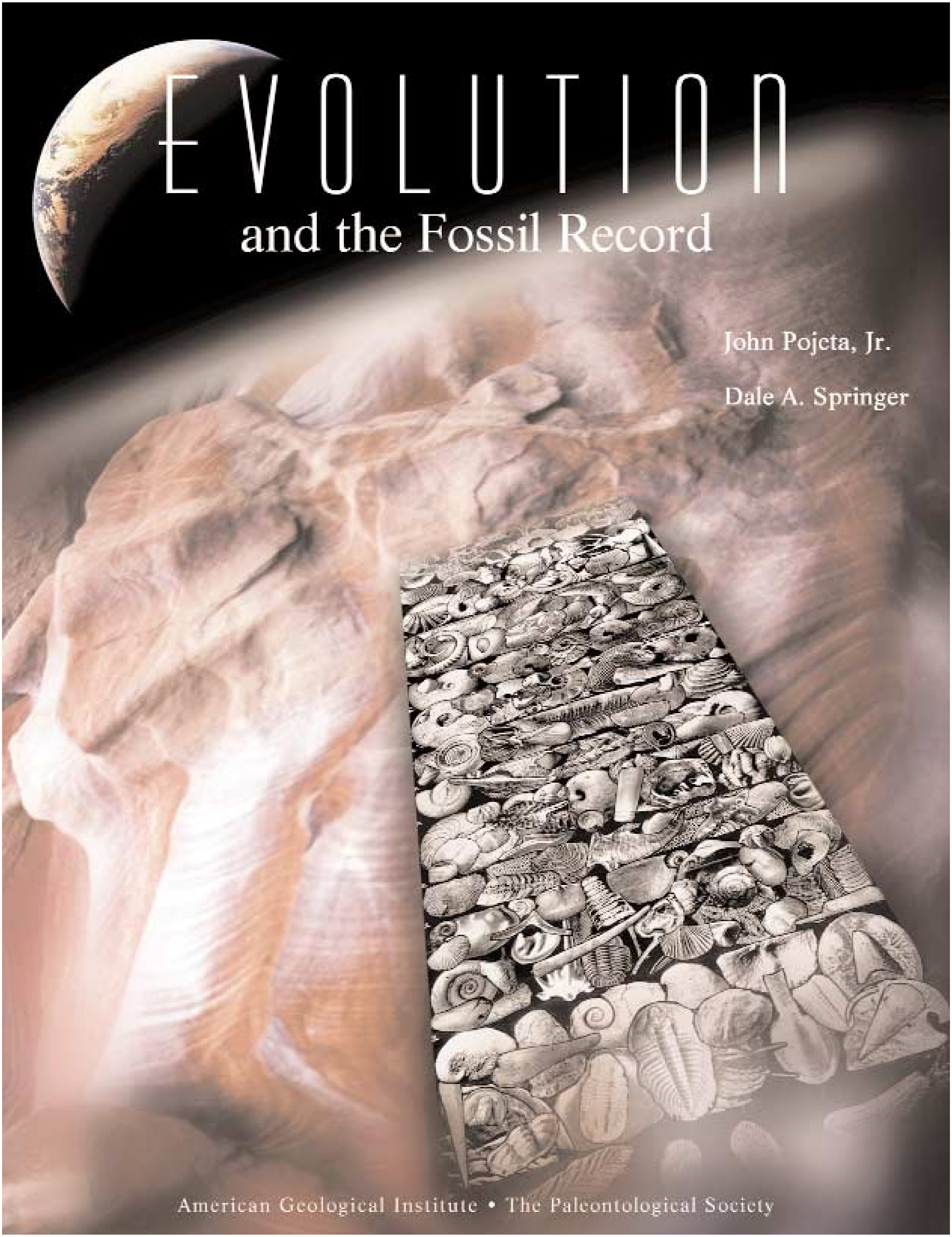
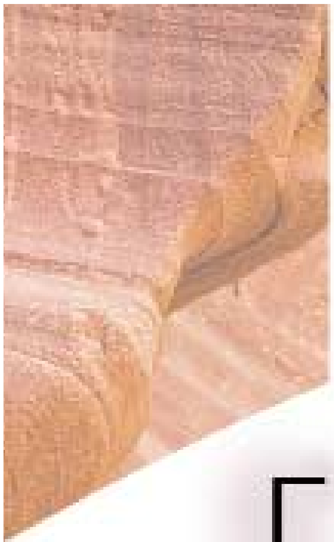


EVOLUTION
and the Fossil Record

John Pojeta, Jr.

Dale A. Springer

American Geological Institute • The Paleontological Society



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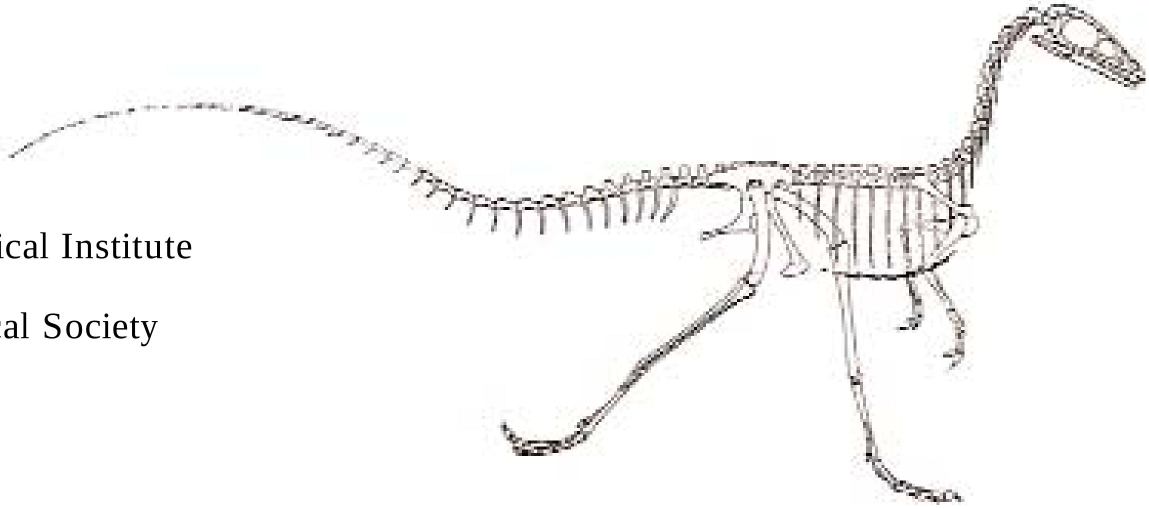

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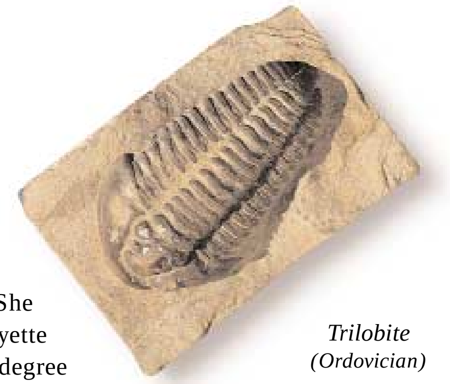

Trilobite
(Ordovician)

John Pojeta, Jr. has been an active paleontologist since 1957. He is a Scientist Emeritus with the U.S. Geological Survey (USGS) and Research Associate with the Department of Paleobiology, Smithsonian Institution. He earned his B.S. degree at Capital University, Bexley, OH, majoring in biology and chemistry and earned his M.S. and Ph.D. degrees from the University of Cincinnati, majoring in geology and paleontology. In 1963, he joined the USGS, Branch of Paleontology and Stratigraphy, where he spent his career. His research has centered on early Paleozoic mollusks, and has taken him to many American states, Antarctica, Australia, Canada, China, Czech Republic, Senegal, Sweden, United Kingdom, and elsewhere. He has been Secretary and President of The Paleontological Society; President of the Paleontological Research Institution; Chief, Branch of Paleontology and Stratigraphy, USGS; and a member of the National Academy of Sciences Committee on Paleontological Collecting.

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Credits

Front cover — Adapted from "Fossils Through Time," a U.S. Geological Survey poster and photographic collage of life on Earth over the past 600 million years.

Inside Cover and title page — Ammonite fossil (G. James), Modern coral reef (J. Pojeta, Jr.), Ferns (Adobe)

Page ii-iii — Trilobite (M.L. Pojeta, photo: G. James), Fossils (J. Pojeta, Jr.)

Page iv-v — Ammonite, fossil fern (G. James)

Page vi — Geologic Time Scale (De Atley), Adapted from various sources

Page 1— Ammonite (G. James)

Pages 2-3 — *Chesapecten* fossils (adapted From Ward and Blackwelder, 1975**;** Bryce Canyon (M. Miller)

Pages 4-5 — Trilobite, brachiopod (J. Pojeta, photo: G. James), *Tyranosaurus rex* skull (Smithsonian Institution); Jurassic Dinosaur Footprints (modified from Haubold, 1971), Devonian and Ordovician trilobites (adapted from Moore, 1959)

Pages 6-7 — Charles Darwin (1875 portrait), Silurian and Devonian fishes (modified from Fenton and Fenton, 1958), Eocene fish fossil (G. James), Jurassic/Cretaceous fishes (modified from Romer, 1966)

Pages 8-9 — Early Jurassic mammal skeleton (modified from Jenkins and Parrington,1976), Diversification diagram (modified from Novacek, 1994)

Pages 10-11 — Shark's tooth, Fossil seed fern, Petrified wood (G. James)

Pages 12-13 — Hubble image, Earthrise over moon (NASA), Trilobite (J. Pojeta, photo: G. James)

Pages 14-15 — Ammonite (G. James), Block diagram (Springer/De Atley), Stratigraphic ranges table (modified from Edwards and Pojeta, 1994)

Pages 16-17 — Half-life diagram (modified from Bushee and others, 2000), Ordovician limestone and shale (J. Pojeta)

Page 19 — Forelimb comparison (modified from Daeschler and Shubin, 1998)

Pages 20-21 — Comparison of bird and dinosaur skeletons and limbs (modified from Ostrom, 1975 and 1994; Diagram comparing skulls of reptiles to mammals (modified from Savage and Long, 1986)

Pages 22-23 — Reconstruction of the "walking whale that swims" (modified from Thewissen and others, 1996), Sequoia National Park, California (Digital Vision)

Pages 24-25 — Brachiopod (G. James), Dragonfly and Amphibian Fossils (Hemera)

Page 26 — Nautilus (G. James)

Back Cover — Grand Canyon, Arizona (Digital Vision)

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Contents

Foreword

Evolution is one of the fundamental underlying concepts of modern science. This powerful theory explains such phenomena as the history of life preserved in the fossil record; the genetic, molecular, and physical similarities and differences among organisms; and the geographic distribution of organisms today and in the past. Indeed, evolution forms the foundation of modern biology and paleontology and is well documented by evidence from a variety of scientific disciplines.

