# Introduction to Paleontology

## Course Guidebook

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S tuart Sutherland is a Professor of Teaching in the Department of Earth, Ocean and Atmospheric Sciences at the University of British Columbia (UBC). He attended the University of Plymouth in the southwest of England, where he received a degree in Geology in 1987. In 1992, Professor Sutherland was awarded a Ph.D. in Geological Sciences from the University of Leicester for his studies on Silurian microfossils called Chitinozoa. His thesis examined the distribution and taxonomy of these fossils and considered the enigmatic biological affinities of the group and their usefulness in paleoceanographic studies.

After receiving his Ph.D., Professor Sutherland took a temporary teaching position at Brunel University in west London, where he first realized that he had a passion for teaching geology and paleontology. In 1994, he started postdoctoral research at the Natural History Museum in London, working with other paleontologists in an attempt to understand the Devonian organic-walled microfossils of the Cantabrian Mountains of northern Spain. With his earlier teaching experience still in mind, he acquired a teaching degree from Sheffield Hallam University in 1995 while still working for the museum.

In 1998, Professor Sutherland emigrated to Canada and eventually secured a faculty position at UBC's Vancouver campus. His interests at UBC are diverse but in general center on Earth history and paleontology with a particular focus on teaching. At UBC, Professor Sutherland has received the Killam Teaching Prize and the Faculty of Science Teaching Award, as well as the Earth and Ocean Sciences Teaching Award on three separate occasions. He has

been mentioned as a "popular professor" among students in two editions of *Maclean's Guide to Canadian Universities*.

Professor Sutherland developed his lifelong fascination with rocks and fossils on family hikes in Derbyshire and the English Lake District. He now enjoys studying geology and paleontology in the beautiful environment of Vancouver and British Columbia.

Professor Sutherland's other Great Course is *A New History of Life*. ∎

# About Our Partner

Founded in 1846, the Smithsonian Institution is the world's largest museum and research complex, consisting of 19 museums and galleries, the National Zoological Park, and 9 research facilities. The total number of artifacts, works of art, and specimens in the Smithsonian's collections is estimated at 138 million. These collections represent America's rich heritage, art from across the globe, and the immense diversity of the natural and cultural world.

In support of its mission—the increase and diffusion of knowledge—the Smithsonian has embarked on four Grand Challenges that describe its areas of study, collaboration, and exhibition: Unlocking the Mysteries of the Universe, Understanding and Sustaining a Biodiverse Planet, Valuing World Cultures, and Understanding the American Experience. The Smithsonian's partnership with The Great Courses is an engaging opportunity to encourage continuous exploration by learners of all ages across these diverse areas of study.

This course, *Introduction to Paleontology*, offers a glimpse of our planet's extraordinary history through the fascinating science of paleontology. The course focuses on the flora and fauna that are featured in the collections at the Smithsonian's National Museum of Natural History, where scientists in the Department of Paleobiology have conducted cutting-edge research that helps to piece together Earth's ancient story. The foundation of that story is provided by fossils—the vital words on Earth's history pages—and the museum is full of fossil clues that make possible the exploration of the history of life, from Earth's earliest days to more recent times in our planet's history. ∎

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# Introduction to Paleontology

## Scope

Of all the sciences, paleontology is probably one of the most narrative. It combines elements of geology, biology, ecology, and many other disciplines to peer back through time into vanished worlds. The pages of the story of Earth are written in rocks and fossils that require careful collection and interpretation, though.

In this course, we review the tools and techniques paleontologists use to breathe life into fossils and recreate ancient landscapes and oceans. We also discover how paleontological investigation can unpack complex events in Earth's history and how our understanding of these events is continuing to evolve as new fossils and new technologies present themselves.

We give special attention to the Smithsonian Institution, which has a rich history of paleontological research. For example, we meet the fourth Secretary of the Smithsonian, Charles Walcott, who discovered the now-famous Burgess Shale that changed our understanding of life just after the Cambrian explosion. And we learn how the Smithsonian's important research role has continued, with many new paleontological insights coming from work undertaken in the Department of Paleobiology in the Smithsonian's National Museum of National History.

The first part of the course examines some of the fundamentals of the science. As paleontology is a discipline rooted in time, we begin to come to grips with the immense extent of Earth's time by reviewing the deep history of the United States' capital, Washington DC. Following this, our attention turns to the fossils themselves, their diversity, and the variety of ways in which they can form. Finding, extracting, and preparing fossils will be covered, but also some of the techniques and technologies paleontologists have in their tool kit today.

Not all fossils represent the remains of large creatures, and we investigate how the behavior of organisms can be preserved and how a vast store of paleontological information exists in a plethora of tiny microfossils. Once found, extracted, and preserved, fossils have to be classified, and we consider some of the challenges paleontologists face when bringing taxonomic order to their finds. Fossils tell of the passage of time across eons, but we also discover how more familiar cycles of days, months, and years might be recorded in the fossilized remains of organisms.

Fossils can also help us unravel the geological dance of continents, and we investigate how paleontology is instrumental in the study of paleogeography. In addition, we also examine the evolution of the beautiful mineral heritage of Earth, a turn to geology that highlights the interplay between Earth's evolving mineral heritage and the development of the biosphere.

The rest of the course focuses on some important fossil groups and events in Earth's history, starting with the birth of paleontology at the dawn of life, potentially in the deep, dark ocean. The bewildering diversity of the biosphere today is generally traced to an explosion of life early in the Cambrian period, but we consider the potential roots of this explosion in even earlier times. The most successful group of organisms during and following the Cambrian explosion was arguably the arthropods, so we look to their origins and their fascinating evolution. Life has not had an untroubled journey, though, with 5 major extinctions recorded through time. We investigate the Devonian extinction, which occurred around 360 million years ago and may have had a series of potential triggers, and also the greatest culling event that the planet has witnessed, which occurred at the end of the Permian about 252 million years ago.

We also examine fossils that are still highly debated in the scientific community, such as the enigmatic but wonderfully bizarre *Spinosaurus*, claimed to be one of the largest carnivorous dinosaurs that ever lived, from around 30 million years before the iconic *Tyrannosaurus rex*. Next, we turn to the fossil record for a series of mammals that would progressively throw away their limbs for the sea to become the beautiful and diverse whales, dolphins, and porpoises that thrill us in today's oceans. We also consider the critical role that flowering plants

(including the grasses) have had in the biosphere, from their evolution during the Mesozoic era to the profound influence that they have had in driving the evolution of other creatures.

As we move toward the end of the course, the wonderful Komodo dragons from Indonesia—and the tiny humans, *Homo floresiensis*, that lived with them on the island of Flores—take us to times much closer to our own. Another member of our family, *Homo neanderthalensis*, is covered, as are some of the mammoths and mastodons that wandered the Earth at that time. We will discover what fantastic new insights ancient DNA is providing in our understanding of both mammoths and Neanderthals. We conclude with a survey of the possible challenges the biosphere will face as it marches into the future and the role that the science of paleontology may have in charting that future.

Paleontology is a powerful tool we can use to wander through Earth's ancient past. With every fossil found and new technique developed, our picture of that past comes a little more into focus and the journey becomes ever more fascinating. By the end of this course, you should have a clearer understanding of the science and practice of paleontology—and how it can bring our planet's rich history back to life. ■

# History on a Geological Scale

All fossil creatures, and the vanished worlds they lived in, help us understand our place in space and time. They can also act as a vital benchmark for our appreciation of the Earth as it is today and perhaps provide clues to its future. The National Museum of Natural History is full of fossil clues to Earth's past, and aided by the collections—and some of the cutting-edge research in the Department of Paleobiology—this course will explore the history of life from Earth's earliest days to more recent times in our planet's history.

## A Walk through Geological Time

- The Earth is 4.54 billion years old, a fantastically long time when compared to the lifetime of a human. As such, in an attempt to comprehend the age of the Earth, an analogy is often used. A common tool is to condense all of Earth history into one calendar year.

- On this scale, the Earth forms in the first second of January 1. This is a time when our solar system was a crowded place with a variety of rocky planets zipping around close to the Sun, and there would likely have been collisions on a colossal scale. Some of these encounters would add mass to growing young worlds while others probably obliterated each other in cataclysmic events.

- We start to find the first abundant fossils, those that possessed shells, on the calendar around November 18, fairly late in the year, and animals with 4 legs, or tetrapods, don't stride onto land until around December 1. The dinosaurs went into extinction on December 26, and Stonehenge was built just 30 seconds before midnight on December 31.

- However, given that the National Museum of Natural History is located along the front yard of the United States, better known as the National Mall, let's use that as our timeline. On that timeline, the origin of Earth, 4.54 billion years ago, can be placed at the Washington Monument, with today represented by the United States Capitol building.

- The distance between these 2 iconic Washington DC buildings can cover 4.54 billion years in just 2.87 kilometers, or 1.35 miles. On this scale, depending on your stride length, each step you take will be between 1 million and 2 million years.

- Let's start outside of our timeline—before the formation of Earth. The point that is just 29 meters in front of the Washington Monument makes it around 4.6 billion years ago, or 60 million years before Earth's first day. If you could transport yourself back in time, you would be in open space. There would be no Earth—just a nebula of dust and gas.

- We have places at a similar stage in their evolution in our galaxy today, such as the Orion Nebula, in which gas and dust are collapsing under gravity to form new stars and planets. Our solar system grew in the same way, perhaps initiated by the gravitational nudge from the death of an old star when it went supernova.

- Let's move forward in time to the first day of Earth and the Washington Monument. On our timeline, this is day 1, with the formation of a rocky planetary body that will evolve over the next 4.54 billion years into the Earth we know today. The Earth was heated after it formed, a combination of kinetic energy released from the impacts of the remaining debris in the solar system and from the concentration of radioactive elements in the young planet's interior.

- Washington DC at this time would have been a magma ocean, just like the rest of the planet, and it would take time for the Earth to cool and for its first solid skin, the crust, to form.

- If we go about 19 meters from the Washington Monument, we come to a very significant event in our story: the formation of Earth's Moon, probably the result of a cataclysmic collision with a Mars-sized object, sometimes called Theia, about 4.5 billion years ago. This would have serious consequences for the development of life on our planet, including tides, various lunar cycles, and day length. The Moon has also helped stabilize the Earth's "wobble," allowing for the relatively benign seasons we enjoy.

- Some of the oldest evidence of Earth's solid crust comes from Australia in the form of fragments of an older rock contained in a younger rock. This is called a conglomerate. Isotopic analysis of those fragments, contained in that conglomerate and specifically from crystals called zircons, indicate that Earth had a solid crust at about 4.4 billion years. On our timeline, that places us just 67 meters away from the Washington Monument.

- It would appear that the Earth had a "surface" of sorts very early in its history. In addition, isotopic analysis of those zircons, using different ratios of various stable elemental isotopes, hints at liquid water, too. The presence of liquid water in these distant times opens up the possibility that life may have a much older history than we initially thought.

- At 356 meters from the Washington Monument, on the north side of the mall is the National Museum of American History and on the south side is the United States Department of Agriculture. On our timeline, we are at 3.8 billion years ago—we have completed a little more than 16% of our walk—and at this point in history, Earth, and the rest of the inner solar system, was in a meteor and comet shooting gallery. This would last about 300 million years and is called the late heavy bombardment period.

- If life had evolved around 4 billion years ago, it probably had to survive deep in Earth's crust, because some have suggested that these early impact events may have in effect sterilized the Earth's surface. It is not until around 400 million years later, at 3.4 billion years, that we find our first fossils. On our timeline, we are at the eastern edge of the National Museum of American History.

- By the time we walk past the National Museum of Natural History, at 2.4 billion years, life would be enduring another crisis: a super glaciation called a snowball Earth event that would encase our planet in ice for millions of years. On our timeline, we have covered more than 47% of Earth's history.

- Associated with the end of the snowball event would be a rise in oxygen levels and the deposition of rocks in banded-iron formations, rich in iron oxides, demonstrating that our atmosphere was evolving. This change was caused by photosynthetic bacteria releasing oxygen as a waste product and, in the process, changing our planet forever.

- Following this rise in oxygen, life on Earth would go through a series of significant events. About 2.1 billion years ago, or 1011 meters from the Capitol building, we see the emergence of eukaryotic life. Eukaryotes are essentially all life that is not a bacteria or a virus.

- By 1.2 billion years ago, or 578 meters from the Capitol building, we have evidence of the first multicellular life-form—*Bangiomorpha*, probably a simple red algae—and by 720 million years ago, or 346 meters from the Capitol, the snowballs had returned and then end 650 million years ago, in the middle of the Capitol reflecting pool. We have now completed more than 85% of our walk through time.

- Larger creatures emerge at 541 million years—in front of the Ulysses S. Grant Memorial—and with them, evolution kicks in to overdrive. We can see the world just after that explosion of life at 505 million years. This is the time of deposition of the Burgess Shale, a rock unit from western Canada that was discovered in 1909 by Charles Walcott, former Secretary of the Smithsonian. The fossils preserved in the Burgess Shale provide a unique window into the explosion of complex.

- DC would have looked very different during this explosion of life. In Rock Creek Park, about 8.5 kilometers north of the National Mall, we find sediments deposited at about the same time. They tell us that DC was then on the edge of a deep ocean called Iapetus next to the continent of Laurentia.

- These rocks are called turbidites and formed as sediments tumbled over the continental edge and into deeper water. These rocks often show bands representing individual flows of sediment. Coarser or heavier components would settle out of the flow, first producing a sedimentary structure that is called graded bedding, representing the settling of material out of that sediment avalanche.

- But now things are going to change quickly as DC witnesses a series of tectonic pileups. The first one occurs by First Street Southwest at 460 million years ago on our timeline, with just about 10% of our timeline remaining. A series of volcanic islands that existed in that ocean, into which the Rock Creek Park sediments were deposited, would collide with North America. This raised the ocean floor and started the building of mountains in a north-south direction on the eastern continental edge of this ancestral North American "paleocontinent."

- But this was just the beginning. Around 100 million years later, microcontinents that include parts of what is now western Europe would slam into this part of the world, raising the mountains even higher and causing magmas to be intruded into the deformed rocks.

- Then, at 320 million years ago, Africa collides with this growing continental landmass. This is moving us toward the formation of a supercontinent called Pangaea and in the process raises the mountains even more. The remnants of those mountains are the Appalachians, which were as high as the Alps or the Himalayas when they were young.

- After this collision, and just 32.8 meters closer to the Capitol building, life in DC and around the world goes into crisis at 252 million years ago. Life on Earth would be laid to waste, with more than 90% of all species going into extinction—the greatest of the 5 major mass extinctions our planet has faced.

- This is a time of runaway global warming, probably triggered by titanic volcanic activity centered in what is today Siberia—global warming that may have also led to the production of toxic hydrogen sulphide in the Earth's

oceans and the release of even more greenhouse gases as methane stored in ocean sediments destabilized and escaped into the atmosphere.

- It is the erosion of the mountains that formed due to the continental collisions that give us the next rocks we find in DC, and on our timeline, we have reached the foot of the Capitol building. This is when dinosaurs during the Cretaceous period, dating to 110 million years, fit into our timeline.

- From this point, the dinosaurs would have another 44.5 million years to rule the planet, but then on the steps of the Capitol building on our timeline, at about 66 million years ago, around 2300 kilometers to the southwest of DC, a 10-kilometer object comes screaming into the atmosphere and slams into Yucatán, ending the reign of those magnificent beasts.

- Paleoanthropologists estimate that our species, *Homo sapiens*, evolved around 200,000 years ago. On our timeline, that places us just under 5 centimeters from the front of the Capitol building. The maximum advance of ice, in the last glacial period of the current ice age, was about 22,000 years ago, which is just about 1 centimeter from the end of our timeline.

- The date of arrival, and origins, of the first people in North America is currently somewhat in flux, but an early North American culture known for their stone tools, called the Clovis culture, is generally agreed to be found

from about 13,000 years ago, just more than half of a centimeter on our scale. About 0.1 centimeters later, the last glacial period in the current ice age ends.

- Around 0.3 centimeters before the end of our timeline, at 6000 years ago, many miles away from DC, we have evidence of the founding of one of Earth's first cities, Uruk, in what is now modern-day Iraq. In this last 0.3 centimeters of our timeline is effectively all of what we could call recorded human history. Everything that we consider ancient on a human timescale is dwarfed by the immensity of the age of the Earth.

## Questions to consider:

1. What should we consider to be Earth's day 1?
2. Why is there no complete record of Earth's history on our planet?

## Suggested Reading:

Fortey, *Earth*.

Levin and King Jr, *The Earth Through Time*.

PALEOMAP Project, http://www.scotese.com.

# Life Cast in Ancient Stone

I n this lecture, you will learn about paleontology, including how paleontology developed as a science, what the chances are of becoming a fossil, what the common modes of fossilization are, and what exceptional preservation is. Although only a tiny portion of life on Earth has become fossilized, that portion still represents an enormous cache of material for future paleontologists to examine. New discoveries of fossil bonanzas and new approaches and techniques in paleontology and paleobiology will likely continue to surprise and delight generations of scientists to come.

## The Rise of Paleontology

- Fossils have been a part of human culture for a long time. A very early reference to fossils comes from the 6th century B.C. Greek philosopher Xenophanes, who concluded from his examination of fossil fish and shells that water must have covered much of the Earth's surface at one time in the past, meaning that he understood that there was a deeper historical narrative to our planet that could be told by the use of fossils.

- Similar ideas were proposed in 1088 by the Chinese naturalist Shen Kuo, who found fossils in the Taihang Mountains and decided that they indicated that shorelines had shifted over time. He also found bamboo fossils in Shaanxi province, a part of China that is currently too dry for bamboo to grow, and concluded that climate change must have occurred at some time in the past.

- Thoughts on how creatures could become fossils were proposed in 1027 by the Persian polymath Avicenna, who speculated that fossils may have formed when a carcass was bathed in "petrifying fluids."

- These are all really modern concepts—concepts of sea level and climate change, the passage of vast amounts of time, and the processes that operate in the Earth to form fossils—and in the West, they would be largely ignored or forgotten.

- Things would change, though, as our understanding and appreciation of fossils accelerates when we move into the 17th century, the age of reason. There are many important figures who have contributed to the development of the science of paleontology in this period.

- Among them is Robert Hooke, an English natural philosopher who would make a significant contribution in his famous book *Micrographia*, published in 1665. The book was the first examination of the very small, as revealed by Hooke's microscope. From his study of fossil wood, Hooke would conclude that fossils were once-living organisms that have been transformed into rock by the petrifying action of mineral-rich water.

- Another important figure is George Cuvier, a French naturalist and philosopher who would make several significant contributions, including providing us with the concept of extinction in 1796. When comparing the jaws of living elephants with fossil jaws of something similar but distinct— we know it as the mammoth—Cuvier concluded that some species that used to exist on Earth were no longer around.

- It was one of Cuvier's students, Henri de Blainville, who would give the study of fossils a name. At first, he chose the term "paleozoologie" in 1817, but by 1822, after a number of iterations, he settled on the more inclusive "palaeontologie," which would cover both fossil plants and animals.

- William Smith would demonstrate the usefulness of fossils as a tool for correlating strata. By 1815, he published a groundbreaking geological map of England, Wales, and southern Scotland. Importantly, Smith demonstrated that fossils provided the context for the development of a geological timescale. Once constructed, this scale would allow scientists to correlate across regions, ensuring that they were on the same page of Earth's history and, in doing so, start to tell the story of Earth's deep evolution.

- This is an idea that would be taken up by Smith's brother-in-law, John Phillips, who in 1841 published the first geological timescale. He divided geological time into 3 of the eras we use today: the Paleozoic, Mesozoic, and Cenozoic. Although the names and dates on the timescale would change considerably over time, paleontologists and geologists now had a yardstick that they could use to delve into the past.

- Another important development was the discovery of fossils in a quarry in the Neander Valley of Germany. Described by schoolmaster Johann Carl Fuhlrott and anatomist Hermann Schaaffhausen in 1856, the fossils were identified as belonging to a group of humans that were quite different from any modern people. They would eventually be named *Homo neanderthalensis*. With these fossils, paleontology became part of our story, too. This was just 5 years after anatomist and founder of the Natural History Museum in London Richard Owen gave us the word "dinosaur."

- Charles Darwin, with the publication of *On the Origin of Species* in 1859, would eventually provide the first hints of the mechanism behind the changing suites of fossils paleontologists had been finding. From here, the field of paleontology would explode into numerous disciplines and subdisciplines, becoming an extremely important part of academic studies at universities and museums all over the world.

- North America has its share of famous paleontologists, too. For example, Othniel Marsh and Edward Cope would expand our understanding of dinosaurs during the "great dinosaur rush" in Colorado, Nebraska, and Wyoming in the late 1800s. In 1909, one of the most famous secretaries of the Smithsonian, Charles Walcott, would stumble across the Burgess Shale in British Columbia in the Canadian Rockies.

## Becoming a Fossil

- The chances of anything becoming a fossil are pretty slim. The fact we have fossils at all speaks to the sheer numbers of individuals and species that have existed through time. With all their countless billions, it would

Charles Darwin
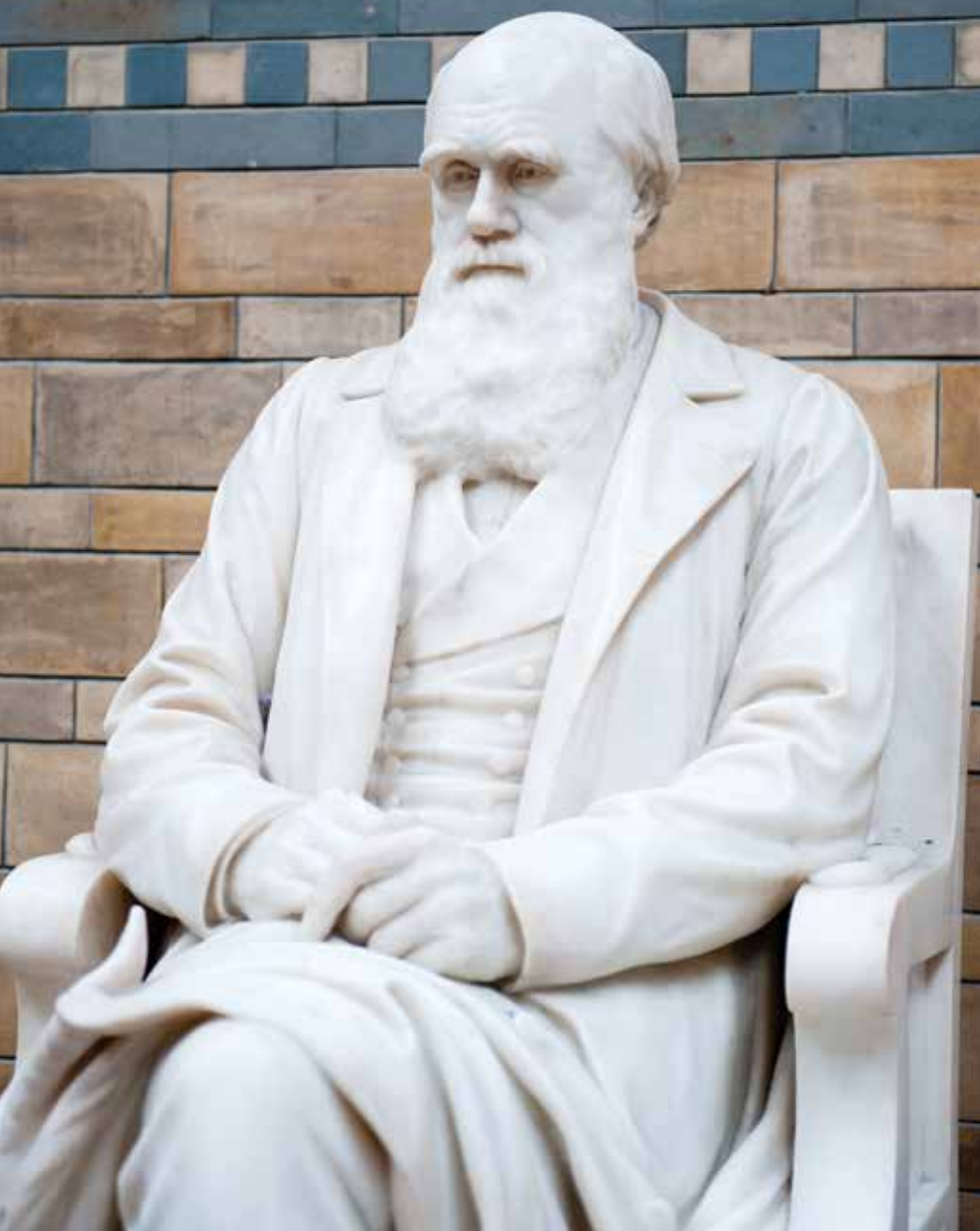
only take a tiny fraction to fossilize to leave a substantial fossil record in the rocks.

- But let's consider those that do make it. What factors did they have in their favor? How do you maximize your chance of becoming a fossil? First, being in the right place increases your chance of becoming a fossil. To form a fossil, you need to get your body buried as quickly as possible—out of the way of scavengers and preferably sealed from oxygen, or in reduced oxygen conditions. That isn't going to happen on an open plain or in a high mountainous region, for example.

- Because being buried in sediments is probably your best bet for becoming a fossil, organisms that live in aquatic environments, such as lakes or rivers, will have a greater chance of becoming a fossil. On the whole, aquatic creatures that live in the oceans and other water bodies that are receiving vast quantities of sediment via rivers and streams will have a greater preservation potential than terrestrial, land-based organisms.

- In addition to where an organism lives, another important factor is what it is made of. Any creature that has a significant development of hard parts has a greater chance of preservation and a greater representation in the fossil record than soft-bodied organisms.

- This is a persistent bias that paleontologists have to be aware of when reconstructing ancient ecosystems from fossil sites, especially when, in some settings, soft-bodied creatures lacking any skeletal components may have made up a large part of the animal assemblage.

- But considering hard parts, life has used a wide variety of materials for protection and structural support. Calcium carbonate, or calcite, is a very common mineral used by many organisms, including bryozoans, corals, brachiopods, mollusks, and many arthropods and echinoderms.

- Examples of silica-secreting organisms include sponges and the radiolarians, tiny marine protists that secrete exquisite ornament-like structures out of biological glass.

- Calcium phosphate, usually in the form of the mineral apatite, is used for the skeletal elements (bones and teeth) of vertebrates and the feeding apparatus of extinct chordates called conodonts.

- The varied skeletal components of all these creatures will behave differently under different environmental and rock-forming, called diagenetic, conditions. Even slightly different forms of the same mineral can react very differently to the processes of fossilization.

- For example, both ammonites and brachiopod use calcium carbonate in their shells, but not all calcium carbonate is the same. Ammonites are composed of a mineralic form of calcite called aragonite, while some brachiopods use the more typical calcite. Organisms composed of aragonitic shells are more likely to be altered to calcite during fossilization, a transformation that very often removes any fine internal details of the shell. If an organism is already composed of calcite, then there is likely a greater chance of detail being preserved.

- Another consideration is the proportion of organic material present in the mineralized material. For example, trilobites would have formed extremely robust cuticles, impregnated by the organic molecule chitin, but with a very high proportion of calcium carbonate.

- Fellow arthropods the Malacostraca (includes shrimps, crabs, and lobsters) and the Diplopoda (the millipedes) have a much higher proportion of organic material in their exoskeletons. As a result, they have a reduced preservation potential and a poorer fossil record.

- Insects also have a modest preservation potential, but because of their sheer abundance, they have a better fossil record than would be predicted from their exoskeletal durability alone.

- But it's not just the durability of the materials that we have to consider. Another factor is how that material is organized. For example, sponges are composed of discrete structural elements called spicules. The various scaffolding units of sponges are more common in the fossil record than

fossils of the original complete organism. Corals, however, secrete a single robust skeletal element, and as a result, the preservation potential of the entire organism is better than that of the sponges.

## Modes of Fossilization

- A common mode of fossilization is the production of molds and casts. Molds are negative impressions of an organism that preserve information about the surface of a creature. A mold will commonly be produced when circulating pore waters moving through a sediment dissolve away the original skeletal material. Paleontologists will occasionally inject epoxy resin into the mold and then dissolve the surrounding rock to free the cast. Casts can form the same way in nature when mineral-rich waters deposit various minerals into fossil molds.

- Fossils can also form by a process called carbonization, in which a process of distillation, caused by the heat and pressure of burial, preferentially removes the hydrogen and oxygen of soft tissue, leaving the carbon behind. This a common mode of preservation of many land-plant fossils.

- Some of the most spectacular preservation occurs when mineralizing fluids percolate through sedimentary units. Minerals are precipitated in spaces between the skeletal material of shells and other original structural materials, hardening and stabilizing the fossil. This mode of preservation, called permineralization, can preserve wonderful detail.

- The same process can occur in some circumstances when organic material becomes completely replaced by mineralizing fluids, a process called petrifaction. This can occur in both plant and animal fossils.

- There are rarer modes of fossilization that can produce spectacular material. Perhaps the most beautiful are those fossils trapped in amber. This is an important mode of fossilization for insects and spiders, but other life-forms, such as small vertebrates and plants, have also been preserved.

- Amber forms when resin, produced by a number of types of trees but particularly coniferous trees, is secreted to heal an injury or act as a defense. This oozes down a tree trunk, sticking and trapping creatures as it goes. Once the resin is buried, pressure and temperature will increase due to the overburden of sediments. This causes the organic chemicals in the resin to oxidize and polymerize, eventually hardening into amber and preserving the creatures it trapped in fantastic detail.

- Another example of exceptional preservation, housed at the Smithsonian, comes from northwest Montana along the edge of Glacier National Park. The particular rocks in question come from a unit called the Kishenehn Formation from the Middle Eocene about 46 million years ago.

- The deposit is called an oil shale due to the high amount of organic material it contains, and it formed in the calm shallow regions of a lake. The sediments are finely laminated and represent seasonal changes in deposition. Such laminations are called varves. During warmer periods, probably during spring and summer, when organic production in the lake was high, dark organic-rich layers are deposited. These alternate with more windblown mineral material from the cooler part of the year.

- Perhaps the most famous example of exceptional preservation is the Burgess Shale, more than 65,000 specimens from which are housed in the Smithsonian's National Museum of Natural History's Department of Paleobiology. The creatures were buried in an underwater avalanche of fine mud in low-oxygen conditions, preserving exceptionally fine details of the structure of their soft parts.

*Questions to consider:*

1. In which environments should we expect the greatest potential preservation?

2. How much of the Earth's biosphere was never preserved in the fossil record?

*Suggested Reading:*

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

Bryson, *A Short History of Nearly Everything*.

# Lecture 3

# Tools of the Paleontological Trade

I n this lecture, you will consider some of the tools and techniques used by paleontologists, and you will discover how new technologies are opening up windows into the past in a way that would have astounded the founding fathers and mothers of geology and paleontology in the 18th century. You will learn how fossils are found in the field, how fossils are collected, how fossils are prepared, what the new tools of the trade are, and how life is given to fossils through scientific illustration and reconstruction.

## Finding Fossils

- Many paleontologists were first trained as geologists before specializing in the study of fossils. There are many very good reasons for this. In part, an appreciation of geology helps place fossils in the context of a dynamic Earth system, which in turn has implications for the way in which we interpret the fossils we find. In addition, paleontologists have to rely on a number of basic geological principles and skills to track down and accurately record the fossils they find.

- In particular, there are principles regarding the manner in which rocks—sedimentary mostly—are deposited one on top of another over time. These ideas basically state that the sequential deposition of sediments means that the oldest layers, or strata, will be at the bottom of the pile and the youngest at the top.

- Geologists know that our dynamic planet rarely allows the thin crust we live on to stay still for long. Horizontal strata more often than not will become tilted or folded over time as the continents wander, collide, and raise

mountains, twisting and distorting the geological pages of Earth's history book.

- This can complicate matters when we are trying to read Earth's story, which is why a vital skill for any paleontologist out in the field is the ability to create and read geological maps.

- Geology is very rarely beautifully exposed. The story we want to tell is often covered by a soil profile, vegetation, asphalt, or an inconvenient shopping mall. A paleontologist is often only presented with a fragmentary glimpse of the geology at the surface in the form of limited "outcrops," with little evidence of what the geology is doing in the subsurface. It is from these limited views that geologists create a map—a hypothesis—of both the seen and unseen geology below the surface.

- Even though aerial and satellite photography and gravity and magnetic surveys can help with mapping today, the geoscientist still has to rely mostly on getting down on the ground and hiking along outcrops of rocks. Like the field kits of the first geological mapmakers, basic field kits include a geological hammer, a hand lens, a compass (with a clinometer for measuring the dip of strata), and a notebook (to record findings). GPS and electronic data storage devices are also used.

- When complete, the map is tested by continued mapping or in some cases by drilling boreholes to see if your subsurface predictions are actually matched by the rocks you recover in core, predictions that might be confirmed by characteristic rock types and/or fossils. In this way, the geology of an area, especially when that area might be geologically complex, is revisited and refined—tweaked so that the model we produce comes closer and closer to the reality of the rocks in the Earth.

- A good geological map can help a paleontologist predict the location of strata of particular interest across the landscape with fossils themselves tying those strata into a temporal framework. A map therefore can help paleontologists zero in on the pages of Earth's history that they are

interested in and also helps them understand the wider temporal context of the fossils that they find.

- Even though a map may help you focus in on the area you should be looking for fossils, there may still be a lot of hunting around to find the fossils once you're in the field. A good start is to eyeball the ground for fragments of fossils in what is called float, or loose pieces of rock that have been eroded from an outcrop that actually contains the fossils.

