland *New History* 77)

acritarch: “a range of unclassified cell-like fossils” (“Ediacaran Biota”)

acritarch: “non-acid soluble . . . microfossils [under 1 mm, .04 in.] consisting of a central cavity, and whose biological affinities cannot be determined with certainty. . . . many are probably related to unicellular marine algae.” (“Acritarch”)

“Some scientists suspect some of these structures belong to the bilateria.” (Sutherland *New History* 77)

If bilateria, the fossils are “some of the [77] earliest evidence we have that diversification within animals had occurred long before the Phanerozoic eon [541-present].” (Sutherland *New History* 77-78)

600m: first metazoan fossils (the Doushantuo embryos) (Erwin)

580-541m: Ediacaran fauna (Sutherland *New History* 78)

Ediacaran fauna have “been found in 30 localities on five different continents and comprise . . . at least 100 species.” (Sutherland *New History* 78)

“These are not just isolated creatures [but an] assemblage of life.” (Sutherland *New History* 79)

“Most Ediacarans lived in fairly well-lit shallow waters, but some earlier forms may not have been photosynthetic and probably inhabited slightly deeper, dimmer waters.” (Sutherland *New History* 79)

Most Ediacarans “passively moved about on the surface [of the ocean floor] or attached themselves to it.” (Sutherland *New History* 91)

The Ediacarans just lay “passively on the ocean floor . . .” (Sutherland *New History* 109)

570m: bilaterians (Sutherland *New History* 81)

bilateria: all animals that are not “cnidaria (corals, jellyfish, sponges).” (Sutherland *New History* 77)

Bilaterians are “animals with bilateral symmetry as an embryo, i.e. having a left and a right side that are mirror images of each other. This also means they have a head and a tail (anterior-posterior axis) as well as a belly and a back (ventral-dorsal axis). Nearly all are bilaterally symmetrical as adults as well; the most notable exception is the echinoderms [e.g., starfish, sand dollars], which achieve secondary pentaradial symmetry as adults . . .” (“Bilateria”)

“The common ancestor of the Bilateria had to be a motile epibenthic animal, and the explosive metazoan diversification embracing the Late Ediacaran-Early Cambrian interval . . . was probably a real event, which was predated by a long (ca. a billion years) period of the assembly of the metazoan genome within the unicellular and colonial common ancestors of the Opisthokonta, and possibly even the entire Unikonta.” (Zhuravlev)

epibenthic: “organisms that live on or just above the bottom sediments . . .” (“Epibenthic”)

metazoa: animal

Opisthokonta: choanoflagellates, animals, and fungi (“Amorphea”)

Unikonta: Opisthokonta and Amoebozoa (“Unikonta”)

The “first major division of the metazoans [was] the split of the bilateria from the rest of the animals.” (Sutherland *New History* 81)

date

“. . . the slow rates of molecular evolution of the vertebrates [suggest a] divergence about 900 million years ago—before the Ediacaran assemblages.” (Sutherland *New History* 81)

A mean bilaterian rate suggests a divergence about 570m, during the Ediacaran (635m-541m). (Sutherland *New History* 81)

555m: “The first evidence of bilateria in the fossil record comes from trace fossils in Ediacaran sediments, and the first bona fide bilaterian fossil is *Kimberella*, dating to 555 million years ago.” (“Bilateria”)

pre-555m: “Earlier fossils are controversial; the fossil *Vernanimalcula* may be the earliest known bilaterian, but may also represent an infilled bubble. Fossil embryos are known from around the time of *Vernanimalcula* (580 million years ago), but none of these have bilaterian affinities. Burrows believed to have been created by bilaterian life forms have been found in the Tacuarí Formation of Uruguay, and are believed to be at least 585 million years old.” (“Bilateria”)

Ediacaran fauna “are largely gone” by 541m. (Sutherland *New History* 79)

Ediacaran shapes

some Ediacaran biota: (“Ediacaran Biota”)

|  |  |  |
| --- | --- | --- |
| *Charnia* | *Dickinsonia* | *Kimberella* |
| A cast of Charnia | DickinsoniaCostata.jpg |  |
| *Marella* | *Spriggina* | artist’s reconstruction |
| Marella.png |  | https://upload.wikimedia.org/wikipedia/commons/thumb/1/15/Life_in_the_Ediacaran_sea.jpg/280px-Life_in_the_Ediacaran_sea.jpg |

The Ediacarans “look odd. With their “quilted” surface, they look a bit like an overinflated air mattress. There is no evidence of shells or internal skeletons. It would appear that they only lived on the surface of the ocean and did not channel through the sediments. That’s in great contrast to the ocean floor today, which is quite actively burrowed by worms, clams, and other creatures.” (Sutherland *New History* 79)

defining Edicarian creatures

bacteria

Some scientists say “the Ediacarans [were] giant bacteria . . .” (Sutherland *New History* 79)

fungi

Some say “they are primitive fungi . . .” (Sutherland *New History* 79)

an unknown phylum

Some say they are a “completely unknown group of animals.” (Sutherland *New History* 79)

Adolf Seilacher (paleontologist, 1925-2014) noted that Ediacarans “are generally preserved in coarse, sandy sediments, which is extremely unusual for creatures that are basically soft-bodied with no skeletons. For soft-bodied creatures, fine-grained sediment is the best medium for preservation because it’s better for taking up an impression. . . ” (Sutherland *New History* 79)

“Seilacher suggested that this meant that the Ediacarans had a super-tough body plan a bit like leather, not seen in soft-bodied creatures today. This idea led Seilacher and others to propose another [79] kingdom of creatures; in addition to the plant and animal kingdoms, they suggested the Vendozoa to cover these Ediacaran creatures.” (Sutherland *New History* 79-80)

“Vendian Period” is a synonym for the Ediacaran Period.

“Vendian fauna” or “Vendian Biota” have principally been used “by Russian geologists and palaeontologists . . .” (MacGabhann)

1994: the Vendozoa were “renamed Vendobionta by Buss and Seilacher . . .” (MacGabhann)

refutation

“However, there is another explanation for the preservation of the Ediacarans. They probably lived in environments rich in biofilms.” (Sutherland *New History* 80)

biofilm: unicellular organisms that stick to each other and/or a surface. Examples: algal mats; dental plaque. (“Biofilm”)

“. . . some organisms will form single-species films under certain conditions.” (“Biofilm”)

But generally, biofilms “contain many different types of microorganism, e.g. bacteria [especially cyanobacteria], archaea, protozoa, fungi and algae; each group performs specialized metabolic functions.” (“Biofilm”)

“We think that when the Ediacarans died, they fell over, and these bio films, or mats, would cover them, protecting them and helping in the fossilization process.” (Sutherland *New History* 80)

“Support that the Ediacarans are primitive forms of today’s animals comes from a number of specimens, including Kimberella [see photo above]; this slug-like creature seems to possess a radula, a specific structure for feeding seen in mollusks.” (Sutherland *New History* 80)

“The radula is . . . sometimes compared to a tongue. It is a minutely toothed, chitinous ribbon, which is typically used for scraping or cutting food before the food enters the oesophagus.” (“Radula”)

roots of the Cambrian Explosion

“The roots of the Cambrian explosion stretch back into the Ediacaran.” (Sutherland *New History* 83)

biomineralization

There was some “biomineralization—production of hard parts, such as shells, bones, and teeth—back in the Ediacaran, although the majority of creatures were soft-bodied.” (Sutherland *New History* 83)

552m: “evidence of biomineralization: small shelly fauna. Ten million years before the first trilobites emerged, we see in some fossils the ability to secrete a small skeleton or series of armored plates.” (Sutherland *New History* 84)

The *Cloudina* are “a group of enigmatic fossils found with Ediacarans that show us that creatures were clearly starting to biomineralize.” (Sutherland *New History* 83)

“During the Ediacaran period, we find scaffolding elements in sponges, called sponge spicules, that provide cell structure.” (Sutherland *New History* 83)

“Spicules are structural elements found in most sponges. . . . The meshing of many spicules serves as the sponge’s skeleton and thus it provides structural support and defense against predators.” (“Sponge Spicule”)

“*Cloudina* also show some early evidence of possible predatory activity in the Ediacaran period.” (Sutherland *New History* 83)

end of the Ediacaran Period

“We find there is a sudden flush of the stable isotope carbon-12. Because photosynthesis uses carbon-12, ocean sediments are relatively enriched in the other stable isotope, carbon-13. Therefore, a negative carbon-13 anomaly suggests the sudden cessation of photosynthesis. Photosynthetic organisms are no longer taking the carbon-12 out of the oceans . . .” (Sutherland *New History* 81)

“. . . perhaps there was a mass extinction event . . . As new creatures evolved in the Phanerozoic [541m-present], the Ediacarans, being very fragile and subject to predation, eventually dwindled.” (Sutherland *New History* 81)

“Another possibility is that the Ediacarans . . . were still there, but they were no longer being preserved.” (Sutherland *New History* 81)

“Recent evidence, in fact, suggests that some Ediacarans survived into the Cambrian.” (Sutherland *New History* 81)

suggested reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Fedonkin, Gehling, Grey, Narbonne, and Vickers-Rich, *The Rise of Animals*.

## Cambrian Explosion

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introduction

541-485.4m: Cambrian Period

“According to biostratigraphy, the base of the Cambrian and the Phanerozoic is found in Newfoundland. It’s here that we drive the “golden spike” to define the transition from the Precambrian to the [83] Cambrian period.” (Sutherland *New History* 83-84)

541m: “an increase in the size and morphologic complexity of bilaterians” (Erwin)

541m-present: Phanerozoic Eon (φανερός, *phanerós*, “visible” + ζωή, *zōḗ*, “life”; coined in 1930. (“Phanerozoic”)

550m-180m: the supercontinent Gondwanaland

But “Baltica, Laurentia, and Siberia were separated from it.” (“Gondwanaland”)

In the Carboniferous (358.9-298.9m), “it merged with Euramerica to form a larger supercontinent called Pangaea. Gondwana (and Pangaea) gradually broke up during the Mesozoic Era [251.9-66].” (“Gondwanaland”)

“The remnants of Gondwana make up around two-thirds of today’s continental area, including South America, Africa, Antarctica, Australia, the Indian Subcontinent, Zealandia, and Arabia.” (“Gondwanaland”)

reefs

“The first true reefs built up in the Cambrian. They were not created by corals, however, but by creatures called archaeocyathids, closely related to sponges.” (Sutherland *New History* 96)

“. . . the consensus is growing that the archaeocyath was indeed a kind of sponge . . .” (“Archaeocyatha”)

Archaeocyathids “steadily declined toward the [96] end of the Cambrian, possibly from competition from other types of sponges.” (Sutherland *New History* 96-97)

485.4-443.8m: Ordovician Period

In the mid-Ordovician, “there was a proliferation of corals—extinct forms, such as rugose and tabulate corals.” (Sutherland *New History* 97)

“Rugose corals formed in a number of ways. Solitary forms were composed of a number of layers; compound, or colonial, corals were all bound together in a mass.” (Sutherland *New History* 97)

“Tabulate corals were exclusively colonial. With the sponges and sponge-like creatures, such as the stromatoporoids, tabulate corals formed extensive tropical reefs throughout the lower Paleozoic [541-419.2].” (Sutherland *New History* 97)

419.2-358.9m: Devonian Period

“. . . the reefs had become very large formations, perhaps rivaling the Great Barrier Reef today. There was a massive reef near the equator in Gondwanaland . . .” (Sutherland *New History* 97)

Ancient reefs “contained an incredible diversity . . .” There were invertebrates (corals, brachiopods, clams) and vertebrates (early sharks, fish). “. . . evolution fast-forwards in reef systems.” (Sutherland *New History* 97) (Brachiopods: see images below.)

298.9-251.9m: Permian Period

“Reefs would come and go in the Paleozoic . . .” (Sutherland *New History* 97)

200m: Capitan Reef in the Guadalupe Mountains

It “is from the middle Permian period, . . . when all the continents were grouped [as] Pangaea.” (Sutherland *New History* 97)

“The Capitan Reef is one of the most well-preserved fossil reefs in the world. The limestone that formed the reef framework at the central portion contained a wealth of creatures, such as algae, sponges, and colonial animals called bryozoans.” (Sutherland *New History* 97)

“Because the back part of the reef was relatively calm, it contained depositions of fairly fine sediments: muddy, calcium carbonate-rich sediments. The water was most likely stagnant with a very high salinity.” (Sutherland *New History* 98)

“High concentrations of magnesium developed in these stagnant waters. This meant that much of the original calcium carbonate sediment was changed into another carbonate mineral called dolomite. Some of the calcium was replaced by magnesium in the crystal structure.” (Sutherland *New History* 98)

“Permian reefs were very complex. They were mostly composed of sponges with calcium carbonate skeletons.” (Sutherland *New History* 98)

the Great Barrier Reef in Australia

It “stretches for about 1600 miles and covers 133,000 square miles in area.” (Sutherland *New History* 96)

“In it are 400 types of coral and roughly 1500 species of fish. The reef has at least 4000 types of mollusks and a host of vertebrates, arthropods, and echinoderms . . .” (Sutherland *New History* 96)

541m: interaction with the environment

In the Cambrian, “life began to interact significantly with its environment, not just sit passively, as most of the Ediacarans had done.” (Sutherland *New History* 84)

“For example, the fossil *Treptichnus pedum* represents a worm-like creature burrowing through the sediment.” (Sutherland *New History* 84)

biomineralization

Biomineralization “was not significant until the Cambrian period.” (Sutherland *New History* 83)

The Cambrian has “large fossils with hard parts, such as shells and skeletons.” (Sutherland *New History* 83)

shells

“A shell offers protection against ultraviolet radiation in shallow marine environments, which are good places to find food.” (Sutherland *New History* 85)

“A shell also gives a creature, such as the snail, the ability to clamp down, seal itself to a rock, and wait for the tide to return.” (Sutherland *New History* 85)

skeletons

A skeleton allows “muscles and joints, which can then move the levers in the arms and legs. This gives . . . greater mobility and greater ability to interact with the environment.” (Sutherland *New History* 84)

A skeleton “allows the organism to develop more complex organs within itself.” (Sutherland *New History* 84)

protection from predation

There is “evidence of teeth in the earliest Cambrian explosion fauna . . .” (Sutherland *New History* 85)

“. . . teeth may have driven an evolutionary race between predator and prey.” (Sutherland *New History* 85)

evolution of the eye

The first eyes were mere eye spots. “. . . concentrations of photoreceptive cells [detected] when a light was on or off and gave some idea of the intensity of that light.” (Sutherland *New History* 85)

“Compressing these photoreceptor cells in a cup-like structure improves the animal’s ability to determine the degrees of brightness of a light source and the direction of light, as well.” (Sutherland *New History* 85)

The cup evolved “into more of a spherical structure, with a small hole at the top, [and] we have, in effect, a pinhole camera. This was a vast leap in vision ability because this structure actually produced an image.” (Sutherland *New History* 85)

“The pinhole camera eye was found in such creatures as the nautilus, a cephalopod. A nautilus looks a bit like a squid but lives in a closed shell. The fact that it had effective eyesight meant that it could evade predators and prey effectively . . .” (Sutherland *New History* 85)

“In even more advanced eyes, the hole has evolved and is covered with transparent cells to protect the eye pit. This structure helped refract light toward a developing retina, an area where [85] photoreceptive cells were concentrated. Further differentiation of those transparent cells led to the development of a lens, which can focus to produce sharp images.” (Sutherland *New History* 85-86)

Andrew Parker of Oxford proposed “that eye evolution drove the Cambrian explosion . . . vision in predators would improve hunting strategy, which would drive prey to develop harder protection in the form of skeletons or shells.” (Sutherland *New History* 86)

“Some scientists believe that one of the driving forces of diversification was the evolution of the eye.” (Sutherland *New History* 85)

Trilobite eyes are “the first true eye system . . .” (Sutherland *New History* 86)

Cambrian phyla

introduction

“. . . the Cambrian explosion had some roots in the Precambrian . . .” (Sutherland *New History* 86)

But the Cambrian (541m-485.4m) saw “the evolution of the majority of phyla that we recognize today, almost—in a geological timescale—overnight.” (Sutherland *New History* 83)

phyla: “basic body types . . .” (Sutherland *New History* 87)

*Microorganisms*

Microbes may live as single cells or as a colony of cells.

Microbes include all archaea and bacteria.

Microbes include protists.

Eukarya Domain: all protists, plants, animals, and fungi (Vidyasagar “Protists”)

In prokaryotes, “DNA floats freely as a tangled mass . . .” (Vidyasagar “Algae”)

In eukaryotes, DNA is in a nucleus, and eukaryotes have organelles to perform cellular functions. (Vidyasagar “Algae”)

protists: eukaryotes that are not animal, plant, or fungus (“Protist”)

“The vast majority of protists are unicellular or form colonies consisting of one or a couple of distinct kinds of cells . . .” (Vidyasagar “Protists”)

Protists share the last eukaryotic common ancestor, but protists are not a clade (since they exclude the other eukaryotes). (“Protist”)

Some are “more closely related to animals, plants, or fungi than they are to other protists . . .” (“Protist”)

Protists include “algae, amoebas, and ciliates” such as parameciums. (Vidyasagar “Protists”)

Algae are photosynthetic. (Missouri)

Blue-green algae (pond scum) are not algae but a phylum of bacteria: cyanobacteria. (Missouri)

“Many, but not all . . . red and brown algae are multicellular.” (Missouri)

proterozoan: a protist that is animal-like

Most are unicellular. (“Protozoa”)

Animal-like: they move; and they are heterotrophs (eat food). (“Protozoa”)

Although not animals, “they are thought to be the ancestors of animals.” (“Protozoa”)

plankton

Plankton are “organisms found in water (or air) that are unable to propel themselves against a current (or wind).” (“Plankton”)

Aeroplankton “live part of their lives drifting in the atmosphere” (e.g., spores, pollen, wind-scattered seeds). (“Plankton”)

“Technically the term does not include organisms on the surface of the water . . .” (“Plankton”)

Most plankton are microscopic, but they include jellyfish. (“Plankton”)

“Plankton are defined by their ecological niche and level of motility rather than by any phylogenetic or taxonomic classification.” (“Plankton”)

1.8b-present: acritarchs (“Acritarch”)

400m: “Acritarchs . . . they date from about 400 million years ago.” (Sutherland *New History* 100)

“Acritarchs, the name coined by Evitt in 1963 which means “of uncertain origin”, are an artificial group. The group includes any small (most are between 20-150 microns across), organic-walled microfossil which cannot be assigned to a natural group.” (“Acritarchs and Chitinozoa”)

“Some of the earliest microplankton were organic-walled creatures called acritarchs.” (Sutherland *New History* 100)

Acritarchs are probably the cysts (sacs) of marine phytoplankton. (Lei)

Acritarchs were “probably part of a life cycle of the flagellated algae—a resting stage that produced a structure called a cyst. These cysts often demonstrated a hole in the side, showing where the creature escaped from its cyst and returned to active living.” (Sutherland *New History* 100)

“Acritarchs were about 15 to 80 microns [.0006-.003 in.] . . .” [100] A human hair is 20-180 microns. (Sutherland *New History* 100-01)

algae

Algae are eukaryotic marine photosynthesizers. (The “other major group” of photosynthesizers is land plants.) (Vidyasagar “Algae”)

Chloroplasts, “the site of photosynthesis in land plants, are adapted forms of cyanobacteria. These early cyanobacteria were engulfed by primitive plants cells sometime in the late Proterozoic, or in the early Cambrian . . .” (Vidyasagar “Algae”)

example: phytoplankton (Vidyasagar “Algae”)

Many are unicellular, but “they can be macroscopic and multicellular; live in colonies; or take on a leafy appearance as in” seaweeds (like kelp). (Vidyasagar “Algae”)

dinoflagellates (unicellular algae)

90% are marine plankton; some live in other organisms. Half are photosynthetic. (UC Museum)

The dinoflagellates were “Possibly related to the acritarchs.” (Sutherland *New History* 101)

“They were important components of more modern microplankton.” (Sutherland *New History* 101)

488 to 359 (Ordovician to Devonian): chitinozoans

“Microfossils called chitinozoans were a little larger than acritarchs, but were still very small,” 60-200 microns (.002-.008 in.). (Sutherland *New History* 101)

“The chitinozoans possessed an organic wall, made of a chitin-like substance, similar to fingernails. They were in the form of vases, sealed at one end by a lid or a simple plug. They were sometimes associated in long chains, with the lid of one attached to the base of another.” (Sutherland *New History* 101)

Some think “chitinozoans were the eggs of some other animal.” (Sutherland *New History* 101)

*Invertebrates*

invertebrates

Invertebrates are “more than 95 percent of all animal species.” (Sutherland *New History* 98)

Hemichordata: e.g., acorn worms, pterobranchs, graptolites (Sutherland *New History* 87)

brachiopods

*brachion* arm + *podos* foot

(In brachiopods, the two sides of each shell (valve) are symmetrical, but the two shells are different sizes. In bivalves, the two sides of each shell may differ, but the two shells are symmetrical. Bivalves include clams, snails, octopuses, and squid.)

|  |  |  |
| --- | --- | --- |
| brachiopod | brachiopod | bivalve |
|  |  |  |

251m: “a type of shellfish [that] dominated the ocean floor in the same way that clams do today . . .” (Sutherland *New History* 99)

Brachiopods “look like clams, but they are not related . . .” (Sutherland *New History* 87)

Brachiopods “had a feeding organ called a lophophore, containing a ring of cilia that they used [for] feeding. Most of them lived on the ocean floor, sometimes attached to the floor by a fleshy stalk called a pedicle.” (Sutherland *New History* 99)

“Brachiopods are not so common today, but they were important in the Cambrian—more important than the clams in the Paleozoic.” (Sutherland *New History* 87)

mollusks

Includes snails, clams, and cephalopods. (Sutherland *New History* 87)

416m-66m: ammonites (McKeever)

Ammonites were “extinct relatives of . . . the modern Nautilus.” (British Geological Survey, bgs.ac.uk)

In Mesozoic oceans (251.9m-66m), “A particularly common [cephalopod] was the ammonite, basically a kind of a squid in a coiled shell. Some ammonites were very small, and some could be up to 6 feet in diameter.” (Sutherland *New History* 100) Artist’s reconstruction (“Ammonoidea”):



gastropods (snails, slugs)

bivalves

“Bivalves are members of the mollusk phylum.” (Sutherland *New History* 100)

251.9m: after the Permian, the bivalves (the true clams) mostly replaced the brachiopods. (Sutherland *New History* 100)

One “ancient bivalve was the Jurassic oyster, or the *Gryphaea*.” (Sutherland *New History* 100)

The bivalves “spread all across the ocean floor, but unlike the majority of the brachiopods, they also exploited the ocean floor by boring deep into the sediments.” (Sutherland *New History* 100)

cephalopods

Cephalopods include squid, octopus, cuttlefish, and nautilus (like a squid in a shell). (“Cephalopod”)

“There were some cephalopods in the Burgess Shale faunas, but they became common in the Ordovician [485.4m-443.8m].” (Sutherland *New History* 100)

arthropods

ἄρθρον *arthron* joint + πούς *pous* foot (gen. ποδός) (“Arthropod”)

pre-Cambrian arthropods: only: (Sutherland *New History* 87)

phylum Cnidaria (corals and jellyfish)

phylum Porifera (sponges)

Cambrian arthropods

Arthropods are “probably the most diverse metazoan group . . .” (Sutherland *New History* 87)

echinoderms (e.g., starfish, sand dollars, sea urchins, crinoids)

The “long arms that developed on [echinoderms] probably helped them gather food and particles in the water.” (Sutherland *New History* 99)



sea urchin:



crinoids

Crinoids are called sea lilies but were not plants. (Sutherland *New History* 99)

“The crinoid, like the trilobite, was composed of calcium carbonate; its stalk was formed of disks called columnals. Its arms gathered food and particles in the water and passed them into its mouth.” (Sutherland *New History* 99)

“By the middle Paleozoic, crinoids formed vast meadows; their disarticulated plates and other remains formed very thick sediments. They were also important because the small gaps between the columnals in the sediment acted as perfect hiding places for oil.” (Sutherland *New History* 99)

The phylum Euarthropoda (true arthropods) “is typically subdivided into five subphyla, of which one [trilobites] is extinct . . .” (“Arthropod”)

trilobites

 (Sutherland *New History* 20)

“The trilobite was a segmented arthropod that represented the first large creature in the third phase of the Cambrian explosion.” (Sutherland *New History* 87)

“In the final phase, in the lower Cambrian, we see large creatures with shells. The most characteristic fossil was known to Darwin and his contemporaries: the trilobite.” (Sutherland *New History* 84)

“Trilobites are segmented arthropods. They have a strong skeleton of calcium carbonate, which is the mineral calcite. We think that most trilobites, especially in the Cambrian, were probably deposit feeders on the sediment surface. They trundled across the surface of the sediment, shoveling it into their mouths and processing it for bacteria, algae, or other organic material.” (Sutherland *New History* 84)

“Trilobites were some of the most common of the arthropods. They had three parts: the head, or cephalon; the body, or thorax; and the tail, or pygidium. The trilobite’s skeleton was made of calcium carbonate, but because it was an arthropod, it had to molt in order to grow. This most likely explains the high abundance of trilobite fossils.” (Sutherland *New History* 98)

“They lived close to the ocean floor, scavenging and processing sediment for organic debris.” (Sutherland *New History* 98)

“Trilobites evolved rapidly, and they are . . . useful for biostratigraphy in the Cambrian. In fact, they are used to divide the Cambrian into five stages.” (Sutherland *New History* 98)

“Trilobites were a very successful group of creatures, in part because of the evolution of eyes.” (Sutherland *New History* 98)

trilobite eyes

“Trilobite eyes, not unlike insect eyes, are compound eyes with many lenses. These lenses are unique to the trilobites; they are composed of calcium carbonate. Trilobite eyes probably could not cope too well with bright sunlight. A trilobite from the Devonian even developed a kind of sun visor over the eye, perhaps to get about in brighter conditions.” (Sutherland *New History* 86)

“The trilobite eyes had a double-lens structure—two lenses of different refractive indices acting in combination. Some trilobites had many small lenses; we call this the holochroal system. Others had fewer and larger lenses; this is known as the schizochroal system.” (Sutherland *New History* 86)

“Many early trilobites also had a conical structure to their eyes, giving them a good field of vision. Perhaps this conical eye system allowed them to exist partly buried in sediment, with just the eyes showing above the surface. Some trilobites had eyes on the top of long stalks, allowing them to peek above the surface of material on the bottom of the ocean and keep a lookout for predators.” (Sutherland *New History* 86)

251.9m: trilobites went extinct in the Permian-Triassic Extinction. (Sutherland *New History* 98-99)

It was in decline, then disappeared in the Permian-Triassic extinction.

myriapods

E.g., centipedes, millipedes.

Each body segment has one or two pairs of legs (or is, rarely, legless).

“They are sometimes grouped with the hexapods.” (“Arthropod”)

hexapods (insects)

hexapods: “insects [and three small orders of insect-like animals] with six thoracic legs.” (“Arthropod”)

chelicerates (including arachnids)

E.g., horseshoe crabs, scorpions, spiders, mites.