Evolution is also one of the most misunderstood and controversial concepts in the eyes of the general public. This situation is unfortunate, because the controversy surrounding evolution is unnecessary. Resistance to evolution stems in part from misunderstanding science and how it is distinct from religion. Science and religion provide different ways of knowing the Earth and universe. Science proceeds by testing hypotheses and thus is restricted to natural, testable explanations. By definition, science is unable to confirm or deny the existence or work of a Creator; such questions are beyond the realm of science. As a scientific concept, evolution therefore can make no reference to a Creator. Many people of faith, including scientists, find no conflict between evolution and their religion; in fact, many religious denominations have issued statements supporting evolution. Science and religion need not conflict.

Numerous lines of evidence show that life has changed through time. Evolution is the best scientific explanation for this change. This booklet describes a small portion of the evidence for this change, especially as documented by the fossil record, and outlines the processes involved in evolution. Many fascinating questions remain concerning the history of life and the process through which it has developed. As we continue to learn about life on Earth, the theory of evolution will itself evolve. That is the strength, adventure, and excitement of doing science!

Patricia H. Kelley
Paleontological Society President, 2001-2002

Marcus E. Milling
AGI Executive Director

Geologic Time Scale

Eon	Era	Period	Subdivision	Events	Boundaries . Million Years Ago
Phanerozoic	Cenozoic	Quaternary	Holocene	Modern humans	0.01
			Pleistocene		2
		Tertiary — Neogene	Pliocene	Mammals diversify; early hominids	5
			Miocene		23
		Tertiary — Paleogene	Oligocene		34
			Eocene		55
			Paleocene		65
	Mesozoic	Cretaceous		Flowering plants common; major extinction including dinosaurs & ammonoids	144
		Jurassic		Early birds & mammals; abundant dinosaurs	206
		Triassic		Abundant coniferous trees, first dinosaurs; first mammals	250
	Paleozoic	Permian		Mass extinction of many marine animals including trilobites	290
		Carboniferous	Pennsylvanian	Fern forests; insects; first reptiles; crinoids; sharks; large primitive trees	314
			Mississippian		360
		Devonian		Early tetrapods, ammonoids, & trees	409
		Silurian		Early land plants & animals	439
		Ordovician		Early Fish	500
		Cambrian		Abundant marine invertebrates; trilobites dominant	540
"Precambrian"	Proterozoic			Single-celled and, later, multi-celled, soft-bodied organisms; first invertebrates	2,500
	Archean			Oldest fossils; bacteria & other single-celled organisms	
				Oldest known fossils	3,800

Although these dates have an accuracy range of about +/– 1%, boundary dates continue to change as geoscientists examine more rocks and refine dating methods.

*T**yrannosaurus*** no longer stalks its prey across North America. There are no pterosaurs sailing majestically overhead. Trilobites no longer crawl on the sea floors of Earth. Today, other predators roam in search of a meal. Birds soar the skies, and crabs scuttle across the ocean bed. Life on Earth has changed through time. It has evolved. Change through time is a widely accepted meaning of the word evolution. We speak of the evolution of the English language, the evolution of the automobile, or the evolution of politics in the United States. In natural history, biological or organic evolution means change in populations of living organisms on planet Earth through time.

Charles Darwin defined biological evolution as “descent with modification,” that is, change in organisms in succeeding generations. Another way of saying this is, “species of organisms originate as modified descendants of other species” *(Hurry, 1993)*. Biological evolution is the derivation of new species from previously existing ones over time.

Evolution is the central unifying concept of natural history; it is the foundation of all of modern paleontology and biology. This booklet presents a non-technical introduction to the subject of evolution. Here you will find straightforward definitions of important terms as well as discussions of complex ideas.

This brief introduction to the rich and fascinating history of the theory of evolution cannot present in detail the vast body of evidence that has led to the current understanding of evolutionary processes. Our aim is to provide a sense of the history, strength, and power of this important scientific theory. We hope that this booklet will help you sense the wonder and excitement that paleontologists and other students of evolutionary science feel when they contemplate the long and intricate history of life on Earth.

Chesapecten Scallops

Changes in the fossil scallop *Chesapecten* through about 13 million years, shown particularly by the variation in the 'ear' on the upper right of each shell *(see arrows)* and in the ribs on the shell. *Modified from Ward and Blackwelder (1975).*

The Fossil Record

Fossils provide the dimension of time to the study of life

For at least 300 years, scientists have been gathering the evidence for evolutionary change. Much of this vast database is observational, and the evidence came to light with the study of fossils *(paleontology)* and the rock record *(geology)*. This essay focuses on the evidence about evolution from the fossil record.

Documentation of ancestor-descendant relationships among organisms also comes from the fields of biogeography, taxonomy, anatomy, embryology and, most recently, genetics — particularly DNA analysis. Information from these fields can be found in the materials listed in the “Suggested Readings.”

The fossil record remains first and foremost among the databases that document changes in past life on Earth. Fossils provide the dimension of time to the study of life. Some of the most basic observations about fossils and the rock record were made long before Darwin formulated his theory of “descent with modification.” The fossil record clearly shows changes in life through almost any sequence of sedimentary rock layers. Successive rock layers contain different groups or assemblages of fossil species.

Sedimentary rocks are, by far, the most common rocks at Earth’s surface. They are formed mostly from particles of older rocks that have been broken apart by water, ice, and wind. The particles of gravel, sand, and mud, which are collectively called sediment, settle in layers at the bottoms of rivers, lakes, and oceans. Shells and other limy materials may accumulate in the oceans. As the sediments accumulate they bury shells, bones, leaves, pollen, and other bits and pieces of living things. With the passing of time, the layers of sediments are compacted by the weight of overlying sediments and cemented together to become the sedimentary rocks called limestone, shale, sandstone, and conglomerate. The buried plant and animal remains become fossils within the sedimentary layers.

Trilobite
(Cambrian)

Change Through Time

The geological time-period terms Cambrian, Ordovician, ...,Jurassic,..., Cretaceous, and on through the Quaternary, define successive changes in species of animals and plants through time on Earth. Thus, Ordovician trilobites differ from Devonian trilobites, Silurian and Devonian fish differ from Jurassic and Cretaceous fish, Mesozoic mammals differ from Cenozoic mammals, and so forth. In addition to changes occurring in many different species found in different geological time intervals, whole groups of organisms that were once abundant and diverse, such as trilobites, can become extinct.

Brachiopod
(Devonian)

The boundaries between the great blocks of geologic time called Eras are defined by major changes in the types of fossils found in the rocks deposited in those Eras: Paleozoic means “ancient animals,” Mesozoic means “middle animals,” and Cenozoic means “recent animals.” Trilobites and shelled animals called brachiopods are common and typical Paleozoic fossils. Dinosaurs, certain large marine reptiles, such as ichthyosaurs and mosasaurs, and the flying reptiles called pterosaurs are found only in Mesozoic rocks. Fossils of mammals, clams, snails, and bony fishes are typical of Cenozoic fossil assemblages. Some species can be found on both sides of a time boundary; however, the overall assemblage of organisms found in the rocks of a given age is recognizably different from the assemblages found in the rocks above and below.

Allosaurus
(Jurassic)