## Collecting Fossils

- But what about collecting the fossils once they have been located? This will vary depending on what fossils you are finding, but most fossils, such as the shells of various marine creatures, can often be collected by the application of hammer, chisel, crowbars, and a little muscle, making sure that eyes are protected by safetly glasses because many rocks have a high silica content and splinter into dangerous shards when hit. Once recorded, the fossils are wrapped to protect them and placed in a bag with an identification number.

- This becomes trickier when dealing with large fossils in rock. Sometimes a small pick and a hammer just aren't going to be enough. That's when you might see a field paleontologist employing a jackhammer or a backhoe.

- In addition, it is generally impractical to extract large fossils from their rock matrix in the field, so once the specimen has been exposed, it is extracted with the adjacent rock matrix still attached.

- Plaster and burlap straps are applied to the specimen, forming a jacket, and once hardened, the fossils can be removed and transported back to the lab. Sometimes, given the remotness of sections being studied, this could require a helicopter.

- The experience of collecting fossils is a little different for micropaleontologists, who don't have the luxury of seeing their fossils in the field. Most microfossils are fractions of a millimeter in size and often

impossible to see, even with a 20x hand lens. The best micropaleontologists can do is find the right kind of rocks that might contain the fossils and hope that they will find the fossils when they get back to the lab.

● Common to all fossil collection is recording as much detail as possible regarding where the fossils were found—not just spatially on a map, but stratigraphically so that their vertical (time) and lateral (geographic) relationship to other specimens can be assessed. To preserve both their original geographic and stratigraphic location, fossils are often recorded on a stratigraphic log, which is a vertical representation of the strata that are being studied.

## Preparing Fossils

- Back at the lab, in the case of larger specimens, the fossils have their plaster jacket removed, and the long and careful process of removing the fossil from the rock matrix begins. A number of tools are used for this, including the air scribe, which acts like a miniature jackhammer, chipping away at the rock matrix. When getting close to removing the majority of the matrix, the air scribe's impacts may "pop off" the last bits of rock, leaving the fossils clean and exposed.

- If a fossil is too fragile, or the matrix is too hard, fossil preparators may use gentle grinding tools to help separate the fossil from the rock. When getting too close to the fossil, tiny picks and needles are used to clean up the specimen.

- Various adhesives are an essential part of a fossil preparator's toolkit, too. Thick solutions are useful for rejoining large broken fossils. For fragile specimens, a thin solution can be applied that penetrates into cracks and pores, strengthening the fossil from within. After a fossil is rejoined, it is often placed in sand that holds the pieces in the correct positions until the adhesive sets. When complete, spectacular detail can be revealed.

- The preparation of fossils at the other end of the scale, with microfossils, is somewhat different. The most common method of preparing microfossils involves the use of various often-nasty acids, such as hydrofluoric acid, to dissolve away the rocky matrix.

## Studying Fossils

- In Robert Hooke's famous publication of *Micrographia* in 1665, a whole new world was revealed—the world of the very small. Hooke's beautiful drawings, such as those of the flea and the compound eye of a dragonfly, were instrumental in promoting the early use of the microscope in understanding the natural world.

- Since then, microscopes have been used in many branches of paleontology for studying various aspects of fossils, commonly by making a thin section of the rock that reveals the anatomy of well-preserved fossils as light passes through them. Optical microscopy has its limitations, though.

- Practically, you have a maximum magnification of about 1500x due to the wavelength of light that limits the resolution of the microscope. In addition, there is a problem with depth of field in viewing specimens that have much relief. As such, optical microscopes essentially provide a flat image.

- Fortunately, we can use something other than photons of light to make images of the very small. A scanning electron microscope (SEM) uses electrons rather than photons. Because electrons have a much shorter wavelength than light, SEMs have a much greater resolution than optical microscopes. The resolution of an SEM can range up to around 300,000x.

- Some of the electrons fired at the object from the SEM travel deeper in the specimen, get absorbed, and cause a release of x-rays. These x-rays can then be used to determine the composition on the object being studied; all you need is an SEM fitted with an x-ray detector. This technique, called energy-dispersive x-ray spectroscopy, has been used by a research team headed by Dr. Conrad Labandeira at the Smithsonian's National Museum of National History to look at exceptionally preserved material in Jurassic lake sediments in northeastern China.

- There are other tools for determining the composition of materials, and in some cases, determining the relative proportions of very specific isotopic components of a material can provide vital environmental information about the past. An isotope is a variant of an element that differs only in the number of neutrons it contains in its nucleus.

- Some isotopes are unstable and decay into more stable elements over various time periods; others are stable and hang around in the environment. Isotopes of carbon, oxygen, sulphur, nitrogen, and a whole bunch of others react in very specific ways to different environmental factors that speak to various events in Earth's past.

- It is usually igneous rocks that are used in radiometric dating. Igneous rocks form as magma or lava cools, forming crystals that trap small amounts of radiometric material. This can then be used to date the rock. This technique has permitted the dating of materials from many periods of Earth's history, including some of the most ancient.

- A technique currently being used at the Smithsonian Institution involves capturing precious fossils in 3 dimensions on a computer. The digitization program at the Smithsonian can capture incredible detail from a specimen, using millions or billions of points of measurement on its surface.

## Illustrating and Reconstructing Fossils

- Just because we have new technologies available to us does not mean that we abandon more traditions tools. This is nowhere better seen than in the power of paleontological art and illustration. Science meets art when we need to reconstruct ancient environments and the organisms that lived in them. The Smithsonian has a rich history of paleontological art.

- Even with all the new advances in imagining and data manipulation, the role of the scientific illustrator is still vital both in research and in public display of materials. Very often, an illustration can highlight features that might be too subtle to be picked out on a photograph and also correct for problems, such as poor depth of field or distortion, that can occur with a camera lens.

- Paleontologists require a wide variety of visual material to illustrate their work, including the reconstruction of fossil specimens, restorations of ancient animals and plants, and various diagrams, graphics, and maps to help illustrate research. Often, drawings reveal structure, anatomy, and features that are not readily grasped in photographic images.

- The collaboration between artist and scientist in the reconstruction of past environments is inspiring. The reconstruction of paleoenvironments begins with consultations between artist and paleontologist, perhaps with the scientist making a rough initial sketch.

- From materials such as specimens, photographs, and a range of other background material, the scientific illustrator begins to bring life to lost landscapes and the animals and plants that populated them. The result is the point at which art and science meet to produce wonderful images that breathe life into worlds long since vanished. These images are the products of all the fieldwork, preparation, analysis, and interpretation that is part of the science of paleontology.

## Questions to consider:

1. What critical information is lost when a fossil cannot be tied to where it was originally recovered?

2. What are the advantages of more traditional artistic representations in paleontology when compared to modern visualization techniques?

## Suggested Reading:

Taylor, *DK Eyewitness Books*.

Thompson, *The Audubon Society Field Guide to North American Fossils*.

U.S. Department of the Interior: Bureau of Land Management, "Hobby Collection," http://www.blm.gov/wo/st/en/prog/more/CRM/paleontology/fossil_collecting.html.

# How Do You Fossilize Behavior?

**Lecture 4**

With the tools of logic and deduction, paleontologists can act as detectives to piece together the lives of long-dead creatures. In this lecture, you will discover a powerful class of fossils that essentially is the fossilized behavior of organisms: trace fossils. You will learn what trace fossils are and how they form; what they tell us about the evolution of life; what traces creatures leave about how they moved, fed, and built a home; and how fossilized behavior can track changes in an environment.

## Trace Fossils

- Trace fossils are found in both marine and terrestrial environments and can be made by a variety of creatures. In sediments, they can be tracks and trails and burrows and borings. In the world of plants and insects, they record plant damage produced by feeding, egg depositing, pollinating, and a whole host of other activities.

- Ever since life became big, it has been interacting with the environment in a very physical manner. Creatures have been disturbing the physical structures that occur in sediments, such as fine laminations or ripple marks, and basically giving things a good mix, what is called bioturbation.

- The study of trace fossils is called ichnology and can essentially be regarded as the study of fossilized behavior. Unlike body fossils, which consist of the actual parts or impressions of an organism, trace fossils have limited use in biostratigraphy—the dividing up and correlation of rocks in a time sense—but trace fossils have several advantages in other areas of paleontology.

- First, trace fossils often develop under specific environmental conditions, making them great for paleoenvironmental interpretation. Another distinct advantage is that you can be certain that a trail or footprint has not been moved. This is a problem with body fossils: If you are using them to interpret an ancient environment, you have to make sure that the creature has not been moved from one environment to another post-mortem. But for a trace fossil, where you find it is where it formed.

- Second, they can also give us an appreciation of the activity of soft-bodied creatures that rarely fossilize. Trace fossils have been studied for a long time, although initially many of these lines and squiggles in rocks were often misidentified as seaweeds or worms. Dinosaur footprints are a little easier to interpret but were often regarded as footprints of huge flocks of birds.

- This misidentification of some of these tracks and trails as worms and plants may explain why trace fossil are named like fossil plants and animals, using the Latin binomial system with a genus and species name.

- The fact that we are not dealing with an individual species but a type of fossil behavior can cause some confusion, though. A trace fossil is given a generic Latin name—for example, *Rusophycus*. However, because this is a type of behavior—in this case, where an organism rested—*Rusophycus* can be produced by a whole range of different organisms.

- Another difference we have to consider relates to the different things organisms may do on a day-to-day basis. Just as a person potentially could leave multiple different traces in wet sand by making sand castles, digging for clams, walking, and running, any individual fossil organism could be responsible for an entire range of traces, depending on what it was doing.

- This potential confusion when studying and naming trace fossils is why we tend to classify them by the behavior they represent and not by the creatures that produced them.

- There are several types of traces that can be found. *Repichnia* are traces that an animal makes as it moves. *Fodichnia* describe various feeding

Trace Fossil

burrow structures. *Domichnia* are interpreted as places where an organism actually lived. *Cubichnia* covers all types of resting traces, such as *Rusophycus*.

- The divisions between some of these classifications might not be hard and fast. Perhaps a creature's living burrow could also act as a feeding burrow. However, these classifications provide a framework on which we can start to hang various types of fossil behavior.

## Evolution and Diversification of Life

- Trace fossils are an important part of a paleontologist's arsenal for interpreting past behavior and environment, but there is another important component to the study of trace fossils: understanding the early evolution of the biosphere and the diversification of animal life.

- The first fossil evidence of life is found around 3.4 billion years ago in the fossil microbes found in the Strelley Pool sandstone of western Australia. In the same section, though, laminated structures have been found that have been interpreted as stromatolites, which are commonly produced by photosynthetic cyanobacteria. These bacteria trap grains of sediment in their sticky, mucilaginous sheath and then move upward through the sediment, creating a new layer. In this way, they commonly "dome upward," producing column-like sedimentary structures.

- Stromatolites can be classified as trace fossils because it is not the cyanobacteria that are being preserved—just the laminations and the structures they produce. For billions of years—although we find individual, single-celled microfossils—stromatolites are really the only large-scale evidence of life we have.

- Their diversity over time also has a story to tell. Throughout the Precambrian period, they are a common component of many shallow marine settings, but by the time we get to the Cambrian period, they are only at about 20% of their former abundance.

- This change in stromatolite abundance tells us that grazing organisms are now an important part of the ocean system. Grazers are now feeding on the bacteria on top of the sediments before they get a chance to form the beautiful columns and domes we see in the Precambrian.

- This change is called the Cambrian substrate revolution, where not only grazing animals were staring to have an impact on the planet, but also burrowing animals, who would churn the sediment still further. After the evolution of various worms and arthropods during the proliferation of life called the Cambrian explosion, sediments in shallow marine environments went from fairly firm, stabilized by microbial mats, to mushier.

- Since the Cambrian, stromatolites have been marginalized, restricted to extreme environments, places where the water may be too salty or too oxygen deficient for grazing creatures. Areas like these provide a rare

window into the way the world must have looked billions of years ago, before the evolution of grazers.

- Another type of trace fossil, coprolites (fecal pellets), may have also made a significant contribution to the Earth system at this time. By producing large fecal structures that sink and deliver carbon rapidly to the ocean floor and sediments, they lessened the oxygen demand of surface waters. This may have promoted oxygen enrichment in the oceans and allowed for the evolution of larger and even more complex creatures.

- Generally, geological boundaries are marked by the incoming of a distinctive fossil species that can be correlated widely. There is one point in geological time, though—probably one of the of the most important points in the history of the planet—where it is trace fossils and not body fossils that are used to define the base of a geological period.

- The trace fossil assemblage *Treptichnus pedum* not only defines the base of the Cambrian period but also the whole Phanerozoic eon, marking a transition from the Precambrian into a new world full of complex life.

- Geological periods are defined at sections called international stratotypes, places where rocks are used to define a particular boundary in time within geological history. For the base of the Cambrian, the transition from the Precambrian to the Cambrian, and the entire Phanerozoic eon, is taken at a place called Fortune Head in Newfoundland.

- It is here that the appearance of *Treptichnus*, and an association of other trace fossils, defines the base of the Cambrian. It is thought that the creature producing this trace fossil was a creature called a priapulid worm, probing and searching in the sediment, either preying on or scavenging for small invertebrates just in or on the surface.

- The significance of this assemblage is profound. It marks a critical event in the biosphere in which organisms are now starting to dynamically interact with the physical environment, an evolutionary change in the behavior of life and the biosphere.

## Advanced Behaviors

- Trace fossils can provide insights into how life leaves a record of some pretty fundamental behavior—specifically, how creatures moved, how they fed, and how some of them built a home.

- A mobile fauna is a big leap forward for the biosphere. By the time we get to the Cambrian, various creatures, such as trilobites, are engaged in a variety of different activities, from furrowing through sediments to skipping across the sediment surface.

- But not all marine creatures simply "meander" around on the surface of the ocean floor. Sometimes, movement is needed in another direction—when a catastrophe occurs. There is a class of trace fossils called *Fugichnia*, or escape traces.

- We can't talk about movement traces without mentioning dinosaur tracks. Although we have to be careful when interpreting such tracks, we can glean some very important information from them. For example, if you have a set of prints, you can calculate stride length. Also, when we shift from a walk and into a run, stride length will increase.

- Trace fossils have also helped answer questions about how marine vertebrates moved. A long paleontological debate has centered around how the Triassic semiaquatic marine reptile *Nothosaurus* swam. Did they sweep their limbs in a figure-8 motion (the mode of locomotion penguins use today), or did they employ a rowing motion with their limbs?

- Paleontologists from the University of Bristol and the China Geological Survey found a series of pairs of slot-like tracks preserved in mudstones from Yunnan in southern China. Analysis of the orientation and size of the traces indicate that they were made by the animal's forelimbs as they moved over the seafloor, using a rowing action in unison—not a figure-8 motion.

- Ever since the biosphere has started purposely moving around, it has been generating trace fossils. But complex life doesn't just move; it also has to eat and, in doing so, produces a whole additional type of trace fossils.

- One of strangest types is *Paleodictyon*, a honeycombed-shaped structure found in quiet deepwater environments from the Cambrian to the present day. A type of trace called *Agrichnia*, a farming trace, has been interpreted as organisms deliberately cultivating bacteria on the ocean floor. But probably the most common feeding traces are those made by deposit feeders, which are animals that process sediment for organic material and nutrients.

- *Domichnia* are dwelling traces. Some can be simple vertical burrows, such as *Skolithos*, or more complex ones, such as *Ophimorpha*, a trace decorated with "sediment balls" that the trace maker stuck on the outside of the burrow. Horizontal-branching dwelling traces called *Thalassinoides* can be generated by a number of creatures, including acorn worms, fish, and crustaceans. Recently, some unexpected dwelling traces have come to light in both western Montana and Victoria, Australia, that show that some dinosaurs dug burrows.

## Environmental Analysis

- As useful as trace fossils are in paleobiology, they are also extremely useful in environmental analysis. Trace fossil assemblages, or ichnofacies, respond rapidly to the environmental conditions in which they form.

- During the 1960s, the utility of trace fossils in paleoenvironmental interpretation really took off. Pioneering work by researchers such as German paleontologist Adolf Seilacher and later Robert Frey have expanded our appreciation of trace fossils in this regard.

- The general character of these trace fossil ichnofacies has remained fairly consistent from the Cambrian to the present day. The implication of this is that although the producers of the traces have changed through time,

the manner in which they were responding to the environment—their behavior—has not changed very much.

- The ichnofacies are named by reference to a particular characteristic trace fossil of each assemblage. *Nereites* ichnofacies are characterized by horizontal, meandering or spiral-feeding surface traces and sometimes the bacterial farming traces. *Cruziana* ichnofacies are very busy trace fossil assemblages full of feeding, moving, living, and resting traces. *Skolithos* ichnofacies are dominated by vertical burrows and are usually associated with coarser sandy material.

- Trace fossil assemblages not only tie down specific environments, but they can also help chart changes in environmental conditions over time, whether that is long-term change, such as with variations in sea level, or short-term events, such as storm surges.

- Sediment-based trace fossils, as well as evidence for the interactions between plants and arthropods, are an extremely valuable tool that we can use to understand the behavior of extinct organisms. They also chart critical environmental changes in a way that body fossils sometimes cannot.

## Questions to consider:

1. What trace fossils might we humans be leaving for future paleontologists to discover?
2. Why can trace fossils rarely be tied to any one particular organism?

## Suggested Reading:

Lockley, *Tracking Dinosaurs*.

Seilacher, *Trace Fossil Analysis*.

# Lecture 5

# Taxonomy: The Order of Life

I n this lecture, you will consider one of the fundamental underpinning pillars of paleontology: the science of classifying and naming organisms—the science of taxonomy. To some, this may sound trivial, but without it, there would be no paleontology. In this lecture, you will learn who Carl Linnaeus was and what Linnaean classification is, how taxonomy is different for paleontology, and why classification is important in paleontology.

## Linnaean Classification

- In 1735, Carl Linnaeus published the first edition of *Systema naturae*, which had a profound effect on biology and paleontology. In this book, all of creation is organized into 3 major kingdoms. Each of those kingdoms is divided into subgroupings of class, order, genus, and species—significantly fewer than the subdivisions we have today. Naturalists before Linnaeus often used a somewhat arbitrary grouping of creatures—for example, groupings that comprise all creatures that live in water or all domestic animals. Linnaeus was one of the first to group genera into higher taxa based on somewhat logical similarities.

- Linnaeus's 3 kingdoms are the animal kingdom, the plant kingdom, and the mineral kingdom.
  - The animal kingdom is comprised of Mammalia (mammals), Aves (birds), Amphibia (including retiles and non-bony fish), Insecta (all arthropods, not just insects), and the Vermes (basically all other invertebrates, including worms, mollusks, and echinoderms).
  - For the plant kingdom, Linnaeus creates a system of 24 classes of plants based on the number and organization of a plant's sexual organs,
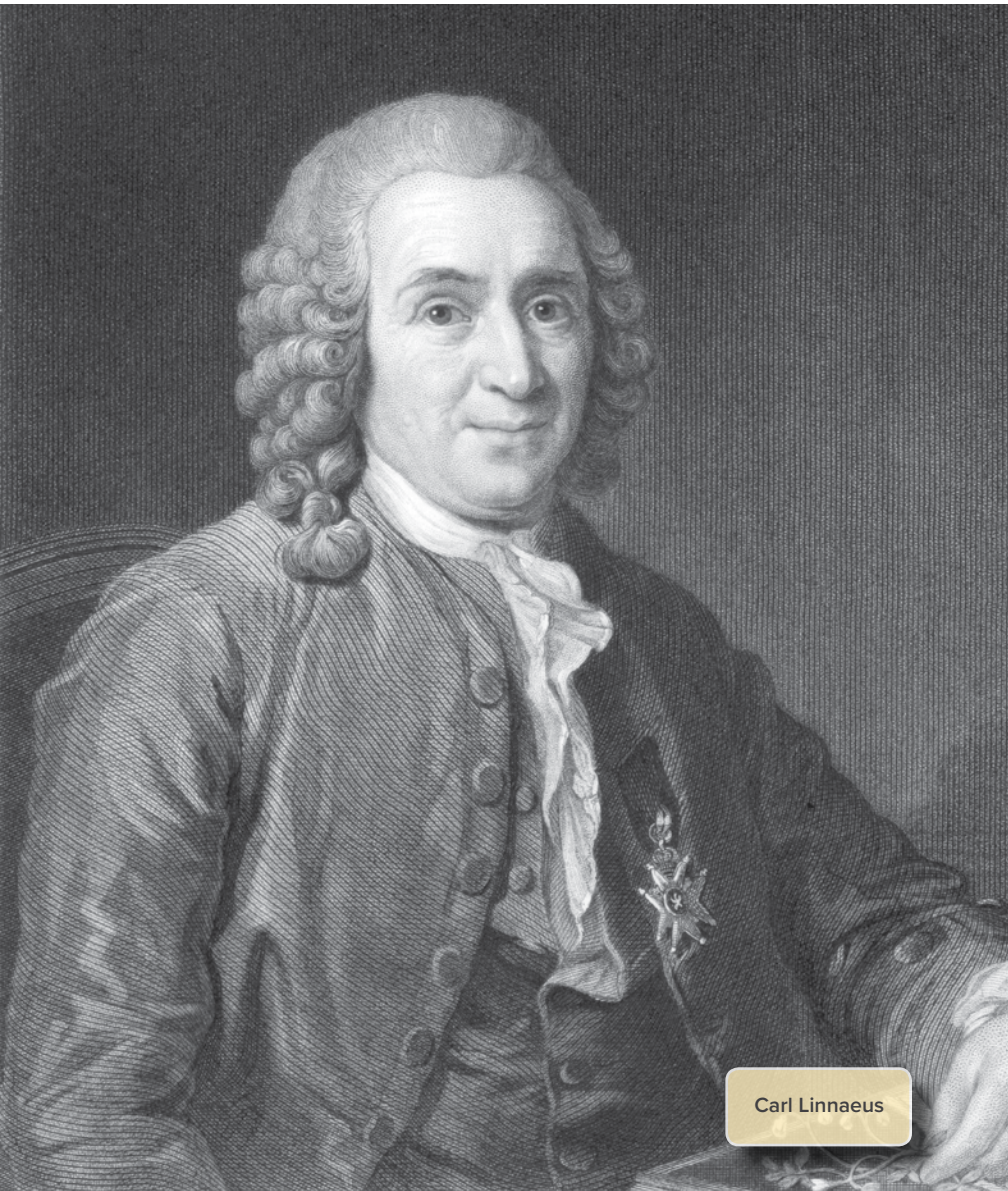
Carl Linnaeus

the male stamens and female pistils and related reproductive features. This wasn't without controversy; the way Linnaeus would focus on the sexuality of his classification offended some.

- In Linnaeus's time, many believed that minerals possessed a basic "life force," and as such, minerals form part of Linnaeus's system of classification. The mineral kingdom was divided into Petrae (rocks), Minerae (minerals and ores), and Fossilia (fossils and aggregates).

● Linnaeus published 12 editions in his lifetime, continually revising and updating his classifications. The manner in which we order life today is quite different than Linnaeus's original efforts, but much of the legacy of his efforts are still with us. We still have a hierarchical organization of life, and we still have the scientific binomial system.

● In the days before the *Systema naturae*, naming creatures could be quite messy. Take, for example, the tomato. Prior to Linnaeus, it went by the rather grand and long-winded name of *Solanum cauke inermi herbaceo, folis pinnatis incises*: "The solanum with the smooth stem which is herbaceous and has incised pinnate leaves." Under the Linnaean binomial system, it becomes *Lycopersicon esulentum*—much less of a mouthful.

● Because of the hierarchical system of *Systema naturae*, you don't need to list all the descriptive components of a species; all you need is the name of the genus followed by the name of the species—for example, *Passer domesticus* (the house sparrow) and *Acheta domesticus* (the house cricket).

● It is a simple but powerful system. The species, or specific, name of any member of a genus could be used for other, different genera, such as *domesticus*, which is also used as the species name of several other plants and mammals. However, genera will always be unique.

● Today, the system of classification used by many biologists and paleontologists is called cladistics, which considers the "shared and derived" characteristics of creatures when classifying them, rather than a superficial "appearance." For example, under cladistics, there is no grouping called "fish," or "class Pisces," as the group is traditionally understood.

- When you actually study the characteristics of certain fish—for example, a lungfish and a cod—you will find that a lungfish shares more features in common with a frog than it does with a cod, even though a lungfish under the Linnaean system would be classified under Pisces, "fish."

- In cladistics, by contrast, groupings that only contain all of their descendants can be considered as a legal classification, or what is defined as monophyletic.

- In classification using cladistics, relationships between organisms are illustrated using a cladogram, a branching diagram of relationships supported by derived character states. Cladograms are not evolutionary trees, and ancestors are not shown at branching points.

## How Is Classification Different for Paleontology?

- Linnaeus placed fossils within his mineral kingdom under Fossilia. Unlike rocks and minerals, the binomial system for paleontology persisted—which is understandable, given that we are dealing with former life—and the zoological or botanical codes of taxonomy that apply to living animals and plants likewise apply to fossil forms, too.

- However, the problem that we have with fossils compared with living creatures is that, as fossils, a lot of the information that could be used to classify these creatures is simply gone. As such, drawing the lines between species can be difficult.

- Imagine how different human beings can look depending on their sex, age, historical background, and environment. Add to that the problem that paleontologists may be dealing with incomplete, fragmentary, or otherwise modified material and the problem is compounded.

- For a biologist, differences within the same species can be tested by simply observing that living species, watching how a species develops and changes over time and recording differences that might occur to the same

species due to environmental factors. And if you observe 2 individuals mating—however different they may look superficially—and producing viable offspring, you can be sure that they are of the same, or at the least very closely related, species.

- Today, biological classification is further aided by studying the genetic similarity between creatures, allowing us now, more than any time before, to start to place life into real groupings based on real genetic similarity. This, with the exception of rare and fairly recent fossils, is not available to the paleontologist.

- Three of the most iconic dinosaurs can help illustrate some of the problems that paleontologists face. *Brontosaurus*, *Stegosaurus*, and *Triceratops* were discovered by famous paleontologist Othniel Marsh in the late 1800s.

- *Brontosaurus* was part of a treasure of dinosaurs recovered from the western United States by famous dinosaur hunters during the 1870s. Marsh discovered the skeletons of 2 partial sauropod dinosaurs—the group to which these 4-legged, long-necked dinosaurs belong—and sent them to the Peabody Museum at Yale. He named the first specimen *Apatosaurus ajax*, or "deceptive lizard."

- In 1903, he named the second skeleton and decided it was sufficiently different—not only to be considered a different species, but also a completely new genus. As such, *Brontosaurus excelsus*, or "noble thunder lizard," was born.

- After Marsh described these 2 specimens, skeletons belonging to similar sauropod dinosaurs were excavated, and upon analysis, it was determined that one species fell on a morphological spectrum somewhere between *Apatosaurus* and *Brontosaurus*. As such, the differences between the 2 end members of the group didn't appear so extreme after all, and the skeletons, including the new species, were all placed in the same genus.

- Taxonomically, the first named specimen has precedence, so all of these animals became apatosaurs, with *Brontosaurus excelsus* renamed *Apatosaurus excelsus*.

- When you make a taxonomic determination, you are effectively proposing a hypothesis regarding the position of a particular living, or fossil, organism within the 4-billion-year-old tree of life. Any new information, such as data from new analytic techniques or additional specimens, may help revise that hypothesis.

- For *Brontosaurus*, new information would be released in 2015 in a paper by British and Portuguese paleontologists Roger Benson, Octávio Mateus, and Emanuel Tschopp.

- Determining when some fossil is sufficiently different from another, to be placed in an entirely new genus, is not strictly governed by any clear taxonomic guidelines. A judgment call has to be made.

- Since the time that the genus *Brontosaurus* had been demoted, however, new sauropod specimens had been recovered, and these paleontologists took advantage of the new discoveries to apply an extensive statistical analysis of the differences between various features of these animals.

- In concentrating their analyses on the broad group to which the apatosaurs (the diplodocid dinosaurs) belong, they found that the difference between widely accepted genera within the diplodocids were at the very least the same as the differences between *Apatosaurus* and what Marsh had originally described as *Brontosaurus*. This shows how taxonomy is dynamic and potentially subject to change with every new discovery that is made.

- An exceptional discovery of a "*Stegosaurus* graveyard" in Montana has permitted the analysis of a large well-preserved population of stegosaurs. Like *Brontosaurus*, this dinosaur was also originally discovered and named by Marsh in 1877 from the Jurassic Morrison Formation in southwestern Wyoming. Initially, Marsh thought that the plates of the *Stegosaurus* lay flat on its back like shingles—hence the name *Stegosaurus*, or "roofed lizard."

Marsh would later rethink his interpretation, giving us the classic spiky-backed dinosaur we know today.

- When considering the overall morphology of the stegosaurs and the microscopic bone structure, graduate student Evan Saitta of the University of Bristol was able to determine that all the stegosaurs found in the deposit were adults and that they all belonged to the same species, *Stegosaurus mjosi*.

- Even so, there was a particular difference he found in the shape and arrangement of plates on their backs: Some specimens had plates that were pointed and tall while others possessed plates that were broader and rounded. Saitta suggests that this could represent sexual dimorphism in the dinosaurs. He proposed that the broad, round plates belong to the males and the tall, pointed plates belong to the females.

- Although this hypothesis is not accepted as evidence of sexual dimorphism by all, this does illustrate how we need to be careful when naming our dinosaurs or any other fossils. It is possible that if fewer, more poorly preserved specimens were recovered, these 2 forms could have been interpreted as 2 different species, rather than male and female of the same species.

- *Triceratops* was first discovered near Denver, Colorado, in 1887 and was originally described by Marsh as a bison, *Bison alticornis*. However, he eventually realized that they belonged to a horned dinosaur he named *Triceratops*. A controversy would erupt regarding this dinosaur in 2009, when paleontologist Jack Horner from the Museum of the Rockies and his graduate student John Scannella would propose a hypothesis that would significantly reduce the number of dinosaurs we have on the books.

- They suggested that *Triceratops* and *Torosaurus*, another horned dinosaur discovered by Marsh, were the same species, with *Triceratops* being the juvenile and *Torosaurus* being the adult. They even proposed an intermediate "teenager" in the genus *Nedoceratops*.

- These dinosaurs look quite different, though. *Torosaurus* has a much larger frill, which is perforated with large oval holes—perforations that are lacking in *Triceratops*. Although these animals overlap in time, they were regarded as being so different that they were not only different species but also different genera. But Horner and Scannella take a different view, claiming that these differences just reflect different developmental stages of the same dinosaur.
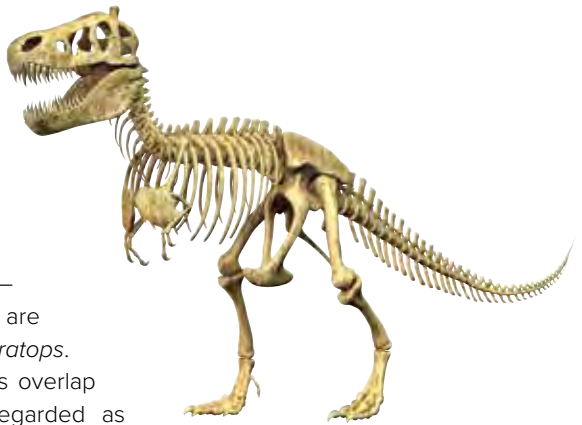
- If Horner and Scannella are proved to be correct, it would mean that we lose *Nedoceratops* and *Torosaurus* as valid Linnaean genera—all of them becoming different growth stages of *Triceratops*, which, as described first, takes taxonomic precedence.

- Horner thinks that this could be part of a wider problem. He estimates that perhaps more than 1/3 of all dinosaur species in the Late Cretaceous, where *Triceratops* is found, may never have existed. He believes that many may just represent different growth stages, misinterpreted as separate species.

## Why Is Classification Important?

- It may appear that questions about classification are very academic, but just consider the debate sparked by the classification of *Triceratops*, *Nedoceratops*, and *Torosaurus*.

- If we accept the views of Horner and Scannella regarding the number of "real" dinosaur species at the end of the Cretaceous, we have a much more impoverished dinosaur population than was previously thought

prior to the impact of the extraterrestrial body that marks the Cretaceous-Paleogene extinction 66 million years ago.

● This gives us a very different understanding of the paleoecology and stresses that this formerly successful and very biodiverse group may have been experiencing prior to their final extinction.

● The ongoing process of the classification of fossils helps deepen our understanding of biodiversity over time. Taxonomy refines our focus through the deep-time window that paleontology affords us. This is vital, as paleontology is our only long-term benchmark against which we can compare modern changes in the biodiversity and current health of our ecosystem. In fact, paleontological taxonomy and classification could prove vital in charting our planet's future.

*Questions to consider:*

1. What problems do palaeontologists face when attempting to classify fossils?

2. With a better understanding of the relationships between organisms, do groups like "fish" and "reptiles" make sense anymore?

*Suggested Reading:*

Blunt, *Linnaeus*.

Foote and Miller, *Principles of Paleontology*.

# Minerals and the Evolving Earth

This lecture will consider the evolution of our planet with a focus on the evolution of Earth's minerals—a perspective that considers how minerals have influenced all of Earth's systems, including the biosphere and its history as revealed by paleontology. In this lecture, you will learn what the first minerals are, which minerals develop after the Earth formed, how we reach the wonderful diversity of minerals we see today, and what role life would have in that story.

## The First Minerals

- The idea of looking at our planet through the lens of minerals was developed by Robert Hazen of the Carnegie Institution of Washington. Hazen and his colleagues, from various research institutions, proposed that many of the 4400 minerals we know of today have "coevolved" with the biosphere through time.