Chelicerae are “appendages just above/in front of the mouth.” In horseshoe crabs and scorpions, they are claws for feeding; in spiders, they are fangs for venom. (“Arthropod”)

crustaceans

E.g., “lobsters, crabs, barnacles, crayfish, shrimp,” etc. (“Arthropod”)

“. . . primarily aquatic (a notable exception being woodlice) and . . . having biramous [dividing into two branches] appendages.” (“Arthropod”)

Bryozoa

The Bryozoa (“moss animals”) don’t appear until the Ordovician (485.4-443.8m). (Sutherland *New History* 87)

“Mineralized skeletons of bryozoans first appear in rocks from the Early Ordovician period, making it the last major phylum to appear in the fossil record.” (“Bryozoa”)

“Bryozoa are a phylum of aquatic invertebrate animals, nearly all forming sedentary colonies. Typically about 0.5 millimetres long, they . . . sieve food particles out of the water using a retractable lophophore, a “crown” of tentacles lined with cilia.” (“Bryozoa”)

small shelly fauna

Most Cambrian fauna “lived on or close to the surface of the sediment.” (Sutherland *New History* 87)

“Most free-moving forms, not unlike the trilobites, were likely deposit feeders, processing the ocean floor sediment for organic material or, [87] perhaps, algae or bacteria and passing that material out of the gut for other creatures to process.” (Sutherland *New History* 87-88)

“There were also suspension feeders, those creatures with their sights toward the water column, trying to extract microplankton or other organic material held in suspension in the water. The brachiopods were suspension feeders, as were the eocrinoids.” (Sutherland *New History* 88)

“The eocrinoids are relatives of the sea urchin; they have an adaptation that suggests that something important had happened on the ocean floor. They have a kind of stalk to raise them up above the sediment-water interface.” (Sutherland *New History* 88)

“It’s possible that by this time in the Cambrian, because of the reduction of microbial mats, the ocean floor had become increasingly soupy.” (Sutherland *New History* 88)

“These stalks would allow these eocrinoids and creatures like the eocrinoids to raise themselves above this soupiness and start to exploit the water column for ocean plankton.” (Sutherland *New History* 88)

“The stromatolites were now pretty well restricted to either extreme environments or to the intertidal zone, which was not colonized in the Cambrian to the extent that it is today.” (Sutherland *New History* 88)

“The intertidal zone is a fairly difficult environment to live in even today. It has vast salinity changes, temperature changes, and of course, a change in water level twice a day. But in the normal shallow marine environments, most of the stromatolites that had been so common in the Precambrian period had been grazed away by the new mobile Cambrian fauna.” (Sutherland *New History* 88)

invertebrate chordates

505m: earliest chordate fossil

The phylum Chordata includes three subphyla: 2 invertebrate (Urochordata, Cephalochordata), 1 vertebrate (Vertebrata).

notochord

Chordates “possess a notochord, [a] flexible axis and support structure.” (Sutherland *New History* 123)

“If a species has a notochord at any stage of its life cycle, it is, by definition, a chordate.” (“Notocord”)

A notochord is “a flexible rod formed of a material similar to cartilage.” (“Notocord”)

A notochord lies front to back and is usually closer to the back than the front. Muscles attach to it. (“Notocord”)

myotomes

“Another typical chordate feature is the group of muscle blocks called myotomes.” (Sutherland *New History* 123)

fin

“. . . another common chordate feature [is] a swimming fin.” (Sutherland *New History* 124)

*Pikaia*

“*Pikaia* was one of the earliest chordates; its fossils are found in the Burgess Shale in British Columbia. Initially, it was thought to be just a worm, but its myotome muscle blocks and the long tube running down its length mark it clearly as a chordate.” (Sutherland *New History* 123)

“*Pikaia* closely resembled the amphioxus, a lancelet.” (Sutherland *New History* 124)

The amphioxus “possessed a notochord and myotomes and . . . a swimming fin. Although there was some cartilage around the mouth and gill slits of this creature, it did not possess a true skeleton.” (Sutherland *New History* 124)

“About 2 inches in length, the amphioxus lived buried in the sand. Its eyes peeked above the sand surface, but it could also swim if need be in open water.” (Sutherland *New History* 124)

520-515m: Maotianshan Shale (Sutherland *New History* 124)

This Lagerstätte is “older than the Burgess Shale: the Chengjiang County exposure in Yunnan Province of China.” (Sutherland *New History* 124)

The fossils are “10 million years older than those in the Burgess Shale.” (Sutherland *New History* 124)

The Maotianshan Shale “demonstrates the speed of diversification after the Cambrian explosion.” (Sutherland *New History* 124)

Like the Burgess Shale, the rock “is dominated by arthropods—they represent about 50 percent of the fauna. Also in the formation are found five species of trilobite, some of which show traces of legs and antennae.” (Sutherland *New History* 124)

“It is estimated that one-eighth of the fauna in the Chengjiang formation were *Problematica*—creatures that really do not fit into any existing group.” (Sutherland *New History* 124)

The Maotianshan Shale “contained six types of creatures similar to *Hallucigenia* . . .” (Sutherland *New History* 124)

“Another strange creature was a member of the Vetulicolia, an extinct phylum of creatures divided into two parts.” (Sutherland *New History* 124)

“Two types of Early Cambrian animal apparently having fins, vertebrate musculature, and gills are known from the early Cambrian Maotianshan shales of China: *Haikouichthys* and *Myllokunmingia*. They have been tentatively assigned to Agnatha [jawless fish] by Janvier. A third possible agnathid from the same region is *Haikouella*.” (“Agnatha”)

“Myllokunmingiidae is a group of very early, jawless prehistoric fish (Agnathans) which lived during the Cambrian period. . . . The group contains three genera, *Haikouichthys*, *Myllokunmingia*, and *Zhongjianichthys*. Their fossils have been found only in the Maotianshan Shales lagerstätte.” (“Myllokunmingiidae”)

*Myllokunmingia*

“Vertebrates originated about 525 million years ago during the Cambrian explosion, which saw rise in organism diversity. The earliest known vertebrate is believed to be *Myllokunmingia*.” (“Vertebrate”)

*Myllokunmingia* was an agnathan. (“Agnatha”)

It was “about the size of a paper clip . . .” (Sutherland *New History* 124)

“It had a distinctive head and myotomes.” (Sutherland *New History* 124)

“The creature had fins and a notochord and, unlike *Pikaia*, evidence of gill slits.” (Sutherland *New History* 124)

“It is also possible that we see the preservation of the pharynx and the digestive tract in this tiny fossil.” (Sutherland *New History* 124)

“By looking at the structure of this creature and the arrangement of [124] the muscles, it is speculated that it swam by flicking its body from side to side.” (Sutherland *New History* 124-25)

*Haikouichthys*

This creature was “about the same size as *Myllokunmingia* but slimmer.” (Sutherland *New History* 125)

“. . . it had other defined chordate features similar to those found in *Myllokunmingia*.” (Sutherland *New History* 125)

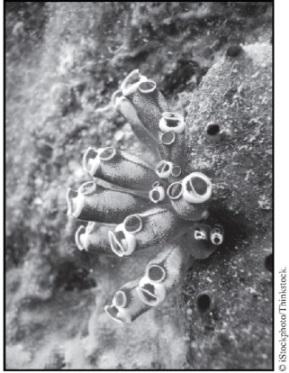
“It had a definite head, and some have suggested evidence of a skull . . .” (Sutherland *New History* 125)

“About 500 specimens of this creature have been found; thus, it is speculated that these creatures swam in large shoals.” (Sutherland *New History* 125)

Some Maotianshan-Shale “forms may represent the first true vertebrates—perhaps even the first fish.” (Sutherland *New History* 125)

tunicates

“The most primitive chordates living today are tunicates, or sea squirts.” (Sutherland *New History* 123)



*Vertebrates*

introduction

The phylum Chordata includes three subphyla: 2 invertebrate (Urochordata, Cephalochordata), 1 vertebrate (Vertebrata).

“In vertebrates the notochord develops into the vertebral column, becoming vertebrae and the intervertebral discs the center of which retains a structure similar to the original notochord.” (“Notocord”)

“In most vertebrates, [the notochord] has been mineralized to form the vertebral column of the spine.” (Sutherland *New History* 123)

“The vertebrates are an incredibly successful group. They [are] in the highest peaks and in the deepest ocean valleys.” (Sutherland *New History* 123)

530m (Early Cambrian): “chordates developed the skull and the vertebral column, leading to the first craniates and vertebrates.” (“Evolution of Fish”)

518m: first vertebrate: (*Myllokunmingia*: 1 in.; it had head, gills, and fins

497-485.4m (Late Cambrian): “the first rare occurrences of demonstrable vertebrates date to the upper Cambrian, but a real boom began only some 100 million years later.” (Mikuláš and Chlupáč)

497-485.4m: conodonts and ostracoderms (“small mostly armoured fish”) (“Evolution of Fish”)

calcium phosphate versus calcium carbonate

“As our ancestors grew larger, eventually, they exceeded the notochord’s ability to act as a stiffened rod against which muscles could flex and allow a swimming motion.” (Sutherland *New History* 127)

“The sharks were probably one of the first creatures to solve this problem. They developed cartilage in their skeletons that allowed them to grow larger. Other vertebrates mineralized that cartilage to produce skeletons of bone—calcium phosphate, the mineral apatite.” (Sutherland *New History* 127)

“Why they would use calcium phosphate and not calcium carbonate is an important question. Calcium carbonate is much more abundant in the oceans. It has been used successfully by many invertebrates and trilobites, corals, brachiopods, and clams.” (Sutherland *New History* 127)

“Richard Cowen of UC Davis, in his book *History of Life*, . . . speculates that the phosphate skeletons in the vertebrates developed as a result of oxygen debt.” (Sutherland *New History* 127)

“As vertebrates, we are active creatures. We are prone to sudden bursts of motion, a process that breaks down sugars in our muscles faster than we can acquire oxygen. This is the process of anaerobic glycolysis. The cost of the oxygen debt is lactic acid—or fatigue in the muscles.” (Sutherland *New History* 127)

“As the oxygen debt is paid back, the levels of acid in the blood start to increase. That temporarily leaches calcium out of the calcium phosphate in our bones. That is not a problem; we can cope with that. But if our skeletons were composed of calcium carbonate, or calcite, the leaching would be catastrophic. In effect, the acid levels in the blood would dissolve our skeletons away.” (Sutherland *New History* 127)

“Perhaps calcium phosphate in our bones points to evidence that our ancestors were highly active creatures.” (Sutherland *New History* 127)

497-251.9m: conodonts (Sutherland *New History* 125)

(497-485.4m: Late Cambrian. 251.9m: Late Permian extinction.)

Conodonts (*kōnos* cone + *odont* tooth) are extinct agnathan (jawless) chordates. (“Conodont”)

Conodonts looked like eels. (“Conodont”)

They “were not our direct ancestors—they were probably not vertebrates . . .” (Sutherland *New History* 126)

Their tooth-like microfossils are index fossils (used to identify geological periods). (“Conodont”)

“Conodont teeth are the earliest found in the fossil record.” (“Conodont”)

“The fossils are toothlike [*sic*] structures composed of calcium phosphate, or the mineral apatite—the same composition as our bones and teeth.” (Sutherland *New History* 125)

The fossils “were less than 0.3 inches in size and are only known from marine sediments.” (Sutherland *New History* 125)

small conodonts (16 in.)

“Until the early 1980s, conodont teeth had not been found in association with fossils of the host organism . . . because the conodont animal was soft-bodied, thus everything but the teeth was unsuited for preservation . . .” (“Conodont”)

But in the 1980s, the Granton Shrimp Bed in Scotland (a Lagerstätte) revealed a conodont. It was “2 inches long, with myotomes, a notochord, a swimming fin, and two large eyes at one end.” (Sutherland *New History* 126)

large conodonts (16 in.)

the Soom Shale

The Soom Shale is a Lagerstätte on Table Mountain in Cape Town, South Africa. (Sutherland *New History* 126)

It was deposited during the Hirnantian Stage (445.2-443.8m), “the glacial phase at the end of the Ordovician . . .” (Sutherland *New History* 126)

“The Soom Shale was deposited in front of a retreating ice sheet. While the ice sheet was busy eroding rock, its runoff provided sediments. Because glacial periods were also fairly dry periods, winds blew silt around. Both these actions fertilized the oceans in the area of deposition of the Soom Shale, causing a bloom of microplankton.” (Sutherland *New History* 126)

“In the Ordovician, that microplankton consisted of acritarchs. These acritarchs sank to the ocean floor and used up all the oxygen, creating an anoxic environment in which creatures could be preserved and giving rise to another Lagerstätte.” (Sutherland *New History* 126)

conodont fossils

Some Soom microfossils (under 1 mm, .04 in.) were thought to be the oldest land plants (if so, the *Cooksonia* would not be). They were called *Promissum pulchrum*, “beautiful promise.” (Sutherland *New History* 126)

But “Richard Aldridge, a well-known conodont paleontologist, realized that these were not plants; they were giant conodont elements.” (Sutherland *New History* 126)

“Aldridge found the animal associated with conodont elements in the Soom Shale. [It] was possibly as long as 16 inches.” (Sutherland *New History* 127)

“Conodonts are extremely useful microfossils; scientists apply them extensively in biostratigraphy. The oil industry uses them to date rocks and to provide a stratigraphic tie in searching for relevant oil strata.” (Sutherland *New History* 125)

518m: first fish: Metaspriggina walcotti (Long)

They were agnathans (jawless fish, superclass Agnatha). (“Evolution of Fish”)

Most jawless fish are extinct; hagfish and lampreys are still extant.

The earliest fish were agnathans in the Silurian (443.8-419.2m) and Devonian (419.2-358.9m) Periods.

“The first abundant fish [were] agnathans . . .” (Sutherland *New History* 128)

“Agnathans were fish without articulating jaws . . .” (Sutherland *New History* 128)

Instead of an “internal skeleton, these creatures stiffened their bodies with plates on external surfaces. They looked a bit like armor-plated fish.” (Sutherland *New History* 128)

“The oldest fossil agnathans appeared in the Cambrian, and two groups still survive today: the lampreys and the hagfish . . .” Hagfish have lost their vertebrae. (“Agnatha”)

Modern agnathans have an “absence of paired fins; the presence of a notochord both in larvae and adults; and seven or more paired gill pouches.” (“Agnatha”)

heterostracans

“An early successful group were the heterostracans; they diversified rapidly in the Silurian, occupying numerous niches. They were found in normal marine conditions, brackish conditions, and freshwater conditions. Not strong swimmers, they probably strained microplankton from the seawater or dug in the sediment. Some had long, swordlike projections to stir up the sediment.” (Sutherland *New History* 128)

osteostracans (*osteo*- bony + *straca* shell)

The osteostracans “appeared in the Late Silurian and diversified through the Late Devonian.” (Sutherland *New History* 128)

“The shield of bone covering the head formed a single piece, and so presumably did not grow during adult life.” (“Osteostracans”)

These were the most advanced agnathans; some reached sizes of 3.2 feet long. Some of them possessed what seem to be pressure sensors around the armored head shield; perhaps they used them to detect movement in the surrounding water. Most of them probably lived in freshwater environments.” (Sutherland *New History* 128)

All that the agnathans “had for a mouth was a simple slit. . . . it would be fairly difficult to be a predator with that kind of mouth.” (Sutherland *New History* 128)

suggested reading

Armstrong and Brasier, *Microfossils*.

BBC News, “Oldest Fossil Fish Caught.”

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Erwin and Valentine, *The Cambrian Explosion and the Construction of Animal Biodiversity*.

Fortey, *Trilobite*.

Gould, ed., *The Book of Life*.

Gould, *Wonderful Life*.

Morris, *The Crucible of Creation*.

## The Burgess Shale

introduction

The Burgess Shale is a Lagerstätte. (Sutherland *New History* 90)

Lagerstätten: areas where “exceptional environmental situations . . . have allowed for unusual and unexpected preservation.” (Sutherland *New History* 90)

The world of the Burgess Shale “was still booming from the Cambrian explosion.” (Sutherland *New History* 90)

Charles Doolittle Walcott (1850-1927)

“Throughout his life, he was secretary of the Smithsonian Institution; was president of the National Academy of Sciences; served on the National Research Council; helped found the Carnegie Institute; was involved with the National Park Service; and sat on the National Advisory Committee for Aeronautics, which is now part of NASA.” (Sutherland *New History* 90)

“In 1909, paleontologist Charles Doolittle Walcott was collecting fossils in British Columbia, Canada. He was in a rather unassuming little quarry (now called Walcott Quarry). He would make a spectacular find: the Burgess Shale.” (Sutherland *New History* 90)

“Looking for samples of fossils from Precambrian and Cambrian strata, Walcott came across a fossil unlike any he had seen before. This fossil was of the species *Marella*, or lace crab. What was remarkable about this fossil is not only that it was most rare but also that the soft parts were preserved.” (Sutherland *New History* 90)

“By 1917, Walcott had amassed more than 65,000 specimens for the Smithsonian Institution. Of the 170 or more species that have been identified in the Burgess Shale so far, 100 were first described by Walcott: an amazing accomplishment.” (Sutherland *New History* 91)

“The work started by Walcott [was] continued in the 1970s by Harry Wittington, a trilobite expert at Cambridge . . .” (Sutherland *New History* 91)

portrait of the Cambrian

60-70% of Cambrian fauna were soft-bodied. (Sutherland *New History* 91)

505m: The Burgess Shale was deposited in “the middle Cambrian, around 505 million years ago . . .” (Sutherland *New History* 91)

“At that time, the land was not mountainous, as the Rockies are today; it was a barren desert, with no grass, no moss, no trees, no birds, no insects—in effect, a sterile environment.” (Sutherland *New History* 91)

“The edge of North America straddled the equator. Spread out over the shallow ocean were a few islands, also barren of life. Beyond the surf line, the water changed from a pale blue to a dark purple—designating the edge of an underwater feature called the Cathedral Escarpment, a massive submarine cliff that runs along the edge of North America, reaching to Walcott Quarry.” (Sutherland *New History* 91)

“The waters contained the animals of the Burgess Shale. Some of them were attached to the sediment, some actually lived in it, and others moved above it. The fauna were obviously much more diverse than the creatures from the Ediacaran, who passively moved about on the surface or attached themselves to it. These new creatures interacted with and exploited their environment.” (Sutherland *New History* 91)

creatures of the Burgess Shale

priapulid worms

“The *Otoia* was a priapulid worm, about 3 inches long. It had a long proboscis, armed with teeth, which most likely extended to grab prey. This worm lived in the sediment, probably in U-shaped [91] tubes, catching prey that trundled along the surface of the sediment. When the prey was consumed and passed down into *Ottoia*’s gut, additional teeth pointing downward prevented the prey’s escape.” (Sutherland *New History* 91-92)

hyoliths

“The priapulid worm ate such creatures as hyoliths, which have been found in the worm’s gut. Hyoliths have no modern descendants. They may be related to the mollusks; scientists think they lived in a little conical shell and probably moved slowly across the surface of the sediment, grazing on bacteria and algae.” (Sutherland *New History* 92)

annelid worms

“The annelid polychaete worms found at Burgess Shale were the ancestors of today’s earthworms. *Canadia*, about 1 inch long, probably crawled around on the surface but may have swum in the water column, as well.” (Sutherland *New History* 92)

sponges

“Sponges, such as the *Vauxia*, were common in the Burgess Shale. Like all sponges, this creature sucked in seawater through the sides of its body and expelled it from a large opening at the top, trapping organic material with its cilia. Some sponges lived close to the ocean floor, but others were starting to exploit higher niches in the water column. Some of them rose to about 8 to 11 inches above the surface of the water.” (Sutherland *New History* 92)

velvet worms

“*Aysheaia*, about 0.5 to 2.5 inches long, is a member of the Onychophora, or velvet worms. We often find *Aysheaia* associated with sponge spicules; thus, it is speculated that *Aysheaia* ate sponges.” (Sutherland *New History* 92)

“In addition to these creatures, in the Burgess Shale are found various brachiopods, algae, comb jellies, sea pens, sea anemones, mollusks, echinoderms, and 0 chordates.” (Sutherland *New History* 92)

arthropods in the Burgess Shale

“. . . probably the most impressive and most dominant representatives of the Burgess Shale are the arthropods.” (Sutherland *New History* 92)

The Burgess Shale “includes a much greater diversity of arthropods than we usually find in other deposits.” (Sutherland *New History* 93)

trilobites

“The most common arthropods in the Cambrian were the trilobites.” (Sutherland *New History* 92)

“*Marella*, Walcott’s lace crab, was about 0.5 inches long and was present in large numbers in the Burgess Shale. These creatures probably swam or crawled on the ocean floor, seeking out organic debris and small creatures to eat. They had an odd kind of bristlelike appendage at the front that was used to sweep material into their mouths.” (Sutherland *New History* 93)

“*Canadaspis* was possibly the ancestor of many of the crustaceans that would follow.” (Sutherland *New History* 93)

“*Sanctacaris*, about 2 to 3.5 inches long, most likely was a predator. An active swimmer, it was the ancestor of horseshoe crabs and spiders.” (Sutherland *New History* 93)

“*Sidneyia*, about 2 to 5 inches in length, was one of the larger arthropods from the Burgess Shale. *Sidneyia* was most likely a carnivore, eating hyoliths and probably the occasional trilobite . . .” (Sutherland *New History* 93)

*Problematica*

“Another feature of the Burgess Shale was a group of creatures called the *Problematica*. We cannot place them adequately or with great confidence into any defined group. Nevertheless, they are remarkable creatures.” (Sutherland *New History* 93)

“*Opabinia* had five eyes on its head; on the front of its head was an odd trunk, at the end of which was a grasping claw. It probably swung by the undulations of lobe-like segments at the sides of its body.” (Sutherland *New History* 93)

“*Anomalocaris* reached lengths of 20 inches. It was definitely the *Tyrannosaurus rex* of the Burgess Shale. Its shrimp-like legs are grasping appendages at the front of the head.” (Sutherland *New History* 93)

environment of the Burgess Shale

The Burgess Shale was “subject to occasional earthquakes that caused movements of sediment under [93] the water. These are called turbidity currents; these currents would push creatures rapidly into areas that were deeper and contained less oxygen.” (Sutherland *New History* 93-94)

“In the process, a great deal of sediment was transported, which would pass up into the water column and then settle back down slowly, covering all the dead creatures that had been transferred into the low-oxygen environment. Two effective ways to advance the process of fossilization are to remove the oxygen and quickly cover dead organisms.” (Sutherland *New History* 94)

“The survival of the Burgess Shale, however, was really something of a miracle. It was formerly deposited in a fairly deep oceanic environment. The sediments that once made up the Burgess Shale were involved in mountain-building processes—the collisions of continental masses that raised the ocean bed to great heights. When that happened, rocks were very often cooked and metamorphosed, which can easily destroy fossils.” (Sutherland *New History* 94)

“But the Burgess Shale was lucky. It was transported from areas of intense deformation along low-angled faults called thrusts to its present location, where it escaped intense deformational processes.” (Sutherland *New History* 94)

evolutionary experimentation

“What scientists believe happened during the Cambrian is a situation in which the genetic rules that define a creature were not so firmly established. Perhaps that could account for all the *Problematica*—those strange creatures that do not seem to fit into any group.” (Sutherland *New History* 94)

“We see this kind of flexibility in form in the echinoderms, as well as the arthropods. Echinoderm genetic rules dictate that they have fivefold symmetry, or symmetries in multiples of five—like a starfish or sea urchin. But consider the *Helicoplacus* and Homalozoa. Both these creatures are echinoderms, but both are very different from the echinoderms we see today.” (Sutherland *New History* 94)

“Today, the genetic rules that govern the organization of the animal—the number of digits, the location of the eyes, feet at the ends of legs—are controlled by Hox genes. Hox genes are pieces of our genes that act like failsafe mechanisms. They ensure that the proper body plan will be followed.” (Sutherland *New History* 95)

“It’s possible that back in the Cambrian, there were fewer failsafe genes; the result was that more bizarre forms could come to term and be expressed. It’s likely that most wouldn’t have survived, but it’s possible that there might have been some viable forms that might explain some of these odd species that we see in the Cambrian. This explains why the Cambrian is sometimes described as a period of great evolutionary experimentation.” (Sutherland *New History* 95)

suggested reading

Gould, *Wonderful Life*.

Morris, *The Crucible of Creation*.

Yale University, “Fossil Find Fills in Picture of Ancient Marine Life.”

## 485.4m-443.8m: Ordovician Period

“Evolution of Fish.” *Wikipedia*. 12 Mar. 2021. 18 Mar. 2021. Web.

“Extinction Event.” *Wikipedia*. 15 Nov. 2020. 17 Nov. 2020. Web.

“Graptolithina.” *Wikipedia*. 20 Feb. 2021. 3 Mar. 2021. Web.

introduction

“The Middle Ordovician period saw a proliferation of life forms that some say was almost as spectacular as the Cambrian explosion that preceded it. Creatures moved into different levels of the ecosystem. They burrowed deeper; they grew higher above the ocean floor.” (Sutherland *New History* 109)

continental fragmentation

750m (Tonian, 1000-720m): supercontinent Rodinia begins to split up (Sutherland *New History* 110)

“The Ordovician was a period of continental fragmentation.” (Sutherland *New History* 110)

remnants of Rodinia: (Sutherland *New History* 110)

Gondwanaland (a “large block”): “parts of Africa, South America, Antarctica, India, and Australia”

Laurentia: “much of North America”

Baltica: “much of northwest Europe”

Avalonia: “southern Britain, Atlantic Canada, and the East Coast of the United States”

“The Ordovician was a tropical paradise. Life was diversifying and spreading all through this period in a wonderful greenhouse world.” (Sutherland *New History* 110)

the biosphere interacts

burrowing

“In the Ordovician, creatures began to chew through the sediment and churn it up a bit . . .” (Sutherland *New History* 109)

“The Ordovician saw increases in burrowing bivalves, as well as certain trilobites.” (Sutherland *New History* 110)

“Colonies of creatures began to grow upward. For example, crinoids started to develop extensive communities, their stalks getting higher and higher, lifting them above the Ordovician ocean floor.

reefs

“This was also the time of the first true tropical coral reefs; tabulate and ghost corals were common in the Ordovician.” (Sutherland *New History* 110)

graptolites

500m-340m: graptolites: *graptos* written + *lithos* rock (hieroglyph-looking fossils) (“Graptolithina”)

They were colony hemichordates, strung together in a tube (of collagen or chitin). (“Graptolithina”)

500m-400m: earlier graptolites were mostly attached to the ocean floor, with ciliated arms. (“Graptolithina”) (Sutherland *New History* 109)

Later, some floated on the surface, with few ciliated arms. The latter were “the most important animal members of the plankton . . .” They went extinct c. 300m. (“Graptolithina”)

419.2m-358.9m: “Graptolites were present in vast numbers in the Ordovician, during which they underwent rapid diversification.” (Sutherland *New History* 109)

useful fossils

“They evolved many short-ranging forms, which defined short packets of geological time.” (Sutherland *New History* 109)

“Graptolites died and sank in vast numbers, sometimes almost completely covering the deep ocean floors. . . . Because they were planktonic, they had a wide distribution, as well.” (Sutherland *New History* 109)

They are “the kings of correlation and biostratigraphy in the Ordovician.” (Sutherland *New History* 109)

“There’s a very fine-scale, high-resolution subdivision of the Ordovician based on the evolution and extinction of graptolites all the way through the period.” (Sutherland *New History* 109)

458.4-443.8m (Late Ordovician): jawed vertebrates (“Evolution of Fish”)

“They are first represented in the fossil record from the Silurian by two groups of fish”: (“Evolution of Fish”)

placoderms (armored fish), “which evolved from the ostracoderms”

spiny sharks (Acanthodii)

488m: Ordovician extinction (Sutherland *New History* 109)

445m-443m: End Ordovician extinction (Ordovician-Silurian, O-S) (“Extinction Event”)

445.2m-443.8m (Hirnantian stage): glaciation (last Ordovician stage)

“. . . this glacial period was short—no more than 1 million years in duration.” (Sutherland *New History* 111)

It “was not a snowball event.” (Sutherland *New History* 110)

“The continental mass called Gondwanaland started to move closer to the South Pole. Temperatures dropped, and ice started to form. The amount of ice on Gondwanaland started to grow with each winter, and the continent ultimately became completely icebound.” (Sutherland *New History* 110)

proofs of glaciation

Sahara rocks show glacial features. (Sutherland *New History* 110)

“The paleomagnetic evidence in the Sahara rocks shows that these rocks were definitely at the South Pole when the glacial features [110] were formed.” (Sutherland *New History* 110-11)

Oxygen has isotopes. (Sutherland *New History* 111)

oxygen-16: the lightest and most common

oxygen-17: almost absent from Earth

oxygen-18: the heaviest; a smaller proportion than 16O

“Water, with the light oxygen-16 isotope, is preferentially evaporated. During the glacial period in the Ordovician, however, that light water was trapped in glaciers; it could not get back to the oceans. Therefore, there was a relative enrichment of the heavy isotope, oxygen-18, in the oceans. This signature was recorded in the chemistry of creatures that secrete shells.” (Sutherland *New History* 111)

sea levels drop

Glaciers locked water on the continents, so sea levels dropped. (Sutherland *New History* 112)

“Land was eroded because rivers ran across it, in effect, trying to come into equilibrium with the new lower sea levels.” (Sutherland *New History* 112)

Many Ordovician sediments show an erosion surface. (Sutherland *New History* 112)

drop in greenhouse gases

Gondwanaland “moved over the South Pole some millions of years before the glaciation occurred. . . . Something [else] changed to move Earth into a cooling phase . . .” (Sutherland *New History* 112)

“One explanation was the effect of greenhouse gases.” (Sutherland *New History* 112)

“During the Ordovician, two continents, Baltica and Avalonia, moved toward Laurentia. There was a shrinking ocean, the Iapetus Ocean, between them. That ocean was not really shrinking, of course; it was being removed by subduction at the continental margins. As the Iapetus Ocean diminished, mountains started to rise. As those mountains rose, they were subject to fairly intense erosion.” (Sutherland *New History* 112)

“The erosion of rocks uses up carbon dioxide in the atmosphere through silicate weathering.” (Sutherland *New History* 112)

“Usually, the drawdown of carbon dioxide from the atmosphere by this erosion is matched by the addition of new carbon dioxide by volcanic activity. However, it has been suggested that during the Hirnantian, volcanic activity had dropped; thus, there would be a net drop in atmospheric carbon dioxide.” (Sutherland *New History* 112)

“. . . a drop in carbon dioxide levels . . . drove the Earth into a sudden glacial episode . . .” (Sutherland *New History* 113)

gamma rays?

“Brian Thomas, an astrophysicist at Washburn University, believes that the cause of the Ordovician extinction had a more distant and even more alarming origin: a gamma ray burst.” (Sutherland *New History* 113)

“Gamma ray bursts were first detected in 1967 by satellites searching for evidence of nuclear emissions during the Cold War. These gamma emissions . . . were coming from space. Sometimes they were microseconds in length; sometimes, several minutes long.” (Sutherland *New History* 113)

“The longer bursts are thought to be caused by the death of a hypergiant star. Hypergiants are many millions of times more luminous than our Sun and have a life span no longer than around 3 million years.” (Sutherland *New History* 114)

The Sun will burn 10 billion years; we’re at 5 billion. (Sutherland *New History* 114)

“. . . hypergiants die in a spectacular event—a hypernova, which releases 100 times the amount of energy released in a standard supernova. Because of the sheer mass [the hypergiant] not only forms a black hole, but it also emits jets of plasma at nearly the speed of light. It is speculated that these jets produced the longer gamma ray bursts.” (Sutherland *New History* 114)

“It is thought that these gamma ray bursts then depleted ozone on Earth—the O3 molecule that absorbs harmful ultraviolet radiation.” (Sutherland *New History* 114)

“Paleontologist Bruce Lieberman from the University of Kansas thinks that [depleted ozone] could potentially account for the extinction in trilobites. Although adult trilobites lived on the ocean floor and had a large protective body of water above them, it’s likely that trilobites had a planktonic juvenile stage that was affected by the radiation.” (Sutherland *New History* 114)

“Many other creatures besides trilobites would have been severely affected by increased ultraviolet levels. The gamma rays may have wiped out an entire generation of progeny and caused the extinction of many groups.” (Sutherland *New History* 114)

the extinction

The extinction was only “about 1.9 million years long . . .” (Sutherland *New History* 111)

85% of species went extinct. (Sutherland *New History* 111)

“The first pulse . . . was severe in reef faunas and . . . warm water.” (Sutherland *New History* 111)

50 “out of the 70 genera of tabulate and rugose corals suddenly went extinct.” (Sutherland *New History* 111)

“Cooler-water forms [could] migrate toward the equator . . .” (Sutherland *New History* 111)

Tropical forms began to go extinct. (Sutherland *New History* 111)

“The second pulse of extinction at the end of the glacial period was related to sea levels and temperatures rising again. It wasn’t as severe as the first pulse; it is speculated that it occurred in cold-adapted forms that struggled to switch back to their warm adaptations.” (Sutherland *New History* 112)

suggested reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

California Institute of Technology, “Mass Extinction Linked to Ancient Climate Change, New Details Reveal.”

Hallam, *Catastrpphes and Lesser Calamities*.

NASA/Goddard Space Flight Center, “Explosions in Space May Have Initiated Ancient Extinction on Earth.”