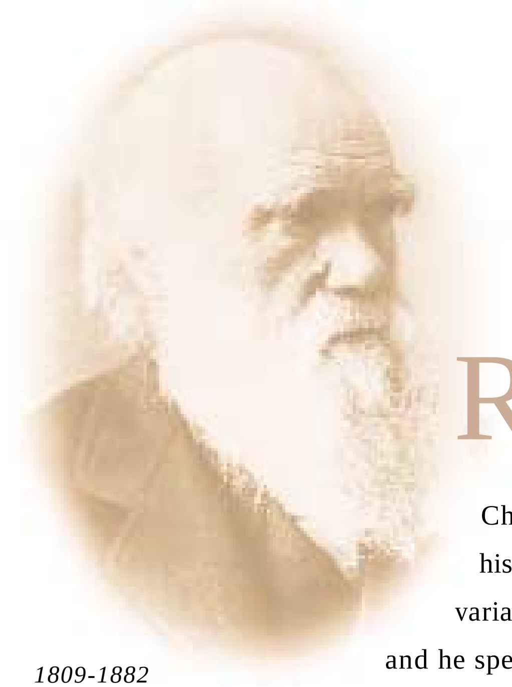
Devonian Trilobites

409-360 Million Years Ago

Ordovician Trilobites

500-439 Million Years Ago

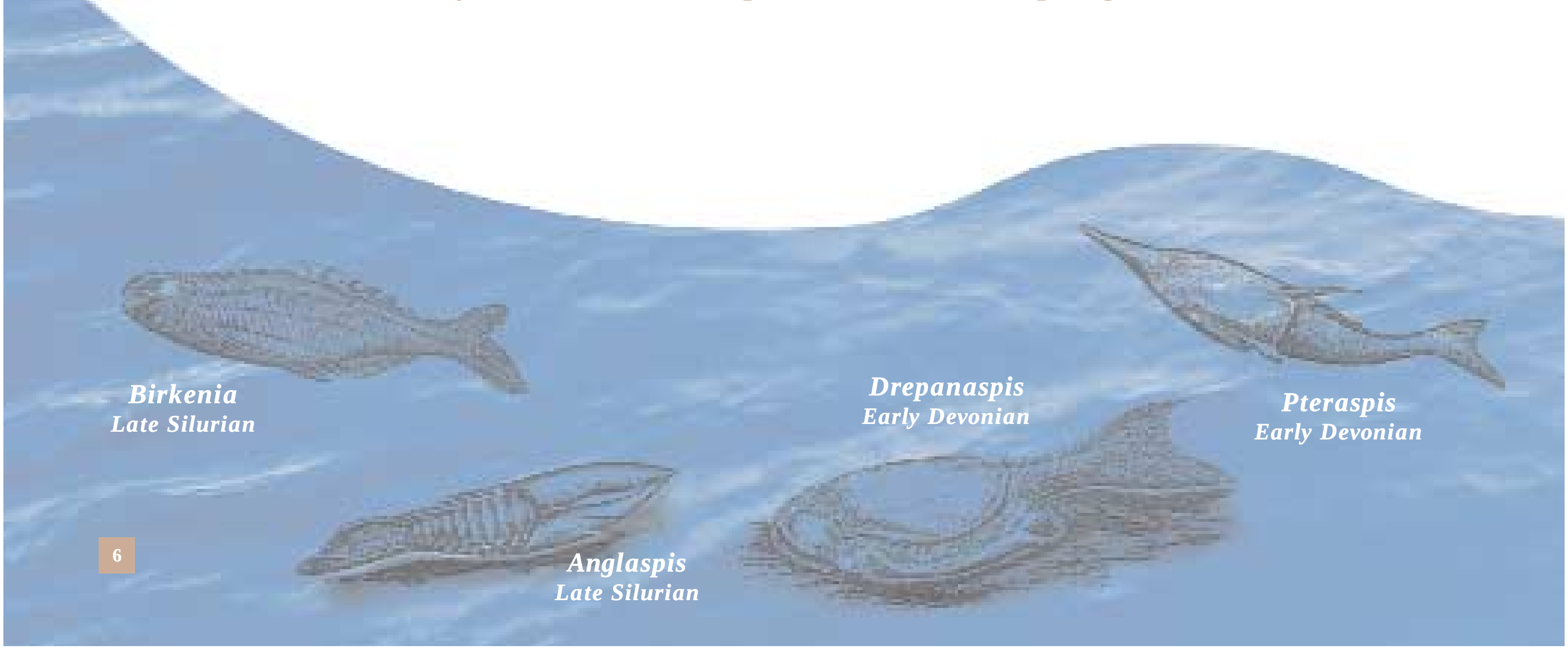
Four species of Devonian trilobites (upper row) compared with four species of Ordovician trilobites (lower row). Size varies from 1 inch (25 mm) to 4 inches (100 mm). *Modified from Moore (1959).*



1809-1882

Darwin's Revolutionary Theory

Charles Darwin used information from several disciplines in developing his theory of evolution. He was particularly impressed by the amount of variation that occurs within living species, especially in domestic animals, and he spent a great deal of time studying breeding programs. Even in Darwin's day, the human effort in breeding variants of domestic animals had resulted in many breeds of dogs, cats, horses, sheep, and cattle. As an example, consider the tremendous variation in domestic dogs. The Chihuahua and the Saint Bernard are about as different in size, shape, hair length, and other features as one could imagine; yet both breeds are domestic dogs with the scientific name *Canis familiaris*. The differences between them were produced by human-engineered selective breeding programs. Artificial selection is the term for what we do when we choose plants and animals with desirable features and breed them to produce or enhance these features in their offspring. As different as they look, Chihuahuas and Saint Bernards ... and Poodles, Pomeranians, Pekinese...all domestic dogs share the same gene pool. This shared gene pool means that all dogs have the ability to interbreed, and this is why all domestic dogs are placed in one species. The common gene pool of dogs also allows for the great variation we see in "man's best friend." A standard definition of species in animals is the ability to interbreed and produce fertile offspring.



Charles Darwin was born in Shrewsbury, England. He began studying medicine at Edinburgh University at age 16, but his interests changed. Ultimately he went to Cambridge University and prepared to become a clergyman. After receiving his degree, Darwin accepted an invitation to serve as an unpaid naturalist on the H.M.S. Beagle, which departed on a five-year scientific expedition to the Pacific coast of South America on December 31, 1831.

The research resulting from this voyage formed the basis of Darwin's book, *The Origin of Species by Means of Natural Selection* (1859), in which he outlined his theory of evolution, challenging the contemporary beliefs about the creation of life on earth.

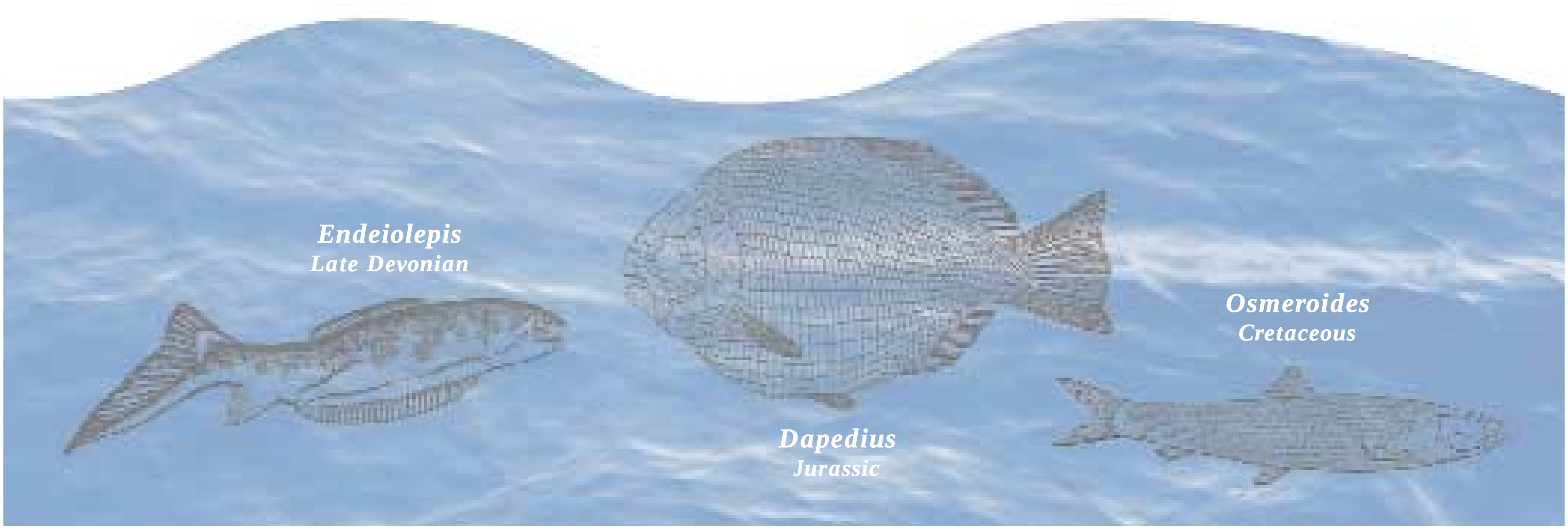
Darwin gathered data and honed his theory for 20 years before publishing his well-known book in 1859, *The Origin of Species by Means of Natural Selection, or The Preservation of Favoured Races in the Struggle for Life*. Darwin and his fellow naturalist Alfred Wallace independently came to the conclusion that geologically older species of life gave rise to geologically younger and different species through the process of natural selection.

Darwin's theory of evolution can be summarized in four statements.

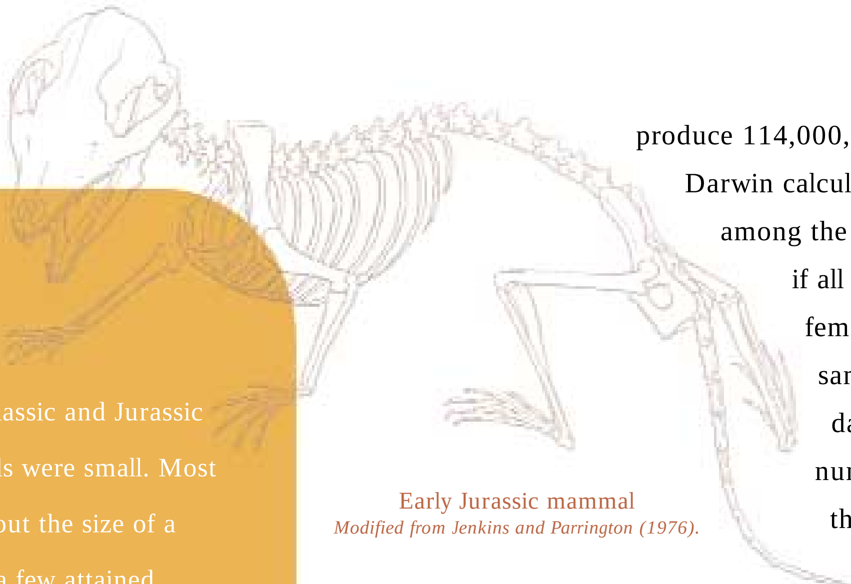
1. Variation exists among individuals within species. Anyone who looks at their friends and relatives, or their pets, can see variation. Breeders of animals and plants use these diverse characteristics to establish new varieties of dogs, cats, pigeons, wheat, cotton, corn, and other domesticated organisms. Scientists who name and classify plants and animals are acutely aware of variation in natural populations. For example, the level of resistance to insecticides varies among individuals within species of insects. This variation enables some individuals to survive application of insecticides and produce offspring that inherit this resistance to these insecticides.

Fish Fossil (Eocene)

2. Organisms produce more offspring than the environment can support. All living things produce more individuals than can survive to maturity. Think of the thousands of acorns that one mature oak tree produces every year. A female salmon produces about 28,000,000 eggs when spawning. One oyster can



Fish diagram was modified from Fenton and Fenton (1958) and Romer (1966).