- Obviously, minerals don't mutate and evolve in a biological sense, but they have changed over time, both reflecting and influencing our evolving planet. As such, considering the changing mineral makeup of our planet also helps paleontologists appreciate factors that might be influencing the fossils they find through Earth's history.

- Hazen and his colleagues proposed 3 eras and 10 stages of Earth's mineral evolution. Each stage sees dramatic changes in the diversity of Earth's near-surface recoverable minerals.

- In the beginning—about 13.7 billion years ago, at the time of the big bang— there were no minerals. It is estimated that by about 377,000 years after

the big bang, the first hydrogen and helium atoms started to form. It is likely that during these cataclysmic events, some of the first microscopic crystalline minerals, around a dozen, would form, including diamond, graphite, and various silicates.

- These few primordial minerals have been named ur-minerals by Hazen, a reference to the ancient Sumerian city of Ur that marks some of the earliest evidence of complex civilization. These early ur-minerals would combine, mix, and react over time to form much of the complex world we know of today.

- To understand the mineral story of Earth, though, we have to move forward in time to about 9 billion years after the big bang—that's 4.6 billion years ago. This is a time before our familiar planets had formed. In their place was a vast cloud of hydrogen, helium, and dust—the dust probably comprising some of the early ur-minerals.

- This cloud was contracting and spinning under its own gravity, forming a concentration of material at its center. This is known as the T Tauri phase of a star's development. The star is not yet able to fuse hydrogen and initiate nuclear fusion but is still bright and radiant as it collapses under gravity.

- Even at this stage, though, it is still energetic and hot, with the young protostar heating up a disk of material that surrounds it. This is the protoplanetary disk, and it from this that the planets will eventually form. It is thought that around 60 mineral species get cooked, and thus form, in this particular stage of the solar system's development.

- Some of those early mineral phases have been preserved and occasionally fall to Earth as a class of meteorites called primitive chondrites. These developed as the dust and Sun-bathed minerals started to accrete together, initially due to electrostatic attraction, a bit like dust bunnies, and later, as they became larger, under gravity.

- An interesting feature of these meteorites are the small (around 1 millimeter) spherical chondrules. These probably represent molten droplets that were formed by flash heating as the early Sun cooked the materials in its surrounding protoplanetary disk—fascinating echoes of conditions in that early cloud before the Earth was born.



Meteorites

- Over time, these small chondrites would accrete together to form larger bodies. If larger than about 200 kilometers in diameter, heat from the decay of radioactive isotopes trapped inside these rock piles and heat generated by collisions would cause the interiors of these larger bodies to melt, or at least partially melt, and produce new suites of minerals.

- These so-called planetesimals would also differentiate under gravity, with heavier components, such as nickel and iron, sinking to the center of the mass. This creates a protoplanet with a basaltic, relatively light, lavalike crust surrounding a dense metallic core.

- Meteorites called achondrites are thought to represent the shattered crustal fragments of some of these protoplanets. Iron-nickel meteorites are likely their shattered metallic cores.

- This also tells us that the early solar system was a busy shooting gallery with multiple mergers, titanic collisions, and destruction of some of these early planetary bodies. By the end of this stage, all this activity would see the cumulative count of minerals rise to about 60.

# Mineral Development after Earth's Formation

- After the Earth had formed and differentiated, the light scum of less dense minerals that remained close to the surface would have cooled to form a blackened basaltic skin. This black crust would be repeatedly recycled though, melting and generating magma that would undergo an important processes called fractional crystallization.

- As magma cools, its composition changes. This is because different minerals crystallize out of the melt at different times, depending on their melting point. As the magma continues to cool, minerals crystallize in order of their melting points, continually changing the composition of the remaining magma and the composition of the minerals it generates.

- This stage of magma differentiation is probably the level of mineral evolution that the Moon and Mercury reached but went no further. It is probably the presence of liquid water on Earth that allows mineral evolution to progress further. Our planet may have been cool enough for liquid surface water as early as 4.4 billion years ago. The interaction of minerals with water would allow for the number to rise to about 500 in the Earth system. This is also possibly the stage that the once-wet Mars may also have reached.

- Another significant development would be the formation of granitic rocks, rocks that contain lots of quartz and feldspar, which started to form in Earth around 4 billion years ago. As magmas were continually injected into the early crust, they would partially melt the surrounding crustal rocks, but with only the relatively less dense minerals melting, as it is these that have the lowest melting points.

- As a result, these magmas had a very different composition of less dense minerals than the parent rocks that were melted to form them. It is this process that would produce the granitic magma that would rise into higher levels of the crust, cool, crystalize, and form granites.

- Because granites are significantly less dense that basaltic rocks, they are very buoyant and tend to float on the surface of the dense rocks in the mantle. These accumulations of buoyant granitic rocks would be the seeds of the first continents.

- Granitic melts would continue to differentiate, helping concentrate rare and mostly lighter elements into granitic rocks. Through these processes, our mineral count is now around the 1000 mark.

- Earth, and possibly Venus, reached this stage of granite production and mineral evolution, but our own planet—probably uniquely in the solar system—would have more stages to pass through before its current final inventory was reached.

- The next stage involves the initiation of a process that we think is only found on our planet, at least in our solar system: plate tectonics, which describes the large-scale motions of the fractured plates that make up the Earth's outer surface, the lithosphere.

- At plate boundaries, parts of the lithosphere can slide past each other, but the lithosphere can also spread apart, generating new oceanic lithosphere. Some boundaries are marked by the collision of plates, forming large mountains, or by plates being destroyed as one is forced under another in a process called subduction.

- As far as we know, Earth is the only planet to have initiated extensive and prolonged plate tectonics. Plate tectonics is a significant reason for the complexity and diversity of Earth's geology and biosphere.

- The temperature and pressure regimes caused by different types of plate movements generated new minerals. Plate tectonics would also elevate mountains, exposing these newly formed minerals to weathering process and generating even more minerals. This process is still going on today.

- In addition, oceanic water, seeping into the crust at ocean-crust-generating mid-ocean ridge systems and also taken down into the mantle on

subducting slabs of oceanic lithosphere, would alter preexisting rocks, creating new minerals. This process is still occurring at hydrothermal vent systems located at mid-ocean ridges today.

- It is at these vent systems where metals, in combination with sulfur, generate massive sulfide ore deposits. These processes have concentrated large quantities of metal ores.

- All this plate tectonics–related activity brings our mineral count to 1500.

## The Role of Life

- The presence of abundant and very evident life probably explains the overwhelming bulk of the 4400 minerals on our planet today. We have paleontological evidence of life at around 3.4 billion years ago—bacteria that were metabolizing sulfur-based compounds. It would appear, however, that life initially had very little effect on increasing the mineralogical diversity of our planet.

- That would change dramatically, though, about 2.5 billion years ago, when we start to see significant numbers of certain microbes spreading across the planet—microbes that had developed a photochemical trick called photosynthesis.

- The earliest form of photosynthesis used hydrogen sulfide as a hydrogen donor to power the reaction, but later forms of photosynthesis would use water. The consequence of this would be the release of oxygen. This period in history is known as the great oxidation event and is probably the most important event in the diversification of Earth's mineralogy.

- Of the approximately 4400 known mineral species we have today, more than half of them are oxidized and hydrated products of other minerals, a situation that can only develop on a planet rich in free oxygen. It is at this point where we see the diversity and complexity of minerals outstripping anything else in our solar system.

- Another consequence of this availability of oxygen would be a dramatic change in the chemistry of the oceans. Prior to the great oxidation event, the Earth's oceans had been largely anoxic—that is, they contained little to no dissolved oxygen. As a consequence, unoxidized iron was the common form found dissolved in seawater.

- With the introduction of oxygen into this system, unoxidized iron was oxidized into insoluble minerals, such as magnetite and hematite, which would effectively form rust in the oceans that would settle out in layers on the ocean floor of continent shelves, alternating with layers of less iron-rich chert. These so-called banded-iron formations are some of the most iron-rich ores on Earth today and are the result of this significant change in the Earth system around 2.3 billion years ago.

- At around 1.85 billion years ago, the deposition of banded-iron formations ceases abruptly. This change marks the transformation of the land as oxygen, now no longer captured to form rust in the oceans, is released to the atmosphere and would start to oxidize minerals on the continents, turning many parts of the surface red.

- What follows, from 1.8 to 1 billion years ago, is known as the boring billion, which sees no new major innovations in life or minerals.

- Between 1 billion to 542 million years ago, the Earth would suffer a series of super glaciations, or snowball Earth events. It is thought that the end of each snowball would be associated with extreme weather conditions, which would thoroughly mix the oceans, flooding them with nutrients and causing a bloom of oxygen-producing cyanobacteria.

- The resulting increase in the availability of oxygen provided opportunities for creatures to evolve bigger bodies. This would set the stage for our next leap in the Earth system: the explosion of multicellular life-forms. By the time we get to the base of the Cambrian period, 542 million years ago, biology would be the main driving force in the formation of new minerals.

- The colonization of the planet by organisms—and, in particular, the movement of plants onto land—would see a vast increase in the amount of clay minerals being produced by biological weathering. Particularly important would be the effect land plants would have on the development of new types of organic-rich soils and the opportunities for more mineral formation. This expansion of the biosphere and organic carbon production would see the formation of more carbon-rich deposits.

- The explosion of biologically driven mineralogy would increase the total number of mineral species to the current level of about 4400—a product of our planet's long and complicated evolution and the prolonged development of its biosphere.

### Questions to consider:

1. Because a mineral is loosely defined as a naturally occurring crystalline solid, is ice a mineral?
2. Could a complex mineralogy be used in the search for life on other planets?

### Suggested Reading:

Chesterman, *The Audubon Society Field Guide to North American Rocks and Minerals*.

Hazen, "The Evolution of Minerals."

# Fossil Timekeepers

How do fossils speak to time and cycles of time? They are obviously representatives of times past, but is there more to them than simply being old? This lecture will address several questions: Do we need fossils as clocks? How do fossils act as the time keepers of geology? Do days fossilize? Can fossils record changes in the cycles of the solar system over hundreds of thousands of years, or even longer?

## Do We Need Fossils as Clocks?

- Our ability to date our planet and its history is becoming more and more sophisticated. Scientists such as Marie and Pierre Curie and Ernest Rutherford advanced our understanding of radioactivity and radioactive decay and, with it, our ability to date our planet.

- Radiometric dating is based on an understanding of the principles of radioactive decay. It considers the ratio of an unstable radioactive isotope, the parent material, such as uranium 238, to its decay product, the daughter material, which for uranium 238 is lead 206. The uranium doesn't decay entirely into lead all at once but, rather, follows a decay chain with various forms of radiation being emitted as a chain of unstable isotopes is produced along the path to lead 206.

- Because we know the rate at which the parent material decays into the daughter material, we can calculate how long decay has been progressing. The technique assumes that no parent or daughter material has been added to the sample—what is called a closed system.

- Fortunately, crystals in igneous rocks, rocks that cool from a magma, form great closed systems that trap small quantities of radioactive isotopes and, as such, act as clocks, ticking away as time passes by.

- The time it takes for half of the parent to decay into the daughter material is called the half-life. For uranium 238 to lead 206, that is about 4.47 billion years. So, even in Earth's oldest rocks, if there is material to analyze, there should be enough parent material left to work out the ratio and calculate an age.

- Although the vast majority (around 90%) of rocks in Earth's crust are igneous rocks, the vast majority of the rocks that cover the surface of the crust—those that contain the majority of the history of life—are sedimentary rocks. Clastic sedimentary rocks that form from the erosion of older rocks may contain datable crystals from igneous rocks.

- But if you find such a crystal that has not been compromised by the erosion that created the sedimentary rock, it will not provide a date for the sediment or the fossils it contains. It will only provide a date for the igneous rock from which it was derived.

- How do we place fossils in a sequence that makes chronological sense? This was an issue that William Smith solved in the late 1700s. He recognized that various types of fossils followed one another in a predictable order. Once you knew the order, you could place any geological stratum that contained fossils into a time frame relative to another exposure, perhaps at some considerable distance, based purely on the fossils it contained.

- For the first time, scientists had the ability to order the geological strata they found based on the order of the fossils they were finding in them. This also permitted geologists and paleontologists to correlate between areas in time.

- This would allow William Smith to create the first large time-based geological map. This development is the start of the science of biostratigraphy, in which we consider the distribution of a particular fossil species from the time it first

Sedimentary rocks

originated to the time it becomes extinct. The time this represents is called a fossil's range.

● Such fossil ranges are collected from many different sections and cross-correlated with other fossils and dating techniques. In this way, we can get a pretty good estimate of the slice of time a particular fossil species represents.

● As such, a species that has traveled far and died young makes the best fossils for dating. This is because they define a focused slice of time over a wide area. Not all fossils are great time keepers, though; some species just existed for much too long and, as a result, don't provide us with sufficient time resolution.

● Given that, some of the best fossils for correlation are fossils that would range far and wide across the oceans, such as free swimmers or planktonic floaters, who are found in many locations and across many environments. Microfossils—a broad group of tiny fossils, generally less than 1 millimeter

long—are also great for biostratigraphy, as many were planktonic and distributed widely through the oceans.

## Can Days Fossilize?

- As the Earth rotates, a circadian rhythmicity is generated that can impact the behavior and even the anatomy of organisms. For example, the orbital position of the Earth will impact the amount of incoming solar radiation, generating the seasons with various effects on organisms. By careful analysis of certain fossils, it is potentially possible to read these time-related changes recorded in their tissues.

- For example, consider creatures with shells or skeletons that live in shallow marine environments that respond to daily tidal variations. Although care has to be taken to account for other environmental factors, creatures such as bivalves (clams) show growth lines that correspond to daily, monthly, seasonal, or yearly environmental changes. These correspond to packets of different thicknesses of growth bands; collectively, this accounting of time is known as sclerochronology.

- One of the first studies to apply this technique was in 1963, when John Wells of Cornell University interpreted fine ridges on the surface of fossil corals from the Devonian period as being circadian in nature. The ridges were further grouped into regular bands thought to be lunar-monthly breeding cycles. He also identified major annulations that he suggested corresponded to seasonal-yearly environmental changes. From his calculations, Wells estimated that the Devonian year consisted of about 400 days.

- This means that the Earth's rotation about its axis has been slowing down. The Earth's initial spin at the time it formed was due in part to the angular momentum of the initial spinning nebula from which the solar system formed.

- Other factors probably also affected the Earth's rotation, including an impact with Theia, a hypothetical Mars-sized body that collided early in Earth's history and is probably responsible for the formation of the Moon.

Following this event, the Earth may have zipped around on its axis in just 6 hours.

- Since then, the Earth's rotation has been slowing down, mostly due to the Moon's effect on ocean tides. The Moon's gravity is dragging on a tidal bulge in the oceans, slowing the Earth down like a brake on the wheel of a car.

- There are other factors that can affect day length, too. For example, it has been estimated that the devastating 2004 Sumatra-Andaman earthquake in the Indian Ocean effectively shortened the length of the day by about 2.68 milliseconds. This megathrust earthquake saw a large portion of the Indo-Australian plate suddenly shoved under Indonesia and into the planet. In the same way that ice skaters pull their arms into their body, their center of mass, to make them spin faster, the earthquake sped up the planet and shortened, very slightly, the length of our day.

- Fossils provide snapshots through time of the rate of Earth's rotation. For example, by the time of the extinction of the dinosaurs at the end of the Cretaceous, there were 371 days in a year. The Middle Permian year was 390 days long, with around 397 days in the Late Devonian.

- Abundant fossils of animals with mineralized skeletons only really occur after the Cambrian explosion, about 542 million years ago. Can we go any further back with our day-length estimates? We probably can, with a little help from bacterial mats and structures they produce call stromatolites, some of which date back to 3.5 billion years ago.

- Stromatolites are layered structures that form in shallow water. They grow as microbial mats—commonly composed of cyanobacteria—trap, bind, and cement sediments. The bacteria move upward daily, forming a new layer, creating the laminations seen in the fossils.

- These daily laminations have been used by a number of authors to estimate year length in the Precambrian. For example, in 1984, James Vanyo and Stanley Awramik from the University of California, Santa Barbara, estimated

that stromatolites studied form the Bitter Springs Formation in central Australia indicate that there were 435 days in a year at 850 million years ago.

## What about Longer Cycles in Earth History?

- A particular cycle that has a great influence on global climate over hundreds of thousands of years are Milankovitch cycles, which are caused by 3 properties of Earth's orientation and movement around the solar system: obliquity, precession, and eccentricity.

- Obliquity is the change in the tilt of the Earth's axis, which is never vertical but ranges from 21.1° to 24.5° and back again over a period of about 41,000 years. The tilt of the Earth's axis doesn't always stay pointing at the same place in the, sky though; like a top, it moves in a circular manner that is called precession over a period of around 23,000 years. This "wobble" is largely controlled by the gravitational influences of the Sun and Moon. Eccentricity describes the change in the shape of Earth's orbit over time, from more circular to more elliptical over a period of about 100,000 years. This change is caused by the gravitational influence of Jupiter and Saturn.

- Each of these cycles will affect the amount of solar radiation striking the Earth, but their greatest effects will be felt when these cycles all add together. It is thought that in the current ice age, it is these cycles that are a major influence in the retreat and expansion of ice over time. We are currently in an interglacial time interval.

- During a warmer period of Earth's history, we can still detect these cycles when the Earth doesn't plunge into a glacial period under their influence by using fossils. A good example comes from research of Dr. Brian Huber, a micropaleontologist in the Smithsonian's National Museum of Natural History's Department of Paleobiology.

- Changes in the amount of solar radiation can have impacts on a whole range of Earth systems beyond ice formation, including changes in oxygen distribution in the oceans, sea-level fluctuations, nutrient availability,

and temperature. These changes will produce different signals from different fossil communities, but one of the most sensitive are marine microorganisms, such as the foraminifera that Dr. Huber studies.

- Dr. Huber and his collaborators were studying sediments extracted by the Ocean Drilling Program that were deposited during the last stage of the Cretaceous. The Cretaceous was an extremely warm period, with likely little to no ice at the poles. The sediments they recovered showed distinctive variations in color between red and green. Using paleomagnetic data contained within the sediments, they could calibrate these changes with other variables, and they determined that these changes may have been controlled by a 21,000-year precessional cycle.

- Fossils are useful in highlighting cycles over tens, perhaps hundreds, of thousands of years, but what about even longer—perhaps hundreds of millions of years long? Things become a little more difficult when dealing with extended timescales. This is in part due to the incompleteness of the sedimentological record. The older you get, the more incomplete the record becomes.

- One of these long-term cyclical proposals comes from David Raup and Jack Sepkoski of The University of Chicago, who described, based on changes in biodiversity over time, a periodic pattern of mass extinctions with a 26-million-year periodicity. A popular explanation for this was an increase in impacts of comets from a remote zone of the solar system.

- The increased frequency of impacts was explained by Michael Rampino of New York University as being due to the vertical oscillation of the solar system as it periodically passed through the plane of the galaxy. This would disturb these comets and cause them to start to tumble into the inner solar system, some of which would impact the Earth, causing extinction events.

- Raup and Sepkoski's suggested periodicity of mass extinctions met with a lot of criticism, though. Some have claimed that the apparent periodicity was just a statistical artifact. Some, such as Robert Rohde and Richard Muller of the University of California, Berkeley, have proposed an alternate

periodicity of 62 million years and another at around 140 million years, with possible causes in comet showers and mantle plume–generated volcanism, among others.

## *Suggested Reading:*

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*, chap. 7.

Winchester, *The Map That Changed the World*.

# Fossils and the Shifting Crust

E xotic fossil assemblages can be set adrift on continents and continental fragments to beach thousands of miles away in a completely different part of the world. In doing so, they leave a story of their origin and journey through time. In this lecture, you will learn what paleobiogeography is, what the fossils in Alfred Wegener's jigsaw puzzle were, how fossils can time the closing of an ocean, and how fossils trace the dance of continental fragments through time.

## Paleobiogeography

- Why are creatures where they are? We obviously don't live on a planet where life-forms are spread in a homogeneous manner; different types of animals and plants have distributions and concentrations. Basically, all creatures have a geographical range, some broad and some narrow. Endemic species are only found in a specific area, while cosmopolitan species are found in a range of environments.

- On a very broad scale, life can be divided up into several biogeographical provinces, or ecozones, which are geographical areas of the world that have characteristic communities of species. The Nearctic ecozone includes North America and Greenland. Europe, Asia, and North Africa are in the Palearctic. Others include the Neotropic, Afrotropic, Indo-Malaya, Australasia, and Arctic.

- Ecozones can also be recognized from Earth's geological past, but in this case, we have to consider the additional complication that wandering continents add to the story. The first thing we need to consider is the manner in which diversity changes, very broadly, across our planet. To do

that, we also need to think about how our planet's magnetic field intersects with the ground.

- It has been suggested that the movement of liquid metal in the outer core around the solid metal inner core, due to convection and the Coriolis effect of the spinning Earth, produces electric currents that, in turn, generate Earth's magnetic field. The Earth is like a giant bar magnet, with lines of force running from the North Pole to the South Pole. Just like a bar magnet, on our planet, the magnetic field is inclined toward the vertical at the poles, and at the equator it will be parallel to the surface of the ground. This means that magnetic inclination and latitude are linked.

- This signal can be locked into certain fine-grained sediments and basalt lava when iron-rich minerals take up the magnetic inclination at the time of their formation. So, if you can record the inclination of the magnetic field in the rocks, you can also estimate the paleolatitude of that rock at its time of formation. There is a relationship between latitude and the diversity of organisms, too: The diversity of organisms is highest at the equator and drops off toward the poles.

- Both the magnetic inclination and the diversity data provide potentially useful information about where on the surface of the planet, in a latitudinal sense, a particular rock was when it formed. These are important clues that we can use when trying to recreate the history and movement of areas of our restless planet.

- The second point we need to consider is the concept of barriers to the migration of species. On land, barriers could be an inland
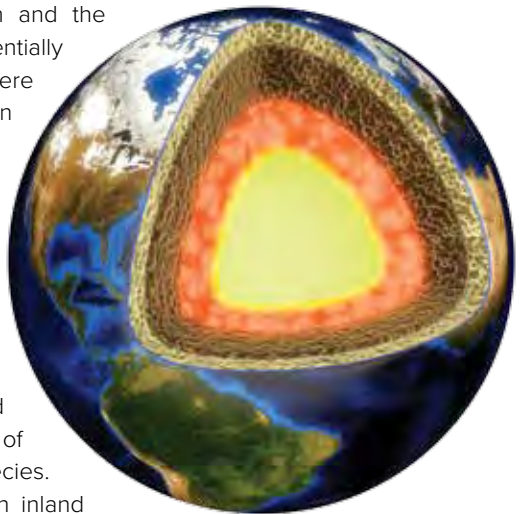
sea, mountains, or even dense forest. In the ocean, barriers can include swift currents or deeper parts of the ocean, where food resources may be limited. Barriers could also be due to different temperature and climatic regimes.

● Paleontologists are also concerned with a dimension beyond the currently geographical one: They want to know what happens to the distribution of plants and animals over time, what is called dispersal biogeography.

● One of the first people to consider such migrations was American paleontologist George Gaylord Simpson, who imagined species originating at a central location and then dispersing over time. Dispersal would vary depending on the ease of movement of creatures.

● Simpson referred to a corridor as a place where creatures can mix fairly easily. Other migration routes are more selective, allowing the passage of only a restricted selection of creatures. Simpson termed this type of feature a filter bridge. The third dispersal mechanism Simpson termed sweepstakes, which describes migration due to the relatively rare but still important effect that luck has in the movement of organisms from one place to another. Simpson also recognized that dispersal, and associated isolation, is a powerful force in evolution.

● When considering the distribution of species, we have to consider that it is not only creatures that migrate—continents do, too. Simpson was no fan of the idea of drifting continents, so his view of the dispersal of organisms through time was essentially a static one, with the continents and the ocean basins occupying their current locations for more than hundreds of millions of years.

● But with the dawn of plate tectonics, and the dynamic movements of continents over time, a whole new way of looking at the dispersal of fossil species came to light.

# Wegener and Continental Drift

- German climate scientist Alfred Wegener challenged the static view of continents. He amassed a wealth of data to suggest that the continents were once joined, including similarities of the stratigraphic record on distant continents, evidence of glaciations that once covered a united supercontinent, and the fit of coastlines on either side of the Atlantic.

- In 1915, he proposed the existence of a supercontinent called Pangaea that existed more than 250 million years ago. Accordingly, the current continents represent the fragments of that united landmass that have subsequently drifted to their current locations.

- But perhaps some of his most compelling evidence for continental drift came from fossils, many of whose current distribution is puzzling in the context of a static planet. For example, fossils of *Cynognathus*, a meter-long predator from the early Middle Triassic period, have been found in South Africa and China. It could have walked to those locations based on earlier views of static, immobile continents.

- But specimens were also found in Argentina and Antarctica. Physiologically, these creatures were not adapted to swimming, so how they could be found on such distant continents separated by enormous oceans? This distribution only makes sense once the continents are drawn back together.

- But there was a problem with the mechansim Wegener proposed to explain how the continents drifted. He suggested that the gravitational pull of the Sun and Moon and the spin of the Earth were "dragging" the continents around the planet. This was a very difficult pill for many scientists to swallow, because these forces are nowhere near what would be needed to move a continent. The hypothesis of drifting continents was largely ridiculed.

- The distribution of Wegener's fossils was explained away by the rafting of creatures, the presence of land bridges, or island hopping. It is difficult,

though, to see how these mechanisms could operate over large oceans and how they could account for the distribution of so many fossil species.

## The History of the Iapetus Ocean

- Eventually, the idea of drifting continents would be revived, but this time with the more plausible mechanism of seafloor spreading. Scientists such as Harry Hess, Marie Tharp, Bruce Heezen, and John Tuzo Wilson would pull together information from ocean-floor topography, seismic records, and ocean-floor magnetism to give us the theory of plate tectonics that we are familiar with today.

- Wilson proposed—on the basis of fossils and his understanding of tectonic plate motions—the existence of a large ocean in the Northern Hemisphere. He called this ocean the proto-Atlantic and claimed that this ocean, later called Iapetus, closed during the Silurian and Devonian periods.

- Although of the same geological age, Cambrian trilobites of western Newfoundland are different from those of eastern Newfoundland. The association of fossils in the west are called the Laurentian fauna, and those in the east are called the Avalonian fauna.

- The western Newfoundland faunas have more in common with those of Scotland, northwestern Ireland, and most of the rest of North America. By contrast, the eastern Newfoundland faunas, which also occur in New Brunswick, Nova Scotia, and Massachusetts, share more fossil biogeographical connections with most of Europe, including England, Wales, and southeastern Ireland.

- Before the advent of plate tectonics, this mismatch of trilobite faunas across the Atlantic was explained away by a bunch of geological and oceanographic gymnastics. But in a plate tectonics context, this tells us that Newfoundland is a sutured landmass. In other words, the 2 halves were once associated with different continents on either side of an ancient

ocean that subsequently have been brought together and fused by plate tectonics.

- The fossils are different because the western and eastern parts of Newfoundland were in different climatic zones during the Cambrian on opposite sides of the Iapetus Ocean, with the ocean being sufficiently wide at that point to even prevent the mixing of marine species. The 2 faunas were brought together when the ocean closed. Where the 2 faunas now meet represents the line along which the eastern (Laurentian) and western (Avalonian) terranes were sutured together in what today is Newfoundland.

- When the Atlantic Ocean opened up, splitting the continents apart again, fragments of the Avalonian or Laurentian faunas were stranded on either side of the ocean. Fossils would not only uncover the presence of this ancient ocean; they would also help document its closure over time.

- It is thought that Iapetus opened in the Late Precambrian as an older supercontinent, called Rodinia, fragmented. British paleontologists Stuart McKerrow and Leonard Robert Morrison Cocks would record changing faunas found on either side of the Iapetus Ocean as this body of water narrowed. They found that faunas in Europe and North America were most different during the Cambrian and Ordovician, with only planktonic species—which floated in the ocean and would have been able to mix relatively freely across a large body of water—being found on both sides of the ocean. It is estimated at its widest point that Iapetus would be about 4000 kilometers wide.

- As the ocean started to close and the distance between North America and Europe was reduced, creatures that had a planktonic larval stage started to mix on either side. In addition to planktonic forms, nektonic, free-swimming organisms were also able to make the crossing. As the ocean narrowed even more, less mobile forms were able to make it across. By the end of the Devonian, the Iapetus Ocean was sufficiently narrow that even freshwater fish were similar in western Europe and eastern North America.

## Exotic Terranes

- Since the early days of plate tectonics, our understanding of the complexity of the wandering continents has increased considerably. One of the ways our understanding has become more complex is an appreciation of what are called exotic terranes. In addition to large continental masses lumbering around the planet, it was realized that small fragments of continents have also been rifting off larger parent bodies, zipping around the Earth like marbles, colliding with other areas, potentially thousands of miles from where they originated.

- Exotic fragments can generally be recognized by geologists in the field when mapping highlights major fault zones that represent lines of disjunction between the rock units to either side. The exotic blocks themselves differ dramatically from the surrounding geology, with paleontology and even sometimes paleomagnetic inclination very different from the surrounding geology, suggesting a more exotic, perhaps significantly distant, origin.

- Fragments can be composed of ancient volcanic islands, oceanic ridges, various ocean-floor volcanic features, and fragments of other continents.

- This so-called accretion tectonics is probably a common process through geological time but is most easily recognized in relatively recent rocks with relatively less deformation, where traces of these fragments can still be uncovered.

- In considering how fossils help us in our understanding of the movement of terranes, we need to appreciate how populations, or species, of organisms differ in relation to the geographic distance between them. In other words, the farther away they are from their original source, the more dissimilar they become.

- The similarity between populations can be calculated using the Simpson coefficient, in which the higher the coefficient, the greater the similarity

between 2 populations. This is a powerful tool when attempting to reconstruct the movement of terranes.

● Diversity gradients and paleomagnetism are useful tools in determining the ancient latitude that a particular terrane occupied, but there is an obvious drawback: We have no idea about the longitude of the terrane, and this is where fossils and similarity coefficients come into play.

● Studies of exotic terranes have helped us unravel a picture of what is today a fairly complicated geology, the product of the collision between various bits and pieces zooming across the Pacific and colliding with the main North American continental landmass.

*Questions to consider:*

1. Should we expect greater biodiversity during times of continental amalgamation or fragmentation?
2. How much of the ancient history of the dancing continents and continental fragments is lost to us?

*Suggested Reading:*

Keary, Klepeis, and Vine, *Global Tectonics*.

Plummer, Carlson, and Hammersley, *Physical Geology*.

Paleogeographic and Tectonic History of Western North America, http://cpgeosystems.com/wnampalgeog.html.

# Our Vast Troves of Microfossils

Micropaleontology is a world of paleontology that often gets overlooked—quite literally—because it is the world of the very small. In this lecture, you will learn about microfossils. You will also learn about foraminifera, including how these fossils chart global climate over 120 million years and what they tell us about the death of the dinosaurs. You will also discover what microfossils tell us about how evolution works.

## Microfossils

- There is no fixed definition of what a microfossil is. Basically, if it's very small and needs a microscope to be seen, you can call it a microfossil. Most microfossils are less than 1 millimeter in size, but some are much larger. Given such a broad definition, microfossils can come from a wide variety of sources. They are also the first fossils we find in the geological record, given that first life was probably microbial.

- In addition to microbes, microfossils also include many important components of microplankton, which form the base of almost all aquatic food chains. Microplanktons' sensitivity and reaction to events in the wider Earth system are critical in any narrative we are trying to develop about the evolution of life on our planet.

- Planktonic microfossils include those with organic walls, such as the dinoflagellates, a group of marine protists that move around using a whiplike flagellum. Many dinoflagellates are photosynthetic, but some are tiny predators that feed on other protozoa. As fossils, dinoflagellates are

mostly known from those species that have an encystment stage as part of their life cycles.

- Not all microplankton have a test, or shell, made of organic material, though; many secrete mineralized skeletons. For example, protozoa called radiolaria secrete beautiful silica skeletons. Together with the diatoms, one of the most important components of microplankton today, they are important sediment producers, covering the deep ocean floor with a fine sedimentary rock called a siliceous ooze.

- Larger organisms can also contribute to the microfossil assemblage. Spores and pollen from plants are an important component of the paleontologist's toolkit, both for environmental analysis and for the correlation and dating of rocks. We find the first plant spores at about 470 million years ago, possibly produced by the first plant colonizers of the land.

- By the time we get to some of the first plant macrofossils, we start to see an increasing diversity of spores, reflecting the spread and diversification of plants across the coastal landscape.



Radiolaria
magnified 200x

- But larger animals are in on the microfossil game, too. Perhaps some of the most famous are the conodonts. Initially, the conodont animal was known only from its conodont elements: tiny teeth-like objects composed of calcium phosphate. They are found from the Cambrian period all the way through the end of the Triassic, which is associated with a probable extinction event at about 200 million years ago.

- Conodonts are diverse and evolved many species, some of which had quite short geological ranges, making them very useful in biostratigraphy. However, even though the conodont elements were discovered in the mid-1800s, we still didn't know what conodonts actually were.

- Because conodonts were commonly found in assemblages of paired elements, it was assumed that they formed some sort of articulated apparatus. But it would not be until the early 1980s that the soft parts of an eel-like chordate were found with conodonts arranged as teeth at the feeding end of the animal. Conodonts turned out to be chordates—not a direct ancestor of us, but certainly one of our early cousins.