## 443.8m-419.2m: Silurian Period

introduction

During the Silurian, the biosphere produced a “world full of tropical reef systems.” (Sutherland *New History* 114)

And creatures would move onto land. (Sutherland *New History* 115)

“By the Devonian, plants and arthropods had populated the land.” (Sutherland *New History* 122)

obstacles to land living

“. . . in the ocean, the buoyancy of water supports the body; on the land, creatures need a system of internal or external structures.” (Sutherland *New History* 116)

“Aquatic animals and plants can extract water and nutrients from their surroundings; land animals and plants cannot.” (Sutherland *New History* 116)

“Temperature extremes are greater in the air than in water.” (Sutherland *New History* 116)

Land Plants

selective advantages driving the evolution of land plants

wind

“John Raven, from the University of Dundee, has proposed a scenario that explains how an aquatic alga adapted into a land-living plant. Imagine algae in shallow freshwater, fairly close to the land. If the algae were able to raise their sporangia above the water surface, the breezes blowing across the surface of the water would help distribute the spores and their genetic material.” (Sutherland *New History* 116)

light

“Another selective advantage . . . was light.” (Sutherland *New History* 116)

“In water, plants are restricted in their distribution; they tend to be concentrated in an area called the photic zone—the depth to which light can penetrate the water.” (Sutherland *New History* 116)

“Land plants have access to sunlight for longer periods of time than aquatic plants.” (Sutherland *New History* 116)

CO2

“On land, it’s easier to extract carbon dioxide than it is in water.” (Sutherland *New History* 116)

development of plant cuticles, roots, and stomata

cuticle

“Land plants are more susceptible to dehydration than aquatic plants. The solution to plants’ losing water was the plant cuticle, a waxy covering of the surfaces of the plant exposed to air. The cuticle not only reduced the effects of desiccation, but it also acted as a repellent to stop films of water from collecting on the plant. These films cut down the uptake of carbon dioxide from the atmosphere.” (Sutherland *New History* 117)

“The cuticle provided rigidity, so the plant could get higher. The cuticle also may have acted as a barrier to excess ultraviolet radiation from the sun.” (Sutherland *New History* 117)

roots

“The problem associated with the cuticle is that now the plant cannot absorb nutrients from the surroundings. It’s thought that this led to the developments of roots—specialized areas of plants that gathered nutrients from the soil and passed them up to the parts that could no longer extract those nutrients.” (Sutherland *New History* 117)

stomata

“The plant cuticle also prevented the plant from absorbing carbon dioxide. This probably led to the development of stomata, or pores. Cells on either side of the pore opened and closed to allow gas exchange and to protect the plant from excess water loss during warm periods.” (Sutherland *New History* 117)

“The stomata linked to an intercellular gas transport system between the cells, solving yet another problem—the transport of food to the roots. The plant roots, although adapted now to transport nutrients and water upward, were cut off from the light, so they couldn’t photosynthesize and produce food themselves.” (Sutherland *New History* 117)

vascular plants

xylem

“. . . one of the first developments in plants that made it to land was a simple conducting strand, or piping system, to carry water to the upper parts of the plant from the lower parts.” (Sutherland *New History* 116)

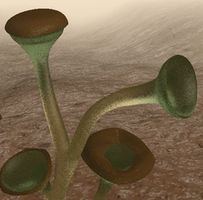
The xylem is “a structure of cells placed end on end to form a tube to improve the flow of water through the plant. In a process called evapotranspiration, water moved up from the root as a result of negative pressure generated by the evaporation of water on the surface of the plant. Plants with such a xylem system are called vascular plants.” (Sutherland *New History* 117)

“Because the evapotranspiration process created high pressures in the xylem, plants needed to strengthen and encase this system. Development of the material called lignin allowed plants to strengthen and grow even larger than the original cuticles had allowed.” (Sutherland *New History* 118)

phloem

“Plants developed another type of transport system within themselves called phloem, which moved products of photosynthesis, such as sugars. That was important for areas needing more energy—for example, the growing tips of plants and the roots.” (Sutherland *New History* 118)

433.4-427.4m (Middle Silurian, Wenlock Epoch): first land plant: *Cooksonia*



As “the oldest known plant to have a stem with vascular tissue [*Cooksonia* is] a transitional form between the primitive non-vascular bryophytes and the vascular plants.” (“Cooksonia”)

It was “just over an inch tall [and] had sporangia, or fruiting bodies, that produced spores.” (Sutherland *New History* 118)

With no leaves, “it probably photosynthesized along the length of its stem.” (Sutherland *New History* 118)

It was “linked underground by a common root structure” (a rhizome). (Sutherland *New History* 118)

It was “restricted to low-lying freshwater marshlands.” (Sutherland *New History* 118)

by 419.2m (Early Devonian, 419.2-393.3m): *Cooksonia* “had evolved xylem, cuticles, and stomata. Also by this time period, plants probably started to look fairly modern.” (Sutherland *New History* 118)

427.4-419.2m (Late Silurian): cartilaginous fish (Chondrichthyes) and bony fish (Osteichthyes)

Bony fish will evolve into ray-finned fish (Actinopterygii) and lobe-finned fish (Sarcopterygii). (“Evolution of Fish”)

From lobe-finned fish will evolve tetrapods (amphibians, reptiles, birds, mammals).

Fish are not a monophyletic group but a paraphyletic one, since they exclude tetrapods (amphibians, reptiles, birds, and mammals). (“Evolution of Fish”)

Land Animals

preadapted arthropods

“Plants were the first to move onto the land. The newly established plant ecosystem, however, created a rich and diverse environment for animals to exploit.” (Sutherland *New History* 119)

Animals had obstacles similar to plants’ . . .” (Sutherland *New History* 119)

“They had to address problems of body support and breathing and problems with dehydration.” (Sutherland *New History* 119)

“Because seeing and hearing are vastly different in land and water, their senses would need to be modified, too.” (Sutherland *New History* 119)

The first land animals were arthropods. (Sutherland *New History* 120)

“Arthropods were almost preadapted to move onto land. They had already developed an exoskeleton and a variety of limbs . . .” (Sutherland *New History* 120)

eurypterids

The first land arthropods “were probably the eurypterids, or sea scorpions. A diverse group, the eurypterids were the “top dogs” of the Silurian. Related to today’s scorpion, many were predators; some species, such as *Pterygotus*, were up to seven feet long.” (Sutherland *New History* 120)

“It has been suggested that these creatures had book lungs—structures that modern arachnids use to breathe. Even the most terrestrially adapted eurypterid was still a fully aquatic animal, however. Perhaps they moved briefly onto land to molt and then went back into the water. They were not true land animals.” (Sutherland *New History* 120)

427.4-419.2m (Late Silurian): first land animal

“The first true land animal, discovered in Scotland . . ., was a fossil millipede from the Late Silurian period, about 428 million years ago.” (Sutherland *New History* 120)

It had “spiracles—holes on its side that connected to a vast network of tubes that allowed air to circulate in the creature. This first air breather was called *Pneumodesmus newmani* . . .” (Sutherland *New History* 120)

419.2m-358.9m: DEVONIAN PERIOD

“30th Parallel South.” *Wikipedia*. 22 Feb. 2021. 4 Mar. 2021. Web.

“Rhynie Chert.” *Wikipedia*. 26 Jan. 2021. 18 Mar. 2021. Web.

Sutherland, Stuart. *A New History of Life*: *Course Guidebook*. Chantilly VA: The Great Courses, 2013.

412-400m: the Rhynie Chert (Sutherland *New History* 119)

The Rhynie Chert, in Scotland, shows Devonian plants developing. (Sutherland *New History* 119)

“The Rhynie chert is an Early Devonian [419.2-393.3m] sedimentary deposit . . . [It] contains exceptionally preserved plant, fungus, lichen and animal material preserved in place by an overlying volcanic deposit. The bulk of the fossil bed consists of primitive plants (which had water-conducting cells and sporangia, but no true leaves), along with arthropods, lichens, algae and fungi.” (“Rhynie Chert”)

The Rhynie Chert was subject to “permineralization—detailed preservation at the cellular level through atom-by-atom replacement of organic material. The formation was produced by the action of silica-rich hot springs killing off the Rhynie flora, but as they did, silica was precipitated on the plants and replaced some of their carbon.” (Sutherland *New History* 119)

Land Plants

introduction

The Rhynie Chert “contains seven types of vascular plants, as well as [other] plant material, such as fungi, algae, and lichen.” (Sutherland *New History* 119)

“The Devonian saw plants with a significant elevation from the surface of the land.” (Sutherland *New History* 119)

“*Asteroxylon*, a lycopod, had small scales all along its length—the beginnings of leaves.” (Sutherland *New History* 119)

“*Rhynia*, at eight inches, was taller than *Cooksonia* and branched much more.” (Sutherland *New History* 119)

trees

“Plants continued to evolve through the Devonian and develop new structures. One of the surprising new structures was secondary [120] xylem—or wood. Plants had become trees. The terrestrial ecosystem was set to dramatically expand upward.” (Sutherland *New History* 120-21)

382.7m-358.9m: *Archaeopteris*

“*Archaeopteris* was a Late Devonian tree about 39 feet tall. These types of plants had a profound effect on the land ecosystem. They shaded the ground below them, which created new challenges and habitats for the flora . . . below.” (Sutherland *New History* 121)

“*Archaeopteris* had another innovation, as well: seeds.” (Sutherland *New History* 121)

“Until plants produced seeds, vegetation was tied to the water’s edge. Conditions had to be damp for sperm to swim to the egg.” (Sutherland *New History* 121)

“But in seed plants, fertilization was internal. Seeds allowed plants to colonize the barren continents.” (Sutherland *New History* 121)

“the greening of the Devonian” (Sutherland *New History* 121)

Plants developed “up into the atmosphere . . .” (Sutherland *New History* 121)

Plants also expanded “down into the geosphere.” (Sutherland *New History* 121)

And “Plants spread across barren landscapes that were formerly only fringed with areas of green.” (Sutherland *New History* 121)

Land Animals

The Rhynie Chert preserves two types of creature. (Sutherland *New History* 120)

“detritus feeders, such as millipedes and springtails, who fed on decaying plant matter”

“predators, such as centipedes and an extinct group of arachnids”

“A new ecosystem was developing.” (Sutherland *New History* 120)

400m: mesozoans appeared

(On the date: Pawlowski says that “the Mesozoa branch [off] . . . closely to nematodes and myxozoans [microscoptic parasitic metazoans].” And Poinar says nematodes [roundworms] appeared around 400m.)

The name does not come from the Mesozoic Era (251.9m-66m).

Mesozoans (*mesos* middle + *zoon* animal): “are often regarded as intermediate in organization between the protozoans and the metazoans . . .” (“Metazoan.” *Merriam-Webster*)

Now, though, many think “they may be degenerate descendants of more highly organized [metazoan] forms.” (“Metazoan.” *Merriam-Webster*)

They are “Marine invertebrates with tissue organization and life cycles more complex than sponges, but without organ systems.” (“Mesozoan.” *Oxford Reference*)

“The phylum Mesozoa comprises small, simply organized wormlike parasites of marine invertebrates and is composed of two classes, the Rhombozoa and the Orthonectida. . . . data indicate probably separate origins of rhombozoids and orthonectids, suggesting that their placement in the same phylum needs to be revised.” (Pawlowski)

400m: jawed fish

“The diversity of jawed vertebrates may indicate the evolutionary advantage of a jawed mouth . . .” (“Evolution of Fish”)

Fish do not represent a monophyletic group, but a paraphyletic one, as they exclude the tetrapods.” (“Evolution of Fish”)

metazoans

419.2-393.3m (Early Devonian): transitional tetrapods (amphibians, reptiles, birds, and mammals) (“Evolution of Fish”)

382.7-358.9m (Late Devonian): first tetrapods

375-360m: End Devonian extinction (Devonian-Carboniferous)

plant weathering

“. . . enhanced root systems, as well as fungi, occurred in the Devonian.” (Sutherland *New History* 121)

“. . . these were powerful agents of rock erosion [which caused] a drawdown of atmospheric carbon dioxide.” (Sutherland *New History* 121)

Apparently the “drawdown of atmospheric carbon dioxide caused global cooling toward the end of the Devonian. Tillites and other glacial features . . . reached about 30 degrees south of the equator . . .” (Sutherland *New History* 121)

30° latitude south crosses South Africa, ⅓ of the way to the South Pole. (“30th Parallel South”)

This was the second mass extinction.

40% “of the marine genera were wiped out completely.” (Sutherland *New History* 121)

“Cooling and lowering of sea levels eliminated the habitats of tropical reef fauna, including the corals.” (Sutherland *New History* 121)

The Late Devonian extinction ends the ostracoderms and placoderms. (“Evolution of Fish”)

suggested reading

Cowen, *History of Life*.

Gee, ed., *Shaking the Tree*.

## Evolution of Jaws

“pH.” *Wikipedia*. 1 Mar. 2021. 4 Mar. 2021. Web.

introduction

This lecture examines: (Sutherland *New History* 130)

vertebrates’ development of an internal skeleton

vertebrates’ development of jaws

“the adaptive radiation of fish, that is, the evolution of new species from a common ancestor in a relatively short period of time”

“the Orcadian Basin in Scotland, dating from the Devonian” (a Lagerstätte of fossil fish)

the search for evolutionary advantage

“In the Cambrian, the evolution of vertebrates was impeded by killer arthropods.” (Sutherland *New History* 130)

“In the Ordovician, the jawless agnathan fish, including the conodonts, remained less competitive compared to other creatures.” (Sutherland *New History* 130)

“The vertebrates were not especially competitive in the Silurian, either.” (Sutherland *New History* 130)

“What the vertebrates needed to change their position in the ecosystem was more size and strength. This called for the evolution of a more substantial internal skeleton and a jaw system.” (Sutherland *New History* 130)

external skeletons

“Some of the oldest fish . . . covered themselves in outer bony plates—a kind of external rather than internal mineralization.” (Sutherland *New History* 131)

480-470m (Ordovician): “*Arandaspis*, one of the contenders for earliest vertebrate, was covered with armored nobs called scutes. Its head was protected by a very large plate.” (Sutherland *New History* 131)

internal skeletons

arthropods molt

In arthropods, “such as the trilobites and crabs, . . . The size of their shells limits how much more they can grow; therefore, they have to molt.” (Sutherland *New History* 131)

“Molting is costly in energy . . .” (Sutherland *New History* 131)

Molting “leaves the animal vulnerable for a period before the new shell becomes hard.” (Sutherland *New History* 131)

cartilage

“The vertebrate skeleton is composed of either bone or cartilage. Cartilage is unmineralized and flexible, made up of collagen and fibers that heighten elasticity.” (Sutherland *New History* 130)

Human embryos develop a cartilage skeleton, which then ossifies (mineralizes). (Sutherland *New History* 130)

“The first skeletons were probably cartilage. Unfortunately for paleontologists, cartilage rots away very rapidly compared to bone.” (Sutherland *New History* 130)

bone

“Bone itself is composed of needle-shaped crystals of the mineral [130] hydroxyapatite. It forms in a network of organic collagen fibers.” (Sutherland *New History* 130-31)

Bone “is strong because of the hydroxyapatite, but the collagen makes it flexible.” (Sutherland *New History* 131)

An internal skeleton “enables an animal to get larger. The skeleton can grow with the animal.” (Sutherland *New History* 131)

Bones provide support. (Sutherland *New History* 131)

Bones “protect our internal organs.” (Sutherland *New History* 131)

“They generate and transfer forces and allow muscle movements.” (Sutherland *New History* 131)

“They provide shape to the body . . .” (Sutherland *New History* 131)

They “allow for the transfer of sound by the evolution of tiny bones in the ear.” (Sutherland *New History* 131)

“Bones produce blood in the marrow and store vital minerals.” (Sutherland *New History* 131)

“They can also isolate toxic heavy metals and remove them from the blood. They help buffer the blood against excessive pH.” (Too much base.) (Sutherland *New History* 131)

“At 25°C [77°F], solutions with a pH less than 7 are acidic, and solutions with a pH greater than 7 are basic. Solutions with a pH of 7 at this temperature are neutral (e.g. pure water).” (“pH”)

jaws

Probably “jaws did not evolve for predation; they evolved . . . to aid respiration.” (Sutherland *New History* 131)

“It’s likely that jaws developed as structural supports in the gill systems of jawless fish, such as the agnathans.” (Sutherland *New History* 131)

“Once [131] jaws had evolved, however, they could be utilized in other ways.” (Sutherland *New History* 131-32)

“The front sets of these supports migrated forward to become the parts of the brain case.” (Sutherland *New History* 131)

“After jawed fish evolved, they started to radiate rapidly into three mayor groups.” (Sutherland *New History* 132)

placoderms

“The placoderms were the first jawed fish, most of which were predators.” (Sutherland *New History* 132)

They were heavily armored. (Sutherland *New History* 132)

“In addition to jaws, they also had a new innovation: a neck joint.” (Sutherland *New History* 132)

Also new was an “embryo attached by an umbilical cord to the adult. This was a fish that produced live young, an example of viviparity and internal fertilization—possibly the first example of this in the vertebrates.” (Sutherland *New History* 132)

acanthodians

“The acanthodians were less than 8 inches long and look a little more familiar than the heavily armored placoderms. It is probable that modern fish evolved from this group. They were characterized by spines on their fins and bellies. The head had forward-pointing eyes and a lateral line down the side of the body; it also had a sense-organ to detect movement. The acanthodians are found fossilized in vast numbers; researchers suspect that they swam around in large shoals at mid-levels in the water column.” (Sutherland *New History* 132)

chondrichthyes

“The chondrichthyes include modern sharks and rays. Although the fossil record of this group is poor, a section preserving some very early forms was found in the Cleveland Shale on the south shore of Lake Erie.” (Sutherland *New History* 132)

megalodon

“Sharks are a very successful group. There are many different species, but they are all similar in form, shape, and body plan. Perhaps the most terrifying of all the sharks was called megalodon. It lived relatively recently, 25 to 1.5 million years ago, and may be the contender for one of the largest and most powerful vertebrate species that has ever lived.” (Sutherland *New History* 133)

“Megalodon was about 52 feet long and had teeth about 7.1 inches long. (*Megalodon* means “big tooth.”) The bite force generated by this creature was probably about 10 times that of a great white shark. It is thought that this creature preyed on the whales that existed at the same time.” (Sutherland *New History* 133)

“Megalodon became extinct as the oceans cooled and the most recent ice age began. Whales moved to cooler waters for much of the year, [133] but because the megalodon was most likely a tropical creature, it could not follow its prey and died out.” (Sutherland *New History* 133-34)

“During the Upper Devonian [382.7-358.9m], the bony fish with powerful fins emerged—the most common fish that we find in today’s oceans. It is from this group that vertebrates would make the move onto land.” (Sutherland *New History* 132)

an evolutionary arms race

“Interestingly, we see a pulse of evolution in the sharks matched by a pulse of evolution in the bony fish. We think what we are seeing here is an evolutionary arms race. Innovations in one group were being countered by another and pushing on the diversity of both forms of fish.” (Sutherland *New History* 132)

385m: Orcadian Basin

“The fossil fish Lagerstätte of the Devonian is the Orcadian Basin, named for the Orkney Islands in northeast Scotland.” (Sutherland *New History* 134)

“During the Middle Devonian [393.3-382.7m], about 385 million years ago, a continent called Euramerica developed that comprised parts of North America, Greenland, and Europe.” (Sutherland *New History* 134)

“At that time, Scotland existed in a semi-arid environment south of the equator, close to a mountain belt formed from the collision of those different continental fragments. The remains of that mountain belt formed the Appalachians, the Caledonians in Scotland, and mountains in Scandinavia.” (Sutherland *New History* 134)

“Where continents collide is often represented by fault lines. We can see those fault lines today in Scotland as a line of lakes that includes the famous Loch Ness. This is the setting of the Orcadian lake area. During Devonian times, as the fault moved, sedimentary basins opened up along its length, some of them filling up with sediment from the surrounding Caledonians, which were rising all around them.” (Sutherland *New History* 134)

“The fish fossils found in the Orcadian Basin are composed of blackened shiny apatite or sometimes isolated scales; they are commonly concentrated into beautiful fish beds.” (Sutherland *New History* 134)

The Orcadian-Basin sediments show “repeated cycles in sedimentary type—probably reflecting changes in the level of the lake, which itself might represent fluctuations in climate. [The sediments show a] cycle every 25,000 years or so.” (Sutherland *New History* 134)

climatic cycles and the Orcadian Basin

“The climatic regimes were probably generated by long-term variations in the Earth’s orbit. During times of warm climate, warm surface waters developed. These waters maintained a kind of [134] warm lid on the surface of open bodies of water, which were cold underneath. This boundary is called the thermocline.” (Sutherland *New History* 134-35)

“The thermocline and the lid above it acted as a barrier to circulation. The deeper parts of the lake remained cold and still. The warm surface layers of the lake, of course, were in contact with the atmosphere; thus, plenty of oxygen diffused into them.” (Sutherland *New History* 135)

“These conditions—a good deal of oxygen and warmth—were ideal for algae production, leading to an algal bloom. The surfaces of lakes turned green as the algae died, decayed, and sank to the bottom of the lake. The oxygen conditions that were already present within those colder waters paid a price now, however. As the algae started to decay, it rapidly used up the oxygen, causing virtually anoxic conditions and killing the fish. We call this process lake eutrophication.” (Sutherland *New History* 135)

“Algal blooms were probably responsible for the fish beds that we find in the Orcadian Basin. As the oxygen was used up, low-oxygenated waters would encroach onto the lake margins, causing many of the armored agnathans to die. They were swept into deeper parts of the lake by currents.” (Sutherland *New History* 135)

“As the hot, arid climes continued, the lake became shallower, and the cycle would ultimately end. Sedimentary structures recorded the shallower water conditions. There was evidence of fossil ripples created by surface winds moving the sediment into ripple structures. Polygonal mud cracks appeared, indicating that the water was getting shallow and evaporating away. However, the cycle repeated as wet climates returned and the lake filled again.” (Sutherland *New History* 135)

“Some of the fish of the Orcadian Basin lived very close to the land-water interface. They would diversify into a variety of fantastic forms. [See] the next lecture . . .” (Sutherland *New History* 135)

suggested reading

Gould, ed., *The Book of Life*.

## Evolution of Tetrapods

“Acadian Orogeny.” *Wikipedia*. 16 Jan. 2021. 6 Mar. 2021. Web.

“Acanthostega.” *Wikipedia*. 25 Feb. 2021. 22 Mar. 2021. Web.

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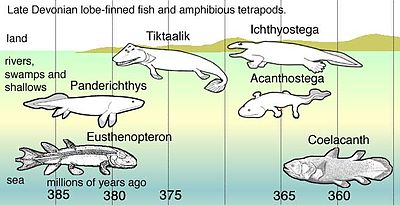
introduction

“In the ancient oceans, vertebrates enjoyed the benefits of being in the water: its buoyancy, relatively stable temperatures, and no problem with dehydration.” (Sutherland *New History* 137)

“It has long been known . . . [that fish became tetrapods] about 370 million years ago during the Devonian period.” (Uppsala University)

“In this lecture, we’ll [consider] living fossils, by introducing the paleontological superstar *Tiktaalik* . . .” (Sutherland *New History* 144)

We’ll also consider “new finds and possibilities in the story of tetrapod evolution.” (Sutherland *New History* 144)



(“Evolution of Tetrapods”)

living fossils

“A living fossil is a species that has been in existence for a long time but has evolved very little.” (Sutherland *New History* 144)

example: *Lingula*

“*Lingula* is an inarticulate brachiopod, which means it cannot open its shell and gape, as articulate brachiopods do.” (Sutherland *New History* 144)

“*Lingula* is definitely a survivor. The family of brachiopods to which *Lingula* belongs has remained relatively unchanged since the dawn of the Cambrian [541m]. It was one of the few creatures to prosper through” the Permian extinction (252m). (Sutherland *New History* 144)

example: Lazarus taxa

“Another type of living fossil is from the Lazarus taxon . . . Creatures rediscovered as living forms that were previously thought of as extinct are called Lazarus taxa.” (Sutherland *New History* 144)

example Lazarus taxon: *Metasequoia*, or dawn redwood. “About 50 million years ago, it was part of extensive forests that spread as far as northern Canada.” (Sutherland *New History* 144)

“It was considered extinct, a fossil, until 1941, when it was discovered in a canyon in the Sichuan-Hubei region of China. An extensive breeding program followed, and now, *Metasequoia* has become widespread again.” (Sutherland *New History* 144)

example Lazarus taxon: coelacanths

Coelacanths appeared in the Devonian (419.2-358.9m) but disappeared after the K-Pg extinction (66m). (Sutherland *New History* 145)

1938: they reappeared in South Africa. (“Coelacanth”)

“. . . only coelacanths in shallow waters went extinct at the end of the Cretaceous; the deepwater forms continued to exist.” (Sutherland *New History* 145)

Coelacanths are plump “lobe-finned fish that can grow to more than 2 meters (6 feet 6 inches) and weigh around 90 kilograms (200 pounds). They are estimated to live for 60 years or more. Modern coelacanths appear larger than those found as fossils.” (“Coelacanth”)

The “fleshier fin . . . could be a precursor to true tetrapod limbs.” (Sutherland *New History* 145)

“James Smith, of Rhodes University, . . . [said] the fish probably used its fleshy fins to walk on the ocean bottom; the coelacanth was preadapted for walking on land.” (Sutherland *New History* 145)

But “it showed no evidence of walking on the ocean floor. This coelacanth swam; it was clearly a fish.” (Sutherland *New History* 145)

The coelacanth is not a transitional form linking lobe-finned fish to tetrapods. (Sutherland *New History* 145)

evolution of limbs

“At first, scientists speculated that limbs evolved to drag fish out of shrinking ponds in a hot Devonian desert environment. Natural selection would favor the fish with strong limb-like fins.” (Sutherland *New History* 142)

“The current view of scientists is that limbs and digits didn’t evolve to help tetrapods stride purposefully across the land; they evolved to help the mostly aquatic tetrapods navigate their way through swampy, plant-tangled environments. It makes more sense to have very flexible limbs—rather than fins—to move around in this environment.” (Sutherland *New History* 142)

“The Devonian ecosystem was not all [arid] . . . by the end of the Devonian, we start to see the first forests. A new ecosystem was emerging—a swampy, plant-tangled environment close to the river’s edge. . . . There were invertebrates and small fish that would attract predators, such as *Acanthostega* and *Ichthyostega*. This was also a good environment for a small tetrapod [to hide from] the fierce predators that patrolled the open waters.” (Sutherland *New History* 142)

fishapod

The first land vertebrate was a transitional form “from the water onto the land. What we’re looking for” is tetrapod fossils. (Sutherland *New History* 139)

“Humans are tetrapods. Tetrapods are animals that have—or, in the case of whales and dolphins [and snakes], had—four limbs. The classic structure of a tetrapod is this: a pelvis attached to a backbone, a spine with a series of interlocking spurs, a curved rib cage to support and protect the internal organs, nostrils for breathing, and limbs that follow a [139] specific pattern—from one bone to two bones and then to five digits at the end.” (Sutherland *New History* 139-40)

“The hypothesis is that the first land vertebrate would look a bit like a fish that has some of the features of a tetrapod. Some paleontologists refer to this as the elusive fishapod.” (Sutherland *New History* 140)

“Fish went through radiation and diversification in the Devonian, producing the bony fish. It is in this category that we will most likely find the fish that became a tetrapod.” (Sutherland *New History* 140)

lobe-finned fish

“Scientists believe this fish is from the lobe-finned fish group. Slow swimming, these fish beat their lobe-like fins from the sides of their bodies. The fins were joined to the fish by one bone.” (Sutherland *New History* 140)

397m: tracks in Poland (Amos)

“In January 2010, in the journal *Nature*, a paper was published that . . . recorded a spectacular find made in the Zachelmie Quarry, in the Holy Cross Mountains in [southeast] Poland: trackways made by some sort of unknown creature.” (Sutherland *New History* 148)

This is “The oldest evidence of four-legged animals walking on land . . .” (Amos) (Or on the ocean floor?—Hahn)

It was 8 feet long. (Sutherland *New History* 148) Amos says 2 meters (6´6´´). (Amos)

The “trackways indicated that the creature probably had four limbs. That creature may have been walking; it may have been a tetrapod. On the trackways was evidence of toes on the ends of feet.” (Sutherland *New History* 148)

|  |  |
| --- | --- |
| Fossil trackway (Per Ahlberg et al) (Amos) | Fossil trackway (Per Ahlberg et al) (Amos) |

“Per Ahlberg, at the University of Uppsala in Sweden, speculated that the creature walked like a salamander with a kind of a swinging gait.” (Sutherland *New History* 148)

“Numerous trackways [in the quarry] represent the movements of many animals as they scurried around what would have been a tropical muddy shoreline in the Middle Devonian Period . . .” (Amos)

“The animals were probably crocodile-like in appearance and lived an amphibian-like existence . . .” (Amos)

The animals “moved their “hips”, “elbows” and “knees”. .. This confirms that only true four-legged animals, or tetrapods, could have left the marks.” (Amos)

But the tracks are “Middle Devonian, about 395 million years ago, predating *Tiktaalik*. . . . even before *Tiktaalik* . . ., tetrapods were in existence.” (Sutherland *New History* 148)

“This find . . . changes our understanding of the environment in which tetrapods evolved.” (Sutherland *New History* 148)

“*Tiktaalik* and its kin evolved in deltaic, swampy, freshwater environments.” (Sutherland *New History* 148)

The Zachehnie Quarry records “a marine environment. Poland, at this time, was in the tropics. The environment would have been an intertidal mudflat baking in the hot Sun. The tides in these environments washed up [148] and concentrated dead fish and organic debris—setting a rich dining table for anything that could get out of the water.” (Sutherland *New History* 148-49)

Per Ahlberg: “In the intertidal setting, you’ve got a smorgasbord laid out twice a day. Every time the tide goes out, it leaves behind this drift-line of dead and moribund animals. All this was just left there for vertebrates—our ancestors—to emerge on to land and pick them off.” (Amos)

385m: *Eusthenopteron*

“Within the lobe-finned fish is a group called the Rhipidistia, including *Eusthenopteron*. This was a Late Devonian fish, from about 385 million years ago.” (Sutherland *New History* 140)

“. . . it possesses a pattern of bones very similar to the later tetrapods. *Eusthenopteron* had a humerus, an ulna, and a radius in the pectoral fins; it had a femur, a tibia, and a fibula in the pelvic fins—mirroring the pattern in our four limbs. A fish similar to this probably gave rise to all the tetrapods.” (Sutherland *New History* 140)

382.7-358.9m (Upper Devonian): *Hynerpeton bassetti*

Red Hill

375-325m: creation of Euramerica (“Acadian Orogeny”)

(Sutherland says Middle Devonian [393.3-382.7m] to Early Carboniferous [358.9-346.7m]. *New History* 146)

Laurentia, Baltica, and Avalonia collided to create Euramerica. (Sutherland *New History* 146)

“This mountain-building event in North America was called the Acadian orogeny.” (Sutherland *New History* 146)

382.7-358.9m (Upper Devonian): the “Devonian Catskill Formation” (mostly terrestrial deposits) (Sutherland *New History* 145)

“. . . rivers and streams carried sediments eroded from the rising Acadian mountains. These rivers moved out across a broad coastal plain and eventually dumped their sediment in a series of deltas in the Catskill Sea.” (Sutherland *New History* 146)

Red Hill itself

“It was within these delta complexes that the rocks in Red Hill were originally deposited as sediments.” (Sutherland *New History* 146)

Red Hill is an exposure in the Catskill Formation. (Sutherland *New History* 145)

“The sediments at Red Hill are generally red, reflecting the hot, oxidizing climate under which they were deposited. The deposit also has thin green strips of sediment; most likely, these were ponds and pools that lay on top of the delta between the meandering river channels. The green color arose as the organic material around the edges fell into the ponds, rapidly using up all the oxygen in the water. The green color represents minerals in a semi-reducing environment.” (Sutherland *New History* 146)

early 1990s: discovery of *Hynerpeton bassetti*

Neil Shubin of the University of Chicago investigated Red Hill. (Sutherland *New History* 145)

“Shubin, who was particularly interested in tetrapods, collected fossils from this spectacular section [Red Hill, or the green strips?—Hahn]. He found *Hynerpeton bassetti*, a creature that lived in the shallow margins of the river channels and ponds. It was a tetrapod, but it was not a fishapod—the transitional form.” (Sutherland *New History* 146)

375m (Upper Devonian): *Tiktaalik*

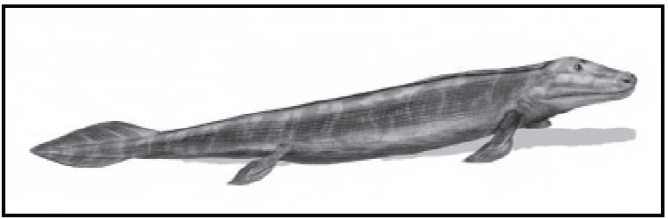
Ellesmere Island

Shubin concluded “that deltaic environments were reliable places to find early tetrapods . . . [So he] looked for similar environments but in older rocks.” (Sutherland *New History* 146)

“Logically, the missing link should be somewhere between the emergence of lobe-finned fish, 390 million years ago, and the deposition of the Red Hill rocks [382.7-358.9m].” (Sutherland *New History* 146)

“Shubin mounted an expedition to Ellesmere Island in Nunavut, Canada. During the Devonian, this area was [146] . . . close to the equator. Rocks here belonged to a group of rocks called the Fram Formation, from the Middle Devonian, deposited by rivers and streams. . . . Both the sediments and fossils in some strata indicated freshwater conditions.” (Sutherland *New History* 146-47)

2006: “the team found an odd-looking fish.” (Sutherland *New History* 147)



(Sutherland says 2004; Uppsala University says 2006.)