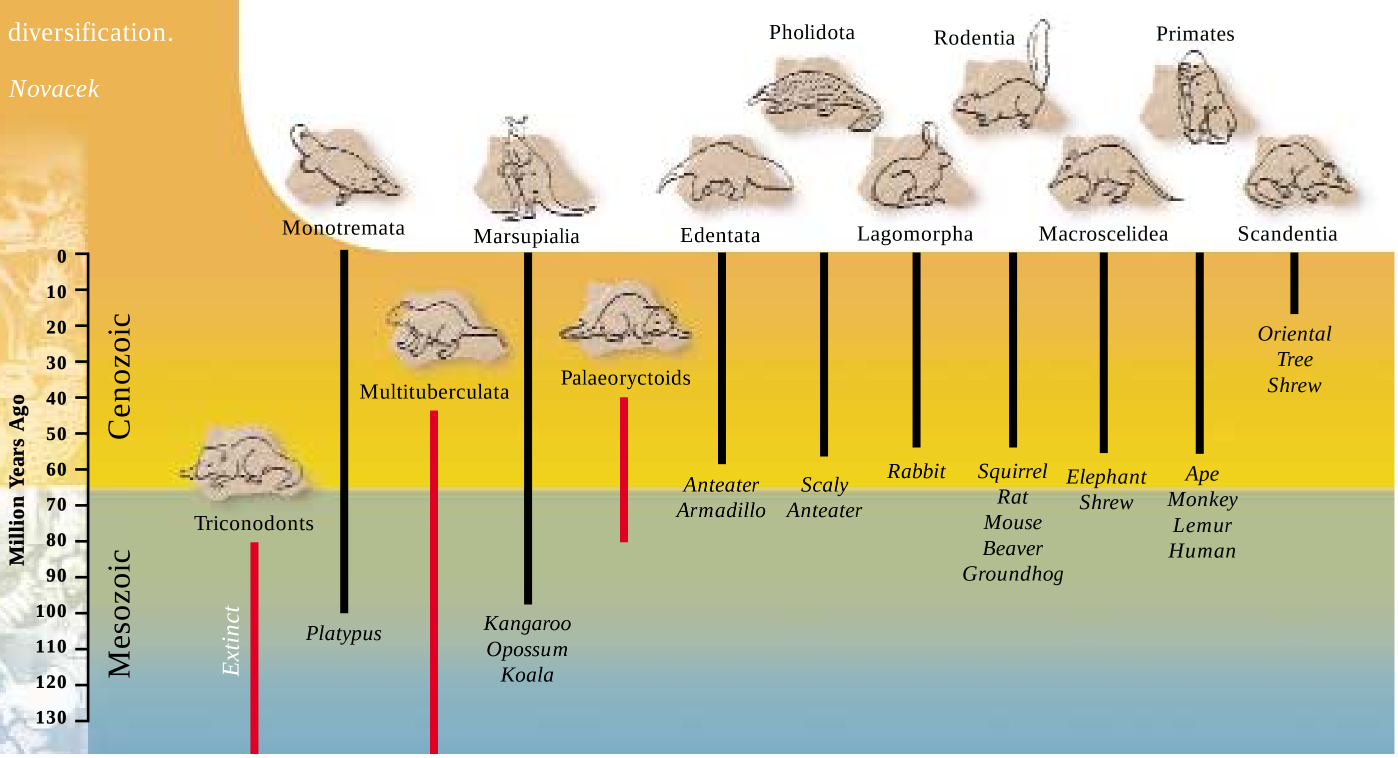


Early Jurassic mammal
Modified from Jenkins and Parrington (1976).

produce 114,000,000 eggs in a single spawning. Darwin calculated that in elephants, which are among the slowest breeding land mammals, if all of the potential young of a single female survived and reproduced at the same rate, after 750 years the descendants of this single mother could number 19,000,000! Clearly, if all of these seeds, eggs, and young survived to become adults who also reproduced, the world would soon be overrun with oak trees, salmon, oysters, and elephants.

3. Competition exists among individuals. Regardless of the rate of reproduction in a species, all of the young do not survive to become reproducing adults. This fact indicates that large numbers of offspring somehow are eliminated from the population. Some certainly die by accident. But most of them succumb to competition with other individuals. The most intense competition may be among individuals of the same species who compete for nearly identical environmental requirements. Competition may be as simple as a race to get a rabbit — the first fox there gets lunch; the others go hungry. Competition may involve obtaining a choice nesting site, or being able to find the last available hiding hole when a bigger fish comes looking for dinner. Those individuals who catch the rabbit or find the hiding hole survive to pass on their genes to the next generation.

Late Triassic and Jurassic mammals were small. Most were about the size of a mouse; a few attained domestic cat size. Most were insect eaters or omnivores; a few were probably herbivores. By Cretaceous time, mammals the size of opossums occur in the fossil record; these existed with mouse-sized animals that were the ancestors of living marsupials and placentals. In early Cenozoic time, mammals underwent a tremendous radiation and diversification. *Modified from Novacek (1994).*



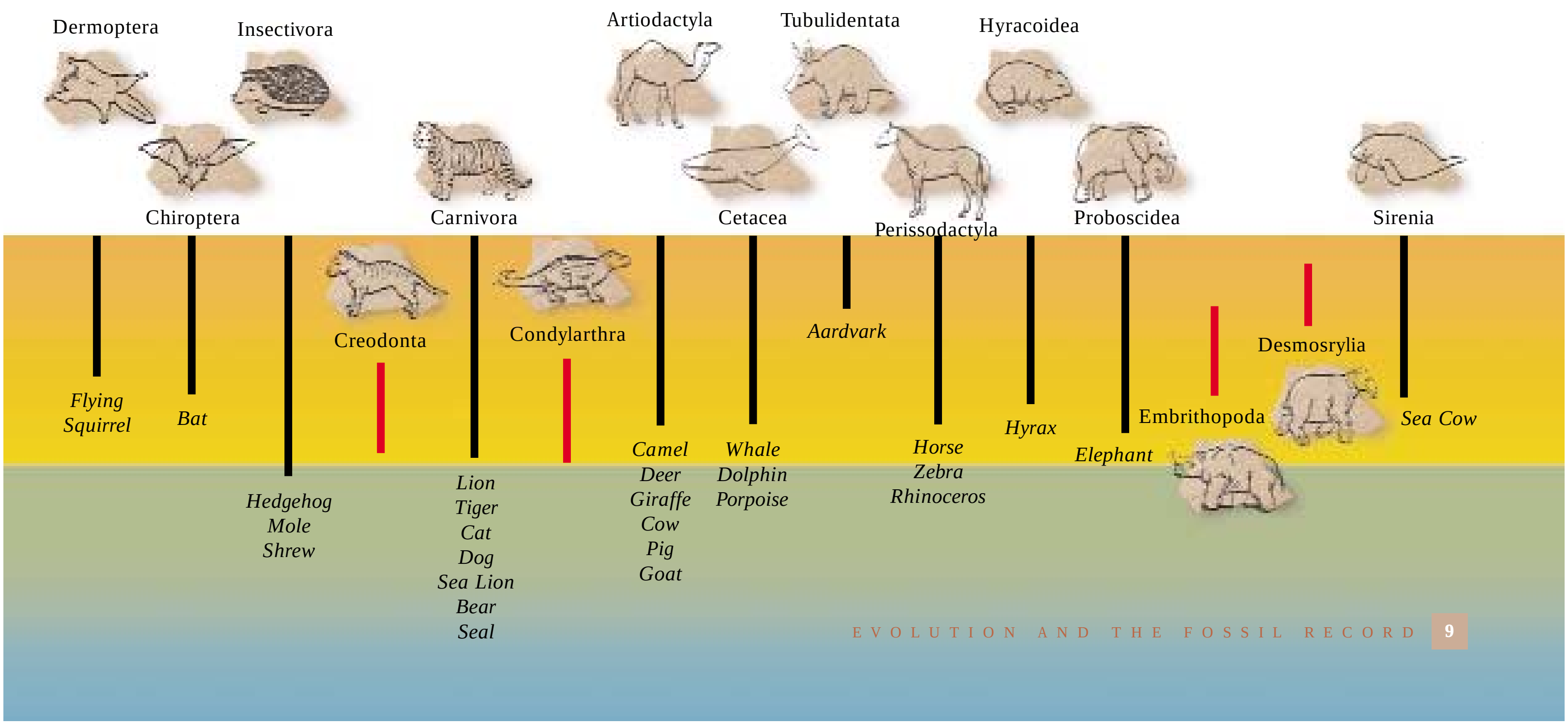
4. The organisms whose variations best fit them to the environment are the ones who are most likely to survive, reproduce, and pass those desirable variations on to the next generation.

Many of the natural variations we observe in species do not seem to be either particularly helpful or particularly harmful to an individual in its struggle for survival. Hair and eye color may be such neutral variations in human beings. Some variations certainly lower the chances of survival, such as hemophilia in mammals, albinism in many wild animals, or an unusually thin shell in clams living where there are numerous hungry snails.

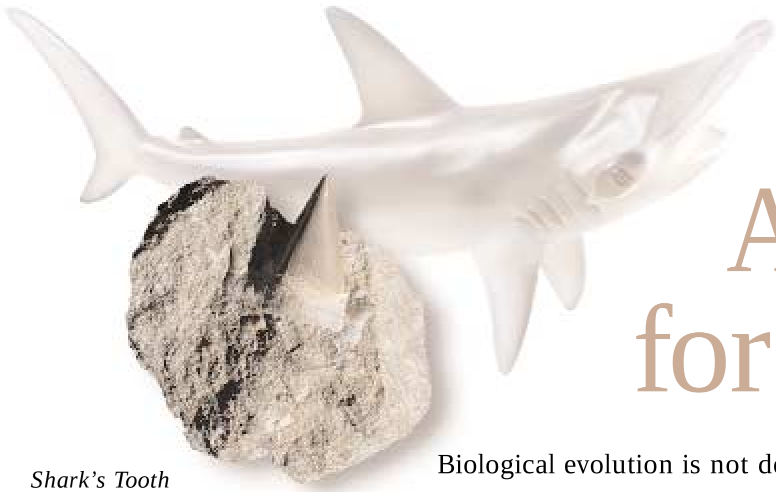
Some variations are helpful. For example, any variation that increases an antelope's speed may help it elude predators. Any variation that increases water retention in a desert plant will favor survival of that plant to reach maturity. Those animals and plants that survive to maturity and are able to reproduce become the parents of the next generation, passing on the genes for the successful variation.

Darwin called the process by which favorable variations are passed from generation to generation natural selection. He made many important observations on the relationship of individual variation to survival. During his stay in the Galapagos Islands, Darwin noted that the populations of tortoises on each island had physical features so distinctive that people could often tell from which island an animal came simply by looking at it.

We commonly hear natural selection referred to as "survival of the fittest." This popular phrase has a very specific biological meaning. "Fittest" means that organisms must not only survive to adulthood, they must actually reproduce. If they do not reproduce, their genes are not passed on to the next generation. Evolution occurs only when advantageous genetic variations are passed along and become represented with increasing frequency in succeeding generations.