## Foraminifera

- A particularly long-lived group of microfossils that have become invaluable in our understanding of the Earth system over time is foraminifera, or forams for short. Forams are a group of protists that secrete a test. Forams are found in many diverse environments, from the shallow to the deep ocean, with some even in moist terrestrial environments. They are found in climates that range from the tropics to the poles.

- Forams are an extremely powerful tool in paleontology and Earth history. Because they are widely distributed by ocean currents, they can be found in many different sediment types, making them great for correlation between different areas. And, importantly, they have a relatively continuous fossil record in ocean basins since the Jurassic.

- They also occur in high numbers—sometimes in the tens of thousands for a relatively small volume of sediment. And, very importantly, they evolved rapidly, producing short ranging forms that define short packages of geological time. This makes them excellent biostratigraphic tools.

- Perhaps one of their most significant contributions is in our understanding of long- and short-term climate change in the past. Forams are excellent paleothermometers. Their usefulness in this regard comes from the isotopic composition of the calcium carbonate shells that forams secrete, which gives us a proxy for the temperature of seawater at the time of formation of a particular shell.

- Oxygen isotopes data gained from forams have provided us with insights into the climate change in the most recent era of Earth's history, the Cenozoic, which runs from the end of the Cretaceous 66 million years ago to the present day.

- At around 55 million years ago, the record of forams shows a period of warming known as the Paleocene-Eocene thermal maximum. This warming matches the time of migration of many tropical mammals toward the poles. This warming was possibly triggered by carbon dioxide emissions related to volcanism associated with the breakup of the supercontinent of Pangaea and perhaps the release of methane, another greenhouse gas, from the oceans.

- Forams also record a major cooling event at the Eocene-Oligocene boundary, about 34 million years ago. This signals the development of the first major ice sheet in Antarctica as the continent drifted to the South Pole and started to become isolated by the Antarctic circumpolar current.

- There is another drop in temperatures at about 14 million years ago, called the Middle Miocene climate transition, which by 8 million years ago would see temperatures drop to levels that would establish ice cover present at the current levels on Antarctica.

- That is the picture from the Cenozoic, but can we take this back any further in time? This is just what Dr. Brian Huber of the Smithsonian's National Museum of Natural History's Department of Paleobiology has been doing—pushing the record of temperature changes back 120 million years, well into the last period of the Mesozoic era, the Cretaceous, when dinosaurs still ruled the land.

- One of the reasons Dr. Huber can make this trip back in time is due to the nature of the geological materials that he samples. One of the largest depositories of Earth's sediments, forams, and therefore climatic records, are the oceans. But oceans are continually being opened up at mid-oceanic ridges and destroyed at subduction zones, destroying or altering the record such that sensitive isotopic information is lost.

- Fortunately, Dr. Huber has found a number of locations where Cretaceous sediments are present and the level of preservation of forams within them is excellent. From the forams he has collected, Dr. Huber has extended the climate record for the Cenozoic, starting at 66 million years ago, back another 55 million years to 120 million years ago. Dr. Huber and his colleagues have uncovered a remarkable record of climatic changes that can be described as varying from warm to very warm over 55 million years.

- The end-Cretaceous extinction event is probably one of the most well-known crises is Earth's history, probably because of its link to the death of the dinosaurs and the massive impact centered on the present-day village of Chicxulub on the Yucatán Peninsula 66 million years ago. Because forams were, and still are, an extremely important part of the ocean system, they are useful during events like this, both for timing and for providing insight into the causes of the extinction.

- One of the questions regarding the Cretaceous-Paleogene extinction concerns the state of the biosphere prior to the Cretaceous-Paleogene boundary. The vast majority of scientists accept that an impact occurred at the end of the Cretaceous and that it had a severe and detrimental effect on the biosphere. But was this the only cause?

- An additional finger of blame is often pointed toward India and a sequence of rocks found on the Deccan plateau called the Deccan Traps. These are a vast outpouring of basalt lava that occurred at the end of the Cretaceous thought to last around 30,000 years, producing lava flows that might have originally covered around 1.5 million square kilometers. It is not lava that was the problem, though; creatures can always migrate away from centers of volcanism. It is the carbon dioxide and associated global warming that could potentially cause the most serious impact to the biosphere.

- Dr. Huber's research shows that warming started at 65.9 million years ago. This trend began just before the impact occurred at Chicxulub. This temperature increase reversed a long, slow cooling that had been progressing throughout the Late Cretaceous. Forams don't record any major extinction throughout this interval of time.

- With regard to the meteor impact at Chicxulub, forams tell an interesting story. Cores taken from the Pacific and Atlantic Oceans will often tell a familiar story across the Cretaceous-Paleogene boundary: a dramatic change in strata from white, chalky sediments into a much darker horizon that contains molten material sprayed out of the impact site, some of which fell into the oceans. These strata are capped by a thin, rusty fireball layer, representing fine debris and soot that rained down out of the atmosphere after the main event.

- Forams appear to be doing fine before the impact occurred, but after it, they register a 90% extinction of the group. For forams, it was likely darkness that would be the killer. Fine ash and soot thrown high into the atmosphere would cut off the Sun and shut down photosynthesis both in the oceans and on the land. And once the food-web support was removed, the Mesozoic biosphere collapsed.

## Microfossils and Evolution

- Microfossils hold great potential in detailing changes in climate and recording the progression of major events in Earth history, such as mass

extinction events. This is in part due to their shear abundance when compared to large (macro) fossils. This abundance also allows us to investigate some of the fundamental processes of evolution, an opportunity that was taken up by Dr. Gene Hunt of the Department of Paleobiology at Smithsonian's National Museum of Natural History.

- Dr. Hunt studies ostracods, tiny crustaceans that are typically around 1 millimeter in size. They secrete a bivalved organic or calcareous shell and are found from the Ordovician period to the present day.

- When Darwin first proposed his theory of evolution, it was criticized by some as not being supported by evidence from the fossil record. Since Darwin's time, the numbers of fossils in the collections of museums, universities, and research institutes has expanded considerably, leaving no doubt that evolution has occurred, but with the question of how evolution occurs still up for debate.

- It is in part this question that Dr. Hunt has been trying to answer using ostracods. Does evolution occur in a gradual linear manner, often called phyletic gradualism, or does evolution progress in a series of rapid pulses separated by periods of apparent stasis with little change? The latter is a hypothesis proposed by Niles Eldredge and Stephen Jay Gould in 1972 that they called punctuated equilibrium.

- There is another process, though, called random walks. This describes how trends in various features of a fossil group can develop that are not necessarily driven by natural selection. In random walks, a particular characteristic of a feature—for example, its size or complexity—may increase or decrease randomly if there is no selective pressure.

- Random walks are very rarely completely random. There will often be a bounding wall, which will prevent a certain feature from varying above or below a particular value. For example, consider the size of ostracods. Although they are very small, there will be a size below which it would be impossible for these little crustaceans to exist, bounded by such things as the functional size of organs or the ability to efficiently respire.

- Dr. Hunt tested 251 data sets of the morphological characteristics from 53 different evolutionary lineages of fossils, including ostracods, and found that directional trends only best fit about 5% of examples. About 50% could be described as random walks and 45% as stasis, with no appreciable trend. This fits nicely with what you would expect from punctuated equilibrium, with most fossils demonstrating either stasis or random walks between punctuated bursts of rapid evolution, with just a minor component of what could be described as directed phyletic gradualism.

### Questions to consider:

1. Why are microfossils so valuable in correlating rocks (biostratigraphy) and in elucidating environmental change in the oceans?

2. Why are microfossils the oldest fossils we will likely ever find?

### Suggested Reading:

Armstrong and Brasier, *Microfossils*.

Knell, *The Great Fossil Enigma*.

# Ocean Fire and the Origin of Life

Lecture
10

This lecture will examine an intriguing hypothesis regarding the origin of life, and ultimately the origin of the science of paleontology, in the ocean depths. The lecture will address these questions: How do we explore the Earth's mid-oceanic mountain chain? Do we have geological and paleontological evidence for ancient undersea volcanic ecosystems? Why are oceanic volcanoes a good candidate for life's origins? Could life have arisen in a similar manner on other worlds?

## HMS *Challenger* and *Trieste*

- Interest in the ocean floor is not a recent development. People have speculated about "what is down there" for a long time. But the first systematic survey of the ocean floor would have to wait for the HMS *Challenger*, which would sail out of Portsmouth, England, on December 21, 1872. The HMS *Challenger* would travel about 70,000 miles (130,000 kilometers), taking ocean-floor dredges, recording the temperature of the ocean at various depths, performing open-water trawls, and, in the process, discovering 4700 new species of marine life.

- As recently as the late 19th century, knowledge of the ocean was basically restricted to the topmost few fathoms, about 18 feet. The *Challenger* would perform one of the first systematic surveys of the ocean floor, using 181 miles (291 kilometers) of Italian hemp and a lead weight. On March 23, 1875, between Guam and Palau in the southwestern Pacific, the line they tossed overboard just kept on going down, eventually recording around 4475 fathoms—about 5 miles, or more than 26,000 feet, deep.

- In the 1930s, Swiss physicist, inventor, and explorer Auguste Piccard, whose first interest was the upper atmosphere, constructed pressure spheres that he attached to high-altitude balloons to measure cosmic rays. Later, he realized that he could modify his sphere to withstand pressure at depth, too.

- He invented the bathyscaphe *Trieste*, which was launched on August 26, 1953, operated by the French Navy but later purchased by the U.S. Navy. The dive began on January 23, 1960. Shadowed by the USS *Lewis*, the *Trieste* descended toward the Challenger Deep—the location that the HMS *Challenger* had sampled about 85 years earlier. At 4 hours and 47 minutes, they reach the ocean floor at 35,814 feet (10,916 meters). Just before touchdown, they spotted a flat fish swimming by—quite a surprise, as it was not known that fish could survive at these great depths and pressures.

- This mission ran at a time when the paradigm about how the world looks and operates was changing. We now know that magma oozes up at ridges in the ocean crust, forming new material and pushing the older oceanic lithosphere away to either side. Continents are carried as the plates spread away from the ridges. Ultimately, oceanic lithosphere descends into the mantle at the ocean trenches.

- This project provided vital information about one of those trenches. The Challenger Deep is just part of the Mariana Trench, a feature 2550 kilometers (1580 miles) long with an average width of 69 kilometers (43 miles). This is just one of many trenches surrounding the Pacific Ocean, marking the point where the Pacific Plate is being subducted into the Earth's mantle.

- The groundbreaking work of the *Trieste* would pave the way for exploration of another feature of the newly resolved ocean floor—the plate-generating ridges that traverse the Earth's oceans—and with the exploration of these features, a new possibility regarding the origin of life would emerge, too.

# Earth's Mid-Oceanic Mountain Chain

- Ocean ridges produce new ocean crust, and as such, they are a hot, active, dynamic feature of our planet. They form a chain of volcanic mountains about 31,000 miles (50,000 kilometers) long, rising an average of about 2.7 miles (4500 meters) above the seafloor. Although the global mid-oceanic ridge system is mostly hidden beneath the ocean's surface, it is the most prominent topographic feature on the surface of our planet.

- By the 1970s, sonar and magnetic mapping of the ocean floor had pinpointed the location of Earth's ocean ridge systems, but no one had ever seen them up close. Even so, some had speculated that they might be the site of hydrothermal activity, areas where ocean water would sink into cracks in the newly formed crust, become heated by magmatic fluids and the still-warm rocks, and get expelled again as hot water. These underwater hot springs may hold the key to the origin of life on Earth.

- We had hints of the existence of these hot springs going back as far as the early 1880s. A Russian ship, the *Vital*, was sailing in the Red Sea when it sampled water at 200 feet that appeared to be warmer than water at the surface. The presence of hot, mineral-rich water in this area was confirmed by later exploration. In 1965, the research vessel *Atlantis II* recorded water temperatures at 133° Fahrenheit.

- The U.S. National Science Foundation sent the research vessel *Chain* to take more readings. They took sediment cores of the ocean floor. The sediment they retrieved was bizarre—rich in metals such as copper, zinc, and manganese. By now, the idea of spreading ocean floors was being widely accepted, with the Red Sea identified as a young and newly formed oceanic rift.

- The hunt was on for other oceanic hydrothermal sites. In 1972, a promising site in the Galapagos rift zone was selected by the presence of hot water found on earlier expeditions and was explored by the research vessel *Thomas Washington*. Robotic and submarine-mounted cameras recorded curious mounds encrusted with minerals around 15 to 75 feet

high sticking above the ocean-floor sediments about 10 to 20 miles south of the Galapagos rift. They also detected hot fluids rising from the ridge and recorded bursts of earthquakes where the water temperature was particularly high.

● In 1977, the DSV *ALVIN* visited the Galapagos rift. In addition to finding hydrothermal vents, they also found a rich and bizarre biological community. The inhabitants included mussels and white clams, some more than a foot long, and bacteria-laden beard worms, many times larger than their shallow-water relatives, that covered the lava rock.

● Something other than the Sun must be powering life down here. The water collected by *ALVIN* contained hydrogen sulfide, which is produced by primitive microscopic microbes called archaea living in and on the hot rocks and sediments. They take sulfate that occurs in seawater and reduce it by chemically removing oxygen, producing energy and releasing hydrogen sulfide as a waste product. Higher organisms feed on archaea, making this a chemosynthetic-based ecosystem rather than a photosynthetic-based one.

## Ancient Undersea Volcanic Ecosystems

● There is evidence of these hydrothermal vent systems in the geological past. In fact, these systems are an extremely important source of metal ores. The vents form as cold ocean water descends into cracks in the ocean floor, where it is heated by hot rocks still close to the magmatic source at the ridge.

● The seawater starts to alter, and get altered by, minerals present in the surrounding rocks. The altered seawater is then expelled as a superheated metal-rich brine through hydrothermal vents, such as so-called black smokers. These volcanogenic massive sulfide deposits are important sources of ores containing copper, zinc, lead, gold, and silver. But these metal sulfides are not the only indicators of these ancient ecosystems; we also find whole fossilized vent communities.

- One of the oldest fossil vent systems we currently have comes from northeastern China. In 2007, an ancient Precambrian community was described by Jiang-Hai Li of Peking University and Timothy Kusky of Saint Louis University, who discovered evidence of a volcanogenic massive sulfide deposit dating to 1.43 billion years ago—well before the diversification of multicellular creatures. These sections preserved some of the black smoker hydrothermal vent chimneys, just like the ones we find under the ocean today.

- In addition, within these ore deposits were the fossilized remains of microbes that were living in and on this ancient hydrothermal system. The microbial community was probably sulfate-reducing, just like microbes in modern vent settings.

## A Candidate for Life's Origins

- Given that the oldest vent fossils we find are much younger than those at Strelley Pool in western Australia, why are scientists still so keen on hydrothermal vents as the location for the origin of life?

- There are a lot of raw materials—all those metals to act as catalysts for the generation of useful organics—in these hydrothermal pressure cookers. And it appears that the last universal common ancestor of living things today was an extreme thermophile, a microbe that liked the heat, just like we find in modern oceanic hydrothermal settings.

- Our job now is to come up with a hypothesis that bridges the gaps from an inorganic environment to organic molecules to the first living cells on Earth. Some ideas center around the production of self-replicating molecules as a precursor for life, although probably not DNA, which requires enzymes to reproduce themselves, which are encoded on DNA—a chicken-and-egg scenario. Perhaps a simpler self-replicating molecule, such as RNA, was the earliest form of life.

- Recently, scientists have speculated that a metabolism-first rather than genetic-first model makes more sense. Work at University College London by chemists Nora de Leeuw and Nathan Hollingsworth has shown how the mineral greigite, found inside hydrothermal vents, might be acting like enzymes in living organisms, providing a catalytic site for carbon dioxide dissolved in seawater. In addition, vent systems also provide a lot of heat to power chemical reactions that can generate complex organic molecules.

- But it has also been suggested that, although hydrothermal systems are our best bet for the location of the origin of life, perhaps we have been looking at the wrong type of hydrothermal system. In 2000, a National Science Foundation–funded project found an area called the Lost City in the Atlantis Massif, 62 miles (100 kilometers) west of the Mid-Atlantic Ridge. They found a field of hydrothermal vents that are very different from those sitting on the spreading ridges.

- In 2003, the submersible vessel *ALVIN* found white-colored chimneys composed of calcium carbonate rising from 30 to 60 feet off the ocean floor. Unlike the dark-colored black smokers of a ridge axis, these structures are not releasing significant amounts of carbon dioxide or hydrogen sulfide. Instead, they are producing high quantities of hydrogen and methane, with some hydrogen sulfide, and in alkaline rather than acidic waters.

- Areas containing white smokers could be a better location for the generation of life. They have a proven record of producing important quantities of organic molecules and have the energy and catalysts present to power an interesting biochemistry. In addition, the chimneys at the Lost City have been forming for about 30,000 years—much longer than most black smoker systems, which will only be active while they are over the hot magmatic rocks of the spreading center. This system, therefore, may provide a longer-term site for the evolution of a complex biochemistry and perhaps life.

- The rocks of both hydrothermal systems also possess an interesting microstructure: tiny pockets where organic chemistry could be concentrated and perhaps develop other features, such as a cell membrane. At a certain point in time, these primitive cells may have become sufficiently resilient to leave the vent system and start to populate the ocean.

## Other Worlds

- Vent discoveries have also opened up possibilities for the search for life elsewhere in our solar system. In particular, astrobiologists are interested in moons like Europa, which orbits Jupiter, and Enceladus, which orbits Saturn.

- It is thought that Europa may have a liquid water ocean below its icy crust that would massage the interior of the planet, generating heat and perhaps allowing for the existence of hydrothermal vents, around which life might
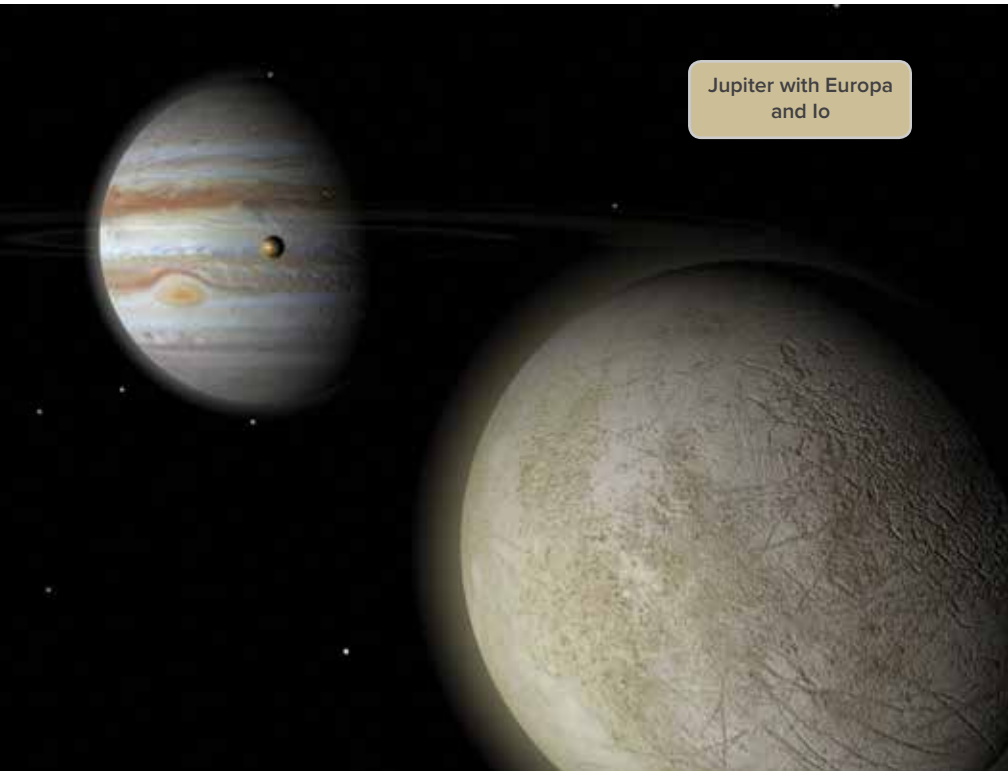


Jupiter with Europa and Io

develop. These ideas might be tested if a NASA mission is launched in the 2020s.

● We also have spectacular evidence of a similar ocean on Enceladus from 2005, when NASA's *Cassini* satellite detected jets of water being released from the moon. *Cassini* was able to fly through these plumes and detected not only water vapor but also nitrogen, methane, and carbon dioxide—all useful building blocks for the formation of interesting organic chemistry, perhaps leading to the biochemistry of the simplest organisms.

● It is possible that there may be hydrothermal vents deep in Enceladus, too—and, if so, perhaps life as well. This is an exciting possibility—not only in the search for extraterrestrial life, but also for the history of life on our planet. If life is found around such vent systems on other worlds, then perhaps anywhere we have liquid water and hydrothermal vents we should expect life processes to initiate.

*Questions to consider:*

1. Is plate tectonics a vital component of planets that might develop life?
2. On how many other worlds might life have started in our solar system?

*Suggested Reading:*

Corfield, *The Silent Landscape*.

Knoll, *Life on a Young Planet*.

# The Ancient Roots of Biodiversity

Although we have likely had life on Earth for around 4 billion years, the spectacular biosphere we see all around us today may be relatively new. This lecture will examine how we get the first indications of a diverse biosphere. What was Darwin's dilemma? What are the first stirrings of an enlarged biosphere? How would these new organisms develop? Why did this first explosion of life occur, and what happened to it?

## Darwin's Dilemma

- Charles Darwin's theory of evolution by natural selection elegantly accounts for all the wonderful diversity we see all around us today. His theory predicts that, through time, there should be a lineage of creatures eventually ending with what is today called the last universal common ancestor.

- Darwin was well aware that fossils were useful indicators of past life and ecosystems but also understood that the record was incomplete. Even so, the fossil record should still demonstrate increasing complexity from simple forms following the Early Precambrian dawn of the last universal common ancestor to the more complex biosphere we have today.

- There was a problem, though: Close to the base of the Cambrian period, today dated around 542 million years ago, the fossil record appears to indicate that a diverse array of large, complex creatures apparently materialized out of thin air. This appearance occurred even though life appeared to follow Darwin's predictions after the Cambrian period. This emergence of a complex biosphere geologically in an instant was contrary to what Darwin had predicted.

- Darwin suggested that as paleontological exploration continued, simpler fossil forms would likely turn up in older strata, but for a while this was a problem. Today, we are aware that Darwin's dilemma is related, in part, to the fact that the pace of evolution did not follow the traditional "slow, steady rate" views of the theory that many held at that time.

- Indeed, complex life and all the major plant and animal phyla that we know today did appear in the record rapidly. Essentially, the large biomineralized arthropods, such as the trilobites, that we find at around 521 million years ago, just 20 million years into the Cambrian period, arose geologically very quickly.

- Today, this rapid evolution of large animals is called the Cambrian explosion. Our insights into the world's biosphere just following this explosion of life were greatly expanded by the discovery of an extremely important fossil treasure—the Burgess Shale deposit in British Columbia, Canada—by one of the Smithsonian's most famous secretaries and director of the National Museum of Natural History, Charles Walcott.

- The discoveries of Walcott and later discoveries of Burgess-type deposits span the Early and Middle Cambrian. Together, the Burgess-type faunas paint a picture of a wonderfully diverse biosphere with the majority of all the major phyla represented.

- But was this the only big boom for complex life? Is it possible that there was an earlier explosion of life, a precursor to the explosion represented in the Burgess Shale?

## A Bigger Biosphere

- To answer that, we stay in Canada but travel to the other side of the country, Newfoundland, which lies off the coast of eastern Canada in the Atlantic Ocean. In 1968, at a location known as Mistaken Point, Shiva Balak Misra, a graduate student at Memorial University of Newfoundland, discovered an entire ancient world—an extensive ecosystem preserved on the surface

of a series of gently dipping rocks. Many believe the exosystem to be complete, incorporating all of the life-forms that were present at that time, what is called a biocoenosis, or life assemblage.

- What Misra revealed was an ancient deep ocean floor, complete with the creatures that were living on it. The rocks are now mudstone but were originally muddy sediments. The creatures he found living in these deepwater, low-oxygen conditions are from the latest Precambrian on what is now the Avalon Peninsula. At that time, this area was located between 40° and 65° south latitude, very different from its current location at 46.6° north.

- The quiet, low-oxygen conditions these creatures lived in probably aided in their preservation, but another important feature is their location: close to an ancient volcano. The volcano has long since been eroded away, but the ash that it spewed settled down through the water column, burying the creatures where they lived. The ash helped cast the fossils by forming an external mold, but it also provided an absolute date for the entombing sediments. From radiometric dating, we know that the fossils are about 565 million years old, from a period called the Ediacaran.

- The creatures found here are not like any we see today. Many of these fossils are collectively called rangeomorphs, frond-like creatures that are composed of simple budding elements that divide and repeat over 4 levels of organization in a simple fractal manner. This type of reproduction is a simple yet effective solution to build large bodies from small self-repeating elements.

- These, and related Ediacaran organisms, don't have a mouth or a gut, and some have suggested that they were osmotrophs, absorbing nutrients and organic material directly from the seawater through their bodies. They were certainly not photosynthetic, as they lived well below the photic zone, the depth to which light can penetrate into water.

- This ecosystem from Newfoundland is known as the Avalon Assemblage, and this initial burst of large creatures has been termed the Avalon

explosion. But this is not the only assemblage of creatures known from the Ediacaran period. There are 2 others that are found in different environments: the White Sea and Nama Assemblages.

## The Development of New Organisms

- The White Sea Assemblage was named for a typical occurrence of the assemblage found in northwestern Russia. The Russian Assemblage was not the first group of these particular Ediacaran creatures to be found, though. The first discovery of these creatures came from the Flinders Ranges of Australia in an area called the Ediacara Hills. In fact, it is this area that lends its name to this latest interval of the Precambrian: the Ediacaran period.

- Like the Mistaken Point fossils, these were discovered by a young geologist, Reginald Sprigg, who observed the impressions of the fossils on a rock surface. The fossils are dated at around 550 million years ago, younger than those from Mistaken Point.

- The environment that the White Sea creatures lived in was very different from those discovered in Newfoundland. The White Sea fossils lived on shallow, sandy sediments in sunlit waters in temperate conditions. Storm events occasionally smothered entire communities and preserved them more or less in place.

- The Nama Assemblage consists of forms that are interpreted as being more tropical in their distribution. They have been recovered from sections in Namibia, southern Africa.

- The temporal relationships between each of these assemblages is disputed by some, but in general, the Avalon-type cluster of species appears to be the first pulse of innovation followed by a second wave represented by the White Sea and Nama clusters of species.

- The second wave Ediacaran creatures still contains the frond-like rangeomorphs that we see in Newfoundland. It is possible that the Avalon-type assemblages still existed in the deep, dark waters surrounding the continents, but in the second wave, there are now other creatures, too.

- In the Ediacaran period, there is evidence that the biosphere was no longer static and was beginning to show glimpses of the wonderful animals that were to follow—animals that would differentiate their bodies to perform specialized functions and would move and interact with their environment in a variety of diverse ways. But why did this event occur at this point in time? What was driving the Avalon explosion?

## What Caused the Explosion of Life?

- Around 2.5 to 1.85 billion years ago, it is believed that the photosynthetic bacteria had started to deliver significant quantities of oxygen to the surface sediments, oceans, and atmosphere of the Earth system. Following that interval, the Earth enters into a period called the boring billion between 1.85 and about 1 billion years ago, where nothing much appears to change in the Earth's geochemical or biological systems.

- Things would change, though, with a series of global glaciations, called snowballs—between 850 and 635 million years ago, within a period called the Cryogenian—that were probably related to the breakup of a supercontinent called Rodinia about 850 million years ago.

- A possible explanation may be related to increased weathering rates following a snowball event. This could fertilize the oceans and cause a bloom of photosynthetic microplankton and a release of atmospheric oxygen. The increased erosion rate and delivery of sediment to the ocean would also increase the rate at which organic material was buried. Removing the organic material in this manner reduces the amount of oxygen that would usually be used up in its oxidation, further contributing to the buildup of free oxygen.

- Following the snowballs, oxygen levels would have increased to such a level that it would be possible for creatures composed of multiple cells to exist. Prior to this, oxygen concentrations were only sufficient to power a microbial level of biological organization. This would allow larger creatures to evolve, as oxygen could now diffuse through layers of cells. It has also been suggested that a more oxygenated ocean system would also make available trace elements that would be key in the development of more complex metabolisms.

- That is one hypothesis. The story of oxygen in the Earth system is a complex one and is changing very rapidly. It would appear that oxygen levels fluctuated dramatically through the Ediacaran period and into the Cambrian period.

- Some researchers, such as Douglas Erwin of the Smithsonian's National Museum of Natural History's Department of Paleobiology, have suggested that the actual roots of current diversity may even lie earlier than we thought, perhaps within the Cryogenian period, the age of the great snowballs. He suggests that the snowball events may have been the proving ground where many animals developed their genetic toolkits, priming the fuse of the diversification of the Avalon and Cambrian explosions.

- But what happened to the Ediacarans? At the end of the Ediacaran period, there is a large shift in carbon isotopes recorded in the geological record. With each of the 5 mass extinctions, starting with the extinction at the end of Ordovician about 443 million years ago, a similar perturbation is recorded and often relates to a severe disruption in the biosphere.

- So, does the Ediacaran biota disappear because of an extinction event caused by some unknown perturbations in global geochemical cycles? Or is it possible that their removal from the fossil record may simply be a result of changing conditions of preservation?

- Many Ediacaran organisms are partly preserved as the result of microbial mantling, a "mask" of microbes that grew over dead Ediacarans that

aided in their preservation. With the advent of more sophisticated grazing and burrowing organisms, the unique conditions that preserved these creatures ended and, with it, the record of the Ediacarans. But there is another possibility: one that evokes a replacement of the Ediacarans by other animals.

- In 2015, Erwin and a number of his colleagues from various universities released a paper exploring the possibility that the disappearance of the Ediacarans represents the first mass extinction event. In fact, the paper proposes that life itself may have caused a crisis for the Ediacarans.

- The Early Ediacaran animals, although a fantastic leap forward in complexity, were essentially immobile, probably passively absorbing nutrients from seawater. By the time we see complex animals, the biosphere is starting to actively interact with the rest of the Earth system. Animals have become ecosystem engineers. Is it possible that these new bioengineers changed conditions so much that it made life untenable for the Ediacarans?

- What is suggested is an Ediacaran Assemblage that was becoming increasingly outcompeted and marginalized by a developing Cambrian fauna. In physically interacting with the oceanic substrate, these new Cambrian forms would have competed for resources, increased the delivery of carbon to the ocean floor, and more effectively mixed and oxygenated ocean sediments. For the Ediacarans, the world was changing beyond their ability to adapt, and they faded away, leaving the stage set for the Cambrian explosion.

- Whatever their fate, by the time we see the first large fauna of the Cambrian, the Ediacarans are gone, either suddenly or gradually replaced by other creatures. The putative ancestors of later organisms are gone, too, their ancestors evolving into the wonderful creatures from the Cambrian explosion.

1.  Following the appearance of the Ediacaran animals, was the evolution of even more complex life inevitable?

2.  How important is mobility to the development of our complex biosphere?

Erwin and Valentine, *The Cambrian Explosion*.

Fedonkin, Gehling, Grey, Narbonne, and Vickers-Rich, *The Rise of Animals*.

# Arthropod Rule on Planet Earth

T he Department of Paleobiology at the Smithsonian's National Museum of Natural History has had a long and important association with the study of fossil arthropods. This lecture will examine some of the past history and collections, as well as some of the current research that is being undertaken on this extremely important group of animals. In this lecture, you will learn about the origins of the arthropods and how our perception of arthropods would change after the explosion of life.

## The Origins of Arthropods

- The last common ancestor of the Arthropods is out there, somewhere, in rocks that are more than half a billion years old. By removing all the recent modifications in arthropod design, we can figure out the basic characters of this time-distant creature—or ur-arthropod, as it is sometimes called, after the cradle of human urbanization, the ancient Sumerian city of Ur in Iraq.

- The ur-arthropod is imagined as a segmented, bilaterally symmetrical, highly appendaged creature with each segment covered by its own armor plate, or sclerite. Each undifferentiated segment would be provided with a pair of biramous, or branched, limbs with a mouth positioned underneath the body at the head end. The head would have eyes, often compound, and probably one or more pairs of antennae. Given the nature of some of the very early arthropods, it would most probably feed by processing sediment for organics with quite complicated mouthparts.

- Some of the earliest arthropod-looking creatures in the fossil record come from the Ediacara Hills in Australia. The fossils are found in a geological formation called the Rawnsley Quartzite that were originally sands

deposited in shallow tidal waters around 555 million years ago during the Late Precambrian Ediacaran period.

- One of the members of this diverse, and sometimes strange, fauna of the Ediacaran Hills is a wormlike fossil called *Spriggina*, named for Reginald Sprigg, who discovered the Ediacaran fauna in 1946. *Spriggina* was around 1 to 2 inches (3 to 5 centimeters) long and appears to be segmented, supplied with rows of plates along its back. In addition, unlike many other creatures in the Ediacaran fauna, it has an obvious head, or cephalon, not unlike the head shields we find in trilobites, which are definitive arthropods occurring later during the Cambrian period.

- If it does represent an earthly arthropod, then *Spriggina* is a problematic fossil. First, one of the key features of arthropods, jointed legs, have not been found on any specimen thus far. In addition, although the creature appears to be symmetrical, *Spriggina* actually has a special form of symmetry called glide symmetry, where the segments running down the center line of the creature are imbricated, forming a steplike pattern.