“The elders of Ellesmere Island suggested that Shubin name the fossil *Tiktaalik*, referring to a large freshwater fish in Inuktituk.” (Sutherland *New History* 147)

The fish “was about 3 to 6 feet long . . .” (Sutherland *New History* 147)

It had some fishlike features. (Sutherland *New History* 147)

It had fins and scales.

It had “a primitive fishlike jaw.”

“. . . the flexibility of its fins likely made it an able swimmer.”

It had some non-fishlike features. (Sutherland *New History* 147)

“It had a flat head like a crocodile.”

“It did not have a fused head and shoulder, like other fish; it had a neck.”

“Also, its bones in the limbs, or fins, conformed to the tetrapod arrangement of limbs: one to two to many.”

“There was a suggestion of a wrist joint, allowing this fish to do a kind of push-up on the floor of the water body.”

“The webbing on its fins and elbow joint was also much reduced, allowing its limb-fin [to have] flexibility and range of motion.”

“*Tiktaalik* probably lived close to margins of water, spending its days just partly submerged. It probably ate smaller fish and invertebrates. It’s possible that its push-up ability allowed it to lift itself suddenly out of the water and perhaps snap at a passing arthropod—like a crocodile in many ways.” (Sutherland *New History* 147)

“*Tiktaalik* was heralded as a true transitional form, an authentic missing link between the fish and the tetrapods. The holy grail of transitional forms had been found.” (Sutherland *New History* 148)

Tiktaalik (no italics) was “an almost perfectly intermediate fish-tetrapod . . . but even so a gap remained between this animal and the earliest true tetrapods (animals with limbs rather than paired fins).” (Uppsala University)

372.2-358.9m: *Ventastega* (“Ventastega”)

*Ventastega* is an “extremely primitive tetrapod . . . from the Devonian of Latvia . . .” (Uppsala University)

“. . . Ventastega was more fish-like than any of its contemporaries, such as Acanthostega. The shape of its skull, and the pattern of teeth in its jaws, are neatly intermediate between those of Tiktaalik and Acanthostega.” (Uppsala University)

Per Ahlberg: “the shoulder girdle and pelvis are almost identical to those of Acanthostega, and the shoulder girdle is quite different from that of Tiktaalik (the pelvis of Tiktaalik is unknown), suggesting that the transformation from paired fins to limbs had already occurred. It appears that different parts of the body evolved at different speeds during the transition from water to land.” (Uppsala University)

365m: *Acanthostega* (“Acanthostega”)

419.2-358.9m: Devonian Period

*acanthos* spine + *stega* plate

1987: Jenny Clack of Cambridge led another expedition to Greenland. (Sutherland *New History* 141)

She found a “Devonian tetrapod that she named *Acanthostega*.” (Sutherland *New History* 141)

*Acanthostega* was 2 feet long, “smaller than *Ichthyostega* . . .” (Sutherland *New History* 141)

It had eight toes. That shattered “a basic assumption of what tetrapods were. . . . the number of digits . . . was variable.” (Sutherland *New History* 141)

“Also, its limbs jutted out of the side of the body. That does not make sense for a land-dwelling creature. For an animal to walk on the land, its limbs must be positioned underneath.” (Sutherland *New History* 141)

“*Acanthostega* did not have any wrists or ankles—another feature needed for locomotion on the land.” (Sutherland *New History* 141)

“Its hips didn’t support much [141] weight.” (Sutherland *New History* 141-42)

“*Acanthostega*’s feet apparently weren’t feet at all; they were paddles.” (Sutherland *New History* 142)

355m: *Ichthyostega*

358.9-298.9m: Carboniferous Period

*ichthys* fish + *stega* plate

1930: Swedish paleontologist Erik Jarvik (1807-98), an expert on *Eusthenopteron*, discovers *Ichthyostega* in Greenland. (Sutherland *New History* 141)

*Ichthyostega* was “a fish on legs. It had a fishlike body, and at the end of its legs were feet with five toes.” (Sutherland *New History* 141)

“This creature was clearly adapted to walk on land. It was also quite large—about 5 feet long from its nose to the tip of its tail. *Ichthyostega* was a true amphibian; it was happy in water, but it was also able and mobile on land.” (Sutherland *New History* 141)

“There was a bit of disquiet in the scientific community after this discovery, however. *Ichthyostega* did not look very transition-like. In the reconstructions by Jarvik, it looked far too much like a fully developed tetrapod.” (Sutherland *New History* 141)

suggested reading

Gould, ed., *The Book of Life*.

Laurin, *How Vertebrates Left the Water*.

## 358.9-298.9m: Carboniferous Giants and Coal

“Diapsid.” *Wikipedia*. 1 Feb. 2021. 24 Mar. 2021. Web.

Dlouhý, T. “11—Low-rank Coal Properties, Upgrading and Utilization for Improving Fuel Flexibility of Advanced Power Plants.” *Advanced Power Plant Materials*, *Design and Technology*. Woodhead Publishing Series in Energy. 2010. 291-311.

Laurin, Michel, and Jacques A. Gauthier. “*Amniota*: Mammals, Reptiles (Turtles, Lizards, Sphenodon, Crocodiles, Birds) and Their Extinct Relatives.” *TOLWeb*.*org* (Tree of Life Web Project). 30 Jan. 2012. 24 Mar. 2021. Web. <tolweb.org/amniota>.

“Sauropsida.” *Wikipedia*. 20 Mar. 2021. 24 Mar. 2021. Web.

introduction

359-299m: “Coal mostly formed . . .” (Sutherland *New History* 150)

Bronze-Age Britons (2500-800), Greeks, and Romans used coal. (Sutherland *New History* 152)

“Coal powered the Industrial Revolution . . .” (Sutherland *New History* 150)

The Carboniferous Period “gets its name from coal . . .” (Sutherland *New History* 150)

Coal (“fossilized plant remains”) is “fossil sunlight that . . . was transformed into plant tissues . . .” (Sutherland *New History* 157)

“On some lumps of coal are visible faint imprints that look like leaves, ferns, or stems of some sort. These are, in fact, fossils . . . the products of a hot, steamy, swampy environment.” (Sutherland *New History* 150)

335-175m: Pangaea (Gondwanaland and Euramerica merge) (“Pangaea”)

Mississippian and Pennsylvanian Periods

“In North America, the Carboniferous is split into two subperiods.” (Sutherland *New History* 150)

358.9-323.2m: the Mississippian, which “produced more limestone than coal . . .”

323.2-298.9m: the Pennsylvanian, which “produced vast amounts of coal.”

types of coal

peat

“Coal forms when plant material falls into a body of water that has low oxygen concentrations. The . . . oxygen is rapidly used up.” (Sutherland *New History* 150)

The present-day “swamps of the Mississippi [are] the ideal environment . . .” (Sutherland *New History* 150)

“. . . peat starts to accumulate; that’s the first stage in coal formation.” (Sutherland *New History* 150)

coal

“As the peat is buried by sediment and heat and pressure drive off its volatiles, eventually, [150] the peat is transformed into coal.” (Sutherland *New History* 150-51)

grades of coal

The grades of coal are “ranked by how much heat and pressure produced them.” (Sutherland *New History* 151)

lignite (25%-35% carbon) (Dlouhý)

“a brown coal used for electricity generation” (Sutherland *New History* 151)

subbituminous coal (35%-45% carbon)

One use is “hydrocarbons for the chemical industry.” (Sutherland *New History* 151)

bituminous coal (45%-86% carbon)

One use is “the production of coke, which is used in smelting iron ore.” (Sutherland *New History* 151)

coke:

anthracite (86%-98% carbon)

“the highest rank of coal” (Sutherland *New History* 151)

“Because of the intense heat and pressure that have gone into its production, it’s regarded by some as more of a metamorphic than a sedimentary rock.” (Sutherland *New History* 151)

984 billion “tons of coal reserves exist globally today.” (Sutherland *New History* 152)

cyclothems

“. . . coal is found in sedimentary packages called cyclothems . . . The layers include sediments indicative of river delta, as well as marine deposits.” (Sutherland *New History* 152)

“Cyclothems are sometimes found stacked in vast numbers, as many as 40 to 50 at a time. In some cases, 100 cyclothems have been recorded . . .” (Sutherland *New History* 152)

“In North America, some coal units can be traced for thousands of square miles, indicating the vast extent of the swampy, deltaic coal-forming environment of the Carboniferous.” (Sutherland *New History* 152)

sea levels rose and fell

Cyclothems represent “the repeated rise and fall of sea levels.” (Sutherland *New History* 152)

“The marine sediments represent the period of highest sea level. As sea levels fell, . . . marine sediments were exposed to the atmosphere, and they developed an erosion surface. That surface was then covered as rivers started to migrate across this area; when swamp conditions returned, coal was ultimately formed.” (Sutherland *New History* 152)

“Eventually, sea levels rose again, flooding started, and the cycle was repeated once more.” (Sutherland *New History* 152)

why sea levels rose and fell

Some say “the cycles of sea-level rise and fall were caused by local vertical faults in the crust or the pressures of large accumulations of sediments. These localized effects, however, cannot account for the vast extent of some of the cyclothems recorded in coal deposits.” (Sutherland *New History* 152)

“The cyclothems most likely imply a global change in sea level . . . the Permo-Carboniferous glaciation[s].” (Sutherland *New History* 152-53)

Glaciers locked up water, and sea levels dropped. “. . . lowland swamps emerged and rivers moved across the newly exposed land.” (Sutherland *New History* 153)

In interglacial periods, water returned “to the oceans and rain stayed on the land—the sea levels rose. Then, coal production stopped. There was a return to the marine part of the cyclothem.” (Sutherland *New History* 153)

carboniferous swamps

“Carboniferous swamps were vast—continentally vast.” (Sutherland *New History* 153)

“The plant ecosystem within these swamps continued to evolve vertically upward, even more so than in the Devonian forest. The plants occupying these Carboniferous swamp environments were spectacular but strange.” (Sutherland *New History* 153)

club mosses

“The most spectacular were the ancient club mosses. The club mosses today, like their earlier Devonian ancestors, are very small. But in the Carboniferous, it was a different story.” (Sutherland *New History* 153)

example: *Lepidodendron* was “a club moss over 100 feet tall. It had fronds on the tops of large trunks and looked like a palm tree. It also had distinctive leaf scars on the trunk, creating a characteristic diamond pattern. These are some of the most common fossils found in coal deposits.” (Sutherland *New History* 153)

arthropods of the Carboniferous

“The Carboniferous saw the emergence of the first true spiders, the Mesothelae. Like modern spiders, they had the ability to produce silk.” (Sutherland *New History* 154)

giant arthropods

example: *Arthropleura*

*Arthropleura* was “a millipede-like creature . . . more than 8 feet in length. . . . its tracks are common.” (Sutherland *New History* 155)

It “was probably an herbivore . . .” Some of its fossilized guts and some coprolites (fossilized excrement) have plant spores. (Sutherland *New History* 155)

example: *Meganeura*

“*Meganeura* was a giant dragonfly-like insect with a wingspan of around 30 inches. It probably fed on other insects in the environment, as well as smaller tetrapods.” (Sutherland *New History* 155)

cause: higher oxygen levels

“Insects take in oxygen through holes in their bodies called spiracles. These spiracles connect to a series of branching tubes called the tracheal system, and it’s through these that oxygen diffuses. It’s an effective system for getting oxygen around a body—but only for fairly small creatures.” (Sutherland *New History* 155)

“To get larger, an insect needs to use more tubules. Eventually, it . . . would be mostly tubule and not much else. This, we think, today places an upper limit on how large insects can grow.” (Sutherland *New History* 155)

“The key factor that allowed the giant insects and arthropods of the Carboniferous was oxygen. . . . The continents were turning green, and all those plants were producing a great deal of oxygen via photosynthesis.” (Sutherland *New History* 155)

Oxygen hit 35% of air (today it is 21%). (Sutherland *New History* 156)

“This higher concentration of oxygen permitted oxygen to diffuse more easily through a creature, which probably meant that their tubules could be thinner. As a consequence, these insects—these arthropods—could grow very large.” (Sutherland *New History* 156)

The high oxygen level turned Earth “into a tinderbox. Fires sparked by lightning were probably common. Fusain, which is a dark, dusty deposit on coal, could be the possible remnant of some of those ancient forest fires.” (Sutherland *New History* 156)

anamniotes and amniotes

anamniotes

fish and amphibians

Amphibians, even now, “return to the water to spawn.” (Sutherland *New History* 154)

They “typically lay their eggs in water.” (“Amniote”)

amniotes

Amniotes are “a clade of tetrapod vertebrates comprising the reptiles (including dinosaurs, which includes birds) and mammals . . .” (“Amniote”)

amniotic egg

“The reptiles’ major adaptation was the amniotic egg: a water-impermeable membrane surrounding a fluid-filled cavity.” (Sutherland *New History* 154)

“The shell itself had tiny pores to permit waste gases to diffuse out and oxygen to diffuse into the developing embryo.” (Sutherland *New History* 154)

Amniotes “lay their eggs on land or retain the fertilized egg within the mother . . .” (“Amniote”)

advantages

Their eggs “survive out of the water, allowing amniotes to branch out into drier environments.” (“Amniote”)

“Another great advantage to egg laying was that eggs can be buried. As the embryo passed through the vulnerable tadpole stage, it would not be visible . . .” (Sutherland *New History* 154)

Carboniferous amphibians

“The tetrapods had evolved from the Devonian . . . the Carboniferous had an entire suite of amphibians that were much more diverse than the amphibians found in today’s ecosystem.” (Sutherland *New History* 153)

“Today’s amphibians are fairly diminutive creatures. A salamander in the Carboniferous and Permian, however, was as large as a [153] crocodile.” (Sutherland *New History* 153-54)

“Other amphibians became the amphibian equivalent of water snakes.” (Sutherland *New History* 154)

example: “*Ophiderpeton* was about 28 inches long and had 230 vertebrae in its backbone.” (Sutherland *New History* 154)

*Seymouria*

*Seymouria* was “well adapted to living on land. *Seymouria* had powerful, muscular legs, and it adapted a tough, dry skin to help reduce water loss while crossing the land surface.” (Sutherland *New History* 154)

315.2-307m (Middle Pennsylvanian): earliest known amniotes (Laurin and Gauthier)

Reptiles descended from large amphibians. (Ross and Ross)

“. . . a few primitive and generalized reptile fossils” are Carboniferous. (Ross and Ross)

Carboniferous reptiles were rather small. (Sutherland *New History* 154)

312m (Middle Carboniferous): *Hylonomus* (“*Hylonomus*”)

“The ancestor of the amniotes is a primitive lizard, *Hylonomus*.” (Sutherland *New History* 160)

“It was probably one of the earliest fossil reptiles . . .” (Sutherland *New History* 154)

It was “8 inches long, and looked very much like a lizard.” (Sutherland *New History* 154)

It had “a flexible neck and a lightly built skeleton.” (Sutherland *New History* 154)

“It had hands and feet with long digits . . .” (Sutherland *New History* 154)

It had “very sharp teeth [and] was most likely an early insectivore, as were many of the early reptiles.” (Sutherland *New History* 154)

classification of amniotes

traditional: by fenestrae

The three groups “are most easily differentiated by the presence and number of holes in the skull behind the eye socket. Those gaps, or holes, are called fenestrae, meaning “windows.”” (Sutherland *New History* 160)

Anapsids are the most primitive. “They have a complete skull, with no gaps. *Hylonomus* belongs to this group, which places it at the base of the evolutionary tree.” (Sutherland *New History* 160)

Diapsids have two fenestrae at the side of the head, one at eye level and one slightly above. They are “an extremely successful group . . . ” (Sutherland *New History* 160)

They include “all crocodilians, lizards, snakes, tuatara, turtles, and birds.” (“Diapsid”)

Lepidosauria (overlapping scales: lizards and snakes) (“Diapsid”)

Archosauria (dinosaurs; crocodiles and birds)

Aves

On turtles as diapsids: “The traditional classification of reptiles is based on a single key character, the presence and style of fenestration in the temporal region of the skull. Snakes, lizards, crocodiles, dinosaurs and others are ‘diapsids’, in that they have (at least primitively) two holes in the temporal region. Reptiles in which the skull is completely roofed, with no temporal fenestration, are the ‘anapsids’. These include many Palaeozoic forms such as captorhinomorphs, procolophonids and pareiasaurs, but also include Testudines (turtles and tortoises). Consistent with this assumption, recent analyses of the affinities of Testudines have included Palaeozoic taxa only, placing them as akin to captorhinomorphs1 or procolophonids or nested within pareiasaurs. [But] Here we adopt a broader perspective, adding a range of Mesozoic and extant taxa to the analysis. Our result robustly supports the diapsid affinities of turtles, and so requires reassessment of the use of turtles as ‘primitive’ reptiles in phylogenetic reconstruction. More generally, it illustrates the difficulties of treating groups, such as the Testudines, that have extant members with peculiar morphologies that mask phylogenetic affinity; the hazards of relying on key characters such as temporal fenestration, which may mislead; the problems of outgroup choice for wide-ranging, inclusive analyses that include data from Recent and extinct groups; and the difficulties of judging the value of parsimony when applied to such inclusive analyses.” (Rieppel and deBraga)

Synapsids have one fenestra, even with the eye socket. (Sutherland *New History* 161)

323-299m (Pennsylvanian subperiod of the Carboniferous): pelycosaurs (earliest synapsids: all synapsids except therapsids and their descendants)

299-251m: they dominated the Permian. (Sutherland *New History* 161)

They “ultimately gave rise to the mammals.” (Sutherland *New History* 161)

tetrapod phylogeny: (“Sauropsida”)

Tetrapoda

Amphibia

Amniota

Mammalia (class)

Cheloniidae (family; marine turtles; 6 species)

Diapsida (crocodilians, lizards, snakes, tuatara, turtles, and birds [“Diapsid”])

amniote phylogeny: (Laurin and Gauthier) (“Sauropsida”)

clade Sauropsida (formerly class Reptilia): reptiles and birds

Anapsida (including Testudines: turtles, tortoises, and terrapins)

Romeriida (including Diapsida: lizards, crocodiles, birds, tuatara [genus Sphenodon], and their extinct relatilves)

clade Synapsida: mammals and their extinct relatives

*Hylonomous*’ descendants

From *Hylonomus* three groups of amniotes evolved: anapsids, diapsids, and synapsids. (Sutherland *New History* 160) (*Apsis*, arch, referrring to bone between fenestrae.)

*Hylonomus* was an anapsid. (Sutherland *New History* 160)

evolution flourishes

“All modern classes of fungi had evolved by the Late Carboniferous.” (Sutherland *New History* 156)

“In the oceans, fish continued to diversify, and bony fish continued to evolve.” (Sutherland *New History* 156)

Sharks radiated in the Carboniferous. (Sutherland *New History* 156)

“. . . extensive Carboniferous coral reef systems composed of rugose and tabulate corals” developed. (Sutherland *New History* 156)

There were “beautiful meadows of crinoids” (marine echinoderms). (Sutherland *New History* 156)

suggested reading

Beerling, *The Emerald Planet*.

Lane, *Oxygen*: *The Molecule That Made the World*.

## 298.9-251.9m: Permian Period (Amniotes)

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“Synapsid.” *Wikipedia*. 23 Feb. 2021. 6 Mar. 2021. Web.

“Therapsids.” *Wikipedia*. 20 Feb. 2021. 6 Mar. 2021. Web.

introduction

“. . . the oceans were full of rich coral reefs.” (Sutherland *New History* 164)

“. . . more modern-looking plant flora” evolved. (Sutherland *New History* 164)

“. . . herbivores came into being . . .” (Sutherland *New History* 164)

“. . . vertebrates took to the skies.” (Sutherland *New History* 164)

fenestrae

Permian reptile fossils

protorosaurs: “aquatic reptiles ancestral to archosaurs (dinosaurs, crocodiles, and birds)” (Ross and Ross)

captorhinomorphs: “stem reptiles,” “large for their day” (2-3 meters, 7-10 feet). (Ross and Ross)

eosuchians: “early ancestors of the snakes and lizards” (Ross and Ross)

early anapsids: “ancestors of turtles” (Ross and Ross)

synapsids: “mammal-like reptiles”; they give rise to mammals in 247.2-237m (Ross and Ross)

pelycosaurs: “developed long spines on their vertebrae that supported a membrane, or “sail.”” They were 3.5 meters (11.5 feet), with “large, differentiated teeth.” (Ross and Ross)

therapsids

“highly diversified”; “mammal-like dentition and bone structure”; warm-blooded (Ross and Ross)

diapsids: archosaurs

Archosaurs are “ancestors of the large ruling reptiles of the Mesozoic.” (Ross and Ross)

Archosaurs are a clade. (“Archosaur”)

Extinct archosaurs include dinosaurs, pterosaurs, and crocodile relatives. (“Archosaur”)

Living archosaurs include only crocodiles and birds. (“Archosaur”)

synapsids: pelycosaurs

298.9-292.95m (Early Permian): the Texas Red Beds include some “spectacular” pelycosaurs. (Sutherland *New History* 161)

Pelycosaurs are “all synapsids excluding the therapsids [see below] and their descendants.” (“Pelycosaurs”)

The group is paraphyletic, so “pelycosaur” is no longer favored. (“Pelycosaurs”)

*Dimetrodon*

“A top predator of that environment was the pelycosaur *Dimetrodon*.” (Sutherland *New History* 161)

“*Dimetrodon* was not a dinosaur . . .” The dinosaur did not appear for “millions of years after *Dimetrodon* had become extinct.”

“*Dimetrodon* was about 13 feet long and had a large jaw with a set of slashing teeth. Perhaps its most prominent feature was its sail, which probably aided in thermoregulation. Because these were likely cold-blooded creatures, they would have to rely on the external environment to either cool them or heat them.” (Sutherland *New History* 161)

*Edaphosaurus*

“Another pelycosaur in the Texas Red Beds was *Edaphosaurus*, a herbivore of more than 600 pounds—probably one of the earliest herbivorous vertebrates on the scene.” (Sutherland *New History* 161)

Why did we have to wait more than 50 million years for the herbivorous vertebrates to appear?” (Sutherland *New History* 161)

“. . . most plant material contains a great deal of cellulose, [so] it’s very difficult to digest.” (Sutherland *New History* 161)

“Cows have solved this problem by recruiting the aid of fermenting bacteria in the gut. These fermenting bacteria, however, require fairly stable temperature environments. The cow accomplishes thermoregulation through its sophisticated mammalian metabolism.” (Sutherland *New History* 161)

For cold-blooded creatures, a “way of maintaining a fairly warm inner core of the body is to get big. Thus, it was likely that herbivory in vertebrates at this early stage had to wait until the creatures got sufficiently large.” (Sutherland *New History* 161)

“Pelycosaurs are sometimes called mammal-like reptiles. True mammals would not evolve for a long time, but eventually, they would evolve from relatives of the pelycosaurs, later in the Triassic, about 200 million years ago.” (Sutherland *New History* 162)

295.1-251.9m (Late Permian): “by the middle of the Late Permian, all of the pelycosaurs had either died off or evolved into their successors, the therapsids.” (“Synapsid”)

275m: synapsids: therapsids (“Therapsids”)

259.1-251.9m (Late Permian): therapsids evolved from pelycosaurs.

“. . . pelycosaurs were relatively restricted to tropical regions . . . [But] therapsids started to explore the massive supercontinent called Pangaea.” (Sutherland *New History* 162)

“They had larger skull openings behind their eye sockets, which may have indicated more muscle mass to operate very powerful jaws. They had powerful canine teeth.” (Sutherland *New History* 162)

Therapsids “were probably much more agile” than pelycosaurs. (Sutherland *New History* 162)

|  |  |
| --- | --- |
| Therapsida 3.jpg | top to bottom, left to right:  genus Biarmosuchus (extinct clade: Biarmosuchia)  genus Moschops (extinct clade: Dinocephalia)  genus Myosaurus (extinct group: Anomodontia)  genus Inostrancevia (extinct clade: Gorgonopsia)  genus Pristerognathus (extinct suborder: Therocephalia)  genus Adelobasileus (clade Cynodontia: extinct except for mammals) (“Therapsid”) |

synapsids: therapsids: dicynodonts

The “herbivorous dicynodont . . . made up more than 90 percent of therapsid diversity. It was probably the first truly abundant vertebrate herbivore on the surface of the planet.” (Sutherland *New History* 163)

“Dicynodonts were herbivorous animals with two tusks, hence their name, which means ‘two dog tooth’. They [were] non-mammalian therapsids, . . . varying from rat- to elephant-sized.” (“Dicynodont”)

“Part of the success of the dicynodont was the evolution of a secondary palate, which allowed the creature to chew and breathe at the same time. This is an important feature. The vertebrates that preceded these herbivorous creatures had been meat eaters. Meat contains a great deal of energy; plants, in comparison, contain much less. For a plant eater, it helps to be able to keep eating while breathing, to consume more.” (Sutherland *New History* 163)

“Dicynodonts had a variety of lifestyles and specializations. Some of them had cropping jaws; some had crunching jaws. These diverse varieties suggest a climate that was reasonably mild and relatively stable, so that it supported a relatively constant food supply.” (Sutherland *New History* 163)

“Many therapsid specimens are found in the South African karoo.” (Sutherland *New History* 162)



therapsids: theriodonts

“Theriodonts have very mammal-like features, including teeth that are differentiated to perform different functions. They had fully developed temporal fenestrae and rear legs that were more pulled in underneath the body. Also in common with humans, they developed small bones in their ears that allowed them to hear.” (Sutherland *New History* 163)

The theriodonts include mammals. (Sutherland *New History* 163)

example: gorgonopsians

259.1-251.9m (Late Permian): “The top predators . . . were the gorgonopsians, whose name comes from the fearsome creatures in Greek mythology called the gorgons. These were the first real saber-toothed killers on the planet. They had a massive gape, with giant saber-like teeth that would sink into their prey.” (Sutherland *New History* 163)

The three gorgon sisters had snakes for hair, and their gaze turned to stone. (“Gorgon”)

suggested reading

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Foote and Miller, *Principles of Paleontology*.

Gould, ed. *The Book of Life*.