A Mechanism for Change



Shark's Tooth
(Paleocene)

Biological evolution is not debated in the scientific community — organisms become new species through modification over time. "No biologist today would think of submitting a paper entitled 'New evidence for evolution;' it simply has not been an issue for a century" *(Futuyma, 1986)*. Precisely how and at what rates descent with modification occurs are areas of intense research. For example, much work is under way testing the significance of natural selection as the main driving force of evolution. Non-Darwinian explanations such as genetic drift have been explored as additional mechanisms that explain some evolutionary changes. Darwin proposed that change occurs slowly over long periods of geologic time. In contrast, a more recent hypothesis called punctuated equilibrium proposes that much change occurs rapidly in small isolated populations over relatively short periods of geologic time.

Modern Fern

Fossil Seed Fern
(Pennsylvanian)

In Darwin's time, the nature of inheritance and the cause of variation were very poorly understood. The scientific understanding of heredity began with the work of Gregor Mendel in the 1860s in Brno, Czech Republic. This understanding accelerated throughout the 20th century and now includes knowledge of chromosomes, genes, and DNA with its double helix.

Evolution could not occur without genetic variation. The ultimate source of variation can now be understood as changes or mutations in the sequence of the building blocks of the genetic material carried on the chromosomes in eggs and sperm. Many of these changes occur spontaneously during the process of creating copies of the genetic code for each egg or sperm. For example, the wrong molecule may become attached to the newly formed strand of DNA, or the strand may break and a portion can be turned around. Certain forms of radiation and chemical toxins can also cause mutations in the DNA.

Because the sequence of building blocks in DNA is the genetic foundation for the development of an individual's features or characteristics, changes in the sequence can lead to a change in the appearance or functioning of an individual with that mutation.

Although some changes may prove to be harmful or fatal, other changes produce variations that convey a survival advantage to the organism. It is these variations, when passed on, that give advantages to the next generation.

The Nature of Species

Individuals change throughout their lifetimes; they grow, receive injuries, color their hair, or pierce their eyebrows. These changes are not evolutionary, because they cannot be inherited by the next generation. The changes are lost when the individual possessing them dies. Individuals do not evolve, only populations evolve. Species evolve over successive generations as their local populations interbreed and change. The biological definition of a species embodies this concept: a species is a group of naturally occurring populations that can interbreed and produce offspring that can interbreed. This point is very important: species always consist of changing and interbreeding populations. There never was a first ‘saber-toothed cat,’ ‘first mastodon,’ or ‘first dinosaur.’ Instead, there was a first population of interbreeding individuals that we call ‘saber-toothed cats,’ or ‘mastodons,’ or ‘dinosaurs.’ At any given time in the past, members of populations of a species were capable of interbreeding. It is only with ‘20/20 hindsight,’ the perspective of time, that we designate the breaks between ancestor and descendant species at a particular point.

Although we can often test the biological definition of species directly when studying populations of living organisms, we cannot do the same with fossils. No matter how long we watch, no two fossils will ever breed. Therefore, we must look for other ways to determine relatedness among fossil organisms. Because genetically similar organisms produce similar physical features, paleontologists can use the bones, shells, and other preserved body parts to help us recognize species in the fossil record.

Fossil Wood
(Pleistocene)

The Nature of Theory

In the middle of the 19th century, Darwin presented the world with a scientific explanation for the data that naturalists had been accumulating for hundreds of years — the theory of evolution. The term theory does not refer to a mere idea or guess. Scientific theories provide interpretations of natural phenomena and processes so that they are understandable in terms of human experience. In science, as opposed to common usage, the term theory is applied only to an interpretation or explanation that is well-substantiated by evidence. Useful theories incorporate a broad spectrum of the information available at the time the theory is proposed. Facts, inferences, natural laws, and appropriate well-tested hypotheses are all part of the construction of a strong theory. Thus, a theory is very different from a belief, guess, speculation, or opinion.

Scientific theories are continually modified as we learn more about the universe and Earth. Let's look at three examples.

➢ In 18th century science, combustion was explained by a complex theory having to do with the supposed presence of an undetectable substance called phlogiston. Then Joseph Priestley discovered oxygen and Antoine Lavoisier showed that fire was not a material substance or element, it was the combining of a substance with oxygen. The phlogiston theory was abandoned.

➢ In the 20th century, the theory of continental drift was a step in the direction of recognizing that continents change their geographic positions through time. Continental drift was succeeded by the much more comprehensive theory of plate tectonics, which provided a mechanism for movement of continents, opening and closing of ocean basins, and formation of mountains.

The term theory does not refer to a mere idea or guess

➢ People once thought that diseases were caused by evil spirits, ill humors, or curses. The germ theory showed that many diseases are caused by microbes. In turn, the germ theory of disease has been modified as we have learned that diseases can be caused by things other than germs, such as dietary deficiencies and genetic factors.

Notice that while a particular theory may be discredited or modified, still-valid observational and experimental data, as well as our knowledge of natural laws, are not abandoned; they are incorporated in a new or revised theory.

We have tested some observations so thoroughly that we accept them as facts. For example, we consider it a fact that the sun appears in the eastern sky each morning or that an object released from the top of a building will fall to Earth. Some explanations are so strongly supported by facts, and describe so well some aspect of the behavior of the natural world, that they are treated as scientific laws. Good examples of these include the laws of thermodynamics, which govern the mechanical action or relations of heat; or the laws of gravitation, which cover the interactions between objects with mass.

We continue every day to learn more about the world and the universe in which we live. Thus, scientific theory is always subject to reaffirmation, reinterpretation, alteration, or abandonment as more information accumulates. This is the self-correcting nature of science; dogma does not survive long in the face of continuous scrutiny of every new idea and bit of data. When scientists do not understand how some aspect of our universe operates, they do not assume an unknowable supernatural cause. They continue to look for answers that are testable within the realm controlled by natural laws as we understand them at any given moment. It may be years or centuries before scientists unravel a particularly difficult problem, but the search for answers never stops. This quest for understanding is the wonder and excitement of science!

Trilobite
(Ordovician)

Paleontology, Geology, and Evolution

Paleontologists generally come much too late to find anything but skeletons. However, they find something denied to the biologist — the time element. The crowning achievement of paleontology has been the demonstration, from the history of life, of the validity of the evolutionary theory *(paraphrased from Kurtén, 1953)*.

Ammonite
(Cretaceous)

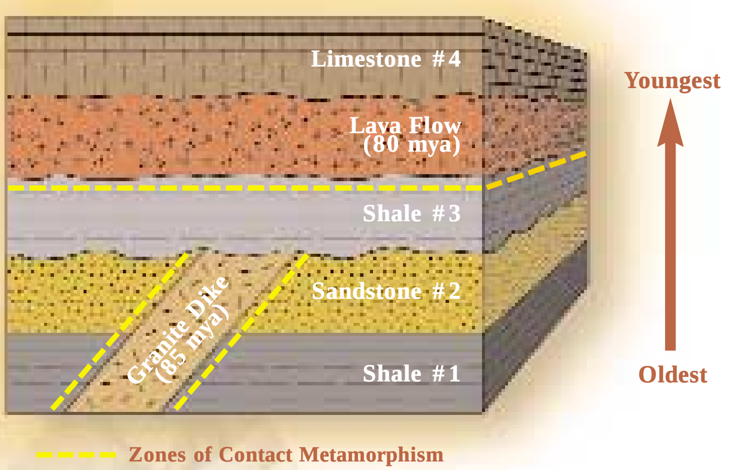
In Darwin's day, the fossil record was poorly known, but this is no longer true. A major focus for geologists is establishing the times of origin of the rock formations in the crust of Earth — the science of geochronology. For paleontologists, it is important to know which rock formations were formed at the same time and thus can be correlated, which rocks were formed at different times, and to put the formations into a time sequence from oldest to youngest in any area under study. Fossils are key to establishing the sequence of the ages of layered sedimentary rocks, and they are the direct proof of the changes that have occurred in living organisms through time on our planet.

In the mid-1600s, about 200 years before Darwin published his theory of evolution, the Danish scientist Nicholas Steno found that it was possible to establish the order in which layered rocks were deposited. He recognized that particles of sand, mud, and gravel settle from a fluid according to their relative weight. Slight changes in particle size, composition, or transporting agent result in the formation of layers in the rocks; these layers are also called beds or strata. Layering, or bedding, is the most obvious feature of sedimentary rocks. The study of layered (sedimentary) rocks is called stratigraphy.

Testing the Superposition Principle

Sedimentary rocks are formed particle by particle and bed by bed, and the layers are stacked one on another. Thus, in any sequence of undisturbed layered rocks, a given bed must be older than any bed on top of it. This Principle of Superposition is fundamental to understanding the age of rocks; at any one place it indicates the relative ages of the rock layers and of the fossils they contain. Because rock types such as sandstone, limestone, and shale are formed repeatedly through time, it is usually not possible to use rock types alone to determine the time in which rock formations were formed, or to correlate them to other areas. To determine the age of most

How old are layers 3 and 4?



The oldest rocks, layers 1,2, and 3, were deposited in succession, and they contain fossils that establish their relative age as Late Cretaceous. The granite dike cutting through the shale (#1) and sandstone (#2) must be younger as it shows contact metamorphism with those rocks. Scientists verify this observation by using isotopic methods to determine the age of the dike in years (85 mya). Since the dike is younger than the shale and sandstone deposits, they must be older than 85 mya.

The lava flow on top of layer 3 has been dated isotopically at 80 mya. Therefore, we can deduce that layer 3 and its fossils must have been deposited between 80 and 85 mya. Contact metamorphism occurred when the hot lava flowed onto layer 3, but there is none between the lava flow and the limestone (#4). Why? The lava (80 mya) had cooled and solidified before the limestone was deposited, and so layer 4 must be younger than 80 mya.