Fossil trilobite imprint in the sediment

- Another contender for the arthropod ancestor from this time is *Parvancorina*, which has also been compared to trilobites. This is a fairly simple creature with a shield-like body and blunt head. It is bilaterally symmetrical, but no segments or limbs have been found.

## Changing Perceptions of Arthropods

- The Burgess Shale is located in the Rocky Mountains of British Columbia. It was discovered by Charles Walcott, former Secretary of the Smithsonian, at the end of his 1909 field season and named for nearby Mount Burgess. He would return a number of times and amass a wonderful collection of fossils. Walcott's fossil quarry is now in part of Yoho National Park.

- In total, Walcott would recover more than 65,000 specimens that he would faithfully record, extract, and return to the Smithsonian, forming one of the most important collections of Cambrian fossils in the world. Although its full importance was not really realized until the 1970s, Walcott's discovery sheds light on an incredible ecosystem—a world that had recently gone through the Cambrian explosion and that would see the relatively simple animals from the Ediacaran diversify into all the body plans of animals we see today.

- There were organisms fixed to the ocean floor, such as algae photosynthesising in the dim filtered light, and numerous sponges, filter-feeding organic material and microplankton raining down from above. Most of the mobile creatures were dominated by forms that moved around on the ocean floor, probably eating mats of algae and microbes or processing sediment on the ocean floor for organic material. Some creatures lived in the sediment. Compared to today, there was not the diversity of creatures swimming in the water column.

- If it were not for the exceptional preservation of the soft-bodied Burgess Shale animals, our picture of the Cambrian world would have been very different—one that would appear impoverished, with only shelly, hard-parted creatures represented.

- Like today, the dominant life-form in the Burgess Shale, in sheer numbers of species, were the arthropods. There were a variety of trilobite as well as early ancestors of the crustaceans.

- By the time of the Burgess Shale at 510 million years ago, an entire suite of arthropods is present, with most of the major arthropod subgroups represented—not only here, but in all of the other Burgess-type sites around the world.

- But there are also some odd arthropod-like creatures associated with our Burgess arthropods. One is the *Tyrannosaurus rex* of the Cambrian oceans: *Anomalocaris*, some specimens of which from China are up to 6 feet long. The giant limbs in front of this creatures were used to capture and hold its prey.

- On the underside of its head is a strange squared-ring mouthpart full of sharp teeth, probably designed to crunch arthropods or other prey. It had well-developed eyes, and its body was flanked with flexible lobes, which would have made it a strong swimmer.

- A recent discovery of a new anomalocarid has shed more light on the relationships among the arthropods of the Burgess world. This particular find doesn't come from the Cambrian, though; it was found in Morocco in Ordovician rocks, 30 million years after the Burgess Shale.

- The creature was enormous, about 6.5 feet (2 meters) in length, but rather than the fierce predator from the Cambrian, *Aegirocassis benmoulae* appeared to have its front appendages modified for filter feeding, probably swimming through the ocean filtering microplankton.

- But what is significant for our understanding of the evolution of the arthropods is the nature of the swimming lobes in this fossil. All previous anomalocarids were assumed to have a single set of flaps per segment for swimming, but *Aegirocassis* possessed 2. The upper flaps were equivalent to the upper limb branch (called the exopodite) of modern arthropods,

while lower flaps are the equivalent of the lower walking limb branch (called the endopodite) of modern arthropods.

- An examination of the Cambrian anomalocarids has shown that these, too, had paired flaps but had been overlooked. The reason they were found in *Aegirocassis* is the nature of the preservation, which is less flattened than the Cambrian forms.

- Before this came to light, the anomalocarids were an anomaly in our understanding of arthropod evolution and did not quite fit comfortably in the general arthropod story.

- The discovery that they possessed 2 flaps on their segments and not one and that those 2 flaps were separate and not branched put them on a stem leading to what some call the Euarthropoda, or true arthropods. They represent a stage before the fusion of exopodite and endopodite into the modern arthropod biramous limb we see today.

- In other words, anomalocarids are more basal than the trilobites and today's arthropods. As such, the more we find out about their morphology, the more hints we get regarding the evolution of arthropods—in this particular case, an insight into the typical Euarthropodan biramous limb.

- We are still a long way from a complete understanding of the evolution of the early arthropods, but new discoveries, particularly of beautifully preserved Burgess-type material, are certainly helping to clear the fog that has surrounded the origins of this most important phylum.

## The Trilobites

- Dr. Robert Hazen, a senior scientist at the Carnegie Institution of Washington, has one of the most wonderful trilobite collections in the world. In 2007, he donated the collection to the Smithsonian's National Museum of Natural History's Department of Paleobiology.

- The trilobites first appeared about 521 million years ago, about 21 million years before the abundant arthropod and trilobite fauna we find in the Burgess Shale. They were a very diverse group, with 20,000 species, so far, described.

- Trilobites, meaning 3 lobes, have quite an association with the number 3. Their bodies are divided into 3 segments, and they have 3 major longitudinal lobes. The living Paleozoic trilobite was provided with jointed legs, gills, and antennae like many other arthropods. In general, though, it is only the hardened calcium carbonate of the outer shells that get preserved. Like all arthropods, trilobites had to molt to grow.

- We even have some clues as to how at least some trilobites would mate. There are a number of instances where trilobites of one species, a monospecific assemblage, have been found preserved in large clusters that appear to represent a life assemblage. A remarkable discovery in Portugal of some large trilobites was published in 2009 by The Geological Society of America. Researchers from Portugal and Spain describe incredible clusters and long lines of trilobites. They suggest that this may be equivalent to a mass spawning like we see in their closest relatives, the horseshoe crabs, of today.

- Trilobites are probably some of the first animals to gaze upon the world they lived in, as they possessed fairly sophisticated eyes. Some trilobite even had extremely enlarged eyes.

- Their adaptability is seen in the variety of habitats they lived in; they have been found in virtually all marine environments, from the shallow to the deep ocean. They were not restricted to the ocean floor, either. Some trilobites with extremely enlarged eyes are thought to have been pelagic floaters. Some larger forms were likely active swimmers.

- Their diversity is also seen in the different ways in which they fed. Important clues come from a structure on the underside of the animal called the hypostome situated by the trilobite's mouth. There is a whole range of different types of hypostome, probably reflecting the different

types of food these creatures were scavenging or hunting.

- The trilobites would also develop a whole range of spines and complicated structures, some of which are pretty difficult to interpret. Perhaps some of the most bizarre are those that have been extracted from the Anti-Atlas Mountains of Morocco. For example, *Walliserops*, a trilobite that comes from the Lower-Middle Devonian period, is not only provided with various long curved spines and processes, but at the front end is a long 3-pronged trident.

- The trilobites would suffer major extinctions at the end of the Ordovician and then again at the end of the Devonian. They would recover a little through the Carboniferous but never regain the diversity they attained in the Cambrian and Ordovician periods.

- By the end of the Permian, their numbers had dwindled to 5 genera. At the final devastation that rocked the biosphere 252 million years ago, the trilobites were in a very precarious position, with a restricted distribution in shallow marine environments that would be hit hard during the extinction. Even with the sad passing of the trilobites, arthropods would continue to spread and diversify.

# Making a Break for the Land

- Arthropods were probably some of the first animals to make the break from the ocean to the land. Their external exoskeletons could act a bit like a spacesuit on land, and many groups of aquatic arthropods had already evolved limbs, placing them a step ahead of our group, the vertebrates. We would have to turn limbs into fins through transitional forms.

- Some of the oldest obligate terrestrially adapted creatures on land were probably related to the myriapods, the group that contains millipedes, centipedes, and the gigantic Late Paleozoic arthropleurids. The oldest terrestrial animal fossil, *Pneumodesmus newmani*, is a species of millipede-like myriapod dating to the Late Silurian of Scotland, about 428 million years ago. These initial invaders of the land were probably feasting on plant litter, just like their modern equivalents do today, and were likely an important factor in the development of soils.

- These detritus feeders were rapidly followed by a wave of other arthropods, the Chelicerata, the group that includes mites, scorpions, and spiders.

- Another major group of arthropods, the crustaceans, would also get in on the terrestrial act. Examples today include wood lice, or pill bugs, and coconut crabs.

- Another important group of arthropods are the hexapods, from whom we gain the incredibly diverse insects. Research into the paleontology of insects and other arthropods is continuing to flesh out the dynamic history of this important group of animals.

*Questions to consider:*

1. Why are arthropods not the dominant large creatures on Earth today?
2. Could our world function without arthropods?

*Suggested Reading:*

Conway-Morris, *The Crucible of Creation*.

Fortey, *Trilobite*.

# Lecture 13

# Devonian Death and the Spread of Forests

Alfred Sherwood Romer was a U.S. paleontologist whose research points to a drop in diversity in the fossil record of early tetrapods—vertebrates that have 4 limbs—from 360 to 345 million years ago during the first 15 million years of the Carboniferous period. Prior to the gap, during the Late Devonian, there was an expanding population of early tetrapods. This gap has been a matter of great debate. One explanation is that diversity had crashed at the end of the Devonian period. In this lecture, you will consider what happened at the boundary between the Carboniferous and the Devonian.

## The Late Devonian Earth

- The climate at the start of the Devonian was generally warm and dry, with the situation getting more tropical and sometimes rainy as the Devonian continents started to move toward the equator. During the Late Devonian, however, there are indications of successive advances and retreats of glacial ice at the poles.

- Glacial indicators—such as glacial sediments called till, grooves on bedrock, and dropstones (which form as rocks are released from floating icebergs and fall into the sediment beneath)—have been found in various locations in Africa and South America, at this time part of Gondwana. This suggests the presence of ice sheets at various times in the southern polar regions, with perhaps a number of expansions and retreats of ice over the South Pole. This period of glaciation in Gondwana lasted until the mid-Permian.

- An important feature of the later Devonian oceans is the development of black shales in many ocean basins around the world. The black color of the

shale is in part caused by the presence of the mineral pyrite that is finely dispersed throughout the rock, but also due to its high organic content. These sediments often give off a very characteristic rotten-egg stench, the marker of hydrogen sulfide, and bacteria that like to live and respire in such low-oxygen conditions. This hydrogen sulfide is also responsible for the high pyrite content of these rocks.

- Black shales are common in the oceans from about the Middle Devonian, but prior to this, extensive reefs were very common in the shallow oceans that surrounded the still-fragmented continents of the Devonian world. An example of a spectacular Devonian reef can be found in the Canning Basin of Australia. This reef developed during the Middle to Late Devonian, when a shallow tropical sea covered this area of Australia. The reefs were constructed by calcareous algae, corals, and spongelike encrusting creatures called stromatoporoids. Reefs were much more common in the Devonian than they are today and supported a thriving community of invertebrates.

- But the Devonian had seen considerable innovations on land, too. The Devonian boasts the first tetrapods that were starting to tentatively explore the land.

- But one of the most striking features of the Late Devonian world was the spread of green along coastlines of the continents, perhaps extending inland in more favorable settings. Plants were expanding their colonization of the land.

- Plants had made it to land earlier, during the Silurian about 430 million years ago, but plants would remain pretty small, inauspicious, and tied to open sources of water in those times.

- Even by the time we get into the Early Devonian, the landscape was still dominated by small wetland-dwelling plants. But by the early Middle Devonian, plants had risen off the ground with the evolution of horsetaillike forms and the beginnings of the fern lineage. But it was not until the late Middle Devonian that the real revolution occurred, with the evolution of

seeds, true roots, wood, and multiple origins of leaves. This dramatically changed the reproductive biology and stature of land plants.

- It is important to note that each time we see an innovation in plants, there is an associated increase in the diversity of herbivores. Dr. Conrad Labandeira, a paleoecologist in the Smithsonian's National Museum of Natural History's Department of Paleobiology, notes that herbivory (eating plants) in arthropods developed just 20 million years after the first land plants had evolved during the Silurian. Herbivory was an important development that became a major driving force in the processing of live plant tissue into organic carbon.

- Innovations in the plants permitted tall trees to spread across the landscape and into highland and more inland areas, finally breaking ties with standing water. This was the start of the greening of the Earth beyond the coastlines and the first forests.

## Crisis in the Late Devonian

- The Late Devonian was a time of change, not only in the biosphere, but also in the state of the oceans and atmosphere. Oceanic anoxia was present in some areas, as demonstrated by the presence of black shales in many Late Devonian strata. There is also evidence of global cooling with the advance of glaciers and associated sea-level changes, and it is possible that these changes would stress the biosphere over a period of around 20 to 25 million years, producing a series of about 8 to 10 extinction pulses.

- There would be 2 particularly intense spikes of extinction at 372 million years ago called the Kellwasser event, lasting about 2 million years, and another at the end of the Devonian period around 358 million years ago called the Hangenberg event, lasting about 1 million years.

- The earlier Kellwasser event would mostly affect marine species and in particular the beautiful Devonian reef systems. Many invertebrate groups that lived in and around those reefs would be severely impacted. For

example, the number of trilobite families, each of which represented numerous species, would be reduced from 9 to 5.

- Reef systems following this Kellwasser event would tend to be dominated by those spongelike stromatoporoids and microbially constructed, laminated structures called stromatolites. Corals, which had played such an important part in younger reef systems, would be decimated. Overall, tropical warmwater forms were hit the hardest in this extinction.

- It is the final extinction pulse, the Hangenberg event, that marks the boundary between the Devonian and the Carboniferous periods, in which invertebrates and many of the surviving reefs are hit again. It would also affect both the marine and freshwater environments. It is estimated that around 44% of the higher-level vertebrate groups are removed.

- In total, around 19% of families and about 50% of genera would go extinct, but the decimation was probably more severe in the oceans, with perhaps around 22% of families dying. It is possible that around 79 to 87% of all species in the ocean went into extinction. This extinction is referred to as the Devonian mass extinction event.

## The Trigger of the Crisis

- What could cause all of these changes at the end of the Devonian? The Devonian extinction is recognized as one of the big 5 mass extinctions that have occurred during the last half a billion years on Earth.

- All of these extinctions, with the exception of the first one at the end of the Ordovician, have been associated with large volcanic events that produced extensive flood basalts. It is well known that such intense volcanic episodes can have varied effects on climate, including global cooling and ozone destruction but also global warming.

- There are at least 2 glacial episodes about the same time as the Kellwasser and Hangenberg events. A cooling scenario for extinction is supported by

a decline in the number of warm-tropical–adapted species and a spread of cooler-water–adapted species toward the equator.

● Other culprits for the Late Devonian extinctions have been suggested. It is known that there were at least 2 impact events in the later Devonian. A large enough impact could have serious and sudden consequences for the biosphere.

● The idea that something we equate today with a healthy biosphere— namely, plants—could cause a mass extinction is kind of counterintuitive, but this is just the scenario suggested by researchers such as Thomas Algeo at the University of Cincinnati.

● Consider these features of the Devonian extinction: Both the Kellwasser and Hangenberg events are associated with the development of black shales in shallow marine settings and are associated with an increase in $^{34}$S isotope, an isotope of sulfur. These anomalies are regarded as good indicators of anoxia in ocean water. There is also an associated drawdown in atmospheric carbon dioxide and an increase in sediment delivery to the oceans. Algeo suggests that these effects were caused by plants colonizing new habitats.

● As we move through the Devonian, the depth and complexity of root systems increase. This would cause a short-term increase in global weathering as plants colonizing new areas started to break up rocks with their root systems and increased the production of sediment. This sediment, delivered to the oceans by rivers and streams, would muddy the water, making it cloudier.

● This weathering also produces lots of calcium and magnesium carbonates, using a lot of carbon dioxide in the process. This effectively pumps carbon dioxide out of the atmosphere and into the soil. In addition, increased burial of organic plant material helps lock organic carbon away from oxygen and prevents carbon dioxide from being produced by the oxidation of organics.

- Through these mechanisms, it is possible that levels of atmospheric carbon dioxide would be reduced, decreasing the greenhouse effect and initiating a period of global cooling, perhaps allowing the advance of glaciers and the fall of sea level.

- Weathering would also increase rates of nutrient flux and organic delivery to the oceans, causing vast algal blooms in the upper well-lit/oxygenated levels of the ocean. The organic material produced in such blooms would sink, rapidly use up available oxygen in bottom waters, and help generate black anoxic shales and the associated positive $^{34}S$ anomalies.

- Evidence has been recovered that suggests that oxygen-poor hydrogen sulfide–charged bottom waters would spread through the shallow Devonian oceans, poisoning creatures living on the ocean floor. It is possible that hydrogen sulfide–charged water could have risen to the surface, causing problems for other creatures higher in the water column. In addition, release of hydrogen sulfide into the atmosphere would cause associated problems for animals on land, not the least of which is assisting destruction of the ozone layer.

- For the Hangenberg event at the end of the Devonian, Algeo suggested that there would be a further proliferation of plants following the development of seeds, a major innovation in plant reproduction. This resulted in a global flora spreading to highland areas with an associated peat accumulation and further drawdown of atmospheric carbon dioxide, locking it away into the geosphere in the form of coal. Advances and retreats in ice continued to stress the biosphere.

- This new diversification of seed plants would likewise be accompanied with increased weathering, nutrient delivery to the ocean, algal blooms, and all the problems associated with hydrogen sulfide. In this scenario, the Late Devonian kill zone was a combination of effects, including glacially driven cooling and sea-level fall as well as sick oceans full of poisonous hydrogen sulfide—all potentially triggered by an unlikely source: the plants.

# Consequences of the Extinctions to Our Modern Biosphere

- The Devonian witnessed a resetting of the biosphere and the whole character of reefs would change with a significant loss of the old Paleozoic reef-building organisms.

- There would also be an important change for the vertebrates. The Devonian did support a wide variety of fish, many of which are extinct today. The Devonian extinction would bring our more modern-looking fish to the fore. Following the Devonian, we see the rise and dominance of the sharks, the rays, and the bony fish. The tetrapods that had evolved from lobe-finned fish would also be put through the sieve of extinction.

- So, a global catastrophe might be the cause of Romer's gap—a catastrophe that the world was still recovering from in the first 15 million years of the Carboniferous period. But this catastrophe was also a pivotal event, as are all extinction events, clearing ecological space and providing opportunities for the evolution of the new life that was to follow.

### Questions to consider:

1. How is it possible that life itself could act as a trigger for a mass extinction?

2. How would the Devonian determine how you put your gloves on?

### Suggested Reading:

Beerling, *The Emerald Planet*.

Levin and King Jr, *The Earth Through Time*, chaps. 11–12.

# Lecture 14

# Life's Greatest Crisis: The Permian

Although most volcanic and seismic activity occurs at plate boundaries, not all of it does. Mantle plumes, which are thought to develop at the core-mantle boundary, might cause volcanic activity away from plate margins. It is possible that the development of a plume below Siberia triggered a cascade of events that would bring all of life to its knees in the greatest extinction this planet has ever seen. In this lecture, you will learn about the Permian extinction.

## Before Catastrophe

- The Permian period was an interval that experienced a gradual warming as the continents came together to form Pangaea, the supercontinent that Alfred Wegener had proposed in the early 1900s as part of the hypothesis of continental drift.

- It was a world with oceans containing beautiful coral reefs, above which would swim numerous creatures. On land, you would see plants colonizing lowland areas.

- In the later Permian, terrestrial vertebrates would diversify into a variety of forms, including archosaurs (ancestors of the dinosaurs), herbivorous reptiles, large predators, and cynodonts (who would evolve into the Triassic and were ancestral to the first true mammals).

- And all of this beautiful world collapses—fundamentally, almost completely. By the end of the Permian, it is possible that up to 95% of species had been driven into extinction in life's greatest crisis in the last 540 million years.

- Paleontologist Dr. Douglas Erwin in the Department of Paleobiology at the Smithsonian's National Museum of Natural History has long wrestled with this most catastrophic event in life's history. The end of the Permian saw the sweeping away of many of the main players of what you could call an old Paleozoic world, a world full of trilobites, corals, and brachiopods. As Dr. Erwin has suggested, the Permian extinction has fundamentally shaped the biosphere we live in today.

## Plumes as the Trigger

- Actually, we now think that 2 plumes could potentially be involved in this event, causing 2 extinction events. The first occurred around 260 million years ago, about 8 million years before the second, more catastrophic event at the end of the Permian.

- This so-called Guadalupian extinction occurred in both marine and terrestrial environments. Marine extinctions were varied among locations and the types of taxa impacted. Brachiopods and corals record severe losses, as did important groups of microfossils.

- Recent research in the Karoo region of South Africa led by Michael Day of the University of the Witwatersrand in Johannesburg, and including Dr. Erwin, has shown that around 74 to 80% of terrestrial species became extinct.

- The plume event that is thought to be related to this extinction occurs in China and produced a volcanic outpouring called the Emeishan Traps. This volcanic event is dwarfed, though, by the next plume to ascend from the depths. This would develop under Siberia at the end of the Permian, generating volcanism known as the Siberian Traps.

- Due to its scale, the Permian extinction receives a lot of research attention. As a result, our understanding of this event changes rapidly. One of the recent updates regards the timing of Siberian Traps volcanic activity. It is still known to be coincident with the extinction event, but it would appear that the duration of the event was shorter and sharper than previously thought.

- It is not the vast amount of lava that would be the most significant problem during these events. Creatures could easily migrate out of the affected area. Rather, the greatest problem are the gases that it produced.

- Research at the Carnegie Institution of Washington by Benjamin Black and Linda Elkins-Tanton investigated inclusions of gas trapped in the lava from the Siberian basalts. In effect, these so-called melt inclusions provide a sample of the gases that were actually being produced during the event. The Carnegie research team had a particular interest in the amount of sulfur, chlorine, and fluorine gases that were being produced.

- From this, they estimated that between 6300 and 7800 gigatons of sulfur, between 3400 and 8700 gigatons of chlorine, and between 7100 and 13700 gigatons of fluorine were released to the atmosphere. If these gases reached the upper atmosphere, they could cause significant environmental impact. Add to this the vast amounts of carbon dioxide also produced by the traps volcanism and you have a deadly cocktail.

- But perhaps an even more significant product of the traps were the vast amounts of the greenhouse gas carbon dioxide that were produced.

- A rise in carbon dioxide would have inevitably led to a rise in global temperatures due to greenhouse warming. It is thought that this could have helped destabilize certain gas-rich deposits in the oceans. These deposits form in offshore continental margins, where it is cold even in tropical areas. The cold temperatures and high pressures cause ice to complex with microbially generated methane, forming what is called a methane clathrate or gas clathrate.

- Clathrates are very sensitive to temperature changes. It's proposed that the traps-induced warming raised ocean temperatures to the point where the clathrates started to destabilize and release their methane, an even more effective greenhouse gas than carbon dioxide. And although methane oxidizes quite readily in the atmosphere, what it produces, when it does oxidize, is more carbon dioxide.

- Today, there is enough methane in clathrates to total twice the amount of carbon to be found in all known fossil fuels on Earth. There were probably plenty of clathrates in the Permian, too. So, not only do we have an initial global warming from the traps-produced carbon dioxide, but gas clathrates may have also contributed to the situation, perhaps raising global temperatures by the end of the Permian by as much as 10° Celsius.

- At the moment, the most likely triggers of the end-Permian crisis are the Siberian Traps and the consequences they would have on global climate. But what were the killing mechanisms?

- On land, we have a signal that suggests the collapse of the flora—a signal that is recorded in the style of the river systems transitioning from meandering "plant stabilized" ones to the more disorganized braided systems, suggesting a sudden decimation of plants on land. This collapse of land flora may also explain the lack of coal in the Early Triassic.

- It has been suggested by some that extinction in the oceans lagged somewhat behind the initial extinction on land. The reason for this is that water bodies act as temperature buffers and respond more slowly. More recent evidence, though, suggests that extinction was more or less simultaneous in both realms. Whenever it hit, the catastrophe was probably even greater in the marine realm, with decreasing oxygen levels and increasing carbon dioxide levels.

## An Acid Nightmare

- As carbon dioxide dissolved in the oceans, they started to become more acidic. This development of acidic oceans matches the patterns of organisms that were hit hardest during the extinction. Creatures that secrete calcium carbonate shells—brachiopods, echinoderms, and corals— were severely affected. This is especially significant when considering that corals, and the organisms that lived on, in, and around them, constituted an entire complex reef ecosystem that soon would also collapse.

- A team led by Dr. Matthew Clarkson at the University of Edinburgh in Scotland has been studying this phenomenon by analyzing carbonate rocks in the United Arab Emirates (UAE), which, at the time of the extinction, laid in a huge embayment encircled by the eastern edge of Pangaea called the Tethys Ocean.

- The team studied changes in the ratio of boron isotopes that are known to vary with pH. Their analysis suggests a decrease of around 0.6 to 0.7 pH units during the extinction. This represents a catastrophic change for ocean chemistry.

- The boron acidity signal occurs about 50,000 years after the initiation of the extinction event. They propose that the Permian-Triassic extinction was a 2-phase event. The first pulse, over 50,000 years, was fairly slow, as carbon dioxide was added incrementally to the Earth's oceans and atmosphere by the Siberian Traps.

- It is possible that the oceans, which are pretty alkaline, were able to buffer the carbon dioxide being dissolved in the seawater until a critical point was reached—when a second pulse of carbon dioxide was released over a period of about 10,000 years.

- They suggest that this pulse released about 24,000 gigatons of carbon dioxide at a rate of about 2.4 gigatons per year. Such a massive flush of carbon dioxide into the Earth system would have overcome the buffering potential of the oceans, seawater would be driven into an acidic range, and the reef ecosystems crashed.

- Acid rain on land would likely have caused problems for the terrestrial ecosystem. Evidence for this has not been forthcoming, although most agree that it is likely to have occurred. However, a team of scientists, including Mark Sephton of Imperial College London, have found some intriguing evidence that might act as a proxy for the acidification on soils on land.

- By investigating a section of soil in the Southern Alps of northern Italy, the team found a pattern that pointed toward a series of pulses of acidity on

land and suggested that these pulses were related to individual episodes of volcanic activity from the Siberian Traps and associated acid rain events. This is still pretty new research, but this study could be some of the first concrete evidence that we have an acid planet both in the oceans and on land during the Permian-Triassic transition.

## The Role of Microbes

- The microbial world is often overlooked, but microbes are a fundamental part of the biosphere. Their presence can be both essential and catastrophic to the health of the biosphere. Given that they can reproduce and spread very rapidly, they can respond very rapidly to environmental changes and opportunities, as may be the case for microbial life at the end of the Permian.

- In a recent paper, a team including Massachusetts Institute of Technology researchers Daniel Rothman and Gregory Fournier suggested a potential source of methane in addition to clathrate methane that may have come from a microbe called *Methanosarcina* that belongs to an ancient group of microbes belonging to the Archaea.

- Their research into the genome of this microbe points to a change that occurred at about the time of the Permian-Triassic extinction. This change would have permitted *Methanosarcina* to produce significant quantities of methane and, as a consequence, more global warming.

- In this scenario, the Siberian Traps still act as a trigger—or, more accurately, a fertilizer. One of the elements that the traps would release into the environment is nickel, which is a vital "fertilizing" element for these particular microbes and would have permitted their rapid blooming and the production of large quantities of methane.

- There is another type of microbe that would likely have had serious impacts on the biosphere, too. The Permian oceans were becoming oxygen depleted, or anoxic. Certain microbes have a preference for

living in such anoxic conditions and gain energy from stripping oxygen off sulfate molecules. In doing so, these sulfate-reducing bacteria produce a dangerous by-product: hydrogen sulfide.

- Hydrogen sulfide is highly toxic to the metabolism of most organisms and would have had a serious impact on oceanic ecosystems. This is not mere conjecture, though, as biomarkers of sulfate-reducing bacteria have been found in Chinese sections that cover the Permian-Triassic boundary.

- Significantly, these sections were originally deposited under shallow-water conditions. The placement of these deposits indicate that oxygen-poor, hydrogen-sulfide–rich water encroached and extended from deeper ocean water well into the shallow well-lit areas of the oceans—just where the Permian coral reefs grew.

- It would appear that during the Late Permian, in addition to increasing temperatures, increasing oceanic acidity, and reduced oxygen levels, the Permian reef systems were being poisoned, too.

## The World That Remained

- What was left was a decimated world, baking in a hot Sun with slow, sluggish, poisoned oceans. The Permian extinction provides an insight into a biosphere that ceased to function. There wasn't any single cause why the extinction occurred, even though there might have been an initial trigger in the plume that rose from the core and impacted the base of the lithosphere in Siberia.

- In dealing with a complex interacting system like the Earth, a catastrophic event like the Permian-Triassic extinction has to be viewed as a cascade of events that rapidly spread and expanded until it impacted almost every corner and level of the Permian biosphere.

- It often takes hundreds of thousands of years for the biosphere to start to recover from such events, but things would be different for the Permian-

Triassic extinction, as 5 million years into the Triassic, the Earth was still a pretty devastated planet.

1. Are the triggers of the Permian extinction absent in the modern world?

2. In which ways do extinctions progress—in a linear manner like a line of dominoes or as a cascade of events?

*Suggested Reading:*

Erwin, *Extinction*.

Plummer, Carlson, and Hammersley, *Physical Geology*, chaps. 4 and 17.

# Life's Slow Recovery after the Permian

**Lecture 15**

I n this lecture, you will examine the world of the Early Triassic just after the end-Permian extinction and attempt to track the biosphere's recovery. This lecture will address several questions: What was the world like in the Early Triassic? What was left of life following the greatest of all extinctions? What was driving the impoverished Early Triassic, and why did it last so long? When did the Earth start to recover? Was there more doom at the end of the Triassic?

## The Early Triassic

- During the Early Triassic, our planet would have looked very different. A giant landmass, Pangaea, dominated one side of a planet surrounded by the vast Panthalassic Ocean. The Early Triassic climate was harsh on Pangaea. Hot, arid deserts covered most of the interior of the supercontinent.

- It is possible that this was the hottest, most arid time in more than half a billion years. In fact, there is likely no ice at the poles. Indeed, it is possible that the poles might have been relatively temperate places, where forests and a more diverse biota of plants, fungi, and animals could survive.

- This is the inverse of what we have today, because in the Early Triassic, the temperate polar regions were more habitable than the equatorial regions.

- Analysis of oxygen isotopes taken from conodonts, the toothlike mouthparts of an early chordate, paint a disturbing picture of the temperature change during the Early Triassic.

- Research in equatorial deposits from southern China, spanning the period of the extinction at the end of the Permian and continuing into the Early Triassic, show a rapid warming in the oceans from 21 to 36° Celsius. The warming peaks at around 252.1 million years ago, the end of the Permian.

- There is a cooling following this, and then a second rise in temperatures occurring around 250.7 million years ago, a period of the Early Triassic called the Early Olenekian when temperatures in the water column rose again to about 38° Celsius and perhaps even exceeded 40° Celsius at the surface. At such marine surface temperatures, organisms such as corals cannot survive.

## What Life Remained

- The life-forms that would limp across the Permian-Triassic boundary boundary would inherit a truly impoverished world. In general, they are referred to as disaster taxa.

- Dr. Conrad Labandeira is a paleoecologist at the Smithsonian's National Museum of Natural History's Department of Paleobiology with a particular interest in plant-insect interactions over geological time. His research shows the dramatic changes that occurred in insect faunas across the extinction boundary, an event that he describes as being one of the most profound in the evolutionary history of insects.

- Dr. Labandeira asserts that the Permian extinction divided the history of insects into 2 evolutionary faunas. Many Paleozoic lineages became extinct; in fact, we lose most insect species. This is a linked plant-insect ecological event that would have profound effects on the associations between plants and insects.

- But the situation on land was just half of the story. Life in the oceans had been decimated, too. The oceans, just like the continents, were dominated by high-abundance but low-diversity faunas. The rich invertebrate assemblages of the pre-extinction Permian world were reduced to just

a few species, such as the brachiopod *Lingula* and the bivalve *Claraia*—classic disaster taxa found in the oceans at this time.

- This is also a world with no corals. In fact, just like the coal gap on land, there is a similar reef gap in the oceans, with coral reefs not returning to the planet until about 9 million years after the start of the Triassic period.

- The only reefal structures at this time would be stromatolites, columns of cemented sediment created by laminated mats of microbes. Stromatolites had been pretty well absent from most environments since the Ordovician, 190 million years earlier, but probably make an appearance in the Triassic due to the decimation of all the grazing creatures that would usually keep them in check.

- There is also a geographical pattern to the impoverishment of the taxa during the Early Triassic in both the marine and terrestrial realms. This pattern is particularly noticeable during the peak temperature rise during the Olenekian. At this time, a disturbing gap in fossils occurs at the equator—it appears that the equator had become a dead zone, with most life absent at low latitudes.

- In the oceans, fish, marine reptiles, and corals are missing. Life in these zones tend to be invertebrates of limited diversity and stromatolites. The situation is the same on land. The majority of the impoverished fauna that survived the extinction at the end of the Permian retreated toward the more hospitable poles.

- Contrast that with the distribution of life today, where a latitudinal band north and south of the equator shows overwhelmingly the greatest biodiversity on the planet—a biodiversity that typically decreases as you move toward the poles.

## Driving the Impoverished Early Triassic

- It appears that the increase in lethal temperatures during the Early Triassic, especially at equatorial latitudes, pushed organisms beyond their thermal tolerances and were responsible for driving this period of extremely low biodiversity. But isn't this just what we should expect? After all, we have just come through the largest mass extinction ever, at the end of the Permian.

- While it would obviously take time for the Earth to cool down and recover, in most extinctions, the biosphere is well on the way to recovery within hundreds of thousands of years. For the Permian extinction, however, things were still pretty awful up to 5 to 7 million years into the Triassic. In fact, the only reason why another mass extinction is not registered at this time is that there is very little life on the planet left to go extinct.