## Permian-Triassic extinction

“Breccia.” *Wikipedia*. 17 Feb. 2021. 6 Mar. 2021. Web.

introduction

“. . . the tropical paradise of the Ordovician ended suddenly in ice. The biosphere of the Permian would end, too—but this time with heat.” (Sutherland *New History* 164)

251m: “The world laid waste, with a complete breakdown of all its interrelated systems, [is] called the End-Permian extinction or the Permian-Triassic extinction event.” (Sutherland *New History* 165)

“The feedback mechanisms that had maintained Earth’s homeostasis simply failed . . . This was a key point in the evolution of the Earth . . .” (Sutherland *New History* 165)

extent of the Permian Extinction

“Rocks that cross the Permian-Triassic boundary on land all tell the same story. They reveal a healthy biosphere for most of the Permian and then utter devastation in the last part of the Permian and the early part of the Triassic.” (Sutherland *New History* 165)

“Trilobites and the eurypterids disappeared, as did the rugose and tabulate corals. In fact, coral reefs would not recover for many millions of years to come. The tropical rain forests vanished. By the end of the Permian, acanthodian fish—extremely important in the Devonian—were gone forever . . .” (Sutherland *New History* 165)

“There were extinctions in every species group . . .” (Sutherland *New History* 165)

“. . . this is the only time that insects suffered a mass extinction event.” (Sutherland *New History* 165)

“Of the vertebrates, more than two-thirds of the tetrapod faunas were lost . . .” (Sutherland *New History* 165)

“Many of the therapsid reptiles were gone.” (Sutherland *New History* 165)

“Snails suffered a 98 percent extinction . . ., and clams, 59 percent.” (Sutherland *New History* 166)

“Plant ecosystems were disrupted . . .” (Sutherland *New History* 166)

evidence of the extinction

There is the sudden change in fossils. (Sutherland *New History* 166)

The sudden change marks not only “the end of the Permian [but also] the end of the entire Paleozoic era . . . 251 million years . . .” (Sutherland *New History* 166)

The “was an incredible concentration of fungi spores in terrestrial sediment. Fungi, of course, are decomposers of [166] the plant material that falls down in forests. Such a high abundance over a period of time could only represent one thing: the destruction of much of the floral biomass in the End-Permian world.” (Sutherland *New History* 166-67)

“. . . coal production suddenly stopped . . .” (Sutherland *New History* 167)

Red beds suddenly appeared, “sediments that indicated hot, arid conditions.” (Sutherland *New History* 167)

“Further, the sedimentary depositing mechanism, which formerly consisted of meandering rivers, was suddenly replaced by a different type of river system called a braided stream deposit. Scientists believe that the large, meandering routes of the Permian suddenly failed because all the flora died off and could no longer stabilize the banks of the river channels. Another type of river system arose—creating an anastomosing, chaotic-looking deposition of sediment in rivers.” (Sutherland *New History* 167)

“There is isotopic evidence . . . Within the Permian-Triassic boundary sediments is a negative carbon-13 anomaly. This indicates that an environment has become suddenly flooded with carbon-12—suggesting the sudden cessation of photosynthesis and the death of creatures composed of carbon-12 organic molecules, with the sudden release of significant amounts of carbon-12 back into the environment.” (Sutherland *New History* 167)

cherts

“. . . exposures of deep-sea sediments . . . were deposited in the Panthalassic Ocean. The sediments, called cherts, have been moved by thrust faults; we find some of these in Japan.” (Sutherland *New History* 167)

“Cherts are fine-grained, siliceous sedimentary rocks produced by the accumulation of the skeletons of particular tiny microfossils called radiolarians. These are amoeboid protozoans that secrete a silica skeleton around themselves.” (Sutherland *New History* 167)

“There are many other important microfossils, such as coccolithophores and the Foraminifera, but these are composed of calcium carbonate. Calcium carbonate is more soluble in water at low temperatures and high pressures. As a result, the most remote and deepest part of the oceans are generally free of these carbonate sediments.” (Sutherland *New History* 168)

“Silica, however, can still be deposited at these low temperatures and high pressures, and microplankton, such as radiolarians and diatoms, formed silica-rich sediments called siliceous oozes. The radiolarian siliceous oozes in Japan record a rather disturbing sequence of events in the world’s oceans.” (Sutherland *New History* 168)

“Initially, things appeared fine. The rocks are red, showing that iron has been oxidized to the mineral hematite. This indicates that the oceans were healthy; they were well ventilated, with oxygen even in these deep, remote areas.” (Sutherland *New History* 168)

“But then the sediments record a change: They turn gray. A greater amount of organic content accounted for the grayish color—meaning that there is less oxygen, because oxygen would oxidize the organic sediments away. The carbon apparently was being preserved.” (Sutherland *New History* 168)

“Finally, the sediments turn black, indicating a high organic content. That black color demonstrates that there were oxygen-free conditions at the bottom of the oceans. The deep oceans, at this time, were suffocating. This was not just a localized event, however; it appeared to be a global phenomenon. At the end of the Permian, it would seem, much of the ocean simply died.” (Sutherland *New History* 168)

cause: an impact from space?

“Some scientists, called gradualists, have suggested that the Permian extinction actually represents a very long period, perhaps as much as 10 million years. However, a period of 10 million years does not define a mass extinction event.” (Sutherland *New History* 168)

“Others, the catastrophists, believe that the event occurred suddenly—overnight, or perhaps within a day or several years.” (Sutherland *New History* 168)

1908: Tunguska event

“. . . a great fireball was seen in central Siberia, followed by a detonation and a huge pressure wave. Because the event caused light skies as far away as London, scientists believe dust from the massive explosion had been thrown up into the atmosphere and reflected the sunlight back down to Earth.” (Sutherland *New History* 169)

1927: Leonid Kulik, “the chief curator of meteorites at a St. Petersburg museum, mounted an expedition to the epicenter. He was looking for a meteor, but he could not find an impact crater. Instead, he found a wasteland where the trees were flattened, covering an area of about 800 square miles.” (Sutherland *New History* 169)

Some “speculate that perhaps the answer to the Permian extinction was not an impact at all but a massive gas explosion.” (Sutherland *New History* 169)

“The current favored hypothesis, however, is that a comet or a meteorite exploded in midair, about 3 to 6 miles above the surface, creating a massive airburst.” (Sutherland *New History* 169)

“Subsequent investigations have found microscopic silicate and silicate spheres in the soils and the tree resins in the area. They have a high nickel-to-iron signature, common to extraterrestrial sources.” (Sutherland *New History* 169)

“Also, iridium, quite commonly associated with extraterrestrial impacts, has been found in some of the peat bogs in the area, and the layers in which it was found date to 1908.” (Sutherland *New History* 169)

structures supporting the theory

“If the answer to the Permian-Triassic extinction event is an impact from space, the crater would have to be exceptionally large—bigger than Mount Everest, probably hundreds of miles across. There are some interesting structures that may support the theory.” (Sutherland *New History* 169)

the Bedout High

“. . . 155 miles off the northwest coast of Australia is a roughly circular structure about 125 miles in diameter. Called the Bedout High, it may represent the remains of an impact crater [169] that dates to about the time of the Permian-Triassic extinction.” (Sutherland *New History* 169-70)

“However, its impact breccia has been criticized as being more likely a normal basaltic rock that has been altered by contact with seawater and high temperatures.” (Sutherland *New History* 170)

breccia (Ita. “rubble”): “Breccia is a rock composed of broken fragments of minerals or rock cemented together by a fine-grained matrix . . .” (“Breccia”)

“Also, there is no evidence of ejecta preserved at the site.” (Sutherland *New History* 170)

“The Bedout High, in all likelihood, represents the remains of tectonic rifting—the faults that develop as continents started to drift apart.” (Sutherland *New History* 170)

Greenland

“There is some evidence of impact material in Greenland and other areas, but it’s very thin—not on the scale of a Permian-Triassic extinction event.” (Sutherland *New History* 170)

Antarctica

“Another possibility was discovered by a joint NASA and German Aerospace Center satellite called GRACE (Gravity Recovery and Climate Experiment). GRACE, which has been taking measurements of Earth’s gravity field since 2002, detected the Wilkes Land mass concentration in Antarctica. This is a large gravity anomaly concentrated in a ring-like structure. It’s composed, we think, of very dense material—probably mantle material that could have welled up after an impact.” (Sutherland *New History* 170)

“The Wilkes Land mass concentration is 300 miles in diameter, which would be the equivalent of an impact body that was about 30 miles in diameter. The problem, of course, is that it’s under ice and difficult to date. It’s thought to have formed at sometime around the Permian-Triassic period, but we have no precise data.” (Sutherland *New History* 170)

cause: lava? the Siberian traps

“*Traps* comes from the Swedish word *trappa*, meaning “stairs.” It refers to the way that flood basalts commonly form a landscape with many stair-like inclinations in the sides of valleys. Flood basalts themselves are outpourings of lava that cover huge areas.” (Sutherland *New History* 172)

“The Siberian Traps, near Norilsk in northern Siberia, are flood basalts.” (Sutherland *New History* 172)

“. . . the vast extent of the basalts [is remarkable]. In total, they comprise an area about equivalent to Western Europe. Originally, this deposit probably covered 770,000 square miles, with material 0.25 to 1.8 miles deep.” (Sutherland *New History* 172)

“The vast outpourings of lava were caused by upwellings of hot mantle rocks. As the rocks moved upward, the pressure dropped, which allowed the rocks to melt. When they impacted the bottom of the base of the crust, they generated huge quantities of magma. The exact mechanics of these plumes is still uncertain, but we do know that they’re always associated with intense volcanic activity.” (Sutherland *New History* 172)

“The Siberian Traps erupted along very long fissures, stretching for tens or maybe hundreds of miles at times. They formed huge curtains of lava that moved out across Pangaea.” (Sutherland *New History* 172)

“For the species living during the Permian, the lava was actually not the greatest problem. Pangaea was a vast supercontinent. If a lava flow started to encroach on an area, animals migrated away. What’s more, if lava caused the problem, the question remains: How do we account for all the extinction events in the oceans? Another phenomenon must be responsible.” (Sutherland *New History* 173)

cause: increase in sulfur dioxide?

“Volcanic eruptions produce a great deal of gas and dust. The ash in the air can create global dimming, causing global cooling.” (Sutherland *New History* 173)

“Ash suspended in the air after a volcanic eruption can severely disrupt photosynthesis, both on land and in the ocean.” (Sutherland *New History* 173)



“When the sulfur dioxide produced by a volcanic eruption rises into the atmosphere, it is dissolved in rain and eventually forms sulfuric acid. This reflects solar radiation and creates more global cooling.” (Sutherland *New History* 173)

“Sulfate aerosols also cause the destruction of ozone; thus, ultraviolet radiation would more readily penetrate to the surface of the planet. All this can severely disrupt photosynthesis, both on the land and in the oceans.” (Sutherland *New History* 173)

cause: increase in carbon dioxide?

“Probably the greatest problem for the biosphere created by the Siberian Traps is the carbon dioxide produced from the eruptions. All volcanoes release carbon dioxide, but the Siberian Traps erupted through a particular age of rock: Carboniferous rocks. Carboniferous rocks contain a great deal of carboniferous [173] limestone—calcium carbonate—and coal deposits, both of which are prodigious sources of carbon dioxide if melted and heated.” (Sutherland *New History* 173-74)

“This excess of carbon dioxide most likely caused the intense greenhouse effect recorded at the end of the Permian. In some models, average global temperatures rose by about 8 degrees, contributing significantly to the aridification of the interior of Pangaea. Vast areas turned to desert.” (Sutherland *New History* 174)

“The upper layers of the oceans warmed. This created a lid of warmth on open bodies of water, which slowed down oceanic circulation. Normally, the ocean basins were kept well ventilated, but in this case, they became starved for oxygen. The biosphere became tremendously stressed, with the land and the oceans both moving into a crisis mode.” (Sutherland *New History* 174)

“But even this widespread phenomenon cannot explain the massive annihilation during the Permian-Triassic extinction event. We are still missing a significant part of the picture. What we need are new rocks and new information.” (Sutherland *New History* 174)

evidence from Jameson Land

“In Jameson Land in Greenland . . . [are] rocks that spanned the Permian-Triassic boundary and [are] rich in fossils . . .” (Sutherland *New History* 174)

The rocks show two phases of extinction.

first phase of extinction: land

“This phase of the extinction lasted about 40,000 years.” (Sutherland *New History* 175)

“. . . the extinction event was initiated by the Siberian Traps volcanism.” (Sutherland *New History* 175)

The Siberian Traps volcanism caused global cooling and acid rain; those “hit the land flora first and the ecosystem that they supported.” (Sutherland *New History* 174)

“The acid rain included sulfuric acid from the sulfur dioxide, but there were nitric acids and carbonic acids in the atmosphere as well. These acids . . . were [174] washed out of the atmosphere toward the surface of the planet . . .” (Sutherland *New History* 174-75)

“Plants were killed off by the acid rain and dimming conditions . . . The lush forests that produced the coal in Australia disappeared.” (Sutherland *New History* 175)

Without plants, “soil was washed away to the oceans.” (Sutherland *New History* 175)

“The plants that supported the meandering rivers and stabilized the banks were gone.” (Sutherland *New History* 175)

“After the acid rain, carbon dioxide remained in the atmosphere and initiated the greenhouse effect. Pangaea, already a fairly dry place, started to become drier.” (Sutherland *New History* 175)

The ecosystem was a “plant community with animals [insects, amphibians, and reptiles] struggling, lingering near sources of water that were rapidly dwindling.” (Sutherland *New History* 175)

second phase of extinction: oceans

“If the temperature was rising, why didn’t the extinction occur in the oceans at the same time? The reason is that oceans are effective temperature regulators.” (Sutherland *New History* 175)

“In the second phase of the extinction, the wonderfully diverse ocean reef fauna . . . was rapidly destroyed. The complete destruction of the reefs took only about 5000 years—about 40,000 years” of the first phase. (Sutherland *New History* 175)

“Then, the extinction moved back onto the land. The survivors of the first extinction pulse were now hammered for another 35,000 years. The flora was already in ruins. Much of the fauna was gone. . . . the land would probably be eerily quiet.” (Sutherland *New History* 175)

“The total length of the Permian-Triassic extinction event was about 80,000 years. Given the evidence in the rock, the event was long and [175] drawn out; it had not occurred suddenly.” (Sutherland *New History* 175-76)

“An impact event would have caused catastrophic effects that would have been almost instantaneous.” (Sutherland *New History* 176)

“Remember that we’re dealing here with a biosphere that had existed for about 4 billion years; a span of 80,000 years to extinguish nearly all life on the surface of the planet is still is a geological blink of an eye.” (Sutherland *New History* 176)

The Permian-Triassic extinction ended the spiny sharks. (“Evolution of Fish”)

the two excursions

“The new rock sections provided additional isotopic data. There was a negative carbon-13 anomaly associated with the Permian-Triassic extinction event. In fact, there’s a negative carbon-13 anomaly associated with all mass extinction events.” (Sutherland *New History* 176)

“In the Permian, there were two excursions. The first excursion was related to the first phase of extinction—the end of photosynthesis, with carbon-12 released back into the environment.” (Sutherland *New History* 176)

“There was a strong second excursion just after the marine extinction event, however—an excursion much greater than would be expected by the continued failure of photosynthesis or the release of carbon-12 from dead organisms. What caused this excursion?” (Sutherland *New History* 176)

methane clathrates

“The answer is found in methane clathrates. Basically, methane clathrates consist of methane trapped in ice. Clathrates are created in permafrost in land environments. They need a cold environment to form, but they can also occur in deeper marine environments along continental margins.” (Sutherland *New History* 176)

“In the ocean, these clathrates formed by the microbial reduction of carbon dioxide. The microbes lived in the sediments in deep cold-water, high-pressure conditions. They converted various substances, including carbon dioxide, into methane gas.” (Sutherland *New History* 176)

“As the Earth got progressively warmer, eventually, the deep oceans started to heat up, as well, including those areas along the continental margins. This destabilized the clathrates, which released their methane, with catastrophic results.” (Sutherland *New History* 177)

“Because this methane was originally produced by bacterial decomposition of organic material in the sediments, it was rich in carbon-12. This explains the large second carbon-13 anomaly following the marine extinction event.” (Sutherland *New History* 177)

“Methane is about 10 times more effective as a greenhouse gas than carbon dioxide. Temperatures warmed again as a result of the methane, which destabilized more clathrates, which released more methane, which caused more warming. A perfect example of positive feedback.” (Sutherland *New History* 177)

final phase of extinction

“The total methane release caused a further temperature increase on land by about another 8 degrees. This led to the third phase of extinction, and the culling moved back onto the land.” (Sutherland *New History* 177)

“Open water resources became very scarce indeed. Plants retreated further. Animals that had made it through the first wave would go extinct now—80,000 years after the first Siberian Traps eruption.” (Sutherland *New History* 177)

“Another possible consequence of the release of this methane was that the methane reacted with oxygen in the atmosphere. Atmospheric oxygen levels would fall severely on land, as well as in the oceans.” (Sutherland *New History* 177)

“What was left after the Permian-Triassic extinction event was a world utterly devastated. A few remaining species would limp over the Permian-Triassic boundary—but into an environment with very few competitors. Survivors would proliferate into the next grouping of periods, the Mesozoic” (251.9-66m). (Sutherland *New History* 177)

suggested reading

Benton, *When Life Nearly Died*.

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*.

Hallam, *Catastrophes and Lesser Calamities*.

## 251.9-201.3m: Triassic Period

Ross, Charles A., and June R.P. Ross. “Permian Period.” *Britannica*.*com*. 6 Nov. 2020. 23 Mar. 2021. Web.

introduction

“. . . the Permian-Triassic extinction event. It took about 30 million years or so for complete ecological recovery . . .” (Sutherland *New History* 181)

“The three main reptile types—anapsids, diapsids, and synapsids—survived. One of the diapsids would eventually come to dominate the Mesozoic: the dinosaurs.” (Sutherland *New History* 178)

ancestors of the dinosaurs

“Dinosaurs emerged from the reptile populations that struggled through and survived the Permian-Triassic extinction event.” (Sutherland *New History* 181)

“The Early Triassic was still dominated by Pangaea. It saw the beginnings of the Tethys Ocean but certainly no Atlantic. Creatures in this vast landmass migrated freely across the supercontinent. The land was still dry and arid; in fact, warm temperatures probably extended right to the poles. It has been suggested that this was one of the hottest times in . . . the Phanerozoic eon [541-present].” (Sutherland *New History* 181)

“. . . one of the most common reptiles, the therapsid *Lystrosaurus*, roamed in vast herds. In some deposits, *Lystrosaurus* represents about 95 percent of the fossils.” (Sutherland *New History* 181)

“Another therapsid, the cynodont *Thrinaxodon*, . . . looked a lot like a mammal. It may have been [181] covered in fur. Also, it had pits in the skull, possibly indicating the presence of whiskers. It had seven neck vertebrae, like modern mammals.” (Sutherland *New History* 181-82)

archosaurs

“The diapsids had diversified into a number of forms, including a group called the archosaurs. The archosaurs were important because they gave us the crocodiles, the pterosaurs, the birds, and of course, the dinosaurs.” (Sutherland *New History* 182)

“An early archosaur was *Euparkeria*. It is speculated that this was an agile animal, fast-moving, around 24 inches long, and an insectivore. *Euparkeria* also may have been semi-bipedal—the first evidence of a creature on two legs. Although *Euparkeria* was not a direct ancestor of the dinosaurs, it was probably related to the groups of creatures that would eventually evolve into them.” (Sutherland *New History* 182)

earliest dinosaurs

“The earliest known dinosaur fossils are from the Late Triassic, from the Ischigualasto Formation in Argentina. The sediments deposited in this area, originally in a river valley . . .” (Sutherland *New History* 182)

*Eoraptor*

“*Eoraptor* was a small bipedal carnivore or omnivore. It was about 3 feet long and probably weighed about 22 pounds.” (Sutherland *New History* 182)

*Herrerasaurus*

“*Herrerasaurus*, a fully bipedal carnivore, was 10 to 20 feet long.” (Sutherland *New History* 182)

“By the end of the Triassic, dinosaurs were present but were just a component of an ecosystem that had a rich variety of tetrapods. They certainly weren’t dominating that fauna.” (Sutherland *New History* 182)

247.2-237m (Middle Triassic): mammals (Ross and Ross)

“mammal-like reptiles pass into mammals . . . with cheek teeth having only two roots instead of three.” (Ross and Ross)

201.3m: Triassic-Jurassic (Tr-J) extinction event

How did dinosaurs come to “dominate the Late Jurassic [163.5-145m]?” (Sutherland *New History* 182)

“Scientists believe that another mass extinction event at the end of the Triassic allowed the dinosaurs to rise to dominance. The Triassic-Jurassic extinction event occurred both on land and in the oceans.” (Sutherland *New History* 183)

“This extinction event would eliminate the remaining therapsid reptiles that had flourished during the Permian and survived into the Triassic. The dinosaurs, however, would survive . . .” (Sutherland *New History* 183)

“. . . the Triassic-Jurassic extinction event was precipitated by the formation of the Atlantic Ocean. It is speculated that a mantle plume developed underneath the supercontinent Pangaea. In addition to creating large outpourings of lava, it started to split the continent. New ocean crust began to form in between these drifting blocks. The ocean broke through, and the Atlantic was born.” (Sutherland *New History* 183)

Central Atlantic Magmatic Province (CAMP)

“Rifting during the Triassic generated considerable volcanism. The lava flow thus created is called the Central Atlantic Magmatic Province (CAMP). Some have suggested that the activity was similar in intensity to the Siberian Traps volcanism that created the End-Permian extinction.” (Sutherland *New History* 183)

“The detrimental effects would have been similar. Much sulfur dioxide was produced, but the biggest killer in this event would have been the increased carbon dioxide and the associated greenhouse effect.” (Sutherland *New History* 183)

“An interesting indicator of the development of a global greenhouse effect at the end of the Triassic comes from fossil leaves.” (Sutherland *New History* 183)

“In times of high carbon dioxide, the number of plant stomata (pores used for gas exchange) is low. With lower carbon dioxide levels, plants need greater numbers of stomata because they are trying to maximize the amount of carbon dioxide they take in.” (Sutherland *New History* 183)

“Fossil leaves found in Greenland and Sweden show a marked decrease in plant stomata, indicating increases in carbon dioxide that match the timing of the CAMP volcanism.” (Sutherland *New History* 184)

pre-CAMP: “The temperature at the end of the Triassic was about 5 degrees higher than it is today . . .” (Sutherland *New History* 184)

post-CAMP: “The temperature . . . probably rose by another 5 to 6 degrees. This warming created extinctions on land, with the death of plants and . . . all the creatures that relied on the plant base.” (Sutherland *New History* 184)

201.3m: the Triassic-Jurassic extinction ended the conodonts. (“Evolution of Fish”)

suggested reading

Fastovsky and Weishampel, *The Evolution and Extinction of the Dinosaurs*.

Martin, *Introduction to the Study of Dinosaurs*.

## 201.3-145m: Jurassic Period

introduction

163.5-145m (Late Jurassic): “The Late Jurassic was a time of climatic stability. Tropical conditions extended much farther than they do today. The Tethys Ocean was starting to split up the continent of Pangaea from east to west, and a new ocean, the Atlantic, was just starting to form. On land, the forests were filled with conifers, ginkgoes, and giant cycads. And wandering through those forests were” dinosaurs. (Sutherland *New History* 179)

“The Jurassic biosphere was filled with dinosaurs of all different shapes and sizes, occupying different types of niches.” (Sutherland *New History* 180)

Jurassic marine creatures

“The Jurassic oceans were absolutely brimming with life . . .” (Sutherland *New History* 180)

“They contained many [180] species of bivalve.” (Sutherland *New History* 180-81)

“The gastropods, which had struggled through the End-Permian extinction, radiated into the Mesozoic and, by the Jurassic, were prolific.” (Sutherland *New History* 181)

“The echinoderms had also flourished . . .” (Sutherland *New History* 181)

The reefs recovered. (Sutherland *New History* 181)

“Hexacorals, also called square actinians, developed, and sponge reefs were common.”

“A reef-forming bivalve called *Lithiotis* would create important reef structures during the Jurassic.” (Sutherland *New History* 181)

“The ocean ecosystem was full of ammonites, belemnites, and cephalopods.” (Sutherland *New History* 181)

“Fantastic marine reptiles, such as ichthyosaurs, roamed the oceans.” (Sutherland *New History* 181)

“And, for the first time, we see modern fish, the teleosts. From these would evolve everything from a salmon to a seahorse.” (Sutherland *New History* 181)

Jurassic land creatures: sauropods

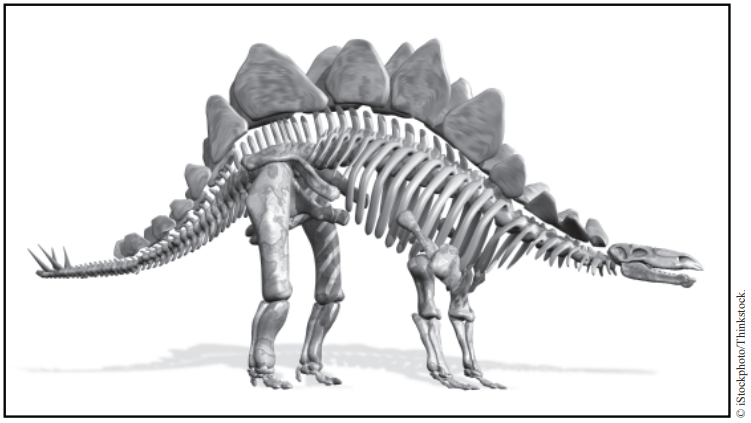
“The largest of the dinosaurs were the sauropods—a classic dinosaur with a long neck and long tail. Sauropods possessed simple, spoonlike teeth, designed to strip away vegetation off branches. Because plant material is low in energy compared to meat, this creature had to feed constantly in order to support its massive bulk.” (Sutherland *New History* 179)

herbivores

*Brachiosaurus* favored “an environment of slow-moving rivers, swamps, and lakes. *Brachiosaurus* was a high browser, nibbling on the treetops. It was probably as tall as 30 feet.” (Sutherland *New History* 179)

“*Diplodocus* was built like a cantilevered bridge and fed on the lower levels, sweeping up vegetation almost like a vacuum cleaner. *Diplodocus* attained lengths of about 90 feet from nose to tail.” (Sutherland *New History* 179)

“*Stegosaurus* was roughly the size of a school bus, about 30 feet long and 14 feet tall. It was a bizarre-looking dinosaur, with a tiny head held low to the ground and short forelimbs. It had a stiff tail armed with nasty-looking spikes. Perhaps its most recognizable [179] features, however, were the large plates running down its back. It is speculated that they were used in thermoregulation. *Stegosaurus* had . . . a somewhat sprawling gait, which is odd because most dinosaurs had brought their legs fairly well underneath the body.” (Sutherland *New History* 179-80)



predators

“An impressive example of the *Allosaurus* was *Saurophaganax*, which was as large as *Tyrannosaurus rex*—about 4.5 tons and 39 to 48 feet in length.” (Sutherland *New History* 180)

“*Tyrannosaurus rex*, however, would not emerge until the Cretaceous period.” (Sutherland *New History* 180)

other land creatures

“The Jurassic . . . saw some of the first birds, such as *Archaeopteryx* . . .” (Sutherland *New History* 180)

The Jurassic had turtles. (Sutherland *New History* 180)

There were “many different kinds of crocodilian.” (Sutherland *New History* 180)

“There were . . . possibly the first representatives of modern-day lizards.” (Sutherland *New History* 180)

“There were also small mammals . . .” (Sutherland *New History* 180)

Why did the dinosaurs dominate?

“After the Triassic-Jurassic extinction event, the dinosaurs were no longer just another component of the tetrapod fauna; they dominated it. A number of theories have been put forth to explain this predominance.” (Sutherland *New History* 184)

“Because they had an upright stance and an advanced metatarsal ankle, dinosaurs were more agile and stable while running.” (Sutherland *New History* 184)

“Robert Bakker, a dinosaur paleontologist, has suggested that dinosaurs were endothermic, or warm-blooded, like humans. He believes that they were active . . .” (Sutherland *New History* 184)

Michael Benton of the University of Bristol thinks “the dinosaurs were just lucky . . . He sees no evidence of dinosaurs outcompeting other creatures. He speculates that dinosaurs dominated because they were the first of their kind in the Jurassic—rapidly moving into ecological niches that had been made vacant.” (Sutherland *New History* 184)

fragmentation of Pangaea

“Dinosaurs in the Early Jurassic were not as diverse as they would become at their high point in the Late Jurassic. Unfortunately, we have very poor records of the intervening period, the Middle [184] Jurassic, often referred to as the problematic Middle Jurassic.” (Sutherland *New History* 184-85)

“Obviously, something important happened during the Middle Jurassic . . . The best possible explanation is related to the fragmentation of Pangaea. From the Middle to the Late Jurassic, the formerly vast supercontinent experienced an accelerated fragmentation. There were more barriers between areas and less mixing of creatures.” (Sutherland *New History* 185)

“This theory is confirmed from rare Jurassic sections found in Patagonia. In the Middle Jurassic, Patagonia still allowed easy access between North and South America. Dinosaurs from the two regions were often indistinguishable from one another.” (Sutherland *New History* 185)

“As time moved on, however, the sediments record that the disparity between the two forms—North American and South American—increased. Because land connections were starting to disappear, the dinosaurs were driven to even more diversity, resulting in the extraordinary dinosaur summer of the Late Jurassic.” (Sutherland *New History* 185)

suggested reading

Fastovsky and Weishampel, *The Evolution and Extinction of the Dinosaurs*.

Martin, *Introduction to the Study of Dinosaurs*.

## Dinosaur Behavior

“Spinosauridae.” *Wikipedia*. 9 Feb. 2021. 7 Mar. 2021. Web.

This lecture discusses: (Sutherland *New History* 186)

“the external appearance of dinosaurs”

“where they lived”

“how and on what they fed”

“their parenting behavior”

“whether or not they were warm-blooded”

reconstructing the dinosaurs

“A dinosaur skeleton tells us a great deal about its external appearance. . . . Using comparative anatomy—comparing dinosaurs to tetrapods, for example—we can make some fairly reasonable guesses about what these creatures looked like.” (Sutherland *New History* 186)

“Muscle scars, which occur on the bone, represent where muscles were attached by ligaments to the bone. Depending on the size of the muscle scar, we can tell how big the muscle was and how powerfully it contracted.” (Sutherland *New History* 186)

“Skin impressions have been found from a number of species of dinosaur. When dinosaurs died in soft mud, an impression of the skin sometimes became fossilized.” (Sutherland *New History* 186)

“. . . the scales of dinosaurs were very much like the scales of modern lizards . . .” (Sutherland *New History* 186)

What color were the dinosaurs?

“Pigment is not very well preserved in the fossil record; thus, the coloration in many dinosaur reconstructions is probably fanciful. However, we can assume that dinosaurs weren’t just a dull, boring grey. Some dinosaurs had crests, frills, or fringes that probably acted as display features. Given that modern-day lizards also [186] possess these structures—which are highly colored—many believe that dinosaurs were also highly colored.” (Sutherland *New History* 186-87)

feathered dinosaurs

“Dinosaur feathers that evolved for display most likely would have been colorful.” (Sutherland *New History* 187)

“Color pigment is produced in feathers by melanin and structures called melanosomes. Different shapes of melanosomes produce different types of colors.” (Sutherland *New History* 187)

“. . . a round-shaped melanosome generally produces blacks and grays . . .”