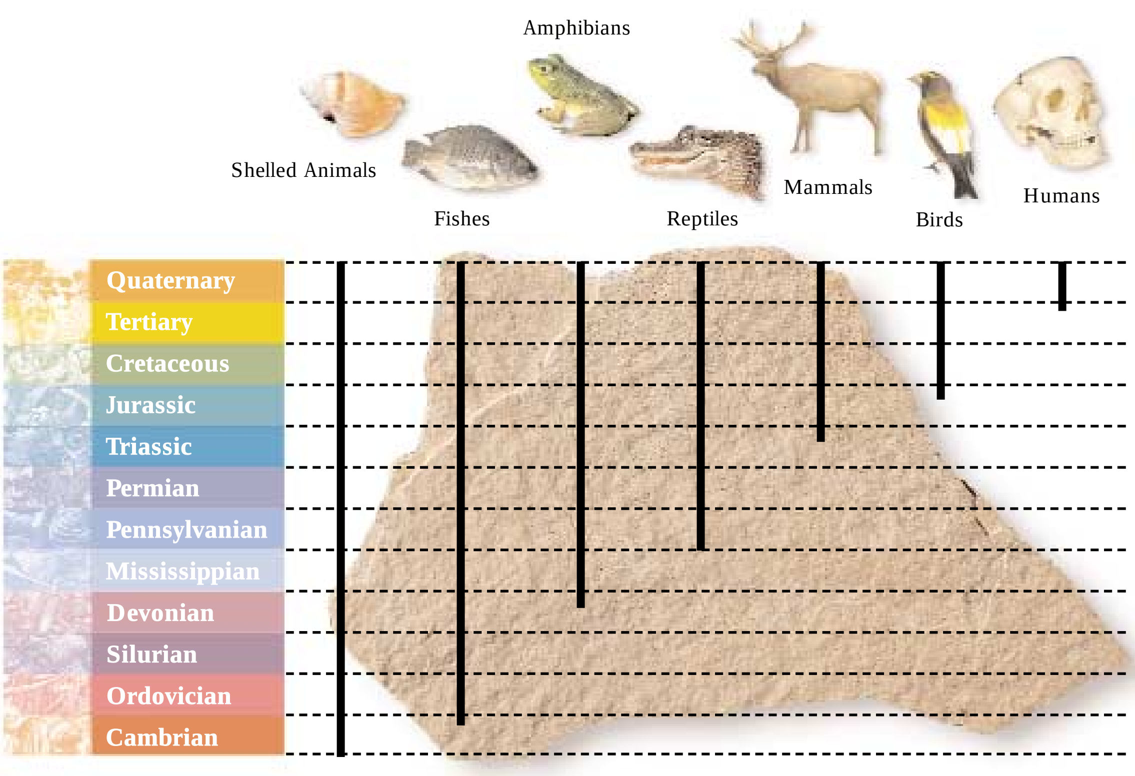
sedimentary rocks, scientists study the fossils they contain.

In the late 18th and early 19th centuries, English geologists and French paleontologists discovered that the age of rocks could be determined and correlated by their contained fossils. Rocks of the same age contain the same, or very similar, fossil species, even when the rock units extend over a large area or the exposures are not continuous. They also noted that there was a distinct, observable succession of fossils from older to younger rocks that did not repeat itself. These geoscientists were the first to use fossils to correlate the time of formation of the rocks in which the fossils occur. Three concepts are important in the study and use of fossils: (1) Fossils are the remains of once living organisms; (2) The vast majority of fossils are the remains of the hardparts of extinct organisms; they belong to species no longer living anywhere on Earth; (3) The kinds of fossils found in rocks of different ages differ because life on Earth has changed through time.

If we begin at the present and examine older and older layers of rock, we will arrive at a level where no human fossils are found. If we continue backward in time, we successively come to layers where no fossils of birds are present, no mammals, no reptiles, no four-footed animals, no fishes, no shells, and no members of the animal kingdom. These concepts are summarized in the general principle called the Law of Fossil Succession. The kinds of animals and plants found as fossils change through time. When we find the same kinds of fossils in rocks in different places, we know the rocks are of the same age.

Principle of Superposition —

In any sequence of undisturbed layered rocks, a given bed must be older than any bed on top of it.



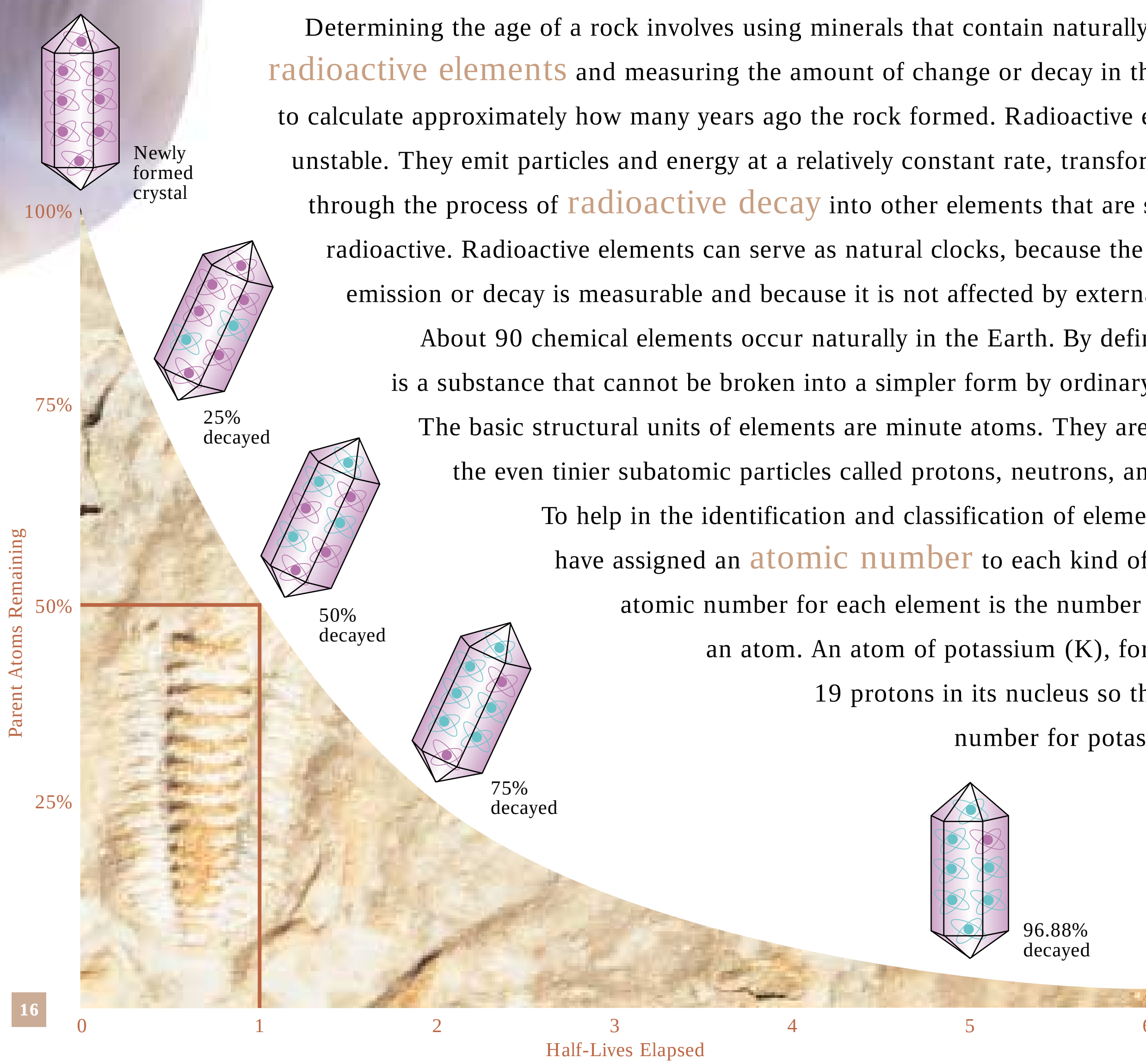
Stratigraphic ranges and origins of some major groups of animals. *Modified from Edwards and Pojeta (1994).*

Dating the Fossil Record

The study of the sequence of occurrence of fossils in rocks, biostratigraphy, reveals the relative time order in which organisms lived. Although this relative time scale indicates that one layer of rock is younger or older than another, it does not pinpoint the age of a fossil or rock in years. The discovery of radioactivity late in the 19th century enabled scientists to develop techniques for accurately determining the ages of fossils, rocks, and events in Earth's history in the distant past. For example, through isotopic dating we've learned that Cambrian fossils are about 540-500 million years old, that the oldest known fossils are found in rocks that are about 3.8 billion years old, and that planet Earth is about 4.6 billion years old.

Determining the age of a rock involves using minerals that contain naturally-occurring radioactive elements and measuring the amount of change or decay in those elements to calculate approximately how many years ago the rock formed. Radioactive elements are unstable. They emit particles and energy at a relatively constant rate, transforming themselves through the process of radioactive decay into other elements that are stable — not radioactive. Radioactive elements can serve as natural clocks, because the rate of emission or decay is measurable and because it is not affected by external factors.

About 90 chemical elements occur naturally in the Earth. By definition an element is a substance that cannot be broken into a simpler form by ordinary chemical means. The basic structural units of elements are minute atoms. They are made up of the even tinier subatomic particles called protons, neutrons, and electrons. To help in the identification and classification of elements, scientists have assigned an atomic number to each kind of atom. The atomic number for each element is the number of protons in an atom. An atom of potassium (K), for example, has 19 protons in its nucleus so the atomic number for potassium is 19.



Modified from Bushee and others (2000).

Although all atoms of a given element contain the same number of protons, they do not contain the same number of neutrons. Each kind of atom has also been assigned a **mass number.** That number, which is equal to the number of protons and neutrons in the nucleus, identifies the various forms or **isotopes** of an element. The isotopes of a given element have similar or very closely related chemical properties but their atomic mass differs.

Potassium (atomic number 19) has several isotopes. Its radioactive isotope potassium-40 has 19 protons and 21 neutrons in the nucleus (19 protons + 21 neutrons = mass number 40). Atoms of its stable isotopes potassium-39 and potassium-41 contain 19 protons plus 20 and 22 neutrons respectively.

Radioactive isotopes are useful in dating geological materials, because they convert or decay at a constant, and therefore measurable, rate. An unstable radioactive isotope, which is the 'parent' of one chemical element, naturally decays to form a stable nonradioactive isotope, or 'daughter,' of another element by emitting particles such as protons from the nucleus. The decay from parent to daughter happens at a constant rate called the **half-life.** The half-life of a radioactive isotope is the length of time it takes for exactly one-half of the parent atoms to decay to daughter atoms. No naturally occurring physical or chemical conditions on Earth can appreciably change the decay rate of radioactive isotopes. Precise laboratory measurements of the number of remaining atoms of the parent and the number of atoms of the daughter result in a ratio that is used to compute the age of a fossil or rock in years.