- It is important to note, though, that it was not just rising temperature that was the problem. Increased temperature had caused a whole cascade of related problems during the Permian extinction—problems that persisited well into the Triassic. These difficulties included reduced oxygen conditions in various parts of the oceans and the possibility of an associated rise in hydrogen sulfide, due to the proliferation of certain sulfur-loving bacteria that like to live in these oxygen-poor conditions.

- Increases in carbon dioxide levels would also mean more dissolved dioxide levels in the oceans, making seawater acidic. This would ensure that creatures that secrete thick calcium carbonate shells and skeletons, such as corals, would have a long wait before they could make a comeback.

- At the moment, it is still unclear what was maintaining these environmental conditions way beyond the Permian-Triassic. It is possible that the Siberian Traps, one proposed smoking gun for the end-Permian extinction, was still active and releasing carbon dioxide. This delay may be responsible for the continued warming we see at the end of the Olenekian. Perhaps this warming also helped destabilize more methane hydrates, further warming the planet. At the moment, though, evidence for this, or another source or warming, has yet to be found.

## The Path to Recovery

- Eventually, though, through the Middle and Late Triassic, in both the continental and marine realms, the numbers and diversities of lineages started to increase significantly. In addition, there is evidence of more complex ecological associations developing.

- For example, by the time we get into the Middle Triassic, we start to see long-term reef development initiated again. In addition, there is a quantum leap in plant-insect activity commencing during the Middle Triassic and expanding, especially throughout the Late Triassic. Innovative interactions between different life-forms were starting to increase, and food webs— an important engine in the evolution of new species and increasing biodiversity—were becoming more complex.

- The Middle Triassic also sees the spread of mollusks, such as bivalves (clams) and gastropods (snails). In addition, the Middle Triassic to Early Jurassic interval would see the expansion of terrestrial and freshwater vertebrate faunas. An early example is the rise of archosaurs, which, by the mid-Triassic, had started to replace the mammal-like therapsid reptiles.

- Archosaurs included rauisuchia, which resembled crocodiles on long legs that ranged in size from 4 to 6 meters. But another archosaur had emerged—not yet quite as imposing and impressive as they would ultimately become, but showing great signs of promise. The dinosaurs had arrived. Dinosaurs did not dominate the Triassic but were a part of rapidly diversifying vertebrate fauna.

- It is likely that some of the earliest mammals had evolved by the Late Triassic from some of those mammal-like therapsid reptiles that had been so common in the Permian and Early Triassic.

## The End of the Triassic

- But as encouraging as this explosion of life in the later Triassic may sound, there would be another setback before the flourishing of the dinosaur world we recognize today. At the end of the Triassic, at around 201.3 million years ago, an event called the Triassic-Jurassic mass extinction occurred—the fourth extinction in the big 5 mass extinctions.

- In the oceans, the conodonts that had been such an important part of the Paleozoic fauna would be extinguished. Reef systems would suffer once again, and ammonites, brachiopods, and bivalves all would suffer significant extinctions. In total, it is estimated that 22% of all marine families, 53% of all genera, and an estimated 76 to 84% of all species would be driven into extinction.

- The Triassic-Jurassic extinction is a difficult extinction to tie down, as was formerly the case with the Permian-Triassic extinction, because there are relatively few sections of sediments that cover the interval of the extinction. In fact, some paleobiologists suggest that no extinction took place.

- It is possible that falling sea levels could have caused the crisis. This would have reduced the area of shallow, warm seas and restricted the spread of reefs. But the reason for these sea-level changes is uncertain at the moment.

- We do know that something very significant was happening in the Earth system at this time, though. Pangaea, a familiar geographical feature of the Triassic period, was really starting to fragment, with a series of rifts opening between the Americas and Africa and Europe. Evidence of this rifting can be seen in sediments, mostly Late Triassic to Early Jurassic in age, located in eastern North America, called the Newark Supergroup. Many of these sediments were deposited in lakes that developed along the line of the rift.

- The rift that would eventually widen to form the Atlantic Ocean was a center of igneous activity. Huge volumes of hot magma were being intruded into this area of Pangean crust at the end of the Triassic period about 200

million years ago. This igneous activity was part of what is known as the Central Atlantic magmatic province (CAMP). Not only were intrusive bodies of igneous rock that never got to the surface being produced, but so were vast outpourings of lava found today in northwestern Africa, southwestern Europe, and North America.

- The CAMP eruptions are concurrent with the extinction producing a volume of magma that would cover an area of about 11 million square kilometers. The CAMP eruptions are the first murmurings of the splitting apart of Pangaea.

- Samuel Bowring and Robert Schrock at the Massachusetts Institute of Technology have radiometrically dated the thickest deposits of lava, found in the High Atlas Mountains of Morocco, and have concluded that all this material was erupted in a fury of activity lasting, incredibly, only 40,000 years—a rapid shock to the Earth system.

- Such vast volcanic activity could have caused the effects of the Permian-Triassic extinction: global cooling due to the release of sulfur dioxide and aerosols, followed by intense warming as carbon dioxide levels started to rise in the atmosphere. Such warming may have also caused the destabilization and dissociation of gas hydrates in sediments on the ocean floor, thereby releasing methane and causing even more global warming.

- Currently, CAMP and possibly sea-level changes are the best explanations for the Triassic-Jurassic extinction. However, there has been a suggestion that the decrease in diversity was caused more by a decrease in speciation than by an increase in extinction. This decrease in speciation is a kind of slowing down of the engine of biodiversity, with normal rates of extinction not being met by a similar rate of new species evolving.

- The world following the Triassic would see a glorious new ecosystem dawn. The Jurassic is sometimes considered the golden age of the dinosaurs, but to many paleontologists, it was a golden age of life—a life that had been proven through earlier, very trying times in Earth's history.

1.  Should we expect generalists or specialists to survive mass extinctions?

2.  Does luck have a role to play in who survives a mass extinction event?

*Suggested Reading:*

Levin and King Jr, *The Earth Through Time*, chaps. 13–14.

Sues and Fraser, *Triassic Life on Land*.

# Dinosaur Interpretations and *Spinosaurus*

New fossils are continually pushing paleobiological research forward, and our insights into ancient creatures are only going to become clearer as new discoveries are made. In this lecture, you will discover how dinosaurs become fossils and how they are found. You will also learn about the 2 broad groups of dinosaurs. In addition, you will learn who first discovered the *Spinosaurus*, why it was puzzling, why it was a "lost dinosaur" for many years, and why it is special.

## Finding a Dinosaur Fossil

- There are many factors that have to come together for a living organism to become a fossil. One of the most important is, in most but not all cases, to cover the carcass of the organism with sediments as soon as possible. This effectively gets it out of the way of scavengers and, preferably, into conditions where oxygen levels may be sufficiently low to help slow decay. This increases the chances that the processes of fossilization may occur and preserve some of the organism.

- The problem is that dinosaurs, along with many terrestrial vertebrate creatures, tended to live in environments that are net areas of erosion rather than deposition of sediment. Although the landscapes might have had lakes and rivers, most of the land was exposed to erosion.

- This explains why the majority of fossils that are found are from aquatic environments and why the majority of dinosaur fossils are from rocks that were deposited in sediments in, or close to, rivers and lakes. So, for a dinosaur to maximize its chance of becoming a fossil, it really needs to be

close to one of these environments when it dies. One notable exception is if dinosaurs gets caught in volcanic ashfall or mudflows deposits.

- To maximize your chance of finding a dinosaur, you need to satisfy 2 basic things:
  - It is vital to look in sedimentary rocks of the right age. The dinosaurs' reign is sandwiched between the largest extinction in Earth's history, at 251 million years ago, and the extinction that wiped them from the planet, probably due to a massive meteor strike centered on the Yucatán Peninsula at 66 million years ago. Dinosaurs probably evolved around 230 million years ago, during the Late Triassic, making their time on Earth about 164 million years.

  - We also need rocks of the right type. These rocks need to be terrestrial and not marine, and they most likely need to be rocks deposited in or near rivers or lakes, although there are notable exceptions, such as volcanic deposits.

## Broad Groups of Dinosaurs

- The earliest dinosaurs, in the Late Triassic, were bipedal, but they were not the terrifying meat-eating giants that would evolve later in the Mesozoic. Dinosaurs would evolve and diversify throughout the Mesozoic, producing a variety of forms and, in general, demonstrating an increase in size through their evolutionary history. Dinosaurs are only very rarely found to evolve into smaller sizes, and the average weight of a Mesozoic dinosaur was about 100 kilograms.

- Dinosaurs can be split into 2 broad groups and are generally differentiated on the basis of the structure of the pelvis.
  - In the group of dinosaurs called Saurischia, also called the lizard-hipped dinosaurs, the pubis bone points forward. This group of dinosaurs includes the 2-legged theropod dinosaurs (such as *Tyrannosaurus rex*) and the sauropod dinosaurs (such as *Diplodocus*).

- The Ornithischia, or bird-hipped dinosaurs, have a pubis that points backward. These forms tend to be more common in the Cretaceous and include dinosaurs such as *Triceratops*.

- Many different types of dinosaurs would evolve within these 2 broad groupings, with only one member surviving to the present day: the avian dinosaurs, or birds.

## *Spinosaurus*

- The first dinosaur fossil discovered in Malaysia was uncovered in 2012 by a team from the University of Malaya in Malaysia and Waseda University and Kumamoto University in Japan. The fossil was recovered from Pahang, but the exact location of the site was kept a secret to deter illegal fossil hunting.

- They discovered a single dark-colored tooth that was quite distinctive, with 2 sharp edges on the front and back called carinas that exhibit serrations.

These are typical features of carnivorous theropod dinosaurs, such as *Tyrannosaurus.*

- But the particular theropod tooth that was found in Malaysia had very specific ridges running down its length and micro-ornamentation on its surface. The tooth was also quite conical in shape. These features are indicative of a particular type of theropod dinosaur: a spinosaur.

- The first spinosaur to be revealed to the scientific community was named and scientifically described by a famous German paleontologist named Ernst Stromer von Reichenbach. It was found by Richard Markgraf, an Austrian fossil collector living close to Cairo, Egypt.

- In 1912, Markgraf uncovered a most remarkable fossil contained in rocks dating to the Upper Cretaceous, about 100 million years in age, near el-Bahariya, about 230 miles (370 kilometers) from Cairo. He shipped this to Stromer, who was in Germany at the time, and by 1915, Stromer had described and officially named the fossil *Spinosaurus aegypticus*, the Egyptian spine lizard.

- Even though it was an incomplete skeleton, it was certainly unlike any other large theropod dinosaur the world had seen before. It had a unique long, narrow, crocodile-like jaw. Its teeth were conical, not blade-like, and rising off its back vertebrae were enormous spines, which might have supported a large sail, perhaps for use in display or thermoregulation.

- The spinosaur was only one of at least 2 other large theropod dinosaurs, including *Bahariasaurus* and *Carcharodontosaurus*, that were around 40 feet (12 meters) long. This just didn't make sense: How could such an ecosystem support so many large apex predators living in such close proximity? This became known as Stromer's riddle.

- The story of Stromer's remarkable dinosaur takes a rather sad turn during World War II. The spinosaur remains, along with many other specimens from his expeditions, were proudly displayed at the Bavarian State Collection for Paleontology and Geology in Munich, southern Germany. On April 24

1944, the Royal Air Force targeted Munich for a nighttime bombing raid. Unfortunately, one of the buildings hit was the museum where Stromer's fossils were held—all reduced to dust.

- All that remained of Stromer's spinosaur were some of his notes and sketches. Even the photographic records of the spinosaur were lost, only turning up in 1995 in a collection of Stromer's records donated to the museum by his son.

- The holotype—the originally described specimen—was lost to science, but other spinosaurid theropods started to be discovered around the world. Spinosaurs are now classified as the family Spinosauridae that consists of 2 subfamilies: the Baryonchinae and the Spinosaurinae, the latter of which includes Stromer's *Spinosaurus aegyptiacus*.

- The family Spinosauridae is now known to be a wide-ranging group of dinosaurs with specimens found in Africa, Europe, South America, Asia, and Australia. They first appear during the Late Jurassic (about 155 million years ago), then start to dwindle in numbers between 93 and 100 million years ago, and are last known around 85 million years ago in the mid–Late Cretaceous.

- They are still puzzling. They all have elongated crocodile-like skulls with conical teeth and spines along their back that likely supported a sail. The crocodile-like skull suggests that part of the diet of this group of dinosaurs consisted of fish. This opens up an interesting possibility: This could be the only known predatory dinosaur that spent at least some of its life in water.

- It is important to address a common misconception. There were plenty of fully aquatic reptiles that lived at the same time as the dinosaurs, but they were not dinosaurs. Dinosaurs are a group of very specific animals with particular diagnostic features, such as the structure of their hips. Like modern whales, though, all of the marine reptiles had evolved from older animals, not dinosaurs, that once lived on land.

- How do we go about testing this hypothesis of an aquatic—or, at least, semiaquatic—dinosaur? The spinosaur's skull and teeth do resemble fish-eating crocodiles, and partly digested fish scales have been found fossilized in the stomach contents of some specimens. However, non-semiaquatic creatures, such as bears and wolves, eat fish, too.

- A paper released in 2010 by a team including Romain Amiot at the University of Lyon in France suggested that oxygen isotopes might be used to determine how much of an aquatic lifestyle the Spinosauridae may have exhibited.

- Oxygen occurs in both light oxygen-16 and heavy oxygen-18 forms. Land-dwelling creatures lose a lot of water through breathing and evaporation, and it is the light form of water that contains the oxygen-16 that gets evaporated. As a result, it is the heavy oxygen-18 that is concentrated in tooth enamel.

- Aquatic animals lose less water than terrestrial creatures and, as such, have less oxygen-18 in their teeth. Aquatic creatures also drink more and are constantly flushing water through their bodies, keeping the oxygen-18 levels low.

- The researchers collected samples from 133 Cretaceous specimens of various species, including spinosaurs, other dinosaurs, and crocodiles, and found that the oxygen-16/oxygen-18 ratio for spinosaurs was more similar to crocodiles than to other dinosaurs. Were the spinosaurs aquatic, then?

- At the time of this paper, there were relatively few, or well-preserved, complete skeletons that could be examined to see if the rest of the spinosaur skeleton demonstrated any aquatic adaptations.

- For his Ph.D. research at University College Dublin in Ireland, Nizar Ibrahim was studying all of the fauna in the Kem Kem beds in Morocco. These are Late Cretaceous sediments deposited between 100 to 94 million years ago. From a fossil found in Erfoud, Morocco, that is the same species as Stromer's spinosaur—*Spinosaurus aegypticus*—Ibrahim, along with Samir

Zouhri from the University of Casablanca and David Martill of the University of Portsmouth in the United Kingdom, was able to deduce that the environment that *Spinosaurus* lived in was a lush plain over which rivers meandered about 100 million years ago, during a short interval between the transition from the Early to Late Cretaceous.

● Ibrahim was able to make a 3-dimensional reconstruction of the spinosaur that suggested that an adult *Spinosaurus aegypticus* would have been about 50 feet (15 meters) long, which would have made it larger than *Tyrannosaurus rex* at 40.5 feet (12.3 meters) long. As a result, *Spinosaurus aegypticus* would have been the largest carnivorous dinosaur that had been discovered at that time.

● Overall the model presented—with a small pelvis; somewhat stumpy paddling back legs; and long, narrow jaws—somewhat resembles the ancestors of the whales, carnivorous terrestrial creatures who had also adopted a semiaquatic lifestyle. If this creature was truly adapted for life in the water, then this is the second reason why Spinosauridae are so special: Not only would they contain the largest carnivorous dinosaurs that ever lived, they would also be the only truly aquatically adapted dinosaurs known.

● If this is the case, it also helps us solve Stromer's riddle: How could the giant *Spinosaurus* live alongside other giant theropod dinosaurs? If *Spinosaurus* is semiaquatic, they would be living in a different environment and mostly preying on aquatic rather than terrestrial organisms.

● *Spinosaurus* was a large creature, probably because it was preying on other large creatures. If we follow the semiaquatic model, the fossils of very large turtles, 8-feet-long lungfish, 13-feet-long coelacanth fish, and 25-feet-long sawfish found in the same sedimentary deposits may have formed some of the prey items for this animal.

● This interpretation of spinosaurs paints this dinosaur as a creature that was in transition between the terrestrial and aquatic environments, a kind of transitional form. But it is important to remember that any model is a

hypothesis, and this one is certainly being highly debated in the circles of vertebrate paleontology.

# Whales: Throwing Away Legs for the Sea

I n this lecture, you will learn about the fantastic evolutionary journey of the group of mammals known as whales and the incredible diversity that can result from natural selection in an instant of geological time. This lecture will address several questions: Why would creatures that evolved on land move back into the ocean? Which group of mammals would start the whales along a path to the ocean? And how can we explain the wonderful paleontological treasure at Cerro Ballena?

## From Land Back to Ocean

- Since we started to consider animals scientifically, comparing them to other creatures in the animal kingdom, it was abundantly obvious that whales, or cetaceans, were mammals that probably had ancestors that lived on land. We see features such as the bones in flippers that very closely resemble the limbs of land mammals, a vestigial hind limb, a vertical movement of the spine when swimming that shares more in common with a mammal running than a fish swimming, and the fact that whales need to breathe air—all of which suggested a land animal link.

- But why make the move back into the water? Vertebrates had to overcome several difficulties in leaving the oceans and adopting a life on land, including how to obtain oxygen from air rather than water, develop a more robust skeleton that would make up for the buoyancy effects that would no longer be enjoyed on land, accommodate hearing in a gas environment rather than a liquid one, and develop limbs rather than fins for getting around.

- Despite all the challenges vertebrates faced, and adaptations they evolved in making the break for land, some of them returned to the water—some so completely that they can no longer survive on land. But why?

- It is important to understand that evolution does not have a goal in mind. Creatures will be selected for in particular environments, or as environments change, based on certain physical and biological shifts through time. The characteristics, or mutations, that organisms possess are not produced because they "choose" to evolve things like flippers or echolocation. These features evolve through natural selection over long stretches of time.

- It is important to understand this while we consider the evolution of cetaceans from their land-based ancestors. The "proto-whales" did not consciously move back into the oceans, forcing their own evolution in some way. Rather, certain forms would have a selective advantage, allowing them to inhabit increasingly more aquatic environments in a step-by-step manner over millions of years. This story is now all the more fascinating, as many wonderful fossils have been found in recent years that have turned mere speculation about the evolution of cetaceans into a true, well-documented family history.

## Whale Evolution

- Genetically, we know that whales fall into a group of mammals called the even-toed ungulates, or the artiodactyls. The Artiodactyla include familiar modern animals, such as pigs, camels, giraffes, and deer, but the closest land-living relatives of the whales today is the hippopotamus.

- This is not suggesting that Whales evolved from hippos; rather, they share a common ancestor somewhere in the biosphere's deep past. Who is the best paleontological candidate for this common ancestor? To answer this question, we need to roll back the clock to around 54 million years ago, about 12 million years after the death of the dinosaurs, during the Early Eocene and in a region of the planet defined by the Tethys Sea.

- Back then, the Earth was much warmer than it is today and climatically more homogeneous, with less difference in temperature between the equator and the poles. The Early Eocene environment had just come off the heels of the Paleocene-Eocene thermal maximum, which was the warmest period of the Cenozoic, just 2 million years earlier.

- The Eocene world had started to look a little more like the planet we know today, with familiar-looking continents and a widening Atlantic Ocean. Australia was still connected to Antarctica, and India was starting to collide with Asia, building the Tibetan plateau and the Himalayas.

- And on India, a small herbivorous deerlike creature about the size of a raccoon could be found living along the edge of rivers and lakes in an area not far above sea level but that is now elevated high in the Himalayas. This creature, about 2 feet long, is *Indohyus*, a member of a sister group of the cetaceans called the raoellids. Most paleontologists now agree that it was from animals like this that the lineage that would give rise to modern whales would evolve, at about 54 million years ago.

- Why do we presume a cetacean relationship to this little beast? Although it doesn't look like a whale, there are similarities. For example, the auditory bulla, the bones that surround the inner ear, are very distinctive—adapted for hearing underwater and only shared by this group and the cetaceans. In addition, the bones of *Indohyus* are thickened, not unlike modern hippos, an adaptation that semiaquatic animals possess to help them overcome buoyancy effects and allow them to stay underwater.

- If *Indohyus*, or a creature very much like it, gave rise to the whales, who is the first true member of the whale lineage, the cetaceans? *Pakicetus* is, so far, the oldest member of the cetaceans for which we have fossil evidence. We are now around 50 million years before present, and the small herbivorous "deer" from which whales evolved has grown to about 6.6 feet long, and this creature has also developed a taste for meat.

- *Pakicetus* lived on the shores of the Tethys Sea in what is now northern Pakistan. It lived in a freshwater floodplain environment but was likely a

poor swimmer. It probably waded through shallow water, ambushing animals that came to the water's edge to drink.

- This creature still doesn't resemble modern whales, but in addition to the whalelike features already present in *Indohyus*, *Pakicetus* is starting to develop an elongate whalelike head.

- The next fossil whale is *Ambulocetus*, or the walking whale, dated to around 49 million years ago. Although a little larger than *Pakicetus*, about 10 feet long from tip to tail, *Ambulocetus* fossils demonstrate an important change in the cetaceans: They are now starting to inhabit marine in addition to freshwater environments. The move to the oceans had started.

- Another important feature is the presence of a large mandibular foramen. In modern whales, this area of the jaw is filled with fat and helps pass sounds to the inner ear, an important feature for hearing underwater.

- Less than a million years later, evolution has continued to shape and alter the cetaceans. *Remingtonocetus*, a member of the family Remingtonocetidae, is found in more diverse marine environments than its older relatives, with fossils being recovered from nearshore and lagoonal sediments. Its limbs are shorter than previous cetaceans, and although it may have swum in the doggy-paddle style used by *Ambulocetus*, it may also have started to undulate its spine as an aid to swimming.

- Another interesting feature of the Remingtonocetidae is a reduction in the size of the semicircular canals of the inner ear, which regulate balance and are particularly important for active creatures moving around on land. Fred Spoor of University College London, and others, suggested that this change in canal size indicates that these creatures had reached a "point of no return." The cetaceans from now on were destined for an aquatic, or at least semiaquatic, existence.

- At around 48 million years ago, and probably living alongside the Remingtonocetidae, we find fossils belonging to the Protocetidae. Unlike the fossils that we have so far described that were only found in India and

Pakistan, the Protocetidae have a much greater global distribution, including Europe and North America, and were probably swimming freely through many of the globe's tropical oceans.

- The Protocetidae are much more whalelike, with the possibility of the development of a fluke, a 2-lobed tail, in some species and the migration of the nasal openings to the top of the skull. For species of the Protocetidae, which may have still been semiaquatic, moving around on land would not have been graceful, probably akin to the way modern seals move today.

- *Basilosaurus* was the first completely aquatic whale. Collectively, these species belonged to a group that are called the Basilosauridae. They were a diverse group, with the basilosaurs themselves at around 60 feet long. These large whales probably occupied the role of top predator in the Eocene oceans between 40 and 34 million years ago, feeding on fish, sharks, and smaller whales.

- It was an odd-looking whale, though—kind of eellike. The vertebrae of *Basilosaurus* were hollow and possibly filled with fluid, which meant that it probably didn't have a deep dive capability and hunted mostly in surface waters. These Eocene monsters also had fairly small brains, meaning that,

unlike modern whales, they probably didn't exhibit much complex social behavior.

- It is thought that a group within the Basilosauridae, the dorudontids, would give rise to modern whales. They were much smaller than the elongate basilosaurs, at about 16 feet long, but had overall proportions resembling modern whales. It is from creatures like this that we get the diverse forms of all of today's whales.

- Whales are broadly divided into 2 groups, toothed whales and the baleen whales, who share a common ancestor about 34 million years ago.
  - Toothed whales are characterized by having teeth, and they hunt using echolocation by making a series of clicks at various frequencies. They range in size from the tiny 4.5-foot vaquita to the sperm whale, which can range in size from 33 to 66 feet in length.

  - The baleen whales gulp large volumes of water and sieve out krill, small fish, and other microplankton by squeezing the water back out through their baleen plates, a substance composed of a protein similar to human fingernails. Humpbacks are a popular favorite with whale watchers, but another species of baleen, the blue whale, is possibly the largest animal that has ever lived, at almost 100 feet long.

## Cerro Ballena

- By the time we examine the whales at a fossil site in the Atacama Desert of Chile called Cerro Ballena, at around 6 to 9 million years ago, modern-looking whales had already evolved from the dorudontids back in the Eocene. A whole range of marine mammals are found at the site, but the fossil baleen whales are probably the most spectacular.

- Dr. Nicholas Pyenson and collaborating scientists from Chile uncovered a fascinating fossil conundrum: Why are there so many fossil marine mammals present in this location, and why, given that under normal conditions these

creatures would be scavenged and their bones scattered, are there so many in such an excellent state of preservation?

● Furthermore, this is not an isolated event. Similar collections of fossils at Cerro Ballena are found in multiple discrete horizons. It would appear that whatever killed and stranded these marine creatures happened around 4 times over a period of 10,000 to 16,000 years.

● Other features of this fossil deposit have helped unravel this mystery. First, these creatures were stranded on a tidal flat, roughly orthogonal to current flow. The whales are also preserved belly up, suggesting that they died at sea and then washed to shore. In addition, high concentrations of iron in the sediments hint at a high algal concentration in the waters in which these animals were swimming.

● It is thought that all of this adds up to a story of a mass stranding caused by a harmful algal bloom. Not all blooms of algae are harmful, but some species of microplankton can cause problems for marine life and have been known to cause whale strandings.

● Our story likely starts with rainfall over the Andes, flushing minerals rich in iron into the Pacific Ocean. This in turn causes a bloom of algae and the death of many marine mammals and fish. A high tide would help wash the animals ashore onto a mudflat, all belly up as decomposing gases start to swell the gut. The ocean hydrodynamically aligned them into neat rows, producing a stranding, just as we find in modern whale strandings today.

● Usually, these whales would be scavenged by creatures living on shore, but back then, as today, a desert existed inland along the coast, restricting the number of creatures and potential scavengers living in the area. Sedimentation rates were also fairly constant, ensuring that the dead were covered rapidly. As such, Cerro Ballena has provided scientists at the Smithsonian's National Museum of Natural History with a wonderful window into marine mammals of the Pacific Ocean more than 6 million years ago.

*Questions to consider:*

1. If modern whales were removed from the biosphere, which group of mammals might take their place?

2. What was the equivalent of whales during the time of the dinosaurs?

*Suggested Reading:*

Carwardine, *Smithsonian Handbooks*.

Thewissen, *The Walking Whales*.

# Insects, Plants, and the Rise of Flower Power

Flowering plants, the angiosperms, have had an important role to play in Earth's transformation beyond an aesthetic one. In providing fruits and cereal crops, they have also helped drive the evolution of human civilization. They are a remarkable part of our biosphere. In this lecture, you will discover what Earth was like before flowers, where and when flowers evolved, how the angiosperms dominated, and how angiosperms and animals were partners in the great floral takeover.

## Earth before Flowers

- The first evidence of plants growing on the land comes from the Silurian period, about 433 million years ago, with fossils of simple plants living on water-clogged floodplains. Fossils interpreted as the reproductive spores from these simple plants have been reported from the Ordovician period, about 470 million years ago, but these finds are still controversial.

- By the time we get to the Devonian, plants are invading drier landscapes, and by the Late Devonian, there is an incredible innovation: the development of the seed. This, along with other important developments, such as leaves, wood, and true roots, would finally allow plants to break ties with the water's edge and spread even farther into the centers of the continents.

- Various seed ferns would flourish throughout the rest of the Late Paleozoic, and the vast forests of the Upper Carboniferous (Pennsylvanian) are responsible for the coal in the Northern Hemisphere that would ultimately power the Industrial Revolution.

- Seed ferns would flourish into the Triassic and even continue into the Cenozoic, but it would be the gymnosperms, such as conifers, cycads, and an array of ginkgo-like plants (Bennettitales and gnetophytes), that would really start to advance across the Mesozoic world.

- Gymnosperm means "naked seed," describing the unenclosed condition of their seed, unlike the fruit-encased seeds of the angiosperms. The seeds of gymnosperms form in a variety of ways: on the surface of scales or leaves, on short stalks in ginkgophytes, in cones as found in conifers, in flowerlike structures that occur in the extinct Bennettitales, and in other specialized reproductive structures in groups of gymnosperms that have no equivalents in the modern flora.

- By the Triassic, the first period of the Mesozoic, gymnospermous plants represented about 60% of flora species and around 80% of Jurassic species. Today, there are more than 10,000 species of gymnosperms.

- Today, some gymnosperms, such as the conifers. produce vast amounts of pollen that they shed into the wind with the hope of reaching a female pollen receptor. Not all gymnosperms are wind pollinated, though; in fact, most are insect pollinated.

- Interesting evidence of early plant-insect relationships in the gymnosperms has come from the chemical analyses of the fossil mid-Mesozoic proboscis of kalligrammatid lacewings. Pollen was found associated with the specimens'

head and mouthparts, which has led researchers, such as Dr. Conrad Labandeira at the Smithsonian, to suggest that they were feeding on pollination drops, drops of sugary fluid secreted by gymnosperms to trap pollen grains.

● Dr. Labandeira, and colleagues in France and Spain, have found additional evidence of an early insect-plant pollination relationship from the Lower Cretaceous (110 to 115 million years ago) of the Basque region of Spain. Trapped in amber are small insects called thrips or thunderbugs.

## The Evolution of Flowers

● Charles Darwin was particularly perplexed by the fossil record of flowers, which appeared to just suddenly emerge, fully formed, in the Cretaceous period. This was one of 2 such problematic fossil "appearances" that gave Darwin a headache. The other was the apparent sudden appearance of complex creatures, such as trilobites, at the base of the Cambrian—often called Darwin's dilemma. New fossil discoveries would provide context to the evolution of flowers and help clarify Darwin's mystery, but as of yet, not completely.

● An ongoing question about the early evolution of flowering plants regards the environment of their evolution. Some researchers suggest that flowering plants evolved on land, but others have contemplated a possible aquatic, or at least semiaquatic, origin. One way we can consider approaching this question is to examine where some of the most primitive angiosperms, called ANITAs (an acronym that stands for some of the basal angiosperm lineages), are found today.

● Researchers such as Mark Chase at the Royal Botanic Gardens in London and collaborators all around the world have been analyzing the DNA of angiosperms to provide direct genetic evidence from which to base a comparison of plant species. From this evidence, the flowering plants with the greatest similarity are clustered together into what we call clades. The

picture that has emerged has required a reassessment of some of the relationships we assumed before this technique was available.

● Modern molecular phylogeny has also revealed a plant that is at the base of the angiosperm family tree. This plant represents the most primitive flowering plant that still exists on the planet today: *Amborella*, the only remaining species of the family Amborellaceae, is found on the island of Grande-Terre of New Caledonia, in the South Pacific.

● Given its basal status, it would seem the tropical upland forest setting of *Amborella* would be a good candidate for the environment in which angiosperms evolved. The problem, despite its primitive status, is a complete lack of fossils of a similar plant early in the evolution of the angiosperms.

● The other possible candidate environment is the aquatic environment. The group of plants that includes water lilies (the Nymphaeales) have an early fossil record going back to the Early Cretaceous (125 million years ago). Although this lineage doesn't occur at the base of the current family tree of flowering plants, it is pretty close.

● Surprisingly, perhaps, support for an aquatic origin also comes from *Amborella*, which, like water lilies, has vestigial gas exchange canals, useful in submerged stems and roots.

● The aquatic hypothesis is further supported by one of the oldest complete flowering plant fossils thus far discovered. The fossil, named *Archaefructus*, was recovered from a rock unit called the Yixian Formation in northeastern China that has become famous for its fossils of feathered dinosaurs, primitive birds, and long-proboscid insects of various kinds.

● Based on other fossils found in the area, it was suggested that *Archaefructus* was growing around 144 million years ago, the Jurassic period, which would easily place it at, or very close to, the origin of flowering plants. But once age-dated, it was found that *Archaefructus* dated to 124.6 million years ago, during the Early Cretaceous—after the

appearance of the first angiosperm pollen. Although we are still looking for the first fossil flower, *Archaefructus* is still an example of a very early angiosperm and, as such, might still provide insight into where flowers first evolved.

- There are serious concerns regarding the rapid emergence of a terrestrial flowering plant from an aquatic ancestor. For example, how could plants that had evolved in the water evolve quickly enough to cope with gravity on land? There is no doubt that some flowering plants did evolve in an aquatic environment early in their history, but was this the environment into which flowering plants first appeared? It is still very much a matter of debate.

- Regarding the timing of the evolution of plants, based on molecular evidence, it is thought that angiosperms and gymnosperms last shared a common ancestor sometime that is very broadly called the pre-Cretaceous. Hopefully, new fossil discoveries will provide us with more insight to the early times of flower evolution.

## Flower Power

- Around 100 million years ago, during the mid-Cretaceous, there was a great radiation in angiosperm diversity initially noted in the fossil record by angiosperm leaf and pollen remains. By the Late Cretaceous, flowering plants started to take over environments that were formerly dominated by ferns, cycads, Bennettitales, and other gymnosperms.

- There is still some uncertainty as to how this replacement occurred. Was it competitive? In this model, the angiosperms, with their short life cycle and rapid growth, were able to muscle in on the gymnosperms and replace them. Or was it noncompetitive? We know that there was an extinction at the end of the Triassic period that drove many gymnosperm lineages into extinction. Were the angiosperms just occupying ecological empty space?