An “elongated, sausage-like melanosome tends to produce more russet colors.”

“. . . the early feathered *Sinosauropteryx* . . . had a ginger coloring and a striped tail.” (Sutherland *New History* 187)

“. . . the dinosaur *Anchiornis* was found to have black, white, and probably red feathers.” (Sutherland *New History* 187)

Where did dinosaurs live?

open ground

“Unlike the stereotype of dinosaurs wallowing in swamps, many roamed the open ground.” (Sutherland *New History* 187)

“Most had long legs placed well under the body and, thus, could run effectively. In fact, the smaller bipedal forms could probably move extremely quickly.” (Sutherland *New History* 187)

air

“It’s possible that some of the dinosaurs went airborne.” (Sutherland *New History* 187)

“*Microraptor*, a feathered dinosaur, was probably climbing up the trunks of trees and gliding between them.” (Sutherland *New History* 187)

underground

“Some dinosaurs also burrowed under the ground. . . . researchers have found *Oryctodromeus cubicularis* in fossilized burrows in southwest Montana. Within these burrows [were] an adult and two juveniles—possibly hinting at some sort of parental care.” (Sutherland *New History* 188)

water margins

“Recent research has also discovered semiaquatic dinosaurs.” (Sutherland *New History* 188)

spinosaurs

Spinosaurs (“spined reptiles,” because for some their vertebrae elongated and formed a sail) were predators up to 49 feet long.” (“Spinosauridae”)

“The osteology of spinosaurid teeth and bones has suggested a semiaquatic lifestyle for some members of this clade. This is further indicated by various anatomical adaptations, such as retracted eyes and nostrils; and the deepening of the tail in some taxa, which has been suggested to have aided in underwater propulsion akin to that of modern crocodilians.” (“Spinosauridae”)

“*Baryonyx walkeri*, a spinosaur, came from the Low Cretaceous, about 130 million years ago. It was about 28 feet long, with a crocodile-like snout filled with piercing teeth (not the serrated teeth of a meat eater). Scientists think this creature was a specialized fish eater.” (Sutherland *New History* 188)

“Oxygen levels can help us determine whether or not a creature was semiaquatic.” (Sutherland *New History* 188)

“Oxygen occurs as light oxygen-16 and heavy oxygen-18. As land creatures lose water through breathing and evaporation, oxygen-16 is preferentially evaporated, which means that the heavy oxygen-18 gets concentrated in the tooth enamel.” (Sutherland *New History* 188)

“Because aquatic animals lose less water, less oxygen-18 is present in the teeth.” (Sutherland *New History* 188)

“. . . the oxygen isotope ratio for spinosaurs was much more similar to crocodiles than to dinosaurs. This discovery is controversial, however, because the spinosaur does not show any aquatic adaptations, such as webbing between claws.” (Sutherland *New History* 188)

What did dinosaurs eat?

“The teeth of *Tyrannosaurus rex*, which look like daggers or steak knives, are clearly designed for eating meat.” (Sutherland *New History* 188)

“The teeth of the hadrosaur [look] like elephant’s teeth: They were adapted for grinding away plant material . . .” (Sutherland *New History* 188)

hunting behavior

To determine “how dinosaurs hunted . . . clues come from dinosaur brain casts . . .” (Sutherland *New History* 189)

allosaurs

Allosaurs were “the top predators of the Late Jurassic,” [189] just as *Tyrannosaurus Rex* was of the Cretaceous. [180] (Sutherland *New History* 180, 189)

Allosaurs’ “closest relatives [were] crocodiles and birds . . .” (Sutherland *New History* 189)

Brain casts of allosaurs show “its brain looks more crocodilian than birdlike. The allosaur’s olfactory bulbs, where smell is detected, were large, while its cerebrum, the processing area of the brain, was small.” (Sutherland *New History* 189)

“*Allosaurus* probably used its keen sense of smell to find its prey and then grabbed it, much as crocodiles do today.” (Sutherland *New History* 189)

killing behavior

“Larger dinosaurs may have preyed on other creatures much like big cats do today—running down [188] their prey and killing it swiftly with a single bite or by suffocation.” (Sutherland *New History* 188-89)

“Some dinosaurs may have used an ambush strategy—waylay a creature, wound it, withdraw, and wait for it to go into shock or die from loss of blood.” (Sutherland *New History* 189)

Perhaps “dinosaurs hunted in packs, as depicted in *Jurassic Park*.” (Sutherland *New History* 189)

parenting behavior

“. . . dinosaurs are often depicted like turtles, who lay their eggs and move on, leaving the baby turtles to fend for themselves.” (Sutherland *New History* 189)

Jack Homer, dinosaur paleontologist, discovered Egg Hill in western Montana. It’s “an area with nests of dinosaur eggs and juveniles that had hatched. The nests were made by *Maiasaura*, which means “caring mother lizard.” The nests themselves were closely packed, less than 7 feet apart, and contained about 30 to 40 ostrich-sized eggs, arranged in circular and spiral patterns.” (Sutherland *New History* 190)

“Scientists don’t believe that this dinosaur sat on the nest but, instead, covered the eggs with vegetation that would give off heat as it started to decompose. . . . this behavior implies some sort of parental care . . .” (Sutherland *New History* 190)

“It’s possible that, after hatching, the juveniles weren’t able to walk . . .” (Sutherland *New History* 190)

“We also have evidence of parental behavior in *Psittacosaurus*, a small bipedal dinosaur found in Early Cretaceous rocks. This wonderful specimen was found curled up over 34 juveniles.” (Sutherland *New History* 190)

Were dinosaurs warm-blooded?

“The traditional, Victorian view of dinosaurs is of slow, lumbering, dim-witted lizards.” (Sutherland *New History* 190)

Robert Bakker, in “a paper published in *Scientific American*, “Dinosaur Renaissance,” . . . proposed that dinosaurs were extremely active, warm-blooded creatures—endotherms, like humans.” (Sutherland *New History* 190)

“Today’s endotherms—birds and mammals—have limbs brought underneath their bodies. Cold-blooded animals—ectotherms—such as lizards and crocodiles, have a sprawling gait. A dinosaur’s gait is more like that of the endotherms.” (Sutherland *New History* 190)

“In isotopic evidence, because endotherms maintain a steady body temperature, the ratio between oxygen-16 and oxygen-18 should be constant throughout the skeleton. Ectotherms, in contrast, should have warmer temperatures in the middle and be colder toward the extremities. Analysis of *Tyrannosaurus rex* skeletons shows that the ratio seems to be the same as in endotherms.” (Sutherland *New History* 190)

“. . . endotherms have to eat more food than ectotherms in order to maintain a high body temperature. For example, a lion has to eat more food than a crocodile; thus, a lion will have a different predator-to-prey ratio than a crocodile. Analysis of the predator-to-prey ratio of the landscape during the time of *Tyrannosaurus rex* . . . suggests endothermy . . .” (Sutherland *New History* 191)

the gigantotherms

“. . . mice have a very high surface area-to-volume ratio; thus, they lose a lot of heat. They eat continuously and employ such techniques as shivering to keep themselves warm. Elephants have the opposite problem. They have a very low surface area-to-volume ratio, which means they retain much more heat. They have to radiate a great deal of heat from the body, which is why they have those huge ears.” (Sutherland *New History* 191)

The body size of large sauropods (herbivorous prey) “was colossal and would have generated far too much heat. These creatures might have had their own special type of metabolism, called gigantothermy.” (Sutherland *New History* 191)

“Because of their great size, sauropods probably generated a great deal of heat, which allowed them to be more active than the average ectotherm. We can see a similar solution in the cold-blooded leatherback turtle. It can reach sizes of up to 1.1 tons and migrates regularly from the tropics to the poles. The turtle has no problem maintaining its heat at the poles; it has more of an issue radiating heat in the tropics.” (Sutherland *New History* 191)

suggested reading

Bakker, *The Dinosaur Heresies*.

Fastovsky and Weishampel, *The Evolution and Extinction of the Dinosaurs*.

Martin, *Introduction to the Study of Dinosaurs*.

## Evolution of Flight

“Archaeopteryx.” *Wikipedia*. 23 Feb. 2021. 7 Mar. 2021. Web.

“Avialae.” *Wikipedia*. 23 Feb. 2021. 7 Mar. 2021. Web.

“Bipedalism.” *Wikipedia*. 6 Mar. 2021. 9 Mar. 2021.

“Mayfly.” *Wikipedia*. 1 Mar. 2021. 7 Mar. 2021. Web.

introduction

Passive flight includes “floating on air currents; parachuting, as a dandelion seed does; or gliding from tree to tree.” (Sutherland *New History* 193)

“But the flight we’ll discuss here is active—that is, flight powered by” wings. (Sutherland *New History* 193)

“In addition to wings, the first creatures that left the ground needed light, strong bodies and some form of advanced respiration.” (Sutherland *New History* 193)

flying plants

Plants probably flew first, just as “they were the first out of the water and onto the land.” (Sutherland *New History* 193)

470-458.4m (Middle Ordovician): “evidence of plant spores” (Sutherland *New History* 193)

flying insects

“The first animals took to the air soon after the establishment of the land-based ecosystem in the Silurian-Devonian.” (Sutherland *New History* 193)

443.8-419.2m: Silurian

419.2-358.9m: Devonian

“The insects were the first to achieve powered flight.” (Sutherland *New History* 193)

“These were probably floating mites or the juvenile forms of some land arthropods, which would then distribute themselves across the burgeoning new ecosystem.” (Sutherland *New History* 193)

“But the origins of insect life are obscure, at least from the standpoint of fossil evidence. The first fossilized insects come from the Carboniferous [358.9-298.9m]. These dragonfly-like creatures were already well adapted to life in the skies. Like all insects, their wings were composed of dead tissue, making them extremely light.” (Sutherland *New History* 193)

pre-wings

“A clue to how insects got into the air is in the limb system. Early arthropod limbs were paired; these creatures had a walking limb [193] and a jointed structure behind each limb called an exite. The exite was used for filtering water, or as a gill. The platelike [*sic*] structures on the insect were also used for locomotion; insects often demonstrated these structures in the larval, nymph stage of their life cycles. Such structures were the precursors of wings.” (Sutherland *New History* 193-94)

mayflies

“For indications of the earliest origins of flight, consider one of the most primitive flying insects still with us today: the mayfly.” (Sutherland *New History* 194)



“The mayfly, unlike the more advanced forms of insects, cannot fold its wings alongside its body. The nymph stage is aquatic . . .” (Sutherland *New History* 194)

“Mayflies exhibit a number of ancestral traits that were probably present in the first flying insects, such as long tails and wings that do not fold flat over the abdomen. Their immature stages are aquatic fresh water forms (called “naiads” or “nymphs”) . . .” (“Mayfly”)

“. . . it has plates along the abdomen that can be flapped in order to increase water movement for respiration, [and] can be used to propel the creature, as well.” (Sutherland *New History* 194)

“These structures appear to be, in some way, preadapted for flight. The insects already have a muscular flapping ability without having to modify an existing limb.” (Sutherland *New History* 194)

flying dinosaurs: pterosaurs

259.1-251.9m (Late Permian): “The first vertebrate to get airborne was a Late Permian diapsid reptile, *Coelurosauravus*. Its body had 20 long, curving bones with a skin membrane stretched across it. The bones were jointed at the bases; thus, this creature could probably fold its wings by the side of its body while scurrying up a tree.” (Sutherland *New History* 194)

“For a vertebrate to move across open areas, however, it needed powered flight. The first vertebrates with powered flight were the [194] pterosaurs, or “winged lizards.” These creatures were fully flight-capable vertebrates built with air spaces in their bones. Their bones were not only strong but also light—an adaptation that birds would later use.” (Sutherland *New History* 194-95)

“The pterosaurs were an extremely successful group, common around the Mesozoic, with a history of 140 million years on the planet.” (Sutherland *New History* 195)

237-201.3m (Late Triassic): “The oldest pterosaur was *Eudimor phodon*, from the Late Triassic, around 210 million years ago. Like many of the pterosaurs, there’s a suggestion that the beast was covered with a fine, downy hair.” (Sutherland *New History* 195)

“The majority of pterosaur fossils are found in shallow marine sediments. Their fossils are often associated with fishy debris, scales, and bones, so it’s likely that many of them were fish eaters.” (Sutherland *New History* 195)

“Some pterosaurs developed filter-feeding mechanisms, similar to flamingos. *Pterodaustro* probably used bristle structures to strain microorganisms and algae out of the water. *Quetzalcoatlus*, from the late Cretaceous, was most likely a scavenger, with a wingspan of 33 to 36 feet.” (Sutherland *New History* 195)

“Scientists have speculated that these creatures maintained internally generated heat, or were warm-blooded.” (Sutherland *New History* 195)

birds: introduction

“Birds are one of the most successful groups in the history of evolution. They were descended from the archosaurs, which also gave rise to the dinosaurs and the crocodiles. From the hummingbird to the albatross, birds show incredible diversity. They’re highly active and warm-blooded animals. They also have a much more efficient respiratory system than mammals do. Birds actively pump air through the lungs to support their flapping motions.” (Sutherland *New History* 195)

ancestors of the birds

*Compsognathus* was “a terrestrial dinosaur . . . [like] *Archaeopteryx*—but without feathers.” (Sutherland *New History* 196)

Like Archaeopteryx (see below), it was found in the limestone of the Solnhofen Formation. (Sutherland *New History* 196)

“Thomas Huxley, a famous supporter of Darwin, suggested that birds may have evolved from creatures that resembled small, bipedal dinosaurs. Today, the dinosaur evolution of birds is widely accepted, and in particular, it’s thought that birds evolved from the therapod dinosaurs—those bipedal dinosaurs that included everything from little *Compsognathus* to the colossal *T*. *rex*.” (Sutherland *New History* 196)

“In the Triassic period [251.9-201.3m] some groups of archosaurs (a group that includes crocodiles and dinosaurs) developed bipedalism; among the dinosaurs, all the early forms and many later groups were habitual or exclusive bipeds; the birds are members of a clade of exclusively bipedal dinosaurs, the theropods.” (“Bipedalism”)

“But this still doesn’t answer the question of how dinosaurs may have developed flight. Researchers have put forth two main hypotheses . . .” (Sutherland *New History* 196)

The two hypotheses are “from the ground up or from trees down to the ground . . .” (Sutherland *New History* 199)

“The arboreal hypothesis suggests that birds evolved from feathered, tree-climbing therapod dinosaurs. The speculation is that they jumped from trees to the ground or from tree to tree, just like a modern-day flying squirrel.” (Sutherland *New History* 196)

The cursorial (aka from-the-group-up) hypothesis “speculates that there was an ancestral feathered dinosaur. The feathers originally evolved to keep the creature warm or for display purposes. It is suggested that as this creature ran along the ground, it leapt into the air to catch insects. In that case, the feathered arms became secondarily useful for adjusting body attitude in midair. These creatures may have acquired a flapping motion to help them get up and climb surfaces.” (Sutherland *New History* 197)

*Archaeopteryx*

150m (Late Jurassic). (Sutherland *New History* 195) (“Archaeopteryx”)

Archaeopteryx is “probably the most famous fossil in the world . . .” (Sutherland *New History* 195)

It was discovered in 1874 in southern Germany, “when Europe was an archipelago of islands in a shallow warm tropical sea, much closer to the equator . . .” The largest were only 20 inches. (“Archaeopteryx”)

“Restoration of *Archaeopteryx* chasing a juvenile *Compsognathus*” (“Archaeopteryx”)



Archaeopteryx may be the “earliest known bird . . .” (Sutherland *New History* 195)

“*Archaeopteryx lithographica* . . . is possibly the earliest known avialan which may have had the capability of powered flight, though it might have been a deinonychosaur instead.” (“Avialae”)

Avialae (“bird wing”) is a clade. (“Avialae”)

“Older potential avialans have since been identified, including *Anchiornis*, *Xiaotingia*, and *Aurornis*.” (“Archaeopteryx”)

“Several older (but non flight-capable) avialans are known from the late Jurassic Tiaojishan Formation of China, dated to about 160 million years ago.” (“Avialae”)

“The Berlin specimen [was] preserved in the [195] Solnhofen limestone that was originally deposited as a rich lime sediment on the edge of the Tethys Sea along an island archipelago. The fine mud preserved the fascinating details not only of its bones but also its body outline and feathers.” (Sutherland *New History* 195-96)

Archaeopteryx has “many birdlike qualities—feathers, in particular. But other features were very much reptilian. It had a beak full of teeth; a long, bony tail; and claws on the wings. Just as Darwin had predicted, this is a true transition of form from a reptile to a bird.” (Sutherland *New History* 196)

“*Archaeopteryx*, in all likelihood, was not a strong flyer. We’re definitely looking at a transitional form . . .” (Sutherland *New History* 196)

“The general view is that such birds as *Archaeopteryx* suggest a close link to the bipedal therapod dinosaurs.” (Sutherland *New History* 197)

120m (Lower Cretaceous): *Microraptor*

The cursorial hypothesis “was the general view until a special fossil—*Microraptor*—was found. It was from the Early Cretaceous, about 120 million years ago . . .” (Sutherland *New History* 197)

“*Microraptor* had feathers on both its forelimbs and its hind limbs. It was a four-winged dinosaur. The feathers on the *Microraptor* were modern looking, asymmetrical around the shaft. This particular structure generates lift. *Microraptor* probably couldn’t flap, but it certainly could glide.” (Sutherland *New History* 197)

“But some researchers, including John Ruben of Oregon State University, speculate that birds are only a sister group of the dinosaurs, not descended from them.” (Sutherland *New History* 197)

“In Ruben’s scenario, birds evolved separately from an archosaur ancestor, developing feathers and flight, as we can see in *Archaeopteryx* and *Microraptor*. Then, some of them lost the power of flight.” (Sutherland *New History* 197)

“The result is the appearance of feathered dinosaurs, such as *Velociraptor*, a *Protarchaeopteryx*, which was found later in the Cretaceous. This, according to the hypothesis, would explain why feathered dinosaurs appear in the fossil record only after *Archaeopteryx*.” (Sutherland *New History* 197)

“This is an area of great debate. Recently, additional feathered dinosaurs discovered in China have been reported to be older than *Archaeopteryx*. Perhaps now, once again, the feathered dinosaurs could be ancestral to birds. The question is, figuratively, up in the air.” (Sutherland *New History* 198)

flying mammals

Flying squirrels are gliders. (Sutherland *New History* 198)

bats

“Bats have a geological history of about 60 million years.” (Sutherland *New History* 198)

Bats fly (flap its wings). (Sutherland *New History* 198)

“Bats are the second most diverse group of mammals (rodents are the first). . . . They’ve evolved into many different niches. Some are fruit and pollen eaters; many are insectivores; some are fish eaters; and a small proportion are vampire bats.” (Sutherland *New History* 198)

“The paleontological record for bats is poor, because their bones are delicate—very light and adapted for flying.” (Sutherland *New History* 198)

52.5m: *Onychonycteris* “lacks features around the inner ear used in echolocation in modern bats. The implication here is that it probably had to rely more on sight to hunt insects.” (Sutherland *New History* 198)

“From what group of animals did bats evolve? The answer to that question is awaiting the true transitional form. . . . The limb proportions and the clawed fingers of [*Onychonycteris*] suggest that the common ancestor may have been a good climber.” (Sutherland *New History* 198)

suggested reading

Martin, *Introduction to the Study of Dinosaurs*.

Oregon State University, “Bird-from-Dinosaur Theory ofEvolution Challenged.”

University of Manchester, “Prehistoric Birds Were Poor Flyers, Research Shows.”

## 251.9-66m (Mesozoic): Oceans

“Ichthyosaur.” *Wikipedia*. 28 Jan. 2021. 7 Mar. 2021. Web.

introduction

“The Mesozoic seas teemed with vast schools of fish of all shapes, sizes, and colors.” (Sutherland *New History* 200)

“In this lecture, we’ll consider”: (Sutherland *New History* 200)

“what was swimming in the vast shoals”

“what competed with the corals and sponges” in the reefs

“monsters of the Mesozoic oceans”

bony fish

“The most common fish today, the bony fish, which had evolved since the Devonian [419.2-358.9m], was abundant . . .” (Sutherland *New History* 200)

cephalopods (invertebrate mollusks)

Cephalopods were “more plentiful” than today. (Sutherland *New History* 200)

belemnites

“The terrors of the Ordovician seas were the orthoconic nautiloids, large squids in a conical shell. By the Mesozoic, these had evolved into many different forms, including the belemnites.” (Sutherland *New History* 200)

“Belemnites looked much like modern squid, but with hooks on their tentacles.” (Sutherland *New History* 200)

Belemnites “were common in the Mesozoic ocean.” (Sutherland *New History* 200)

The belemnites were “gone by the end of the Mesozoic . . .” (Sutherland *New History* 201)

ammonites



Ammonites (extinct) lived “in coiled shells.” (Sutherland *New History* 200)

“Much of the Mesozoic is subdivided, biostratigraphically, into what are known as ammonite zones. Because the ammonites evolved rapidly, produced many short-ranging forms, and were spread across many continents, scientists can use them to subdivide geological finds.” (Sutherland *New History* 200)

“Ammonites matured by adding a new body chamber to the shell . . . The animal lived at the end of the coil in the outermost chamber.” (Sutherland *New History* 200)

“. . . the walls called septa . . . are the chambers of the ammonite expressed on the surface of the shell. The traces are suture lines.” (Sutherland *New History* 201)

“The most primitive form of ammonites, the goniatites from the Paleozoic, had a simple suture line.” (Sutherland *New History* 201)

“Ammonites later developed a highly complex, zigzag suture line. It is speculated that a more irregular surface provided a platform to attach muscles to the shell, or that the zigzags were used to brace the shell, allowing the ammonites to dive deeper in search of prey.” (Sutherland *New History* 201)

“Ammonites moved backwards, pumping water at high pressure through a tube called the siphuncle to achieve a kind of underwater jet propulsion.” (Sutherland *New History* 201)

Many ammonites were probably able and swift swimmers. Some of their fossil shells are extremely thin, hydrodynamic objects, designed to slice through water effectively.” (Sutherland *New History* 201)

“Ammonites are found in many environments, including the open ocean. Scientists are fairly sure that many were ocean-crossing species, which explains why they are reliable for correlation. We find ammonites in very fine ocean sediments with no other shallow-water fossils nearby, indicating a deep-ocean environment.” (Sutherland *New History* 201)

The ammonites were “gone by the end of the Mesozoic . . .” (Sutherland *New History* 201)

reefs

“After corals were decimated in the Permian-Triassic extinction event, new corals—hexacorals, or Scleractinia—evolved in the Mesozoic.” (Sutherland *New History* 201)

“Sponges also became key reef builders during the Mesozoic.” (Sutherland *New History* 201)

rudists

“An important bivalve called the rudist proliferated during the Cretaceous (the last period of the Mesozoic era) and became a component of many tropical reefs. Rudists were particularly prevalent on the margins of the Tethys Ocean. These rudist reefs were many hundreds of feet tall and laterally extensive.” (Sutherland *New History* 202)

“Rudist reefs have been studied in great detail; they are not only unique and interesting but are also of great importance to the oil industry. A rudist reef has many nooks and crannies in it, lots of spaces—a feature called porosity in geology. Given their sizeable extent and high porosity, rudist reefs were ideal places for oil to accumulate.” (Sutherland *New History* 202)

“Why are there no extensive bivalve reefs today? . . . Many of the Cretaceous oceans were saltier and as much as 14° C warmer than they are today.” (Sutherland *New History* 202)

250-90m: ichthyosaurs (“Ichthyosaur”)

“Some of the primitive tetrapods that roamed the Early Devonian [419.2-393.3m] landscape gave up their legs and returned to the seas. For example, . . . ichthyosaurs . . .” (Sutherland *New History* 202)

“Ichthyosaurs overlapped in time with dinosaurs, but are distinct and not closely related to them.” (“Ichthyosaur”)

The ichthyosaurs “looked much like dolphins. These were . . . streamlined fish eaters and very much reptiles.” (Sutherland *New History* 202)

convergence

Many automobiles look similar. “There are certain optimum shapes that reduce drag . . .” (Sutherland *New History* 203)

“Tetrapods that live like dolphins will, in all likelihood, look like dolphins, at least on the outside.” (Sutherland *New History* 203)

“The resemblance between ichthyosaurs and dolphins demonstrates . . . convergence.” (Sutherland *New History* 203)

Ichthyosaurs are reptiles, and dolphins are mammals. But “they look similar, even though they’re separated by many millions of years. Because they lived in similar environments and likely exploited the environment in similar ways, they look the same.” (Sutherland *New History* 203)

*Shonisaurus*

*Shonisaurus* “was about 50 feet long.” (Sutherland *New History* 202)

In Nevada, “37 Triassic specimens of *Shonisaurus* were found fossilized side by side, all pointing in the same direction. Scientists speculate [this was a ]mass-stranding event, as we witness with whales and dolphins today.” (Sutherland *New History* 202)

eyes

“The ichthyosaur had good eyesight; it had large eye sockets in its skull.” (Sutherland *New History* 202)

“It also had odd platelike structures in the eye socket, which were likely adaptations to prevent water pressure from distorting the eye as the creature dived.” (Sutherland *New History* 202)

live births

“Like dolphins, ichthyosaurs . . . gave birth to live young.” (Sutherland *New History* 203)

“There are quite a number of fossils that actually record the death of a female in the process of giving birth to a fully developed baby ichthyosaur.” (Sutherland *New History* 203)

extinction theory

Mary Anning (1799-1847)

Mary Anning, paleontologist, “was the first person to discover and extract an ichthyosaur.” (Sutherland *New History* 203)

She became “the world’s expert on Jurassic marine reptiles.” (Sutherland *New History* 203)

Anning “supported George Cuvier’s theories about extinction.” (Sutherland *New History* 203)

Georges Cuvier (1769-1832)

Cuvier developed “comparative anatomy; he also speculated that some creatures that had existed in the past were now extinct.” (Sutherland *New History* 203)

Some theologians thought extinction implied an imperfect creation. [They] suggested [203] that the fossil forms . . . were probably not extinct—they were just extremely rare. Perhaps they existed in some unexplored area.” (Sutherland *New History* 203-04)

Anning’s impressive creatures were a “problem: Where could they be hiding?” (Sutherland *New History* 204)

112m: plesiosaurs

Anning also found the plesiosaur. (Sutherland *New History* 204)

two types

145-66 (Cretaceous): *Kronosaurus* (Sutherland *New History* 204)

“*Kronosaurus* was a Cretaceous pliosaur . . . About 40 feet long, it hunted fish, ammonites, and probably other marine reptiles . . .” (Sutherland *New History* 204)

long-necked plesiosaurs

“The second group includes the wonderful long-necked plesiosaurs, some of the most iconic of the Mesozoic aquatic reptiles. Like pliosaurs, these creatures used their paddles in a kind of underwater flying.” (Sutherland *New History* 204)

Loch Ness monster

“The plesiosaur . . . is the only Mesozoic aquatic reptile that some say still exists: the Loch Ness monster.” (Sutherland *New History* 204)

“. . . there have been no plesiosaur fossils found [in] the Cenozoic [66m-present].

“. . . it’s unlikely that plesiosaurs could have moved around on land.”

Perhaps “Nessie” is sightings “of sturgeons, ancient creatures that first appeared around 200 million years ago . . . [The sturgeon] is a living fossil. It has a hump on its back, which could explain” humpbacked Nessie. (Sutherland *New History* 204)

other monsters in Mesozoic oceans

*Deinosuchus*

“*Deinosuchus* was a giant alligator.” (Sutherland *New History* 205)

mosasaurs

“The mosasaur was also gigantic; the largest mosasaur found was *Tylosaurus*, more than 57 feet long.” (Sutherland *New History* 205)

“They were probably ambush predators, lying in wait on the ocean floor. Then, using their long tails and powerful flippers, they would swiftly attack the unsuspecting prey from below.” (Sutherland *New History* 205)

“Its jaws were armed with rows of backward-pointing teeth to hold prey securely in its mouth.” (Sutherland *New History* 205)

“. . . a bizarre-looking additional set of teeth . . . could hook into the severed flesh of its victim and push it down its gullet. Mosasaurs didn’t chew; they gulped.” (Sutherland *New History* 205)

suggested reading

Ellis, *Sea Dragons*.

Emling, *The Fossil Hunter*.

## 145-66m: Cretaceous Period

introduction

“During the Cretaceous, the continents were flooded.” (Sutherland *New History* 205)

“Europe was reduced to a series of tropical islands . . .” (Sutherland *New History* 205)

“. . . North America was cut in half from north to south by a shallow body of water.” (Sutherland *New History* 205)

“Much of the Sahara was a tropical sea.” (Sutherland *New History* 205)

“This lecture discusses”: (Sutherland *New History* 206)

“how we determine what the climate was millions of years ago”

“proxies—signs in the geological record—that can be useful for climatic determination”

“how we model ancient climates”

“what was driving the Middle to Late Cretaceous climatic system”

“effects of the Cretaceous hothouse climate”

“In the next lecture, we’ll explain the reasons for such high sea levels and tropical conditions . . .” (Sutherland *New History* 205)

reading ancient climates

“Scientists use a number of different indicators in the geological record to read ancient climatic conditions.” (Sutherland *New History* 206)

“. . . cold climates produce glacial striations, glacial dropstones, and sedimentary deposits, such as glacial till.” (Sutherland *New History* 206)

oxygen isotopes

“Climate conditions are also indicated by the ratio of light oxygen-16 to heavy oxygen-18 . . . in the fossil shells.” (Sutherland *New History* 206)

“In warmer conditions, a great deal of oxygen-16 is evaporated from the oceans and falls onto the land as rain rich in oxygen-16.” (Sutherland *New History* 206)

“But during times of glaciation, that oxygen-16 water gets locked up on the land; it doesn’t return to the oceans. At those times, the oceans exhibit enrichment in oxygen-18 . . .” (Sutherland *New History* 206)

“Extensive red desert sandstones are good indicators of arid conditions.” (Sutherland *New History* 206)

“Calcretes, or concentrations of minerals, are also indicators of hot and arid conditions. As water is drawn to the surface and evaporated, minerals are precipitated out of the water to form nodules of such substances as calcium carbonate.” (Sutherland *New History* 206)

“Other evidence of hot conditions includes mud cracks, which form polygonal patterns.” (Sutherland *New History* 206)

“Stomata, or pores, on fossil leaves tell us something about carbon dioxide levels and, by extension, greenhouse effects. The fewer stomata, the higher the carbon dioxide levels—because the plants [206] don’t require that many porous spaces on their leaves to collect the carbon dioxide they need for photosynthesis.” (Sutherland *New History* 206-07)

“Leaf shape is a good marker for determining climates.” (Sutherland *New History* 207)

“In tropical areas today, leaves tend to have smooth outlines . . .”