Age determinations using radioactive isotopes have reached the point where they are subject to very small errors of measurement, now usually less than 1%. For example,

In this outcrop of Ordovician-age limestone and shale near Lexington, KY, the oldest layer is on the bottom and the youngest on the top, illustrating the Principle of Superposition. The rocks were deposited one layer at a time "from the bottom up" starting about 450 mya.

Isotopic Age Dating

Method	Parent/Daughter Isotopes	Half-Lives	Materials Dated	Age Dating Range
Carbon (C)/Nitrogen (N)	C-14/N-14	5,730 yrs.	Shells, limestone, organic materials	100-50,000 yrs.
Potassium (K)/Argon (Ar)	K-40/Ar-40	1.3 billion yrs.	Biotite, whole volcanic rock	100,000-4.5 billion yrs.
Rubidium (Rb)/Strontium (Sr)	Rb-87/Sr-87	47 billion yrs.	Micas	10 million-4.5 billion+ yrs.
Uranium (U)/Lead (Pb)	U-238/Pb-206	4.5 billion yrs.	Zircon	10 million-4.5 billion+ yrs.
Uranium (U)/Lead (Pb)	U-235/Pb-207	710 million yrs.	Zircon	10 million-4.5 billion+ yrs.

minerals from a volcanic ash bed in southern Saskatchewan, Canada, have been dated by three independent isotopic methods (Baadsgaard, et al., 1993). The potassium/argon method gave an age of 72.5 plus or minus 0.2 million years ago (mya), a possible error of 0.27%; the uranium/lead method gave an age of 72.4 plus or minus 0.4 mya, a possible error of 0.55%; and the rubidium/strontium method gave an age of 72.54 plus or minus 0.18 mya, a possible error of 0.25%. The possible errors in these measurements are well under 1%. For comparison, 1% of an hour is 36 seconds. For most scientific investigations an error of less than 1% is insignificant.

We humans created the classification scheme for life on Earth, and we choose where to draw the boundaries

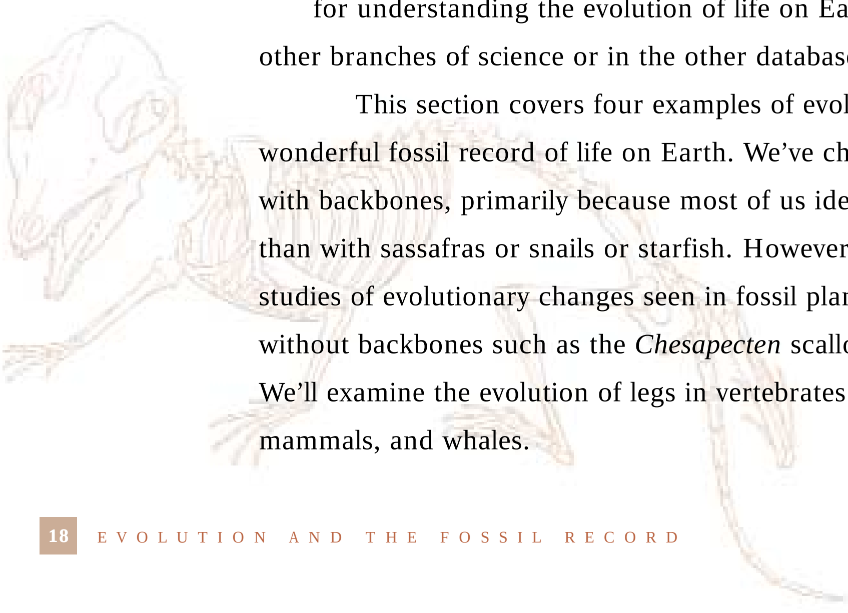
As we have learned more, and as our instrumentation has improved, geoscientists have reevaluated the ages obtained from the rocks. These refinements have resulted in an unmistakable trend of smaller and smaller revisions of the radiometric time scale. This trend will continue as we collect and analyze more samples.

Isotopic dating techniques are used to measure the time when a particular mineral within a rock was formed. To allow assignment of numeric ages to the biologically based components of the geologic time scale, such as Cambrian...Permian...Cretaceous... Quaternary, a mineral that can be dated radiometrically must be found together with rocks that can be assigned relative ages because of the contained fossils. A classic, real-life example of using K-40/Ar-40 to date Upper Cretaceous rocks and fossils is described in Gill and Cobban (1973).

Examples of Evolution

The fossil record contains many well-documented examples of the transition from one species into another, as well as the origin of new physical features. Evidence from the fossil record is unique, because it provides a time perspective for understanding the evolution of life on Earth. This perspective is not available from other branches of science or in the other databases that support the study of evolution.

This section covers four examples of evolution from the incredibly rich and wonderful fossil record of life on Earth. We've chosen examples of vertebrates, animals with backbones, primarily because most of us identify more easily with this group rather than with sassafras or snails or starfish. However, we could have chosen any of many studies of evolutionary changes seen in fossil plants, invertebrates — animals without backbones such as the *Chesapecten* scallops (above), or single-celled organisms. We'll examine the evolution of legs in vertebrates as well as the evolution of birds, mammals, and whales.



Comparison of homologous bones of the forelimbs (pectoral appendages or arms) of a lobe-finned fish from central Pennsylvania (left) with an amphibian-like tetrapod from Greenland (right). Both are right limbs seen from the underside. H = upper arm bone or humerus; U and r = forearm bones or ulna and radius; u and i = wrist bones or ulnare and intermedium. The hand and finger bones are dark. *Modified from Daeschler and Shubin (1998).*

Lobe-finned Fish
(Late Devonian-about 370 mya)

Amphibian-like Tetrapod
(Late Devonian-about 364 mya)

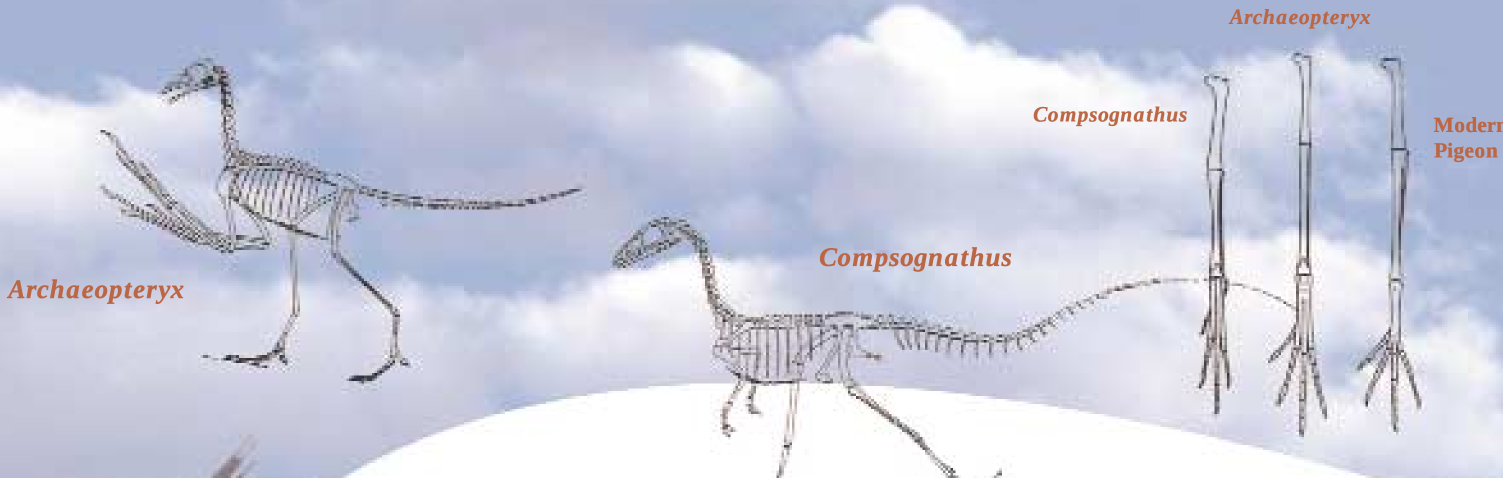
Evolution of vertebrate legs

The possession of legs defines a group of vertebrate animals called tetrapods — as distinct from vertebrate animals whose appendages are fins, the fishes. In most fishes, the thin bony supports of the fins are arranged like the rays of a fan; hence these fishes are called ‘ray-finned’ fish. Trout, perch, and bass are examples of living ray-fins.

Certain fishes are called ‘lobe-finned,’ because of the stout, bony supports in their appendages. Lobe-finned fish first appear in the fossil record in early Late Devonian time, about 377 mya. The bony supports of some lobe-finned fishes are organized much like the bones in the forelimbs and hind limbs of tetrapods: a single upper bone, two lower bones, and many little bones that are the precursors of wrist and ankle bones, hand and foot bones, and bones of the fingers and toes that are first known in Late Devonian amphibian-like animals from about 364 mya. These animals were the first tetrapods. Many similarities also exist in the skull bones and other parts of the skeleton between Devonian lobe-finned fishes and amphibian-like tetrapods. In fact, in certain fossils the resemblances are so close that the definition of which are fish and which are tetrapods is hotly debated.

In 1998, a lobe-finned fish was described from Upper Devonian rocks from about 370 mya in central Pennsylvania (Daeschler and Shubin, 1998). This fish has bones in its forelimb arranged in a pattern nearly identical to that of some Late Devonian amphibian-like tetrapods. The pattern includes a single upper-arm bone (humerus), two forearm bones (radius and ulna), and many little bones connected by joints to the forearm bones in the positions of wrist and finger bones. However, the finger-like bones look like unjointed fin rays, rather than the truly jointed finger bones of tetrapods. Should the animal be called a fish or a tetrapod? It’s hard to say. On the basis of the finger bones, it could be classified as a fish, whereas, on the basis of the large limb bones, the animal could be classified as a tetrapod.

Remember that we humans created the classification scheme for life on Earth, and we choose where to draw the boundaries. When dealing with transitional forms of life this is not an easy task!