- To understand the spread of angiosperms, it would be useful to consider the nature of the world into which they were to rise to dominance. If you

consider some of the earliest fossil angiosperms, dated at about 125 million years ago, the planet they inhabited was very different than it is today.

- The supercontinent of Pangaea had started to fragment, but there were still large continental blocks with Gondwana to the south and Laurasia to the north. It is likely that the interiors of these continents would be pretty dry and arid—environments that are particularly favorable to angiosperms, providing them with large areas of the landscape where they could spread and diversify. Angiosperms also have an ability to propagate and reproduce very quickly, allowing any colonization to be rapid.

- Expanding into the dry interiors of continents may also explain why their fossil record is so poor at this time, as arid upland areas are erosive regions that are likely susceptible to wildfire events and thus difficult areas for fossils to form.

- There is another factor, though. The mid-Cretaceous was a period of intense warming, probably related to the accelerated fragmentation of Pangaea and associated generation of ocean crust and carbon dioxide production. The global warming that resulted would have added to intense drought conditions in the centers of continents and further selected for the morphologically flexible angiosperms.

- Another hypothesis was put forward in 1986 to explain the explosion of flowers by the noted dinosaur paleontologist Robert Bakker, who suggested that it may have been changing dinosaur communities that allowed for angiosperms to spread. Around about 144 million years ago, there was a change in the style of herbivory in the dinosaurs—from high browsers that were cropping leaves from the branches of high conifers to low browsers.

- Low browsing would mean that gymnosperm seedlings would have a reduced opportunity to reach maturity. This would open up the canopy and allow for angiosperms to spread quickly. Due to their rapid life cycle, they were better adapted to reach maturity and thus produce seeds before they were browsed away.

## Angiosperms and Animals

- The sole purpose of a flower is reproduction, and in the vast number of cases, that means reproduction where the male gametes (pollen) are transferred from one plant to another by insects. It is possible that this relationship, and therefore the first flowers, evolved in isolated settings such as islands or an island chain, which might also explain their apparent very-sudden appearance in the fossil record. Such isolated settings may have allowed for the development of a specialized relationship between a plant and an animal—for example, a wasp carrying pollen from one plant to another.

- But pollination via insects was not a new gig, as various insects had been aiding the pollination of gymnosperms before the widespread appearance of flowering plants. It is likely that some insects were preadapted to build this relationship with angiosperms. The angiosperms, though, would take insect—in fact, animal—pollination to a whole new level in a classic example of how 2 major groups of organisms would co-associate over time.

- Angiosperms, and in particular their flowers, would coevolve with animals to produce a whole suite of features—including scent, color, fruit, and

Pollination
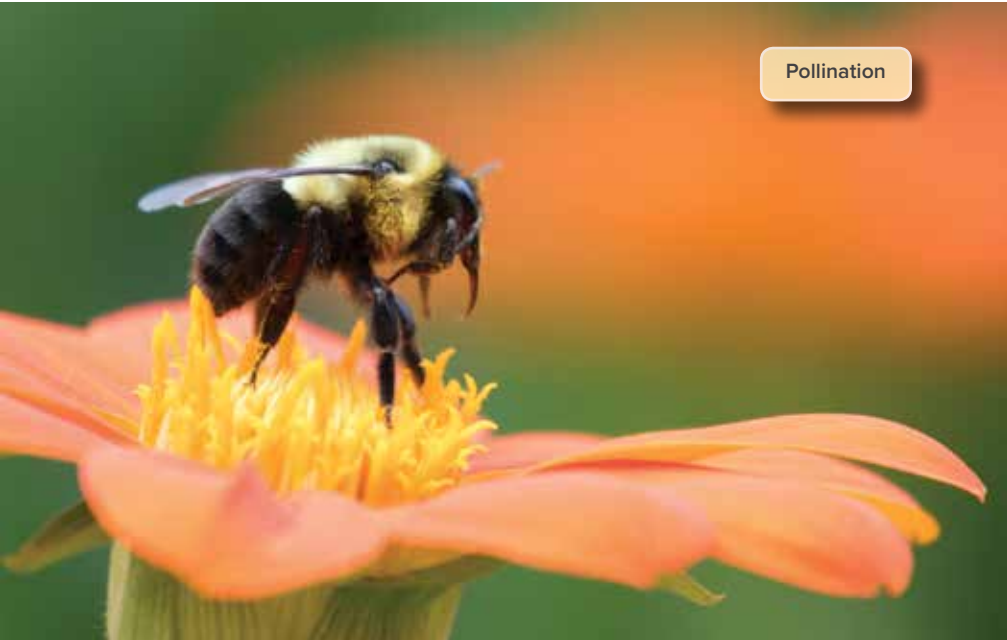
mimicry—that would not have existed if it were not for their intimate relationship.

- Most of the fossil and phylogenetic evidence indicates that the earliest flowers were small and bowl-shaped, not showy. There were some, though, that would have stood out in the Cretaceous landscape. Some of the first true flowers of the Cretaceous may have resembled something like magnolias. These flowers likely only had a pollen reward for their insect pollinators; the pollinators themselves were likely generalist in nature, such as beetles, short-tongued wasps, and flies.

- By the time we get to the explosion of angiosperms in the mid-Cretaceous, new varieties of flowering plants emerge with new structures, such as nectaries (where nectar is produced) and specialized petals designed for a more specialized relationship with insects. By the Late Cretaceous, flowering plants were very diverse. At this time, insects such as wasps and flies were also going through radiations, with species—such as the long-tongued bees and flies—evolving specific structures to exploit flowers.

- The end result of this radiation of the angiosperms during the Cretaceous would be a world with a radically different flora, and companion insect associates to match.

*Questions to consider:*

1. Why were flowers an "abominable mystery" to Charles Darwin?
2. Are insects the only animals to have a special relationship with flowers?

*Suggested Reading:*

Benton and Harper, *Introduction to Paleobiology and the Fossil Record*, chap. 18.

Goulson, *A Sting in the Tale*.

# The Not-So-Humble Story of Grass

Grasses, which are angiosperms (flowering plants), make up the most economically significant plant family today. They include cereal crops, such as maize, wheat, rice, and barley. Some are used as construction materials (bamboo), while others are fermented to make ethanol biofuels (sugar cane). Altogether, it is estimated that there are probably around 10,000 species of grass. In this lecture, you will consider whether grass is a new plant, when the great grass takeover occurred, what triggered the spread of our grassy planet, and how significant grasses have been on the evolution of animals.

## Grasses

- Until recently, the general mantra regarding the evolution of grass was that the first grasses evolved long after the dinosaurs had become extinct at 66 million years ago. The oldest fossil grass came from Tennessee, dated to about 55 million years ago.

- There were hints of earlier grasses from fossil pollen, but grass pollen is very difficult to tell apart from non–grass pollen. As such, images of dinosaurs striding through grass were generally regarded as incorrect renderings of the Mesozoic world.

- A discovery by paleobotanists of Lucknow University and Panjab University in India would turn these ideas around, though. They found coprolites, or fossilized feces, from the Late Cretaceous, toward the end of the dinosaurs' reign on Earth, that appeared to contain phytoliths, which are tiny silica structures found in the leaves of certain plants. They help give grass some of its structural support but may also act as defensive structure, deterring grazing by animals.

- On analyzing the phytoliths, phytolith expert Caroline Strömberg at the University of Washington identified them as coming from various grasses, representing at least 5 species. This is significant, because in addition to showing that they existed at the time of the dinosaurs, the phytoliths demonstrated that grass species in the Late Cretaceous had already diversified. This means that the antiquity of grass was a lot longer than anyone had suspected. Strömberg has suggested that this may have pushed back the origin of grass to about 100 million years ago.

- Dinosaur fossils found in close association with these coprolites come from a rather poorly defined, but still rather exciting, group of sauropod dinosaurs called titanosaurs, which contain some of the largest creatures to have ever walked the Earth. For example, *Argentinosaurus*, weighing in at around 83.2 tons and around 30 meters long, would have dined on a wide variety of vegetation, with other flowering plants, cycads, and conifers forming part of their diets.

- We have recently found evidence of even older grass dated to between 97 and 100 million years ago (early Middle Cretaceous) preserved in amber from Myanmar (Burma). This is research led by Oregon State University's Dr. George Poinar, who is one of the world's leading experts on amber and the fossils found in it.

- Dr. Poinar and his colleagues found a beautifully preserved grass floret preserved in amber, and on its tip is an extinct species of parasitic fungus called *Palaeoclaviceps parasiticus* that is likely closely related to a group of fungi that today we call ergot. Ergot may have a special relationship with grass. It tastes bitter and would deter grazing by herbivores. If an animal ingests enough of it, it can cause serious side effects, such as trembling muscle groups that cause an animal to fall over.

## The Great Grass Takeover

- On a planetary scale, probably more significant than the date of evolution of the first grasses is the development and evolution of the ecosystem that

they would create—the ecosystem we call grasslands, or, more formally, the grassland biome.

- There are many different types of grassland. There are the savannas and velds of Africa. In North America, there are the prairies. In South America are the pampas and llanos, and in Eurasia are the steppes.

- Today, grasslands cover 40% of all our planet's land surface. Because grasses are mostly annual plants that die every year, they develop large and deep soil profiles.

- Grasslands are generally associated with dry but not desert conditions. Because of their high rate of turnover, grasses and grasslands can support a large animal population, unlike trees and shrubs of forests, where a lot of the useful nutrient-rich material is locked up in the plant.

- Another feature is their tendency to burn, creating grassland fires. Rather than being detrimental to grasslands, fires may be an important part of some grassland ecosystems, removing trees and shrubs and allowing grasslands to spread.



Savanna Grassland

- When do we see the advance of this biologically and economically vital part of today's biosphere? Grasses existed during the Cretaceous, but they were not a particularly significant part of the Earth's flora. Even after the Cretaceous, in the first 2 periods of the Cenozoic era, the Paleogene and the Eocene, the world was mostly tropical—warm and wet and mostly covered in forest. Grasses did not yet dominate.

- By about 40 million years ago, as the Eocene was drawing to a close, the Earth's climate started to change, becoming much drier and cooler. Forests gave way to woodlands and eventually into chaparral and other scrub formations and deserts; still lacking, though, were a major component of grasses.

- But by the time we move into to the Oligocene, 23 to 5.3 million years ago, this desert scrub starts to give way to grasses and their deep, loamy soil profiles. By the Late Oligocene, we have evidence of the grassland biome and an association of grassland-adapted mammals spreading across North America.

## The Spread of Our Grassy Planet

- Around 95% of land plants, and some grasses, use what is called the C3 metabolic pathway, a form of photosynthesis that probably evolved in the Paleozoic. Many grasses, and some other plants, use a C4 metabolic pathway. Because of their anatomy, some C4 plants can operate at lower levels of atmospheric carbon dioxide than C3 plants can.

- Because C4 plants don't need as much carbon dioxide, they can afford to keep their stoma (surface pores that allow for gas exchange between the plant and the atmosphere) closed more often than C3 plants can. This means that in dry conditions, plants like C4 grasses have a selective advantage. This makes them perfect plants for arid conditions and for the spread of grasslands.

- Today, C4 plants make up about 5% of Earth's plant biomass and around 3% of known species but account for a massive 20 to 30% of terrestrial plant carbon fixation. It is only in the past 10 million years that C4 plants have become such an important part of the biosphere, with a remarkable C3-to-C4 plant transition occurring globally between 8 and 4 million years ago.

- This transition is highlighted in the geological record isotopically by studying 2 of the stable isotopes of carbon: carbon-12 and carbon-13. Life in general has a preference for carbon using the carbon-12 isotope, but C4 photosynthesis usually will incorporate more of the carbon-13 isotope. This gives us a proxy for the presence of C4 plants recorded isotopically in paleosols (fossil soils) or in the bones and teeth of the animals that were eating the plants.

- The change from C3 to C4 grasslands appears to be associated with the general increase in aridity of global climates, favoring those plants with a C4 metabolic pathway that require less water. This increase appears to occur at different times in different regions, though.

- There were probably other mechanisms that played a role in the spread of the C4 grasses, too. For example, an increase in charcoal in Pacific cores between 12 and 7 million years ago hints at a greater number of fires during this period. This would favor grasses and grasslands due to their rapid recovery rates when compared to trees and shrubs.

- There is also a suggested general reduction in atmospheric carbon dioxide levels during the Cenozoic that may have also favored C4 plants with their more efficient photosynthesis. Even cooler climates may have encouraged the spread of the more efficient C4 grass. This might explain why C4 dominance occurs first in hot equatorial areas such as Kenya, followed by Pakistan, and finally the northern Great Plains.

- The spread of grasslands would encourage more grazers, who, in cropping the tops of plants, would favor the spread of grass over trees and shrubs. It is also likely that there could be local reasons for the spread of grasslands.

- But what would set these changes into motion? A possible cause might be found in India and its dash northward to dock with southern Asia. The Himalayas would rise as India crumpled into Asia over many millions of years, but during the Miocene, the mountains began to rise in a major way.

- This thrust vast amounts of rock up into the atmosphere, which led to the rocks starting to weather. A part of the weathering process involves the transformation of rock silicates into clays by the action of carbon dioxide dissolved in rainwater. In this way, carbon dioxide is effectively washed from the atmosphere, transported down river systems in the form of clay, and deposited as a sediment, causing an overall net drawdown of carbon dioxide.

- Even if there is no direct link between falling carbon dioxide levels, temperature, and the spread of C4 plants, a drawdown of carbon dioxide would certainly impact paleoclimate patterns, such as causing the development of a more arid climate, which might favor the spread of a water-efficient C4 flora across the land surface.

## Grasses and the Evolution of Animals

- How has the evolution of a relatively new ecosystem, the grassland biome, impacted the rest of the biosphere? A traditional view, for more than 140 years, was that the evolution of mammals with high-crowned, or hypsodont, teeth was in response to the spread of phytolith grasses. These large teeth would be an adaptation to eating the gritty grasses, and as such, you could use the presence of hypsodont teeth as a morphological proxy for the presence of grasslands.

- Unfortunately, this doesn't quite work everywhere. Additional research by Caroline Strömberg on a section of sediments representing 800,000 years of deposition at Gran Barranca in Patagonia, Argentina, has turned this idea around. Hypsodont cheek teeth were discovered in Patagonia dating to around 38 million years ago, which, if we take them as a proxy for

grasslands, indicate that grasslands evolved there 20 million years before anywhere else and could represent the cradle of the grassland ecosystem.

- The deposits are composed of river sediments and windblown volcanic ash, probably from the southern volcanic zone in South America. The plant remains, though, do not indicate grassland but, rather, a tropical forest dominated by palms. It is possible that in this particular area hypsodont teeth evolved as a response to the high amount of abrasive volcanic ash and grit in the environment and phytoliths from other phytolith-bearing plants like palms. This effectively undermines the idea that these teeth can always act as a proxy for grasslands—it's not such a simple relationship.

- In other parts of the world, such as North America, there is more of a link between the spread of grasslands and the presence of hypsodont mammals in the fossil record, although even here there does appear to be a 4-million-year lag between grasslands and the first long-toothed (hypsodont) animals.

- But even if the story of teeth evolution in our grazing mammals is not quite nailed down yet, there is certainly a case for co-association, or perhaps coevolution, between grasses and animals. The snout of many creatures became broader and flatter to allow for effective grazing, and jaws became longer and deeper, permitting more efficient grinding of plant material.

- In addition, unable to hide as effectively in grass as they could in a forest, animals started to show adaptations for running, even if they were not grass browsers. The lower parts of limbs started to elongate, feet became more compact, and muscle mass started to increase at the shoulders and hips to help power a quick getaway.

- Grass may have also had an effect on the evolution of humans. The spread of grasslands was proposed by some as a reason why our ancestors started to walk upright. A very significant part of the human story evolved on the open grasslands; this is probably the environment that shaped us the most. The presence of the grassland biome may have also helped genus *Homo* move out of the cradle in Africa and start to populate the planet.

1. How many times has the evolution and spread of flora dramatically impacted the evolution of animals?

2. To what extent has the spread of grasslands impacted our own evolution?

Emling, *The Fossil Hunter*.

Savage, *Prairie*.

# Australia's Megafauna: Komodo Dragons

I n 1926, explorer W. Douglas Burden traveled to Komodo Island, just west of the island of Flores in Indonesia, where he discovered the world's largest predatory lizard: the Komodo dragon. He returned with 12 specimens, 2 of them live and 3 of them stuffed and displayed in the American Museum of Natural History in New York City. Today, the Komodo dragon, an endangered species, is being held from the brink of extinction in part by the efforts of the Smithsonian Institution. In 1992, the Smithsonian's National Zoological Park was one of the first zoos outside of Indonesia to hatch clutches of dragons, with various hatchings distributed to zoos around the world.

## Komodo Dragons

- Komodo dragons were unknown to Europeans until 1910, when reports of a "land crocodile" reached the Dutch administrators of what was then the Dutch East Indies. Lieutenant van Steyn van Hensbroek was the first European to capture and kill a specimen, sparking a great interest in these "ancient beasts." Just 17 years later, 2 live specimens were proudly exhibited when the London Zoo's Reptile House opened in 1927.

- These are big animals; an average male is around 2.5 meters long and weighs about 91 kilograms. It is estimated that they have a life span of around 30 years. They have a long muscular tail that is as long as the body and a long flat crocodile-like head with a rounded snout. They have powerful front limbs and long curved claws, which are formidable weapons, and a long forked yellow tongue that flicks in and out of the dragon's mouth. Their skin is armored with osteoderm bone, forming a kind of chain mail pattern.

- Despite their position as top predator of these islands, they will quite happily eat carrion. The dragons will hunt almost anything: invertebrates, eggs, lizards, and mammals, including monkeys, goats, water buffalo, and other items. They are not fussy eaters and will on occasion eat other Komodo dragons. Attacks on humans have also been reported.

- Komodo dragons are not designed to run down prey like wolves do. In common with other reptiles of this genus, they have legs that stick out to the side, giving them a characteristic gait, with their body swaying from side to side.

- They are ambush predator, using short bursts of speed to quickly lunge at a creature and strike. Small prey tend to get bitten in the middle of the neck, sometimes even being knocked over by a swipe from that powerful tail. For larger prey, they adopt a bite-and-retreat strategy, critically wounding a larger creature and then waiting for it to die.

- A common hypothesis is that Komodo dragons kill their prey with the aid of virulent strains of bacteria found in their mouths. It is presumed that the bite from the dragon infects its prey with so much bacteria including that they go into septic shock and die as a result.

- Recently, though, research published in 2013 by a number of scientists, including Dr. Ellie Goldstein of the R. M. Alden Research Laboratory in California, have questioned this model. They suggest that the bacterial flora of the Komodo dragon is really no different from other large predators.

- In a paper published in 2009, Bryan Fry at the University of Queensland, and a number of other researchers, used magnetic resonance imaging (MRI) to analyze the skull of a Komodo dragon and model its bite. They found that the dragon does not have a particularly powerful bite when compared to that of a crocodile. In addition, the Komodo dragon does not have a strong skull or jaw muscles to subdue its prey.

- So, if it doesn't use "dirty mouths" or powerful jaws, how does the Komodo dragon kill its prey? They have strong muscles behind their skull to resist

prey as it attempts to pull away from the dragon. This action involves the slicing and ripping of flesh, aided by very sharp, inch-long, serrated teeth. There is also a venom gland that delivers venom through cavities between the teeth, getting quickly into the bloodstream of the prey. Fry's research showed that Komodo dragon venom prevented blood clotting, lowered blood pressure, and caused the prey to go rapidly into shock.

● Komodo dragons can see objects about 300 meters (985 feet) away but have difficulty distinguishing between nonmoving objects. They also have rather poor night, or dim-light, vision. Their hearing isn't too great, either, and they have a reduced range when compared to humans. They would have difficulty in detecting low- and high- pitched sounds. But they do have a very keen sense of smell—a sense of smell that can detect carrion over 2.5 miles (4 kilometers) away.

● Most of the smell, though, is not detected through the nostrils. Instead, they use their yellow tongue to continually "taste" the air. The Komodo dragon

assists this detection by swinging its head from side to side as it walks. Like snakes, these scents are passed to a feature called the Jacobson's organ, which can tell if more "scent molecules" are present on the right or left fork of the tongue, and in this way, the dragon can zero in on dinner.

## Big Dragons on Small Islands

- It appears that the presence of the Komodo dragons on a small number of Indonesian islands is part of an older paleontological story that has only relatively recently come to light. Komodo dragons today are found on the islands of Gili Motang, Gili Dasami, Rinca, Komodo, and Flores. This is a pretty isolated distribution and leads to an important question: How do you get a 200-pound lizard to a group of small Indonesian islands?

- One possibility is something called the island effect. A common feature on islands is the way that creatures will either get larger or smaller in response to the conditions they find themselves in.

- For example, consider *Stegodon*, a type of prehistoric elephant with a long geological range, from 11.6 million years ago to relatively recently in the Late Pleistocene. They were large creatures, and like modern elephants, they were probably good swimmers and may have reached the Indonesian islands, such as Flores and others, when sea levels were low. On the islands, they started to shrink, probably as an adaptation to the more limited resources on the island, perhaps becoming about the size of a water buffalo.

- Did the Komodo dragon arrive as a small lizard and grow large as part of the island effect? Or is it possible, as has been suggested by some, that the dragon grew large as a result of a need to prey on the dwarf but still large *Stegodon* elephants that were in the same environment? According to these hypotheses, small monitor lizards get washed onto the islands—perhaps on mats of vegetation, by floods, or even by tsunamis—and then evolve into the large Komodo dragon that we know today.

- An alternative hypothesis is that there has been no change in size in the Komodo dragon. Perhaps they arrived on the islands at their present size, in which case we have the same question: How do you get a 200-pound lizard to a group of small islands?

- We are currently in a relatively warm interval during the current ice age, the last glacial advance of which ended about 12,000 years ago. During the various glacial maxima, sea levels would fall, linking many of the current islands in Indonesia, or at least reducing the amount of ocean between them. At these times, the Malay Peninsula, Borneo, Java, and Sumatra were part of a landmass called Sunda, while Australia and New Guinea were part of a landmass called Sahul.

- The increased landmass and reduced distance between these islands facilitated the migration of certain species into this area. Oceanic channels, such as exist between Bali and Lombok, were still present, which would prevent complete mixing of these islands' biotas, even during times of very low sea level.

- When the ice melted and sea levels rose again, the species that had migrated to these islands were trapped. This led to an isolated evolution of their fauna and flora and explains why this is one of the most biodiverse places on the planet. In a biogeographical sense, this area is called Wallacea, in honor of Alfred Wallace, a coauthor with Darwin on the first paper describing evolution by natural selection.

## Australian Megafauna

- Where did the Komodo dragons come from? Recent paleontological evidence suggests that these wonderful beasts are Australians. They are part of an ancient megafauna and, as such, could be thought of as "living fossils."

- Most of the Northern Hemisphere megafauna—giant mammoths and mastodons, wooly rhinoceroses, and saber-toothed tigers—was extinct by

about 11,700 years ago. Megafauna are considered to be animals that are more than 100 pounds.

- But another megafauna developed on "island" Australia. By 50 million years ago, Australia had separated from other landmasses in the Southern Hemisphere but was still close enough to allow migration of creatures from South America across an ice-free Antarctica and into a northward-drifting Australia. As time progressed, and as the ocean widened, Australia became isolated, and all those creatures were marooned—and evolution in isolation can do some pretty amazing things.

- That original wave of migration from South America included mammals—principally marsupials, which are mammals that commonly carry their young in a pouch. From what were probably small migrants from South America, a whole array of spectacular animals would evolve, including the marsupial lion *Thylacoleo carnifex* and the giant koala *Diprotodon*.

- But it wasn't all marsupials. *Dromornis*, a large flightless bird, inhabited open woodland and is thought by some to have been carnivorous. There were also giant snakes, such as the Bluff Downs giant python from the Early Pliocene of Queensland.

- There were other reptilian components of this megafauna, and lurking around in the Australian bush was a monitor lizard even larger than the Komodo dragon: *Megalania prisca*, or *Varanus priscus*. No complete skeleton has been found, but estimates of the size of this monster vary from 5.5 to 7 meters. Even on the small end of this range, this is still significantly larger than the Komodo dragon.

- Analysis of the fossils of this beast by a team including venom expert Bryan Fry has suggested that, like the Komodo dragon, this lizard was also venomous. This would have made it quite the formidable predator in Australia and one of the largest venomous creatures to have existed.

- *Megalania* fossils are known from Pleistocene deposits of eastern Australia, aged between 2.6 million and 30,000 years ago, which opens

up the possibility that the first humans to range across Australia may have encountered this animal, too.

- Additional research in 2009 from the University of Queensland by Scott Hocknull and colleagues would also put to rest the origin of the Komodo dragon in Indonesia, as fossil evidence shows that the Komodo dragon coexisted with *Megalania*. Their studies show that Komodo dragons had dispersed as far as the island of Flores by 900,000 years ago and to Java between 800,000 and 700,000 years ago.

- The Komodo dragon of today, therefore, represents a relic population of a lineage of giant monitor lizards that was once common in eastern Australia and Wallacea as far as Java. By 2000 years ago, the last remaining member of this group of monster lizards had retracted to Flores and small surrounding islands, such as Komodo.

- In fact, much of the Australian megafauna—with notable exceptions, such as the red kangaroo—were extinct by about 30,000 B.P. (before present), probably due to a combination of factors, including climate change and interaction with humans.

## The Future of Komodo Dragons

- What is the status of the last surviving relic of these giant lizards? It is estimated that the population hovers around 3000 individuals in the wild, placing them in a "vulnerable" status.

- The decline in population is due to a number of factors. The Lesser Sunda Islands are highly active volcanically, and such natural disasters can easily tip a delicate island ecosystem into crisis.

- Human interaction, though, has had a serious effect. The dragons have suffered from loss of habitat and poaching of their prey. They have also been deliberately poisoned, and some dragons have been captured, presumably for personal collections or trophies.

- In 1980, the Komodo National Park was set up to include the islands of Komodo, Rinca, Padar, Wae Wuul, and Wolo Tado as well as reserves on Flores. In total, it covers an area of 1733 square kilometers. In 1991, this area was declared a UNESCO World Heritage Site.

### Questions to consider:

1. How many new species have evolved on islands in isolation?
2. How many species of fossil animals may have been venomous?

### Suggested Reading:

Fichman, *An Elusive Victorian*.

Long, Archer, Flannery, and Hand, *Prehistoric Mammals of Australia and New Guinea*.

Molnar, *Dragons in the Dust*.

# Lecture 21

## Mammoths, Mastodons, and the Quest to Clone

S ome fossils are controversial. Other fossils challenge the way we believed the story of life unfolded on our planet. And a few fossils go beyond that, challenging the very foundations of our perceived reality—our place on Earth. In this lecture, you will learn about one of those fossil species and discover how it is at the center of both a scientific and moral debate that is still raging today.

## A Tooth That Shook the World

- In 1705, a Dutch settler in the Hudson River valley near the village of Claverack, New York, found a tooth. The tooth was then traded to a local politician, who subsequently made it a gift for the governor of New York, Lord Cornbury, who was convinced that this was the tooth of a giant—one of the giants thought to have roamed Earth before the flood mentioned in Genesis.

- The tooth was sent to London and became known as *incognitum*, the unknown species. In South Carolina other giant teeth started to turn up. Slaves in that state noted that they looked very much like the teeth of African elephants.

- In addition, tusks and other bones started to be found in the Ohio River valley—fossils that resembled the woolly mammoths recovered from permafrost in Siberia, and as a result, *incognitum* would incorrectly get grouped with them.

- It took a famous French anatomist, Georges Cuvier, to realize that *incognitum* was something different. It all came down to the structure of

the teeth. Those found in Ohio and Siberia had ridges, a bit like a running shoe, designed for grazing grasses and the like.

- The teeth of *incognitum* are very different. They have raised cones, which reminded Cuvier of breasts. This creature clearly had a different diet than the mammoths. It is from these breast-like cones that this creature got its most common name: the mastodon. Cuvier soon started to realize that the teeth and bones of these creatures, while resembling modern elephants, were not the same species.

- The general view at that time was that there was an unbroken chain of creatures stretching back to their creation in the Garden of Eden. In addition, when Cuvier was studying these troublesome teeth, the accepted date of the creation of our planet was around 4004 B.C. The discovery of these extinct beasts not only shook ideas of a still-intact creation, but also made scholars start to question the perceived age of the Earth. Around 6000 years didn't appear to be enough time to accommodate all these fantastic animals.

- Cuvier came to believe that most of the fossils he was studying were from "older worlds" destroyed by some sort of catastrophe. He was convinced that many of the fossils and geological formations he examined pointed to the Earth progressing by a series of catastrophes that caused the extinction of many species. These ideas were largely replaced by uniformitarianism, the theory that geological features could be explained by present-day slow processes, such as erosion and deposition of sediments.

- Our modern understanding of extinctions has vindicated Cuvier's views, at least to some extent. The Earth does evolve by slow, almost imperceptible changes, as uniformitarianists suggested. But it is also punctuated now and again by extensive catastrophes that today are called mass extinctions.

## The Evolutionary History of the Elephant

- Most of the fossils of mammoths and mastodons that were being found in North America during the 1700s date to around 10,000 to 12,000 years B.P.

The origins of the larger group to which they belong, the Proboscidea, has a much older heritage, originating around 9 million years after the death of the dinosaurs along the shores of a vast oceanic body called the Tethys Sea in what is today North Africa, the Middle East, and extending to northern India.

- A very early elephant ancestor is a pig-sized animal called *Phosphatherium*. Today, the closest living relatives of modern elephants include the manatees, dugongs, and hyraxes. It is from unimpressive looking *Phosphatherium*, though, that a wonderful array of elephant-like creatures would evolve.

- By about 37 to 30 million years ago, *Moeritherium* would be wallowing in African swamps like a small hippopotamus. Contemporaneous with *Phosphatherium* was *Phiomia* (about 2.5 meters in length, a more terrestrially adapted creature with 2 sets of short tusks) and *Palaeomastodon* (standing about 2 meters tall and weighing around 2.2 tons, one of the most elephant-looking members of the group at this time, equipped with a trunk and scoop-shaped lower tusks).

- By about 10 million years ago, though, the king of all elephants would evolve: *Deinotherium*, larger than a modern African elephant, some of which weighed about 14.5 tons.

- Rather than upward-curving tusks, those of *Deinotherium* pointed downward, probably to help strip leaves off trees as it fed. This animal probably persisted in Africa until the start of the ice ages; it is likely, therefore, that these creatures interacted with humans.

- In terms of the story of modern elephants, though, *Deinotherium* and its kind were more of a side branch. For the family history of elephants, we need to turn to the *Gomphotheres*, from which we get mammoths and modern elephants.

- From *Palaeomastodon* through the *Gomphotheres*, there would be a radiation of elephant forms adapted to various lifestyles and environments, sadly with just 2 remaining today: the Asian and the African elephants.

## The Ice Age Kings of North America

- Mammoths evolved in Africa during the Pliocene and would enter Europe by about 3 million years ago. A European species called the steppe mammoth evolved in eastern Asia and, by around 1.5 million years ago, would cross the Bering Strait across "Beringia" when sea levels were lower than today. The Columbian mammoth would evolve from these pioneering steppe mammoths and populate an area from the northern United States to Costa Rica.

- The Columbian mammoth was about 4 meters (13 feet) at the shoulder and weighed up to 11 tons. Specimens of the Columbian mammoth are quite well known, as many individuals were caught in natural traps.

- There would be another wave of mammoth invasion into North America. From the steppe mammoths that gave rise to the Columbian mammoth, another iconic species would evolve about 400,000 B.P. and cross into North America by 100,000 B.P.: the woolly mammoth.

- Woolly mammoths were smaller than their Columbian cousins, about the same size as an African elephant. They were covered by course hair, probably thicker than that of the Columbian mammoth, and, because they lived in more northerly regions, had small ears, probably an adaptation to conserve heat. The characteristic fatty hump on the mammoths' backs may have been used as a reserve source of nutrients in the more extreme northerly environments.

- We know quite a lot about woolly mammoth anatomy because, unlike the Columbian mammoth, specimens have been found preserved buried in permafrost with soft parts still intact.

- Both the woolly mammoth and Columbian mammoth coexisted in North America, with the woolly mammoth living in the colder, more northerly environments. It is possible that the 2 species interbred where their ranges overlapped. Woolly mammoths even interacted with humans.

- But there is one North American elephant we have not covered: *incognitum*, the American mastodon that had very different teeth to mammoths, with raised cones rather than ridges. Initially, some thought that the cones on *incognitum* indicated that this creature was an ice age, flesh-eating monster.

- Benjamin Franklin figured out the true nature of the beast. He reasoned, correctly, that mastodons' tusks would have been an impediment for catching prey and suggested, again correctly, that the cone-like teeth would probably be an adaptation to grinding small branches of trees.

- The American mastodon, or *Mammut*, had shorter legs and flatter, longer skulls, and they were more heavily muscled than the mammoths they coexisted with. Large males reached up to 9 feet 2 inches and weighed 5 tons. They also had tusks that were less curved.

- The American mastodon is from a much older root stock than its mammoth cousins, with *Mammut* diverging from the chain of evolution that would lead to the Elephantidae, which includes modern elephants and mammoths, at about 27 million years ago.

- They ranged across North America during the Pleistocene epoch, mostly inhabiting cold spruce woodlands, browsing on trees. Remains of the mastodon have been found frozen in Alaska, and from these the genome of the creature has been sequenced, allowing us to place it fairly accurately within the elephant family tree.