“. . . in temperate regions, leaves tend to have jagged outlines.”

“Tree rings are proxies for climatic states . . .” (Sutherland *New History* 207)

Thick rings indicate warm periods.

Thinner rings indicate cold conditions.

modeling ancient climates

weather vs. climate

Weather is atmospheric conditions over days. (Sutherland *New History* 207)

Climates are “atmospheric conditions over longer periods—tens of years, hundreds of thousands of years, or even millions of years.” (Sutherland *New History* 207)

“Modeling climate is highly complex because so many factors can affect climate. In studying systems that are extremely complex, we need a simplified model that gives us a hypothesis we can test using additional evidence. Climate models are commonly used to predict climate change in the future, but they can also be used to hypothesize about climates of the past.” (Sutherland *New History* 207)

A general circulation model (GCM) is “a mathematical model of Earth and its climatic system . . . to run tests on various hypotheses.” (Sutherland *New History* 207)

Since “it is impossible to mathematically model the entire planet . . ., we break the planet down into model grids. These grids divide the Earth into a series of homogeneous regions, allowing us to more easily calculate the processes and exchanges between them.” (Sutherland *New History* 207)

“The model uses these factors:” (Sutherland *New History* 207)

“the amount of carbon dioxide in the area”

“the amount of dust (which reflects sunlight)”

“water concentrations”

“level of solar radiation”

“level of radiation reflected back into space from Earth”

And it” considers interactions among the atmosphere, the ocean, and the land.” (Sutherland *New History* 207)

“Once we have a workable model—a model that seems to reflect what goes on today—we can . . . reproduce climatic conditions of the past.” (Sutherland *New History* 208)

“In modeling past climates, the model must account for ancient landforms: paleogeography.” (Sutherland *New History* 208)

“. . . the distribution of the continents is extremely important in the way the climate works . . . [It affects] the circulation of both global air masses and ocean currents.” (Sutherland *New History* 208)

example: 200m (Late Triassic): Pangaea

The “precipitation pattern . . . reveals that the interior of Pangaea was extremely dry. This matches the evidence we find in the geological record. At that time, we find many evaporites—salt deposits that form when an open body of water evaporates.” (Sutherland *New History* 208)

“The center of the continent at this time was a great distance away from the oceans. Because oceans have moderating effects on climate, [Pangaea] experienced extreme seasonal temperature variations: very hot summers and very cold winters.” (Sutherland *New History* 208)

In summer, “air rose over the warm land, creating low-pressure systems. This drew moisture from the warm, shallow Tethys Ocean, creating torrential rains.” (Sutherland *New History* 208)

In winter, “the land cooled, which caused cold air to form and then sink. Low pressure [over the ocean?] caused air and moisture to move out over the ocean; thus, the winters were dry and arid.” (Sutherland *New History* 208)

“This climatic regime is known as a monsoon. Triassic rocks support evidence of episodic seasonal rainfall.” (Sutherland *New History* 208)

ocean heat transfer hypothesis

“At the end of the Mesozoic, during the Middle Cretaceous, about 100 million years ago, there was no ice at the poles and sea levels were considerably higher than today. In contrast to the Triassic, seasonality was much reduced. This is partly explained by the fragmentation of Pangaea. There were more open seaways, which helped modify climatic extremes.” (Sutherland *New History* 209)

“How did the world arrive at this climatic state? The answer may lie in the oceans. Perhaps the Cretaceous oceans transported more warm waters to the poles than they do today. This is called the ocean heat transfer hypothesis.” (Sutherland *New History* 209)

“It’s speculated that distribution of the continents during the Cretaceous led to intense evaporation of the Tethys Ocean. This generated the formation of dense saline waters. Perhaps the dense, warm, salty water in the tropics sank into the deeper parts of the oceans, which would then act as a conveyor belt, moving warmth from the subtropics toward the poles.” (Sutherland *New History* 209)

“This is actually the opposite of what drives oceanic circulation today. Today, cold water sinks at the poles, and that drags in warm water behind it, driving oceanic circulation.” (Sutherland *New History* 209)

the Cretaceous hothouse

“The source of the extra carbon dioxide that made the Middle Cretaceous so warm was volcanic activity in the mid-ocean ridges. The continents were starting to fragment rapidly at this time.” (Sutherland *New History* 209)

“There was other volcanic activity, as well. For example, consider the Ontong Java Plateau, a vast undersea volcanic outpouring created by basalts, 19 miles thick in some places. It was at peak activity during the Middle Cretaceous. Like many other mass basalt outpourings, this was probably related to the movement of hot rocks from the Earth’s mantle—producing a great deal of carbon dioxide.” (Sutherland *New History* 209)

“The Cretaceous hothouse environment had a profound effect on the Earth. Because there was no ice at the poles, most of Earth’s water stayed in the oceans—meaning extremely high sea levels. Mid-ocean ridges were very active, producing a lot of material that displaced water, which sloughed onto the sides of the continents.” (Sutherland *New History* 210)

“The oceans at this time were very warm. Warm water occupies more volume than cold water because of the thermal expansion coefficient. Sea levels were probably the highest seen in half a billion years, with many continental interiors extensively flooded. The flooding formed warm, shallow continental seas.” (Sutherland *New History* 210)

“Large seaways penetrated North America and Africa. Much of Europe was just a series of tropical islands. These seaways helped moderate the continental climatic effects.” (Sutherland *New History* 210)

chalk seas

“Because the shallow, warm oceans were extensive and far from continental input of sediment, they were ideal locations for certain tiny marine creatures to flourish.” (Sutherland *New History* 210)

“The coccolithophores were photosynthetic algae about 5 to 10 microns across. They secreted a calcium carbonate skeleton and lived in the photic zone of the ocean—the depth to which sunlight can penetrate. When they died, their skeletons sank to form extensive sedimentary deposits.” (Sutherland *New History* 210)

“The calcium carbonate from their skeletons formed calcareous ooze. This was only possible if the seas were shallower than the carbonate compensation depth (CCD). The result: chalk.” (Sutherland *New History* 210)

“The famous white cliffs of Dover are almost 100 percent coccolith.” (Sutherland *New History* 211)



polar dinosaurs

“Another important feature of the greenhouse world is the fact that warmer temperatures permitted the existence of dinosaurs in polar regions. Dinosaur Cove in south Australia, from about 106 million years ago, represents a floodplain deposit on a developing rift [210] valley. The rift valley was part of a rift system that would eventually separate Australia from Antarctica. Australia then drifted northward to become the island continent it is today.” (Sutherland *New History* 210-11)

“Although not glacial, temperatures were certainly not tropical. They were just warm enough for extensive forests, where the dinosaurs lived. It’s likely that many species of dinosaur migrated to warmer locations during the winter but perhaps hibernated during colder times.” (Sutherland *New History* 211)

“An example of a polar dinosaur from this part of Australia—which would have been within the Antarctic Circle during the Cretaceous—is *Leaellynasaura*. This dinosaur had extremely large eyes—perhaps adapted for seeing in low-light conditions during the polar night. It is possible that these animals were warm-blooded and foraged for food during the winter. Never before or since have creatures acknowledged as reptiles been so close to the poles.” (Sutherland *New History* 211)

suggested reading

Ruddiman, W.F. *Earth*’*s Climate*: *Past and Future*. 3rd ed. Basingstoke: Macmillan Education; New York: Freeman, 2014.

Wicander and Monroe, *Historical Geology*.

## 66m: Cretaceous-Paleogene (K-Pg) Extinction Event

“Argon-Argon Dating.” *Wikipedia*. 8 Oct. 2020. 7 Mar. 2021. Web.

“Cretaceous-Paleogene (K-Pg) Extinction Event.” *Wikipedia*. 4 Mar. 2021. 7 Mar. 2021. Web.

“Extinction Event.” *Wikipedia*. 15 Nov. 2020. 17 Nov. 2020. Web.

introduction

“In a 2013 paper, Paul Renne of the Berkeley Geochronology Center dated the impact at 66.043 ± 0.011 million years ago, based on argon-argon dating. He further posits that the mass extinction occurred within 32,000 years of this date.” (“Cretaceous-Paleogene (K-Pg) Extinction Event”)

Renne, Paul R., et al. “Time Scales of Critical Events Around the Cretaceous-Paleogene Boundary.” *Science* 339.6120 (7 Feb. 2013) 684-687.

“Argon–argon (or 40Ar/39Ar) dating is a radiometric dating method invented to supersede potassium-argon (K/Ar) dating in accuracy.” (“Argon-Argon Dating”)

“In German, the translation for Cretaceous is spelled with a *K* . . .” Hence “K-Pg.” (Sutherland *New History* 213)

It was called the Cretaceous-Tertiary event, but “The term Tertiary was removed by the International Union of Geological Sciences . . .” (Sutherland *New History* 213)

“Of all the extinction events in paleontology, the K-P is probably the most studied.” (Sutherland *New History* 213)

If birds come from dinosaurs, then only non-avian dinosaurs went extinct. (Sutherland *New History* 218)

the K-P extinction event

“In addition to the dinosaurs, many other creatures—50 percent of all species—were lost in the K-P extinction event.” (Sutherland *New History* 213)

Or: 75% of species. (“Extinction Event”)

“On land, few creatures weighing more than 25 kilograms [55 lb.] survived.” (Sutherland *New History* 213)

Crocodiles and alligators were exceptions. (Sutherland *New History* 213)

“The reason these animals are still with us today is that they are generalists: They will eat virtually anything. They can also survive for long periods with absolutely no food at all.” (Sutherland *New History* 213)

Many generalists that “made it through to the Paleogene . . . were mammals.” (Sutherland *New History* 213)

“Specialists are the ones that suffer the most in extinction events.” (Sutherland *New History* 213)

“The K-P extinction event was even more severe in the oceans—killing off 80 to 90 percent of species. All those magnificent marine reptiles—plesiosaurs, pliosaurs, and ichthyosaurs—and the ammonites and other cephalopods would be gone forever.” (Sutherland *New History* 213)

1981: paper by Luis and Walter Alvarez

Gubbio limestones

“Luis Alvarez received [213] the Nobel Prize for his work on particle physics. His son, Walter, became a geologist at the University of California, Berkeley, studying sedimentary rocks in the province of Umbria near Gubbio . . .” (Sutherland *New History* 213-14)

The limestone cliffs surrounding Gubbio “record the transition from the Cretaceous to the Paleogene [and] cross the extinction event.” (Sutherland *New History* 214)

“The transition is marked by a very thin layer of clay, about 0.4 inches wide.” (Sutherland *New History* 214)

“The area below the cleft contains dinosaurs and ammonites, but above it, they are gone forever. Walter Alvarez took a sample from the clay section that crosses the K-P boundary and asked his father for help. They asked how long it took for the clay to be deposited. Did it accumulate slowly over millions of years, or did it represent a rapid event—something that was deposited in a geological blink of an eye?” (Sutherland *New History* 214)

iridium spike

“The answer lies in . . . the accumulation rates of [iridium in sediments]. Although iridium is scarce in the Earth’s crust, our planet receives a continual rain of micrometeorites rich in iridium; thus, the iridium accumulation rate is known.” (Sutherland *New History* 214)

“The Alvarez team used neutron activation analysis to determine the amount of iridium in the clay sample. [They found] a massive spike in iridium [in] the clay but not in the limestone below or above it.” (Sutherland *New History* 214)

“The sheer volume of iridium could not have accumulated through slow processes. There was really only one reasonable explanation: There was a delivery source with a high concentration of iridium—something like a very large meteor or comet.” (Sutherland *New History* 214)

Also, the “clay layer containing iridium . . . was found virtually all over the world.” (Sutherland *New History* 214-15)

supporting evidence for the impact

ferns

“Among the first plants to colonize an area after fire devastation are ferns. When they reproduce, they release spores, which then become incorporated in the sediments around that area. A vertical core of sedimentation will [show spikes,] a proxy for fire devastation. In fact, just after the K-P boundary, all over the world, a large spike in fern spores has been noted. . . . the entire world experienced fire devastation . . .” (Sutherland *New History* 215)

tektites and microspherules

“Other important features were found in the clay layer: tektites and microspherules. These are produced by molten rock splashing out of an area after a large and energetic explosion. Tektites often take a teardrop shape. Microspherules represent a fine spray of multi-material. Interestingly, a concentration of these features was found between North and South America.” (Sutherland *New History* 215)

shocked quartz

“Another piece of evidence comes from shocked quartz, which develops crosshatched lines in large, energetic explosions. Shocked quartz is also present in high concentrations between North and South America.” (Sutherland *New History* 216)

mega-tsunami

“Sedimentary rocks reveal . . . a mega-tsunami—one so huge that it cannot be explained by normal phenomena. Something at the end of the Cretaceous created tsunamis that penetrated very deep into the continental interiors. The evidence points toward a potential impact in the ocean.” (Sutherland *New History* 216)

Chicxulub crater

“Based on the iridium present in the clay layer, the Alvarez team speculated that the impacting body would be more than 6 miles in diameter. An object this size could not have been vaporized in an airburst; this one would have left a very large hole.” (Sutherland *New History* 216)

“In 1951, a Mexican company was drilling off the coast of Mexico around the Yucatan Peninsula. The deeper the workers drilled, the stranger the rocks became. They started to see evidence of fracturing and melting of rocks, and at the very lowest levels of the drill core, the rocks were completely melted.” (Sutherland *New History* 216)

“In 1978, geophysicists looking for structures indicating the presence of oil found a large circular structure around the coastline of Yucatan, which they imaged using gravity and magnetic analyses. However, due to company confidentiality, they were prevented from releasing the data until 1981 . . . [the year] the Alvarez team published the impact paper.” (Sutherland *New History* 216)

“The crater—called Chicxulub Crater (meaning “tail of the devil” in Mayan)—is about 112 miles across. Tektites and shocked quartz become thicker toward the structure. Analysis of the crater suggests the cosmic body had a fairly shallow entry, at about 20 to 30 [216] degrees. Any more shallow and we might still have dinosaurs with us today.” (Sutherland *New History* 216-17)

“The rock was probably about 6 miles in size. Think of Mount Everest [slamming] the Yucatan Peninsula.” (Sutherland *New History* 217)

“Further evidence in the form of ejecta was found. The impacting body entered from the southeast, which meant that most of the ejecta was thrown out to the northwest. In fact, Texas is blanketed with a thick layer of crater debris.” (Sutherland *New History* 217)

“The energy released was the equivalent of about 6.2 x 107 tons of TNT. That kind of explosion does not simply fracture or melt rock; it vaporizes it. It is estimated that about 62 cubic kilometers of rock was literally vaporized in a flash.” (Sutherland *New History* 217)

last day of the Cretaceous

“At the moment of impact, there was a detonation, a pulse of intense heat and light, vaporizing everything close by. Any organic material farther away spontaneously combusted. The Earth rang like a bell with seismic energy. The shock wave hurled superheated rock debris and molten material around the globe. It generated the largest tsunami seen in more than 600 million years.” (Sutherland *New History* 217)

“Millions of tons of dust and debris were thrown up into the atmosphere, where it would stay suspended, perhaps for many months. This caused the Earth to cool and photosynthesis to cease.” (Sutherland *New History* 217)

“Even after the dust settled, the times of cold and darkness severely affected plant life. Consequently, herbivores starved, and the carnivores followed.” (Sutherland *New History* 217)

“Much of the rock that was vaporized was limestone, or calcium carbonate. When limestone is vaporized, it creates carbon dioxide. The climate would flip-flop rapidly from cold, dark conditions lasting for months, to hot conditions lasting for decades or even longer.” (Sutherland *New History* 217)

“Even worse, the high-yield detonation physically burned the air, combining oxygen and nitrogen to form oxides of nitrogen. These would dissolve in water in the atmosphere and then fall to the Earth as dilute nitric acid—further polluting the soils, killing off more plants, and affecting the base of the food chain to an even greater degree.” (Sutherland *New History* 218)

additional causes?

The extinction may have had causes in addition to an impact. (Sutherland *New History* 218)

Microplankton (*sic*) and dinosaurs “correlate precisely with the extinction event, but other groups, such as the ammonites, were already in decline. [Perhaps] the Cretaceous biosphere was already stressed by volcanic activity.” (Sutherland *New History* 218)

suggested reading

Bakker, *The Dinosaur Heresies*.

Fastovsky and Weishampel, *The Evolution and Extinction of the Dinosaurs*.

Freie Universitaet Berlin, “Prolonged Climatic Stress Main Reason for Mass Extinction 65 Million Years Ago, Paleontologist Says.”

Hallam, *Catastrophes and Lesser Calamities*.

Imperial College London, “Asteroid Killed Off the Dinosaurs, Says International Scientific Panel.”

## The Collision of North and South America

introduction

“Sometimes, we see a gradual turnover in species.” (Sutherland *New History* 220)

“This lecture examines what happened in the Americas—particularly South America—in the period just after the dinosaurs . . .” (Sutherland *New History* 220)

South America isolated

66m: the continents looked much as they do now. (Sutherland *New History* 220)

But “South America and North America were separated . . .” (Sutherland *New History* 220)

“Central America was probably a peninsula of North America, and most likely, a series of islands sat between North America and South America. Sea levels were still fairly high.” (Sutherland *New History* 220)

South America “was isolated from the other continental landmasses by at least the Middle Cretaceous [c. 80m] . . .” (Sutherland *New History* 220) (80m: Sutherland *New History* 222)

“Following the continental isolation of South America 80 million years ago, the animal population evolved independently for 60 million years, with just the occasional invader. As a result, South America would develop a unique ecosystem.” (Sutherland *New History* 222)

“Like Australia, which was a lifeboat for the marsupials, South America also protected unique creatures from waves of new forms that migrated throughout other parts of the world.” (Sutherland *New History* 220)

South America “preserved many Early Cretaceous and perhaps some of the Late Jurassic dinosaurs and mammals that went extinct in other parts of the world.” (Sutherland *New History* 220)

Australian megafauna

“During the Late Cretaceous, marsupials (pouched mammals) and placental mammals (the group humans belong to) were probably able to swim or raft on mats of vegetation between islands. Scientists believe that a certain marsupial in South America migrated all the way to Australia via Antarctica about 50 million years ago.” (Sutherland *New History* 221)

“It has been suggested that from that initial wanderer—a relative of the South American marsupial known as the little mountain monkey, or *Dromiciops*—a radiation of Australian marsupials took place, giving us kangaroos, koalas, and wombats.” (Sutherland *New History* 221)

“An evolution also took place of Australian marsupial megafauna—a unique group of large Australian animals that would grace the continent 1.6 million to 50,000 years ago. Most of them would be extinct by around 46,000 years ago, which appears to match the timeline of the arrival of humans in Australia. It has been suggested that a combination of burning the landscape to drive prey and hunting itself eventually led to the demise of these large creatures.” (Sutherland *New History* 221)

“*Genyornis* was a class of flightless birds, some of which may have been carnivorous.” (Sutherland *New History* 221)

“*Megalania* was a giant monitor lizard, about 23 feet long.” (Sutherland *New History* 221)

“*Meiolania* was an 8-foot turtle that had various horns and protrusions on its shell.” (Sutherland *New History* 221)

“giant marsupials

“*Diprotodon* was a rhino-sized wombat, about 10 feet long and 6.5 feet at the shoulder. It inhabited open woodland and grassland areas, eating leaves, shrubs, and grasses.” (Sutherland *New History* 221)

“The giant short-faced kangaroo, *Procoptodon goliah*, was about 6.5 feet tall. It had teeth adapted for chewing tough desert plants and could probably jump much higher than modern kangaroos.” (Sutherland *New History* 221)

“Another relative of the modern kangaroo was *Propleopus oscillans*, an opportunistic omnivore with large shearing teeth.” (Sutherland *New History* 221)

“The marsupial lion, *Thylacoleo carnufex*, weighed about 220 pounds and had large slicing cheek teeth and a retractable thumb claw.” (Sutherland *New History* 222)

convergent evolution

“Some of the South American marsupials, such as the opossum, can be found in North America today.” (Sutherland *New History* 222)

“Many creatures from this time, however, have gone extinct.” (Sutherland *New History* 222)

“. . . many South American forms, demonstrates convergent evolution—a situation in which creatures that belong to different groups start to resemble each other because they occupy similar ecological niches.” (Sutherland *New History* 222)

*Protypotherium* was a “rabbitlike mammal [and] probably an agile burrower, like modern rabbits.” (Sutherland *New History* 222)

*Diadiaphorus* was a “horselike mammal [with] three toes, one of which touched the ground like a hoof.” (Sutherland *New History* 222)

*Macrauchenia* was “first discovered as a fossil by Charles Darwin . . .” It was a “camel-like mammal . . . about 10 feet long and had a bizarre short trunk on its face.” (Sutherland *New History* 222)

“*Thylacosmilus* was “the South American equivalent of the North American *Smilodon*, a saber-toothed cat.” (Sutherland *New History* 222)

“It belonged to a sister group of the marsupials . . .” (Sutherland *New History* 222)

“It was a 330-pound predator . . .” (Sutherland *New History* 222)

It is “one of the most dramatic examples of convergent evolution between North America and South America.” (Sutherland *New History* 222)

borhyaenids

Borhyaenids “resembled a large Tasmanian devil.” (Sutherland *New History* 223)

“They were about 5 to 6 feet long and had [222] strong, bone-crunching jaws.” (Sutherland *New History* 222-23)

They were a top predator “that preyed on the giant marsupials.” (Sutherland *New History* 222)

“They were definitely marsupial-like, with a pouch to carry their young.” (Sutherland *New History* 222)

*Glyptodon*

“*Glyptodon*, a heavily armored animal, was about the same size and weight as a Volkswagen Beetle.” (Sutherland *New History* 223)

Its evolution converged with that of *Ankylosaurus*, “a Late Cretaceous dinosaur common in western North America.” (Sutherland *New History* 223)

*Megatherium*

Charles Darwin discovered a *Megatherium* fossil “during his voyage on the HMS *Beagle* . . .” (Sutherland *New History* 223)

*Megatherium* was “an elephant-sized ground sloth weighing around 6 tons.” (Sutherland *New History* 223)

It is “Perhaps the most iconic animal of the South American fauna . . .” (Sutherland *New History* 223)

31m (Oligocene): invaders from Africa

“The Atlantic Ocean was not as wide as it is today, and species may have arrived on drifting plant material . . . after heavy rains or flooding.” (Sutherland *New History* 223)

African rodents evolved into “the capybara and the chinchilla.” (Sutherland *New History* 223)

25m: primates “diversified into New World monkeys.” (Sutherland *New History* 223)

“Tortoises were another invader from Africa. Even after they arrived in South America, they continued across the continent and embarked on another sea journey, floating out into the Pacific and eventually colonizing the Galapagos Islands. They would diversify into a number of forms there, where Charles Darwin eventually encountered them—an event that initiated his theory of evolution.” (Sutherland *New History* 224)

invaders to and from North America

9m: “*Megatherium*-like ground sloths worked their way to North America . . .” (Sutherland *New History* 224)

6m: “*Chapalmalania* was a 5- foot, bearlike raccoon.” (Sutherland *New History* 224)

3m: *Titanis walleri* was a “flightless ptera bird . . . Around 8 feet tall, it . . . probably had a large, powerful, hooklike beak.” (Sutherland *New History* 224)

Isthmus of Panama

“Over time, South America drifted toward Central and North America, and the ocean plate below the Pacific became subducted below the Caribbean plate. Above this line of contact, a series of volcanic islands developed. Sediments eroded from the islands and from both North America and South America gradually filled in the gaps between the continents, forming the Isthmus of Panama.” (Sutherland *New History* 224)

by 3m: “the land bridge was in place.” (Sutherland *New History* 224)

from N to S: “Camels, elephants, bears, deer, tapirs, skunks, rabbits, cats, dogs, kangaroo rats, and shrews . . .” (Sutherland *New History* 224)

from S to N: “monkeys, opossums, anteaters, sloths, armadillos, porcupines, and glyptodonts.” (Sutherland *New History* 224)

Many South-American forms went extinct. (Sutherland *New History* 224)

North-American cats and dogs outcompeted the ptera birds. (Sutherland *New History* 224-25)

North-American *Smilodon* outcompeted *Thylacosmilus*. (Sutherland *New History* 225)

North-American bears outcompeted the giant bearlike raccoon. (Sutherland *New History* 225)

North-American savanna grazers replaced most of their equivalents. (Sutherland *New History* 225)

“The only truly successful migrants northward were armadillos, opossums, and porcupines.” (Sutherland *New History* 224-25)

creatures toughened by competition

“Why did the South American forms fare so badly? Scientists speculate that the reason was climate. Creatures that could survive tropical conditions in Central America found similar conditions southward. Those traveling north, however, quickly encountered far drier and eventually colder conditions—placing a cap on their migration.” (Sutherland *New History* 225)

“There may have been a more profound reason, as well—a reason that concerns the playing field of evolution of both groups.” (Sutherland *New History* 225)

“South America had been isolated; thus, competition would come only from within that landmass. North America was not only physically larger, but it also had a landmass near today’s Alaska—called Beringia—that linked North America to Asia.” (Sutherland *New History* 225)

“Beringia was about 1000 miles wide; this large corridor was particularly important during ice ages, when sea levels fell. It was not glaciated and probably experienced only light snowfall; it was a large grassland steppe, ideal for the migration of creatures.” (Sutherland *New History* 225)

“Creatures from as far away as Africa were free to migrate, mix, and mingle with North American forms. The result was a much tougher proving ground for North American animals. . . . The South America native fauna . . . found it difficult to compete with the battle-hardened northerners.” (Sutherland *New History* 225)

great schism

The Isthmus of Panama caused “the great schism” of the oceans. (Sutherland *New History* 226)

“The great schism halted the mixing of Pacific Ocean and Caribbean Sea creatures, which led to independent evolution in some marine forms.”

“In addition, the elimination of nutrient-bearing currents from the Pacific into the Caribbean led to extinctions in forms dependent on those nutrient-rich waters.” (Sutherland *New History* 226)

suggested reading

Gould, ed., *The Book of Life*.

Kemp, *The Origin and Evolution of Mammals*.

Smithsonian Tropical Research Institute, “Sex in the Caribbean.”