## The Disappearance of the Giants

- The mammoths and mastodons of North America did not exist in isolation. Other giant creatures roamed North America, part of a now-extinct Pleistocene megafauna.

- Sharing the Pleistocene landscape were creatures such as the giant ground sloth, *Megatherium*; a North American camel, *Camelops*; giant beavers; the armored *Glyptotherium*, a relative of the armadillo; and the North American bison, who we still have with us today. Giant herbivores like these mean there must have been giant predators, such as the short-faced bear, dire wolves, the bird *Teratornis*, an American lion that was around 25% larger than its African cousin, and the saber-toothed tiger.

- What happened to the megafauna that existed in North America and around the world is still hotly debated, but there are 4 main hypotheses:
  - First, there is hunting. There is a general continent-by-continent extinction of megafauna that follows the migration of humans across the planet. There is archaeological evidence of butchery of some megafauna species by the Clovis people, some of the first human settlers, but some question if small bands of hunter-gathers could have been entirely responsible for the extinction of all these large creatures.

- Some researchers prefer climate change as the vector for extinction. Following a glacial advance during the ice age, there are often associated extinctions of species, possibly related to changes in vegetation patterns as climate warmed during an interglacial.

- A less-favored hypothesis is the possibility of a hyper-disease that killed off many of the large creatures, although it is difficult to imagine how a disease could be fatal to so many different species of animal

- Another less-favored hypothesis is the possibility of an extraterrestrial impact event that caused wildfires, and ultimately a global cooling event, during a period called the Younger Dryas (12,900 to 11,700 B.P.). Evidence for this is somewhat contradictory.

- Perhaps a good explanation could combine aspects of the overhunting and climate change scenarios. Perhaps climate change reduced the population of many of the megafauna genera to such an extent that even low levels of hunting would drive the animals into extinction.

## Back from the Grave

- Because megafauna such as mammoths went extinct relatively recently, the chances of finding genetic material is much better than for that of dinosaurs, for which no viable DNA has been found. For megafauna, we even have fleshy material available in frozen remains in the Arctic.

- Given that we have fleshy material available, could we bring back a mammoth from the dead? To answer that, we have to consider the 3 possible methods that we could potentially use to achieve this.
  - We could try somatic cell cloning. For this, we would need a viable cell from all the frozen mammoth meat in the Artic. However, thus far, there has been no living cell recovered from any mammoth carcass, and according to many experts, there never will be.

- We could take whatever DNA fragments we can find and reassemble the genome. Some progress has been made in this regard, and large portions of the mammoth genome has been mapped. But there are even large parts of the human genome that we can't map, never mind the mammoth genome. Even when we extract fragmentary DNA from mammoth material, much of it is contaminated with DNA from other creatures. And even if we could eventually reconstruct the entire genome, we don't know how to wrap it up into chromosomes and insert them into a nucleus.

- Because we know that the Asian elephant is the closest living relative of the mammoth and that it shares about 99% of the mammoth genome, we could recognize the part that is not mammoth and swap it out with parts of the genome that we have positively identified as mammoth. We have the technology to snip off sections of Asian elephant DNA and insert mammoth sections, but we are still a long way from reconstructing a woolly mammoth.

## Questions to consider:

1. How much of a role did our species have in the extinction of mammoths?

2. Where should we place the dividing line between what is acceptable and unacceptable in cloning?

## Suggested Reading:

Lister and Bahn, *Mammoths*.

Shapiro, *How to Clone a Mammoth.*

# The Little People of Flores

Myths and legends are a wonderful part of who we are. Some myths are unique, but many share a common theme that is repeated across many cultures. One of those common myths is the existence of "little people." This lecture will take you to the island of Flores, part of the Lesser Sunda Islands in Indonesia. You will learn about the paleontological secrets that Flores holds as well as the identity of *Homo floresiensis*.

## The Island of Flores

● Although little people are common characters in mythology, no one would have suggested that any might actually have existed, at least until a team of Australian and Indonesian archeologists made a fantastic discovery on the island of Flores in 2003.

● Tantalizing stone tools had been discovered previously by Father Theodor Verhoeven in the 1950s. Dutch and Indonesian archeologists in the 1990s dated similar tools to around 700,000 B.P., suggesting that human ancestors, probably *Homo erectus*, had migrated to the islands of Indonesia long before the evolution of modern humans about 200,000 years ago.

● So, Flores was probably a good place to hunt for these earliest migrants making their way across the East Indies.

● In 2001, an Indonesian-Australian team co-led by Dr. Mike Morwood of the University of Wollongong in Australia began excavations at a large limestone cave called Liang Bua. They dug for 2 years, first finding an arm

bone and then about a year later a tooth. Then, on September 6, 2003, one of the locally hired excavators, Benyamin Tarus, exposed the top of a skull (LB1) at about 6 meters (around 20 feet) below the cave floor.

- This was a small individual, about 3 feet 6 inches (1.06 meters) and weighing about 66 pounds (30 kilograms). It looked like a female child, until the teeth were examined: The jaw contained wisdom teeth that were fully exposed and also demonstrated signs of wear. This was a tiny adult about 30 years old, dating to geologically very recent times, at about 18,000 years ago.

- Fragments of 12 other individuals were recovered that were associated with this skeleton, as were stone tools. In addition, charcoal was found, suggesting the use of fire. The initial dates obtained for these discoveries overlapped with the time that modern humans are known to have arrived in Indonesia at about 45,000 B.P. Could they have coexisted with modern humans?

- The discovery generated a media storm, and very quickly these little people were named "Flores Hobbits" by the media after the little people in J. R. R. Tolkien's books. Scientifically, they were named *Homo floresiensis*, a member of our own genus and part of the taxonomic tribe called hominins, comprising modern humans and their ancestors.

- The discovery also generated immediate controversy. Part of the problem centered around *floresiensis*' brain, which, at 400 cubic centimeters, places it in the range of chimps. This flies in the face of our understanding of our human evolution, which demonstrates the advance of upright walking apes evolving progressively larger brains. Now here is *floresiensis*, potentially coexisting with modern humans but possessing a tiny brain.

- Many were unhappy with the idea of these fossils being a new species of human. The head Indonesian anthropologist Teuku Jacob, after examining the remains, declared that they resemble modern humans suffering from a condition known as microcephaly. This is a rare neurological disorder generally associated with dwarfism and characterized by people with very

small brains and heads, and often a diminished mental capacity, and a characteristic sloping forehead.

- Finding the skull of *Homo floresiensis* allowed the production of an endocast, an internal cast that gives us a picture of the external surface of the brain. When examined, it was found that, unlike many microcephalic brains, *Homo floresiensis*' brain had very well-developed frontal lobes, and Brodmann area 10, the area of the brain involved with higher cognition, was proportionally of similar size to that of modern humans.

- Does this explain the presence of stone tools in the cave and evidence for the use of fire? Could it also explain the butchered remains of extinct pygmy elephants called *Stegodon florensis insularis*? This animal was about the size of a cow but would still be a challenge for an individual shorter than 4 feet. Could this imply group hunting, a complex social structure requiring advanced cognition and perhaps speech?

- Other explanations by pathology—to try and explain these fossils as human with pathologies—also include congenital hypothyroidism, which can be found in the local population of Flores and could also account for small bodies and brains. In 2014, it was suggested that the LB1 skull demonstrates craniofacial asymmetry, a sign of Down syndrome, although Australian researchers counter this and state that this is likely a feature of the skull's preservation and damage during extraction.

## *Homo floresiensis*

- Supposing that this is a real human ancestor, a close relative but not a member of *Homo sapiens*, where does *Homo floresiensis* fit into our story?

- It is thought that *Homo sapiens* likely evolved from a group of *Homo erectus* in Africa about 200,000 years ago and spread out from there, replacing *Homo erectus* and other human species, such as the Neanderthals, and ultimately becoming the only living species of human on Earth.

Homo neanderthalensis


Homo antecessor


Homo sapiens


Homo erectus

- If *Homo floresiensis* did not evolve from *Homo sapiens*, then from whom in our family tree did they evolve? The most obvious candidate would be *Homo erectus*, our first really human-looking ancestor and the only other human ancestor we have evidence of in Indonesia. But how does a large

human ancestor shrink to 3 foot 6 inches? To answer that, we turn to consider some of the strange things that can happen to animals on islands.

- On islands, former mainland species over a number of generations can start to experience dramatic changes in size, effects called insular dwarfism or gigantism. These changes can be due to a number of factors. Growing large on an island may be due to a lack of predators that you no longer have hide from. Shrinking in size may help if resources are limited and the territory available for your seeking of food is much reduced.

- On Flores, there are examples of dwarfism and gigantism. *Homo floresiensis* might have hunted giant rats about twice the size of the average brown rat. There were also giant storks and pigmy elephants. Although probably not an example of the island effect, the intimidating carnivorous Komodo dragons were also ambling around Flores.

- Could the little creature known as *Homo floresiensis* be a dwarf *Homo erectus*? If this is the case, then this is a branch of an extremely successful and widespread human ancestor that survived, hidden, until very recently. Some are unhappy with the island effect hypothesis to explain *Homo floresiensis*, in part because island dwarfism does not usually see a reduction in brain size, like we see in *Homo floresiensis*.

- Could *Homo floresiensis* represent something much more ancient? Is it possible that *Homo floresiensis* has not undergone island shrinking and could have arrived on Flores already small?

- Dr. Matt Tocheri of the Smithsonian's Human Origins Program notes that there are several features in modern human and Neanderthal wrists that are quite different from the wrist structure of great apes and earlier hominins. It would appear, though, that the structure of the wrist of the LB1 fossil shares much more in common with these earlier hominins and the great apes than it does us.

- So, this research confirms the early status of *Homo floresiensis*. In fact, some have wondered if *Homo floresiensis* could be descended from even

earlier human ancestors, such as *Homo habilis*, or with the even more ancient australopithecines, such as *Australopithecus afarensis*.

- The problem with this is that unlike *Homo erectus*, the australopithecines and *Homo habilis* are not known out of Africa. It is conceivable, however, that the "Saharan pump"—an opening up of a grassland corridor along the eastern Mediterranean due to changing environmental conditions—could have allowed for their migration just as it did for *Homo erectus*, which possibly reached Java by about 1.5 million years ago. If this is the case, *Homo floresiensis* may represent some of our earliest human wanderers. Perhaps we will find their fossils in the future.

- Perhaps we have another way forward, though. We are already mapping the Neanderthal genome, so what about *Homo floresiensis*? Attempts have been made on the teeth found at Liang Bua, but so far without success. This might be due to the tropical conditions in which the fossils were found. When excavated, they were described as having a "consistency of wet blotting paper." Perhaps future fossil finds will provide better-preserved material and put to rest the origin of these remarkable little humans.

## The Fate of Flores's Ecosystem

- What happened to the ecosystem of pygmies and giants on the island of Flores—this ecosystem of tiny humans hunting giant rats and dodging the scary Komodo dragons?

- This is a very volcanically active part of the world. The volcanoes in Indonesia are dangerous, very different from the generally benign volcanic eruptions we see on Hawaii. The volcanoes in Indonesia are explosive and capable of generating pyroclastic flows, hot flows of gas and rock that can reach speeds of 700 kilometers per hour (450 miles per hour) and temperatures of 1000° Celsius (1830° Fahrenheit). They can also be responsible for lahars, a volcanic debris flow composed of a slurry of pyroclastic material and various materials flowing with the consistency of wet concrete.

- The fossils, along with some of the giant storks and pigmy elephants, were found below a thick layer of volcanic ash. Perhaps, then, a volcanic disaster ended the world of the little people of Flores. A large volcanic event in this part of the world could easily disrupt a finely balanced island ecosystem, taking *floresiensis* and the other giants and pigmies of the island into extinction.

- It is possible that they survived only to be wiped out by the modern people of Flores. Unfortunately, the idea that they coexisted with modern humans for an extended period of time may have recently revived a blow.

- Research published in *Nature* in 2016 has provided a much more accurate date for the fossils in the cave at Liang Bua. The oldest fossil remains appear to be about 60,000 years old, with tools dating to about 50,000 years and not the more recent dates that were previously provided. If they ever did coexist with humans, it is likely that as soon as our species started to spread across the Lesser Sunda Islands, they were simply outcompeted and driven into extinction.

- Even so, it would be nice to think that they are still furtively slipping through the forests of Indonesia. Between 2005 and 2009, a camera-trapping project was funded by the National Geographic Society in the hope of snapping a shot of the mysterious creature in the woods—without success.

*Questions to consider:*

1. How much of our genome is the result of species interbreeding?

2. As far as we know, are we the last remaining member of our genus? Are we an endangered genus?

*Suggested Reading:*

Stringer, *Lone Survivors*.

Tattersall, *Masters of the Planet*.

# The Neanderthal among Us

For many years, we had a brutish vision of Neanderthals. The species was regarded as extremely primitive when compared to *Homo sapiens* and not very closely related to us at all. Today, our overall picture of Neanderthals is a rather short, stocky, barrel-chested, and powerfully built people. They had heavier faces than *Homo sapiens* but were a far cry from the brutal shambling ape that was once envisioned. In this lecture, you will learn who the Neanderthals were—specifically, whether they were a species in their own right or just a thick-skulled variety of *Homo sapiens*.

## Cognitive Abilities of Neanderthals

- Did Neanderthals just look like humans, or did they actually demonstrate human intelligence and complex social structures? If you consider pure brain size, Neanderthals actually have us beat. The average cranial capacity of *Homo sapiens* is 1400 cubic centimeters, while the capacity of *Homo neanderthalensis* is around 1600 cubic centimeters.

- Brain size is no guarantee of complex social behavior, though. It is possible that a larger part of the Neanderthal brain may have been devoted to vision.

- Perhaps evidence of intelligence can be deciphered from the Neanderthal diet. It would appear that they ate a variety of foodstuffs, including plants and animals, depending on season and location. Neanderthal wooden spears have been found from sites where big game animals had been butchered. To hunt such large animals implies cooperation, social structure, planning, and—perhaps the hallmark of intelligent animals—some sort of complex language.

- This is a difficult thing to prove, but Neanderthal DNA may help us. We know that on chromosome 7 in the human genome there is a gene called FOXP2 that is required for the development of speech and language, controlling the development of various features in the brain, heart, lungs, and gut. Mutations in this gene can cause speech and language disorders.

- There are only 2 differences in the amino acid code of the FOXP2 gene between humans and chimps, and between Neanderthals and humans there is no difference. Does this suggest that they inherited the gene from a common ancestor even further back in time? If this is the case, could we also infer that Neanderthals were equipped with all the language production capacity that we humans have?

- Neanderthals were adept at making sharp flakes of stone for a wide variety purposes, including cutting and scraping. Neanderthal tools have often been thought of as primitive when compared to those produced by *Homo sapiens*, but they are still very versatile and efficient.

- There are examples of social interaction that may also suggest an intelligent species. In Shanidar Cave located in Bradost Mountain in Iraqi Kurdistan, the remains of 10 Neanderthals have been found. A cast of one of those, "Shanidar 1," is held at the Smithsonian's National Museum of Natural History. He was an old man between 40 and 50 years of age who had a withered right arm that was fractured in a number of places, leaving him with very limited or no use of this lower arm and hand. The fractures had healed, though, implying care by his social group.

- For a long time, one of the features of *Homo sapiens* that was regarded as being unique and distinct was the production of art. Art illustrates an ability to conceptualize—to represent the world you see, or perhaps don't see, what is locked in your imagination.

- For a long time, it was thought that Neanderthals did not exhibit artistic abilities, but a geometric crosshatch pattern found at the back of a cave in Gibraltar in 2012 may change that. These symbols are thought to be around 39,000 years old and were discovered below an undisturbed layer

of sediment in which Neanderthal tools were found. The image appears to have been made by a point, the artist deliberately deepening the cuts in the hard dolomite rock over many hours.

- There are some who still question whether these markings were made by Neanderthals, but if they were, this is significant. Perhaps the image is a map or perhaps a symbol to mark territory. Whatever its meaning, it shows evidence of abstract thought, and if this is the case, and these are produced by Neanderthals, then they are not unlike those produced by *Homo sapiens*.

## Are Neanderthals Related to Us?

- How closely are we related to the Neanderthals? Unlike reading DNA that is many millions of years old, like we would need for the dinosaurs, the prospects of reading DNA that is within the 100,000-year range is much better. Perhaps we can read the genome—the genetic recipe—of Neanderthals.

- There are 2 possible sources of DNA that we can use in genetic studies. Nuclear DNA—that is, the DNA found in the nucleus of our cells—codes for all the structures and functions of our bodies. This is where we store our "blueprints." But there is another source of DNA in small "micromachines," or organelles, that are found in our cells. These are mitochondria, and each of your cells contains around 1700 of them. Mitochondria have their own DNA, independent of the personal blueprint that you have in the nuclei of your cells, that is called mitochondrial DNA (mtDNA).
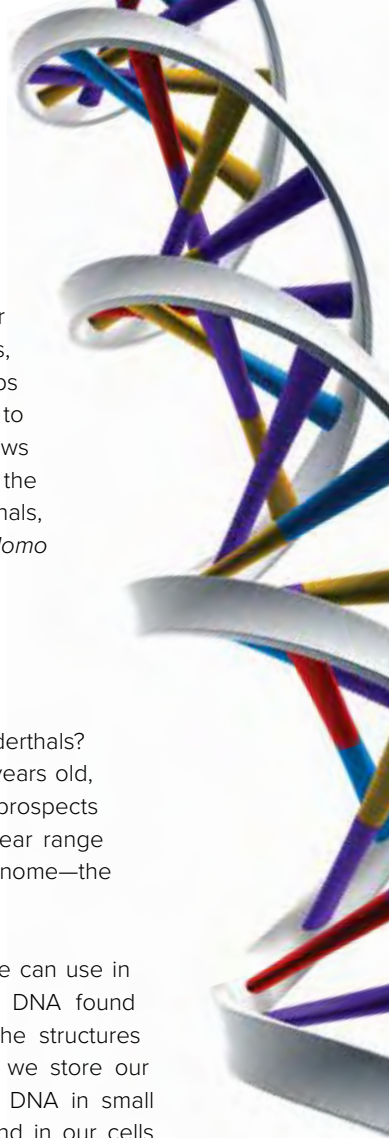
- Sperm and egg cells also contain mitochondria, but when the nucleus of the sperm fuses with that of the egg to give you the mix of genes from mother and father that we are all composed of, the mitochmdria of the sperm most of the time gets left outside. As a result, it is generally only the maternal mtDNA, that of the egg, that gets passed on down the line through the generations.

  - Over time, mtDNA, like nuclear DNA, will undergo random mutations—slight errors when the DNA is copied from one generation to another. We can use these differences between mtDNA in different people and estimate the rate of mutation to determine how far back in time they once shared a common ancestor. We can also find out how long since they shared that ancestor that they have been traveling along their own particular branch of the ancestry road.

    - It was using this principle that researchers in the 1980s were able to determine that the common ancestor of all mtDNA—and, therefore, all humans living today—was a woman who lived in Africa around 100,000 to 200,000 years ago: "mitochondrial Eve."

      - Tracing the last common ancestor of humans and Neanderthals would be attempted by Svante Pääbo of the Max Plank Institute in Germany. For this study, they would use Neanderthal 1, the type specimen of the species, which acts as a taxonomic reference when a species is first described. Even if DNA is present, most of it will be fragmentary, and the vast majority of the DNA will be contaminants from soil bacteria and from scientists and curators who have studied the specimen over the years.

        - Taking these contaminants into account, Pääbo's team finally isolated Neanderthal

mtDNA and then compared it to around 1000 mtDNA sequences of modern humans. Among the modern humans, the DNA differed by about 8 mutations but, between the modern humans and the Neanderthals, the average was around 26. This would place the common ancestor of Neanderthals and modern humans around 500,000 years ago.

- Perhaps *Homo heidelbergensis*, who was known to have lived in Europe and Africa at about that time, is close to the split of the Neanderthal and modern lineages. Some reserach, based on tooth structure, has suggested that the split occured even further back in history, perhaps as much as 1 million years ago. This places it in the range of ancestral humans such as *Homo erectus*.

- This ancient divergence was taken by some to suggest that Neanderthals were a completely separate species to humans and that, with around half a miliion years or more of genetic drift between the 2 populations, it would be very unlikely that a human and a Neanderthal could breed to produce living offspring, let alone offspring that may be viable enough to pass on that genetic mixing into the next generation.

- There had been intriguing fossil finds, though, that suggested some interbreeding had occurred. Had there been inbreeding despite the antiquity of the last common ancestor of the 2 species? To answer this, we would have to find some way to read the nuclear DNA of Neanderthals, the blueprint of the organism held in the cell's nucleus. This was the quest for the Neanderthal genome.

- This is something that we have only just recently achieved for our own species in the Human Genome Project, an international effort to read our own human blueprint. The human genome project was initiated in 1990 and completed in April of 2003.

- The Neanderthal genome would be a more challenging endeavor. There would be problems with contamination and degradation of the DNA, plus the added issue of distinguishing Neanderthal DNA from a very close

relative: *Homo sapiens*. These were the challenges facing Pääbo's team when the Neanderthal Genome Project was initiated in July of 2006.

- Eventually, a Neanderthal genome was sequenced, with an initial draft published in *Science* in 2010. It was concluded that around 98.7% of the base pairs in the 2 genomes were identical. It was from this that comparisons between the FOXP2 gene in humans and Neanderthals could be made.

- In comparing the Neanderthal genome to people from different racial groupings, they found that around 1 to 4% of Neanderthal DNA is in our genome. The only way it could have gotten there is via interbreeding. Despite the distance in time that separates humans and Neanderthals from their last common ancestor, it would appear that we were still sufficiently similar to produce viable offspring.

- Not everyone has the same part of the genome, but in total it is thought that around 30 to 40% of the Neanderthal genome is floating around in the human population. This indicates that there was not one Neanderthal ancestor, but there must be an entire history of Neanderthal-human interactions.

- A discovery by researchers, including Pääbo, reported in *Nature* in 2015 provides data from an individual much closer to the original interaction. A specimen from a cave in Romania dated to 37,000 to 42,000 B.P. has been found with between 6 and 9% Neanderthal DNA, probably indicating a fully Neanderthal ancestor just 6 generations back.

- This is one possible picture of our messy genome that was published by Chris Stringer of the Natural History Museum in London in *Nature* in 2012. Humans and Neanderthals diverged from a common *heidelbergensis* ancestor, with Neanderthals generating another ancient human group, the Denisovans. Each of these forms included an archaic flow back into the *Homo sapiens* population, contributing in varying degrees some small parts of the modern human genome.

# What Happened to the Neanderthals?

- The forerunners of *Homo neanderthalensis* arrived in Europe about 800,000 B.P. *Homo sapiens* arrives at about 40,000 B.P., and just 10,000 years later, the Neanderthals are gone. This could suggest that they were outcompeted for resources or were hunted down and exterminated in acts of interspecies genocide.

- Another possible explanation may relate to rapid climate change. By about 55,000 years ago, climate started to fluctuate rapidly from extremely cold to mild within a few decades, perhaps within the lifetime of an individual. This would have caused rapid changes in the landscape, from woodlands to grasslands, with familiar plants and animals appearing and disappearing.

- It has been suggested that early modern humans during this period would have had more widespread social networks. This would allow them to acquire resources over a greater area. Neanderthals in this model become increasingly isolated and starved of resources. They finally become extinct at about 41,000 to 39,000 B.P., at the start of a very cold snap.

- But perhaps there is another explanation. As modern humans moved into the Neanderthals' territory, perhaps the Neanderthals were just absorbed by interbreeding. Or perhaps there was a combination of all 3 of these ideas: part confrontation, part climate-and-resource related, and part genetic assimilation.

*Questions to consider:*

1. How do we define consciousness, and is it only a trait that evolved in *Homo sapiens*?

2. Was it inevitable that *Homo sapiens* would become the only member of our genus on Earth? Is it possible that different circumstances could have seen the *Homo neanderthalensis* rise to dominance?

*Suggested Reading:*

Pääbo, *Neanderthal Man*.

Papagianni and Morse, *The Neanderthals Rediscovered*.

# Paleontology and the Future of Earth

I n this final lecture, you will consider what the future holds for our species and what role paleontology plays in this inquiry. The future of paleontology is perhaps universal. With new exoplanets being found around stars every year, who knows where a future fossil hunter may tread. And the Smithsonian's National Museum of Natural History is a hotbed of cutting-edge research, charting the history of the Earth system through time. It is in places like this, and others around the world, that the keys to the past, present, and future will be cast—and, with them, perhaps a more secure future for us all.

## Future Changes to the Earth System

- The likely causes of change to the Earth system in the future are difficult to predict. The continents will continue to move about our planet as they have for billions of years. Reconstructions like those of Christopher Scotese from the University of Texas at Arlington predict that a new supercontinent will form in about 1/4 of a billion years from now, part of a supercontinent cycle.

- But printed on the slow movements of the continents are rapid events. Consider Yellowstone, a volcano that is so vast that it is difficult to appreciate that it is actually a volcano from the ground. Yellowstone is a caldera that measures 60 by 32 kilometers that last erupted massively about 640,000 years ago. Yellowstone is "breathing," with the caldera floor rising and falling probably in response to the developing magma chamber below. A major eruption at Yellowstone would likely be catastrophic for human civilization, but even with the park's ups and downs, it is thought it is unlikely to erupt any time soon.

- Other sudden events can strike from the skies rather than rising from the depths. Paleontologists and geologists have been studying the violent end of the Mesozoic biosphere 66 million years ago for decades. The general consensus is that the Earth was hit by a 10-kilometer-diameter object that caused such catastrophic environmental change that it drove the Mesozoic biosphere, including the dinosaurs, into extinction.

- Recently, we have been reminded that impacts from space, like major volcanic events, are still a very reasonable part of our collective future. On February 15, 2013, at around 9:20 am, a bright light was seen streaking above the skies of Russia. The event was captured by closed-circuit television and dashboard cameras all over the southern Ural region.

- It was caused by a 20-meter-diameter object entering the atmosphere at a speed of about 40,000 miles per hour. As a result of its high speed and angle of entry, the object exploded 18.4 miles above the ground, generating a shower of fragments and a significant shock wave. The energy released in this event was equivalent to 500 kilotons of TNT, about 20 to 30 times more energy than the bomb detonated at Hiroshima.

- The event damaged more than 7000 buildings in 6 cities. About 1500 people received injuries, mostly from broken glass, that required medical treatment.

- If this object had hit the ground, it would have generated a substantial crater and probably more damage and potential fatalities—not a mass-extinction-level event, but it certainly shows that the days of impacts from space, just like supervolcanoes, are far from over.

- Another important vector of change in both our short- and long-term future is climate change. The now-famous Keeling curve that shows the yearly changes in carbon dioxide at Mauna Loa, Hawaii, beautifully reflects seasonal variations in the uptake of carbon dioxide by plants over a year. The most startling feature of the data is the increase in carbon dioxide levels over time.

- These results placed in the context of a deeper-time perspective show how current changes in carbon dioxide levels cannot be explained by natural ice age cycles. The increase in global temperature will impact sea level, climatic patterns, species distributions, and a whole range of other potential effects that we cannot yet predict. There is a scientific consensus on climate change that the climate is, in fact, changing and that the changes are in large part caused by human activities.

- We are also witnessing a drop in global biodiversity. As with extinctions, there is often a trigger followed by a cascade of events that cause the actual extinction. Today, as in the past, the cause of these extinctions is varied—including climate change, habitat loss, and pollution—and the trigger this time appears to be us.

- With all these changes to the Earth system, there has been a call by some geologists and paleontologists for the erection of a new geological period, the Anthropocene, to reflect these changing times. In 2008, the International Commission on Stratigraphy received a proposal to make the Anthropocene a unit of the geological timescale.

- There is some debate as to when and how the actual boundary will be drawn. Some favor an "early" boundary around the Neolithic revolution, which saw the transition of many human lifestyles from hunting and gathering to one of agriculture about 12,000 years ago. This, though, kind of places it in conflict with a preexisting period, the Holocene, which begins about 11,700 B.P. and continues to the present day.

- Others favor a more recent definition based on atmospheric evidence of the start of the Industrial Revolution in the late 18th century. It has been suggested that the Thomas Newcomen steam engine, the first practical use of coal and steam power used to drain mines, marks the start of the current changes we are witnessing. That would place the base of the Anthropocene sometime in 1712.

## The Relevance of Paleontology

- With all these changes occurring in the present, why should we be dreaming about the distant past? Paleontology is obviously engaging, and it is still important to industry, particularly in the context of biostratigraphy for mineral and hydrocarbon exploration. Paleontology is also vital in these times of rapid change in the Earth system. Paleontology, and the wider disciplines of geology and biology on which it rests, are the only areas of science that provide context to current changes.

- The biosphere has moved through many interesting times. It teaches us that change is perhaps one of the few constants that we can rely on in Earth's history. Change always comes tapping on the door, even after millions of years of stability.

- By understanding the vectors of slow changes in climate caused by the shifting continents—or sudden catastrophic change caused by extreme volcanic activity, or impacts from space—and by recording the reaction of the biosphere to these changes as preserved in rocks and fossils, we can grasp at that vital context we need to fully appreciate current changes in the Earth system.

- For example, it is accepted that we are in a downward trend with regard to biodiversity—a trend of extinctions that is greater than the usual background rate of extinction that we would expect in the biosphere. The vital question is whether the current trend is much less, the same, or in excess of the loss of species that we know occurred in the big 5 past extinction events. This is a fundamentally important question, and one that only paleontology and biology can really answer.

- Our understanding of the rates and extent of the big 5 mass extinctions are continually being refined and updated as new techniques, geological sections, and fossils come to light. A fine example of this is the end-Permian extinction, which, until relatively recently, was a mystery. Now we are gaining insights into the triggers, cascade of ensuing events, timing, and extent of this "mother of all extinctions."

- In 2015, a team of scientists, including biologist Paul Ehrlich of Stanford University in California, suggested that we may be moving toward a mass extinction event. The study considered past rates of extinctions so that they could be compared to current changes in biodiversity. To address criticisms that previous studies about current extinction rates were flawed, they selected what is considered to be a very high estimate of background extinctions between the big 5 mass extinctions.

- The results they generated suggest that current extinction rates may be 100 times higher than the assumed, probably artificially high, background rate. With their calculated extinction rate, we should have seen around 9 vertebrate extinctions since 1900, but 468 more documented vertebrate extinctions have been recorded, including 69 mammals, 80 birds, 24 reptiles, 146 amphibians, and 158 fish. And we may be unaware of other species going extinct because they have vanished before we could find them.

- If these estimates are correct, then these are disturbing trends. The study claims, though, that with conservation and proper environmental management, these trends could be reversed. Paleontology has a vital role to play in these efforts. It speaks to the time and pattern and recovery of ecosystems after extinction and also to the minimum level of biodiversity required to maintain a healthy biosphere. It also provides a warning regarding how rapidly the biosphere can be plunged into crisis.

## The Future of Paleontology

- Paleontology has an important role to play in the understanding of the past, present, and future of our planet. We have probably only uncovered a minute fraction of the wealth of information that is held in the Earth's crust. You only have to scan through a paleontology journal to see the rate at which new finds are challenging and changing our views of the history of planet Earth. This, in combination with new techniques for studying fossils, is going to open new perspectives of our planet and its 4.54-billion-year journey through time.

- But is there another direction for the science? Perhaps that step has already been made. The supposed bacteria-like fossils described in 1996 on the Martian meteorite ALH84001 have remained elusive, with no definitive evidence that these structures are the product of a Martian biology. Even so, this did start to take paleontology beyond our home planet; for the first time, paleontology had to seriously consider the possibility of fossil life from another world.

- More recent research regarding the possibility of fossils on Mars was published in 2014 by Nora Noffke of Old Dominion University in Norfolk, Virginia. Noffke is an expert in ancient microbially induced sedimentary structures (MISS), not unlike the stromatolites that are produced by biofilms.

- A particular set of photographs taken by the Curiosity rover caught her attention. They were taken in an area called Yellowknife Bay in a dry lake bed that may have gone through seasonal flooding around 3.7 billion years ago. She noticed particular domes, cracks, and pitted structures

that looked like structures that she has seen before in ancient MISS from western Australia. She admits that it is possible that these features could have been produced by erosional processes of salt, water, or wind—but they do strongly resemble ancient MISS from Earth.

● Determining the biogenicity of ancient MISS on Earth is difficult enough, so making determinations from photographs of Mars is speculative, but still intriguing. The only way to sort this out for sure would be to go there. This is why the first mission that takes humans to Mars will most likely include a geologist—at the very least, a geologist with a lot of paleontology and biology under his or her belt. Whether or not these structures turn out to be fossils, paleontology will likely be one of the key tools in determining the possibility of life elsewhere in the universe.

*Questions to consider:*

1. Has technology made *Homo sapiens* immune to mass extinctions?
2. Are we still evolving?

*Suggested Reading:*

D'Arcy Wood, *Tambora*.

Keller and DeVecchio, *Natural Hazards*.

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## Internet Resources

Paleogeographic and Tectonic History of Western North America. http://cpgeosystems.com/wnampalgeog.html. Maps detailing the evolution of western North America, starting 280 million years ago, by Professor Ron Blakey.

PALEOMAP Project. http://www.scotese.com. Reconstructions of the configurations of the continents, covering around 650 million years of Earth's history.

U.S. Department of the Interior: Bureau of Land Management. "Hobby Collection." http://www.blm.gov/wo/st/en/prog/more/CRM/paleontology/fossil_collecting.html. A useful resource for those wishing to start their own fossil collections.

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