## 2.58-0.0117m: The Pleistocene and Mammals

introduction

by 2.6m: “the ice was back. In the next lecture, we will see how the Gulf Stream was changed by the Isthmus of Panama. We will also see how mammals evolved after the dinosaurs—and, ultimately, how they would cope with the return of the glaciers.” (Sutherland *New History* 226)

“This lecture deals with”: (Sutherland *New History* 227)

“the evolution of mammals in the Cenozoic era”

“the mammalian radiation of new forms after the dinosaurs”

“the return of Earth to a grip of ice”

“what happened to the mammalian megafauna”

mammal predecessors

synapsid reptiles

These gave rise to cynodonts. (Sutherland *New History* 27)

cynodonts

“Mammals probably evolved from cynodonts . . .” (Sutherland *New History* 227)

“Cynodonts may have had the first indications of mammalian characteristics, such as whiskers and fur.” (Sutherland *New History* 227)

200m (Late Triassic): first mammals

“Mammals actually evolved about the same time as the dinosaurs . . . but were outcompeted during the Mesozoic.” (Sutherland *New History* 227)

“One of the earliest mammals in fossil form was the mouse-sized *Megazostrodon* from the Late Triassic. Most likely a nocturnal insectivore, it also probably laid eggs like its cynodont ancestors.” (Sutherland *New History* 227)

*Repenomamus* (Triassic) was an “early large mammal . . ., about 1 meter long.” (Sutherland *New History* 227)

“Some of its fossils have been found with a stomach full of young dinosaurs.” (Sutherland *New History* 227)

But most mammals “were restricted to the undergrowth, scurrying around the feet of the dinosaurs.” (Sutherland *New History* 227)

251.9-66m (Mesozoic): “mammals were not very diverse [because] dinosaurs already occupied all the ecological niches.” (Sutherland *New History* 227)

“Even after the extinction of the dinosaurs, mammals remained relatively small insectivores. They did not achieve even moderate sizes until long after the end of the Cretaceous [66m].” (Sutherland *New History* 227)

a forest world

Why didn’t mammals “diversify to form large creatures immediately (geologically speaking) after the extinction of the dinosaurs?” (Sutherland *New History* 241)

“One hypothesis for the lack of mammalian radiation is that much of the Earth at this time was covered in dense forests.” (Sutherland *New History* 228)

66-56m (Early Paleogene): “the Earth was much warmer than it is today. The tropics and subtropics extended farther north and south; deciduous trees grew fairly near the North Pole.” (Sutherland *New History* 228)

“This environment reduced the variety of ecological opportunities for mammals to exploit.” (Sutherland *New History* 228)

66-56m: “Temperatures continued to increase through this period, reaching a high point about [56m]. Temperatures increased by about 6 degrees over 20,000 years. Fossil alligators have been found near the North Pole, and palm trees have been found in parts of Alaska.” (Sutherland *New History* 228)

mesonychids: “The first primitive doglike mammalian carnivores . . .” (Sutherland *New History* 228)

“This period also saw primitive horses, as well as primates.” (Sutherland *New History* 228)

*Ambulocetus* (walking whale) was a transitional form, “a four-legged creature that swam but was quite able to walk on land. It’s likely that all the whales and dolphins in today’s oceans evolved from *Ambulocetus*.” (Sutherland *New History* 228)

56-33.9m (Eocene): the Messel Pit

The Messel Pit in Germany “was tropical forest surrounding a series of lakes.” (Sutherland *New History* 228)

It is “a site for coal and oil shale extraction . . . The bottom of those lakes became rich in organic debris . . .” (Sutherland *New History* 228)

“Because of the anoxic bottom environment, creatures that fell into the lake and settled had a high probability of becoming fossils.” (Sutherland *New History* 228)

“Most of the mammal fossils are small, probably because of the dense forested environment.” (Sutherland *New History* 229)

“*Archaeonycteris* was a primitive bat.” (Sutherland *New History* 228)

*Leptictidium* (2-3 feet) was bipedal. (Sutherland *New History* 228)

*Propalaeotherium* was “a [228] cat-sized ancestor of the horse.” (Sutherland *New History* 228-29)

warming during the Eocene

“What were the causes of high temperatures during the Eocene? Because there was more carbon dioxide gas in the atmosphere from volcanic emissions, there may have been an increased greenhouse effect.” (Sutherland *New History* 229)

“An intriguing possibility, however, is that high temperatures resulted from burning peat; the Paleocene is known for high peat accumulation. Changes in the Earth’s orbit may also have helped keep the planet warm.” (Sutherland *New History* 229)

“Whatever the cause, the warming may have destabilized clathrates—methane gas trapped in ice. The released methane would increase the greenhouse potential for the planet. At this time, the world was at its warmest. Following the Eocene, the Earth moved into a long period of global cooling.” (Sutherland *New History* 229)

mammal domination

“By the end of the Eocene [56-33.9m], mammals started to dominate the Earth.” (Sutherland *New History* 229)

oceans

Some creatures “diversified into a series of fully aquatic mammals.” (Sutherland *New History* 229)

“. . . legs disappeared and became flippers.” (Sutherland *New History* 229)

41.3-33.9m: *Basilosaurus* (2 species of ancient whale), “about 52 feet long, was the apex predator in the Eocene oceans—a worthy successor to the mosasaurs of the Cretaceous.” (Sutherland *New History* 229)

“Despite setbacks, the mammals flourished, at least partly because—unlike fish, amphibians, and most reptiles—they have highly differentiated teeth. This allows them to adapt to a variety of diets and environments.” (Sutherland *New History* 233)

33.9-23.03m: Oligocene Epoch

“The climate was shifting, however. By the Oligocene, . . . The steamy, lush jungles of the Eocene were replaced by a more open landscape.” (Sutherland *New History* 229)

“The world was still warm . . .” (Sutherland *New History* 229)

But “there was ice at both poles.” (Sutherland *New History* 229)

“Sea levels began to drop.” (Sutherland *New History* 229)

The world “was getting more seasonal.” (Sutherland *New History* 229)

“. . . many of the modern frogs and insects evolved.” (Sutherland *New History* 229)

“Apelike and monkeylike primates” appeared. (Sutherland *New History* 229)

“Carnivora, the modern meat-eating mammals, [replaced] earlier carnivorous mammals, such as *Andrewsarchus*.” (Sutherland *New History* 230)

23.03-5.333: Miocene Epoch

The climate became “increasingly seasonal.” (Sutherland *New History* 230)

“. . . the biosphere was starting to look quite modern.” (Sutherland *New History* 230)

“Grasses and herbs spread . . .” (Sutherland *New History* 230)

“The rhino and horse families became less common . . .” (Sutherland *New History* 230)

Deer and the Bovidae (“antelopes, sheep, goats, and cattle”) became more common. (Sutherland *New History* 230)

“Carnivores began to take on their modern forms.” (Sutherland *New History* 230)

5.333-3.6m: Early Pliocene

“There would be a brief return to warm conditions . . .” (Sutherland *New History* 230)

2.58-0.0117m: Pleistocene

“. . . Earth entered the current ice age. This ice age would comprise a number of glacial and interglacial periods.” (Sutherland *New History* 230)

“. . . three ice caps formed: over North America, Greenland, and Scandinavia. Today, only the Greenland ice cap survives.” (Sutherland *New History* 230)

cause of the glaciation: the Isthmus of Panama

“The cause of this glaciation is still is a matter of debate.” (Sutherland *New History* 230)

“Carbon dioxide levels had dropped, but that was 2 million years before the ice age.” (Sutherland *New History* 230)

“Scientists believe the trigger factor for the most recent ice age was the creation of the Isthmus of Panama and its effects on the Gulf Stream.” (Sutherland *New History* 230)

“The Gulf Stream is a rapidly moving warm ocean current. It forms around Florida and follows the east coast of North America. It then moves out into the Atlantic Ocean and toward northern Europe. It was famously mapped by the polymath Benjamin Franklin, who also gave the Gulf Stream its name.” (Sutherland *New History* 230)

“Today, trade winds carry water evaporated from the Atlantic to the Pacific, making the Atlantic more saline than the Pacific. This also makes the Gulf Stream denser, which causes it to sink just north of Iceland.” (Sutherland *New History* 230)

“Before the formation of the Isthmus of Panama, the waters of the Pacific and the Atlantic were free to mingle; the salinities in the Gulf Stream were lower and the water was less dense. This permitted the warm waters from the Gulf of Mexico to flow farther north, keeping the Arctic free of ice. When the isthmus formed 3 million years ago, ice soon began to develop in the northern hemisphere.” (Sutherland *New History* 231)

Milankovich cycles

Milutin Milanković ((1879-1958), “a Serbian civil engineer and mathematician, put forth an explanation for the cycle of glacial advances and retreats. He speculated that the Earth’s movements through space affected the amount of solar radiation reaching the surface of the planet . . .” (Sutherland *New History* 231)

eccentricity cycle: Earth’s revolutions

“The eccentricity cycle, a period of about 90,000 to 100,000 years, describes how the Earth’s orbit changes from a circular orbit, in which conditions will be warmer, to an elliptical orbit, in which they will be cooler.” (Sutherland *New History* 231)

obliquity: axial tilt

“Obliquity describes the axial tilt of the Earth. The maximum tilt is 24.5 degrees; the minimum is 22.5 degrees. Today, we’re at about 23.5 degrees. To move from the maximum tilt to the minimum tilt takes about 41,000 years. During times of minimum tilt, the polar regions get the most heat from the sunlight during the summer.” (Sutherland *New History* 231)

precession cycle: wobble

“The precession cycle, about 26,000 years, describes the way the Earth’s axis moves—like a wobbling top or a gyroscope.” (Sutherland *New History* 231)

“Milankovié speculated that if all those cycles combined to a point where the Earth was receiving minimal sunlight and coincided with low levels of carbon dioxide, a perfect storm of cooling would result.” (Sutherland *New History* 231)

“The glacial periods appear to match the orbital forcing mechanisms.” (Sutherland *New History* 231)

land bridges appear

“The last glacial advance was 35,000 to 12,900 years ago, peaking [231] about 20,000 years ago. Sea levels dropped considerably and large areas of low-lying land opened up.” (Sutherland *New History* 231-32)

“Beringia appeared between North America and Asia . . .” (Sutherland *New History* 232)

Doggerland appeared between the UK and Europe. (Sutherland *New History* 232)

These vast areas of open grasslands allowed creatures to migrate freely.” (Sutherland *New History* 232)

Pleistocene megafauna

“The spectacular megafauna that evolved in a cooler and drier world are familiar to us: wooly rhinos, mastodons, and mammoths.” (Sutherland *New History* 232)

“With spectacular megafauna herbivores come spectacular megafauna carnivores.” (Sutherland *New History* 232)

“The short-faced bear, the apex predator of this environment, was at least 21 percent larger than a Kodiak bear.” (Sutherland *New History* 232)

*Smilodon* was the saber-toothed cat. (Sutherland *New History* 232)

megafauna extinction

“The megafauna disappeared rapidly 15,000 to 10,000 years ago. In North America, 33 taxa became extinct; in Eurasia, about 21 taxa became extinct. This was not a mass extinction event, but it did seem to target the big creatures.” (Sutherland *New History* 232)

“A combination of climate change and overhunting probably led to the animal extinctions.” (Sutherland *New History* 232)

Humans were “a new super-predator . . .” (Sutherland *New History* 232)

“The Lascaux Cave paintings in France illustrate that humans coexisted with these enormous creatures.” (Sutherland *New History* 232)



“In Africa, many of the megafauna—such as giraffes and elephants—still exist, perhaps because they coevolved with humans. When humans migrated to Europe and North America, however, they encountered fauna that lacked the behavioral adaptations that would allow them to survive this new wave of super-predators.” (Sutherland *New History* 232)

“In North America, the appearance of the Clovis culture coincides with some extinctions in the megafauna.” (Sutherland *New History* 232)

suggested reading

Kemp, *The Origin and Evolution of Mammals*.

Martin, *Twilight of the Mammoths*.

## Human Origins

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“Bipedalism.” *Wikipedia*. 6 Mar. 2021. 9 Mar. 2021.

“Order (Biology).” *Wikipedia*. 1 Feb. 2021. 8 Mar. 2021. Web.

“Simian.” *Wikipedia*. 19 Feb. 2021. 8 Mar. 2021. Web.

“When Did They Live?” *PBS*.*org*. 2001. 9 Mar. 2021. Web.

introduction

1859: in “*On the Origin of Species*, Darwin deliberately left human origins alone, stating, “light will be thrown on the origin of man and his history.”” (Sutherland *New History* 235)

“This lecture looks at”: (Sutherland *New History* 235)

“the place of humans on the tree of life”

the origins of primates

“the end of the golden age of the apes”

“the nature of the first ape men”

humans on the tree of life

primates: lemurs, tarsiers, monkeys, apes, humans. (Sutherland *New History* 235)

previous classification

infraorder Anthropoidea (Simiiformes: simians or anthropoids; monkeys and apes) were the “New World monkeys, Old World monkeys, apes, and humans . . .” (“Simian”)

The suborder Prosimii (prosimians) were the tarsiers and strepsirrhines. (“Simian”)

current classification (“Simian”; other web pages)

domain Eukaryota

kingdom Animalia

phylum Chordata

superclass Tetrapoda

class Mammalia

order Primates

suborder Haplorhini (tarsiers and simians)

infraorder Simiiformes (monkeys, apes, humans)

parvorder (or infraorder) Catarrhini (Old World monkeys and apes)

superfamily Hominoidea (apes and humans)

family Hominidae (great apes and humans)

subfamily Homininae (African apes and humans)

genus Homo

species sapiens

Hominoidea: apes: (gibbons, orangutans, gorillas, chimpanzees) and humans

Hominidae: great apes (orangutans, gorillas, and chimpanzees) and humans

“Under the Linnaean scheme, we had the Hominidae all to ourselves.” To emphasize our difference. (Sutherland *New History* 235)

Under cladistic rules, orangutans, gorillas, and chimpanzees must be included or “the grouping is not valid . . .” (Sutherland *New History* 235)

“. . . we are, after all, more than 98 percent chimp.” (Sutherland *New History* 235)

Homininae: African apes (gorillas and chimpanzees) and humans

Hominini: chimpanzees and humans

chimpanzees

Australopithecines

*Homo*: “we are the sole surviving representative . . .” (Sutherland *New History* 235)

66-56m (Paleocene): earliest primates

Probably “the ancestors of the primates evolved during the time of the dinosaurs.” (Sutherland *New History* 236)

63m: *Purgatorius* (“just after the extinction of the dinosaurs”) (Sutherland *New History* 236)

“One of the earliest ancestors of the primates was a shrewlike creature . . . about 6 inches long.” (Sutherland *New History* 236)

Its teeth are definitely primate. It was probably “a diurnal insectivore.” (Sutherland *New History* 236)

“*Purgatorius* was recovered from the Hell Creek Formation in Montana.” (Sutherland *New History* 236)

58m: *Plesiadapis*

*Plesiadapis* was “a fairly small mammal with chisel-like incisors and a long snout that makes it look more like a rodent than a primate.” (Sutherland *New History* 236)

It “was more of a ground dweller than a tree dweller.” (Sutherland *New History* 236)

56m: *Dryomomys*

*Dryomomys* was a “tree-dwelling primate . . . the size of a mouse.” (Sutherland *New History* 236)

56-33.9m (Eocene): prosimians

“. . . in dense tropical forests that covered much of the planet . . . lemur-like creatures evolved . . .” (Sutherland *New History* 236)

47m: *Darwinius masillae* (aka Ida)

Ida was found in 2009 in the Messel Pit. (Sutherland *New History* 236)

Ida is “only distantly related to humans and probably more directly related to lemurs and lorises.” (Sutherland *New History* 236)

23.03-5.333m (Miocene): the golden age of apes

By 23m, “monkeys had evolved.” (Sutherland *New History* 237)

*Aegptopithecus* was “about the size of a house cat.” (Sutherland *New History* 237)

“These monkeys, technically known as anthropoids, probably outcompeted and replaced the earlier prosimians.” (Sutherland *New History* 237)

“Up to about 8 million years ago, the world could be described as the golden age of apes. A diverse group, the apes made up more than 50 species. Some, such as *Sivapithecus*, were large; others, such as *Limnopithecus*, were tiny and probably lived high in the treetops. About 7 to 8 million years ago, however, this golden age of apes suddenly came to an end.” (Sutherland *New History* 238)

1912: Piltdown Man

“Early paleoanthropologists speculated that what drove human evolution was human intelligence. It’s what separates us from the rest of the apes. These paleoanthropologists thought that the missing link between the apes and humans should look like an ape but have a large brain.” (Sutherland *New History* 238)

“In 1912, Charles Dawson, an amateur archaeologist, found what he claimed was this missing link: Piltdown Man. The remains Dawson discovered had a human-sized brain [and] the face of an ape.” (Sutherland *New History* 238)

“The scientific community at the time was utterly persuaded. Piltdown Man was exactly what was and would remain the touchstone for understanding human evolution for more than 40 years.” (Sutherland *New History* 238)

“Unfortunately, of course, Piltdown Man was a complete hoax. The cranium was from a modern human. The jaw had belonged to an orangutan. For good measure, some of the teeth had been filed down to make it look like it ate seeds. The bones had been treated with chemicals to make them look old. We are still not sure who perpetrated this fraud.” (Sutherland *New History* 238)

7-4m: human bipedalism

23.03-5.333m: Miocene

5.333-2.58m: Pliocene

“The evolution of human bipedalism began in primates about four million years ago, or as early as seven million years ago with Sahelanthropus or about 12 million years ago with Danuvius guggenmosi.” (“Bipedalism”)

foramen magnum

The foramen magnum is an opening at the base of the skull; the spinal cord passes through it.

In tetrapods like “cats and dogs, the spine is essentially horizontal, with the foramen magnum more toward the back of the skull.” (Sutherland *New History* 237)

In bipedal creatures, “the skull is balanced on the top of the spine.” (Sutherland *New History* 237)

“Some fossils from this time show the foramen magnum starting to move forward. Early primates were possibly developing a kind of bipedal locomotion—an important sign of what was to come.” (Sutherland *New History* 237)

3.6m: Laetoli footprints (date: “When Did They Live?”)

1976: in northern Tanzania, Mary Leakey found “the footprints of a hominid—either the same species as Lucy or closely related . . .” (Sutherland *New History* 239)

“The footprints are preserved in volcanic ash. After a brief rainfall, the ash was turned into a substance a bit like wet concrete. These hominids passed over the surface, which later dried out in the hot sun, preserving the trail.” (Sutherland *New History* 239)

“These footprints represent our ancestors (or at least closely related cousins) moving purposefully across the landscape. The prints record the passage of three individuals: possibly two males and a small female or a child following close behind.” (Sutherland *New History* 239)

3.2m: Lucy (*Australopithecus afarensis*) (Sutherland *New History* 239)

1974: discovery

“Donald Johanson was looking for hominids in the Afar region of northeast Ethiopia when he [238] [discovered] an elbow joint; later excavation revealed a remarkable skeleton, about 40 percent complete.” (Sutherland *New History* 239)

“While Johanson and his team looked over the fossils, the Beatles song “Lucy in the Sky with Diamonds” played in the background; thus, Lucy got her name.” (Sutherland *New History* 239)

ape-like

Lucy’s teeth had flat surfaces: she was “probably more adapted to eating fruit and berries than meat.” (Sutherland *New History* 242)

“Lucy had the head of an ape, and she did not have a large brain.” (Sutherland *New History* 239)

human-like

*Australopithecus afarensis* used simple tools. (Sutherland *New History* 242)

Lucy “walked like a human being: upright.” (Sutherland *New History* 239)

So bipedalism preceded increased brain size. “Hominids did not have large brains; it would seem that standing erect is what first drove humans on the path away from other apes.” (Sutherland *New History* 237)

2.5m: Australopithecene tool use

“It would appear that walking upright was what drove human evolution.” (Sutherland *New History* 239)

“The theory is that walking upright frees the hands, and when the hands are free, we can make and use tools. This ability encourages the selection of better toolmakers, which means the adaptation of larger brains.” (Sutherland *New History* 239)

“Walking on two legs must have a selective advantage, because walking upright has many severe disadvantages—the least of which is that it makes us slow.” (Sutherland *New History* 240)

2.5m: *Australopithecus garhi* (date: “Australopithecus garhi”)

1996: “in the Afar region of Ethiopia, American paleontologist Tim White discovered the fossil *Australopithecus garhi*, which was either a descendant or relative of Lucy.” (Sutherland *New History* 240)

“This species was found associated with simple tools, dating to 2.6 to 2.5 million years ago. These tools were probably used for butchering animal bones to get to the marrow—which was high in calories and useful for supporting large brains.” (Sutherland *New History* 240)

opportunistic scavengers

2.85-2m (Pliocene): *Australopithecus africanus*

1924: “. . . Raymond Dart, an Australian anatomist and anthropologist,” discovers *A*. *africanus*, “a young primate.” (Sutherland *New History* 240)

“The idea of australopithecines butchering animals was taken to the extreme by Raymond Dart

The “foramen magnum was under the skull, an indication of an upright walker.” (Sutherland *New History* 240)

killer ape theory

“Dart put forward . . . the killer ape theory, which suggested that the animal bones found at the site were used as weapons. He speculated that early hominids organized into vicious predatory groups. Dart believed that violent tendencies in the killer ape drove human evolution.” (Sutherland *New History* 240)

“Dart’s theory of the killer ape is not supported by paleontological evidence.” (Sutherland *New History* 240)

“Australopithecines, like other bipedal apes, were, in all likelihood, more prey than predator.” (Sutherland *New History* 240)

“At best, the descendants of Lucy were probably opportunistic scavengers. They would get meat where they could, but probably only after every other animal on the landscape had taken its pick. They’d go after the marrow, breaking the bones open with their primitive tools.” (Sutherland *New History* 240)

suggested reading

Johanson and Wong, *Lucy*’*s Legacy*.

Sawyer, Deak, Sarmiento, and Milner, *The Last Human*.

## Human Evolution

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introduction

“During most of hominid evolution, there was more than one species of upright, bipedal ape.” (Sutherland *New History* 243)

2.4m: *Homo habilis*, “handy man”

*Homo habilis* is “The first member of our own genus . . .” (Sutherland *New History* 242)

ape-like

“*Homo habilis* still retained many apelike features, such as longer arms.” (Sutherland *New History* 242)

human-like

*Homo habilis* was about 5 feet tall. (Sutherland *New History* 242)

Its brain was “around 600 cubic centimeters (cc) compared to Lucy’s 200 cc.” (Sutherland *New History* 242)

tool use

“*Australopithecus* used simple tools. [*Homo habilis* used] numerous and more advanced tools . . .” (Sutherland *New History* 242)

“*H*. *habilis* likely ate more meat . . .” The molars are sharper than Lucy’s, “designed to shear meat . . .” (Sutherland *New History* 242)

“. . . it’s tempting to think that the larger brains in this group allowed them to hunt more [242] effectively as a team.” (Sutherland *New History* 242-43)

“*H*. *habilis*, though, was probably still prey for large cats, such as the saber-toothed *Dinofelis*.” (Sutherland *New History* 243)

“Our best assumption is that *H*. *habilis* was an effective scavenger—perhaps using group cooperation to scare away other scavengers or predators from a kill.” (Sutherland *New History* 243)

2.3-1m (Pleistocene, 2.58-0.0117m): *Paranthropus boisei* (aka nutcracker man)

*Paranthropus boisei* were robust australopithecenes. (“*Paranthropus boisei*”)

They “inhabited savannah woodlands.” (Sutherland *New History* 243)

“Males were around 4 feet, 3 inches, and weighed about 150 pounds.” (Sutherland *New History* 243)

“Because they had massive jaws and large molars, scientists speculate that they ate tough plants, roots, and nuts.” (Sutherland *New History* 243)

2m: *Homo erectus* (upright man) (date: “*Homo erectus*”)

*Homo erectus* “was tall, over 6 feet . . .” (Sutherland *New History* 243)

ape-like

*Homo erectus* had “an apelike face and a brain of about 860 cc.” (Sutherland *New History* 243)

human-like

*Homo erectus* was “One of the first species to demonstrate a humanlike body . . .” (Sutherland *New History* 243)

“It has been suggested that *H*. *ergaster* had a hairless body and sweat glands to regulate temperature. The development of sweat glands meant that *H*. *ergaster* did not have to pant, perhaps allowing the throat and breath to be used for speech.” (Sutherland *New History* 243)

They are sometimes called “*Homo ergaster*, or “workman”—a reference to [their] more advanced tools . . .” (Sutherland *New History* 243)

“Whether *H*. *ergaster* constitutes a species of its own or should be subsumed into *H*. *erectus* is an ongoing and unresolved dispute within palaeoanthropology. Proponents of synonymisation typically designate *H*. *ergaster* as “African *Homo erectus*” or “*Homo erectus ergaster*.”” (“*Homo ergaster*”)

speech

“Brain casts of *H*. *ergaster* and *H*. *erectus* show development of a particular region of the brain called Broca’s area; in modern humans, this area controls speech.” (Sutherland *New History* 243)

“*Homo heidelbergensis*, fossils related to *H*. *erectus*, have been found to possess a hyoid bone. The hyoid bone supports the root of the tongue and is critical for making the whole range of vocalizations.” (Sutherland *New History* 244)

“The ability to speak would be a distinct advantage.” (Sutherland *New History* 243)

“It would help cement social groups together . . .” (Sutherland *New History* 243)

It would “further success in securing mates.” (Sutherland *New History* 243)

It would “permit planning and coordination of hunting and foraging expeditions . . .” (Sutherland *New History* 243)

300,000: earliest *Homo-sapiens* fossils (from Jebel Irhoud, Morocco)

out of Africa

“*Homo erectus* was the first of our family to get the urge to move on, out of Africa.” (Sutherland *New History* 244)

“The Sahara pump theory explains how and why. It proposes alternating wet and dry conditions in the Sahara.” (Sutherland *New History* 244)

“During wet times, grasslands developed, and animals would use this corridor to move into Arabia and along the coastline of the eastern Mediterranean, extending across Asia. *Homo erectus* was possibly one of the first species to take advantage of this green bridge.” (Sutherland *New History* 244)

“*Homo erectus* was a widely dispersed species; fossils have been found in South Africa, China, Java, and Western Europe.” (Sutherland *New History* 244)

0.774-0.129m (Middle Pleistocene’s Chibanian Age): *Homo heidelbergensis*

*Homo heidelbergensis* is a “close relative of *H*. *erectus* . . .” (Sutherland *New History* 244)

Remains of *Homo heidelbergensis* have been found with “evidence of human culture . . . in the Atapuerca Mountains in Spain . . .” (Sutherland *New History* 244)

They “had a fairly large brain, 1100 to 1400 cc, similar in size to the modern human’s brain (about 1350 cc).” (Sutherland *New History* 244)

They “produced a highly complex array of tools.” (Sutherland *New History* 244)

“Some significant finds have been made in the cave Sima de los Huesos: 28 *H*. *heidelbergensis* skeletons were found there, with evidence that they were deliberately placed.” (Sutherland *New History* 244)

“Also found in the cave was a large and beautiful hand axe made of a red quartzite not from the local area. If this is evidence of a burial, it’s extremely significant because such an event requires preparation of the dead and ritualistic offerings. It also demonstrates an ability to conceptualize an afterlife. From our imagination, our culture is born.” (Sutherland *New History* 244)

the symbolic language of art

“. . . humanity’s use of symbols . . . laid the foundation for language, mathematics and civilization.” (St. Fleur)

“The production of art appears to emerge almost spontaneously around 33,000 years ago.” (Sutherland *New History* 245)

32,000-30,000: Chauvet Cave (SE France)

50,000-12,000: Upper Paleolithic

1994: “. . . Jean-Marie Chauvet discovered a series of connected caves that were not only strewn with bones but also had walls decorated with spectacular paintings . . .” (Sutherland *New History* 245)

This is “The most spectacular example of this early artwork . . .” (Sutherland *New History* 245)

17,000 (early Magdalenian culture): Lascaux (SW France)

“Initially, it was thought that the artists depicted the animals they hunted, but butchered animals found in and around these caves don’t match those shown on the cave walls.” (Sutherland *New History* 245)

“Other forms of artistic expression from this time have also been discovered, such as decorative beads and pendants; complex tools; and blades made from stone, bone, and antlers.” (Sutherland *New History* 245)

25,000: Venus of Willendorf (“Venus of Willendorf”)

“These people also created such figurines as the Venus of Willendorf, dated to about 22,000 years ago and likely some sort of fertility symbol.” (Sutherland *New History* 245)

causes

“What caused the sudden flowering of art and culture . . .?” (Sutherland *New History* 245)

“Even if we allow for the more rapid changes of punctuated equilibrium, the explosion of consciousness is almost instantaneous.” (Sutherland *New History* 245)

“We have found no primitive precursors, no simpler forms of art leading up to the beautiful and complex forms in the French caves.” (Sutherland *New History* 245)

sudden development: the “human revolution” theory

“Richard Klein at Stanford University suggests that a certain genetic mutation simply switched on the human brain. This would explain the . . . explosion of consciousness known as the “Human Revolution.”” (Sutherland *New History* 245)

“Klein speculates that this self-awareness is also why another group of hominids, the Neanderthals, was replaced by our species very [245] soon afterwards.” (Sutherland *New History* 245-46)

But “Neanderthals had a brain that is similar in size to that of modern humans, and recently, evidence has been found that they, too, produced art. Is it possible that Neanderthals were as self-aware as we are?” (Sutherland *New History* 248)

slow development

Henshilwood, Christopher, and Curtis Marean. “The Origin of Modern Human Behavior: Critique of the Models and Their Test Implications.” *Current Anthropology* 44.5 (2003) 627-51.

73,000: first drawing?

Chris Henshilwood “found abstract designs, deliberately created, dating to about 70,000 years ago—well before the proposed flowering of the human mind.” (Sutherland *New History* 246)



artifact from Blombos Cave (200 miles east of Cape Town). 1.5 inches. (St. Fleur)

“The markings consisted of six straight, almost parallel lines that were crossed diagonally by three slightly curved lines. . . . [They] were made from red ocher, a type of natural pigment that was often used to make prehistoric cave paintings. In fact, ancient humans in the Blombos Cave were making ocher paint as far back as 100,000 years ago.” (St. Fleur)

The “crisscross pattern was a drawing, not a painting, made with an ocher crayon tip that most likely measured only about 1 to 3 millimeters in thickness.” (St. Fleur)

“. . . that the red lines were drawn onto a smooth surface. That indicated that the flake was once a part of a larger stone . . . the original red lines most likely stretched past what was seen on the stone flake . . .” (St. Fleur)

The cave only contains *Homo sapiens* remains, so the picture is probably not by some other hominin. (St. Fleur)

“. . . similar criss-cross and hash mark patterns have been found engraved in pieces of ocher found in the cave.” (St. Fleur)

But archaeologist Lyn Wadley thinks the marks might have been “made unintentionally while grinding ocher into powder.” (St. Fleur)

“If these designs are art, culture and awareness were just like any other part of the human story: They developed slowly, in incremental stages, not in a sudden genetic mutation.” (Sutherland *New History* 246)

Anthropocene Epoch

“Some scientists believe that we need to create a new geological period that accounts for the impact *Homo sapiens* has had on planet Earth: the Anthropocene.” (Sutherland *New History* 246)

“This geological period would be marked by large-scale human habitation or, perhaps, the presence in the geological record of plastics or stainless steel.” (Sutherland *New History* 246)

“Another marker would be the presence of radioisotopes from the testing of nuclear bombs, which already form an identifiable horizon in the sediments of the oceans today.” (Sutherland *New History* 246)

the future of the biosphere

“The average lifetime of a species is around 3 million years.” (Sutherland *New History* 246)

“. . . we need to find another place where we could transplant life from Earth.” (Sutherland *New History* 246)

“. . . we have not yet found a planet like ours, with an oxygen-rich atmosphere.” (Sutherland *New History* 246)

We may need to “use tools to alter planets to our needs. This . . . is called terraforming, or planetary engineering.” (Sutherland *New History* 246)

“A likely candidate for this transformation is Mars.” (Sutherland *New History* 247)

Mars once had “a warm atmosphere with liquid water on the surface.” (Sutherland *New History* 247)

“Mars also has some of the main components needed to successfully terraform a world: soil, atmosphere, and water (present as ice).” (Sutherland *New History* 247)

“Mars has carbon dioxide locked up at the poles; thus, warming the planet could start a positive feedback mechanism, releasing more carbon dioxide into the atmosphere and warming the planet further. The warmer . . . atmosphere would start to melt the ice deposits, returning oceans . . .” (Sutherland *New History* 247)

Then “we could add components of Earth’s biosphere, starting with humble cyanobacteria” to make Mars oxygen-rich. (Sutherland *New History* 247)

Who speaks for Earth? We do.

Carl Sagan asked, “Who speaks for Earth?” Sagan answered: “We speak for Earth. Our obligation to survive is owed not just to ourselves but to that Cosmos, ancient and vast, from which we spring.” (Sutherland *New History* 247)

250m ce: a supercontinent?

“It is likely that 200 to 250 million years in the future, the continents will recombine to form another supercontinent.” (Sutherland *New History* 178)

1 billion ce: death of all life on Earth

On exoplanets, “even without oxygen, there could be plenty of single-celled life.” (Whitwam)

study by Kazumi Ozaki and Chris Reinhard (in *Nature Geoscience*)

“. . . in a billion years, the Sun will become so hot that it breaks down carbon dioxide. The levels of CO2 will become so low that photosynthesizing plants will be unable to survive, and that means no more oxygen for the rest of us.” (Whitwam)

“Without oxygen, the ozone layer will evaporate and expose the surface to more intense UV radiation.” (Whitwam)

“. . . it could take [as] little as 10,000 years for oxygen levels to drop to a millionth of what it is now.” (Whitwam)

“Methane levels will also begin to rise, reaching 10,000 times the level seen today." (Whitwam)

suggested reading

Lewis-Williams, *The Mind in the Cave*.

Sagan, *Pale Blue Dot*.

Sawyer, Deak, Sarmiento, and Milner, *The Last Human*.

Stony Brook University Medical Center, “Hobbit’ Skull Study Finds Hobbit Is Not Human.”

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