Evolution of birds

Most paleontologists regard birds as the direct descendants of certain dinosaurs — as opposed to descendants of some other group of reptiles. Paleontologists and zoologists have long accepted that birds and reptiles are related. The two groups share many common traits including many skeletal features, the laying of shelled eggs, and the possession of scales, although in birds, scales are limited to the legs. Among modern birds, the embryos even have rudimentary fingers on their wings. In one modern bird, the South American hoatzin, *Opisthocomus hoazin*, the wings of the juvenile have large moveable claws on the first and second digits. The young bird uses these claws to grasp branches.

The descent of birds from dinosaurs was first proposed in the late 1860s by Thomas Henry Huxley, who was a famous supporter of Darwin and his ideas. Evidence from fossils for the reptile-bird link came in 1861 with the discovery of the first nearly complete skeleton of *Archaeopteryx lithographica* in Upper Jurassic limestones about 150 million years old near Solenhofen, Germany. The skeleton of *Archaeopteryx* is clearly dinosaurian. It has a long bony tail, three claws on each wing, and a mouth full of teeth. However, this animal had one thing never before seen in a reptile — it had feathers, including feathers on the long bony tail. Huxley based his hypothesis of the relationship of birds to dinosaurs on his detailed study of the skeleton of *Archaeopteryx*.

Comparisons of the skeletons of the bird *Archaeopteryx* and the dinosaur *Compsognathus.* Upper right diagrams compare the hindlimbs of *Compsognathus* with *Archaeopteryx* and a modern pigeon. *Modified from Ostrom (1975 and 1994).*

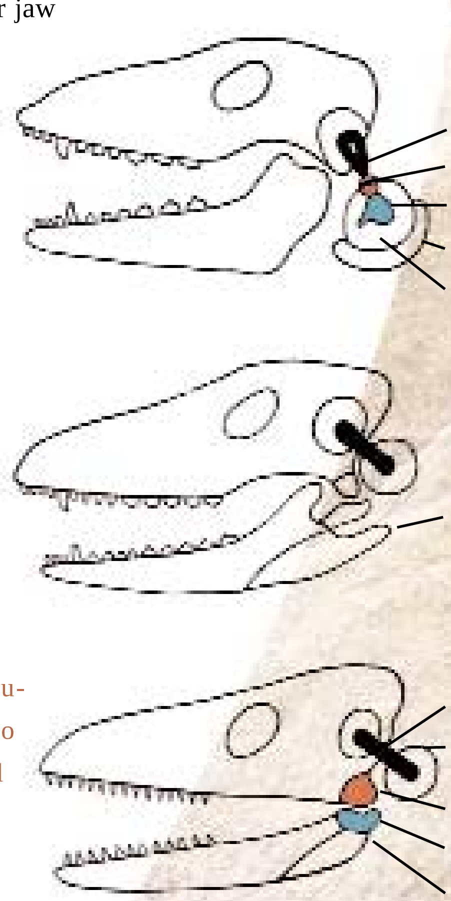
One of the leading scholars of the bird-dinosaur relationship is John Ostrom of Yale University, who has summarized all the details of the skeletal similarities of *Archaeopteryx* with small, bipedal Jurassic dinosaurs such as *Compsognathus*. *Compsognathus* belongs to the group of dinosaurs that includes the well-known *Velociraptor*, of *Jurassic Park* fame, and *Deinonychus*, which Ostrom called the ultimate killing machine. The skeleton of *Archaeopteryx* is so similar to that of *Compsognathus* that some specimens of *Archaeopteryx* were at first incorrectly classified as *Compsognathus*. Ostrom regarded *Archaeopteryx* as being on the direct line of descent of birds from reptiles.

New fossil specimens from Mongolia, China, Spain, Argentina, and Australia have added to our knowledge of the early history of birds, and many paleontologists now reckon that the turkey on our Thanksgiving tables is a descendant of the dinosaurs.

Evolution of mammals

The oldest reptiles having mammal-like features, the synapsids, occur in rocks of Pennsylvanian age formed about 305 mya. However, the first mammals do not appear in the fossil record until Late Triassic time, about 210 mya. Hopson *(1994)* noted, “Of all the great transitions between major structural grades within vertebrates, the transition from basal amniotes [egg-laying tetrapods except amphibians] to basal mammals is represented by the most complete and continuous fossil record.... Structural evolution of particular functional systems has been well investigated, notably the feeding mechanism... and middle ear, and these studies have demonstrated the gradual nature of these major adaptive modifications.”

A widely used definition of mammals is based on the articulation or joining of the lower and upper jaws. In mammals, each half of the lower jaw is a single bone called the dentary; whereas in reptiles, each half of the lower jaw is made up of three bones. The dentary of mammals is joined with the squamosal bone of the skull. This condition evolved between Pennsylvanian and Late Triassic times. Evolution of this jaw articulation can be traced from primitive synapsids (pelycosaurs), to advanced synapsids (therapsids), to cynodonts, to mammals. In mammals, two of the extra lower jaw bones of synapsid reptiles (the quadrate and articular bones) became two of the middle-ear bones, the incus (anvil) and malleus (hammer). Thus, mammals acquired a hearing function as part of the small chain of bones that transmit air vibrations from the ear drum to the inner ear.



Diagrammatic skulls showing the changes in the jaw articulation and the ear region in the evolution from reptile to mammal. In reptiles, the lower jaw is made up of several bones on each side and there is only one ear bone, the stapes, on each side. In mammals, the lower jaw is made up of only one bone on each side and the other jaw bones have taken on new functions in the middle ear. The reptilian articular bone becomes the malleus bone of the middle ear of mammals and the quadrate bone of the reptilian jaw becomes the incus bone of the middle ear of mammals. The angular bone is lost. *Modified from Savage and Long (1986).*

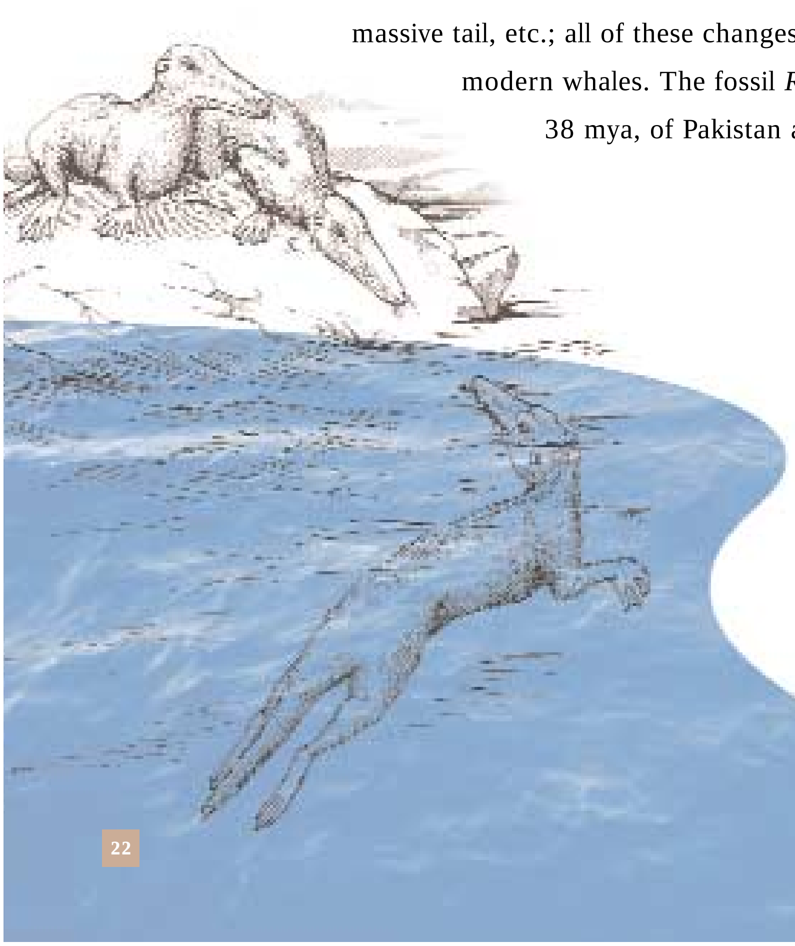
Evolution of whales

During the 1990s our understanding of whale evolution made a quantum jump. In 1997, Gingerich and Uhen noted that whales (cetaceans) "... have a fossil record that provides remarkably complete evidence of one of life's great evolutionary adaptive radiations: transformation of a land mammal ancestor into a diversity of descendant sea creatures."

The trail of whale evolution begins in Paleocene time, about 60 mya, with a group of even-toed, hoofed, trotting, scavenging carnivorous mammals called mesonychians. The first whales (pakicetids) are known from lower Eocene rocks, that formed about 51 mya; the pakicetids are so similar to mesonychians that some were misidentified as belonging to that group. However, the teeth of pakicetids are more like those of whales from middle Eocene rocks, about 45 mya, than they are like the teeth of mesonychians. Pakicetids are found in nonmarine rocks and it is not clear how aquatic they were.

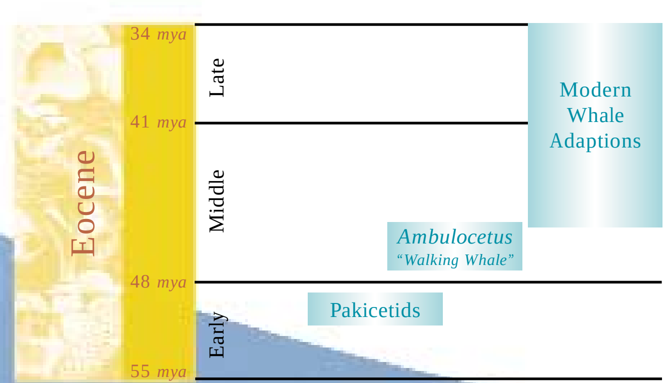
In 1994, *Ambulocetus natans*, whose name means "walking whale that swims," was described from middle Eocene rocks of Pakistan. This species provides fossil evidence of the origin of aquatic locomotion in whales. *Ambulocetus* preserves large forelimbs and hind limbs with large hands and feet, and the toes have hooves as in mesonychians. *Ambulocetus* is regarded as having webbing between the toes and it could walk on land as well as swim; thus, it lived both in and out of the water.

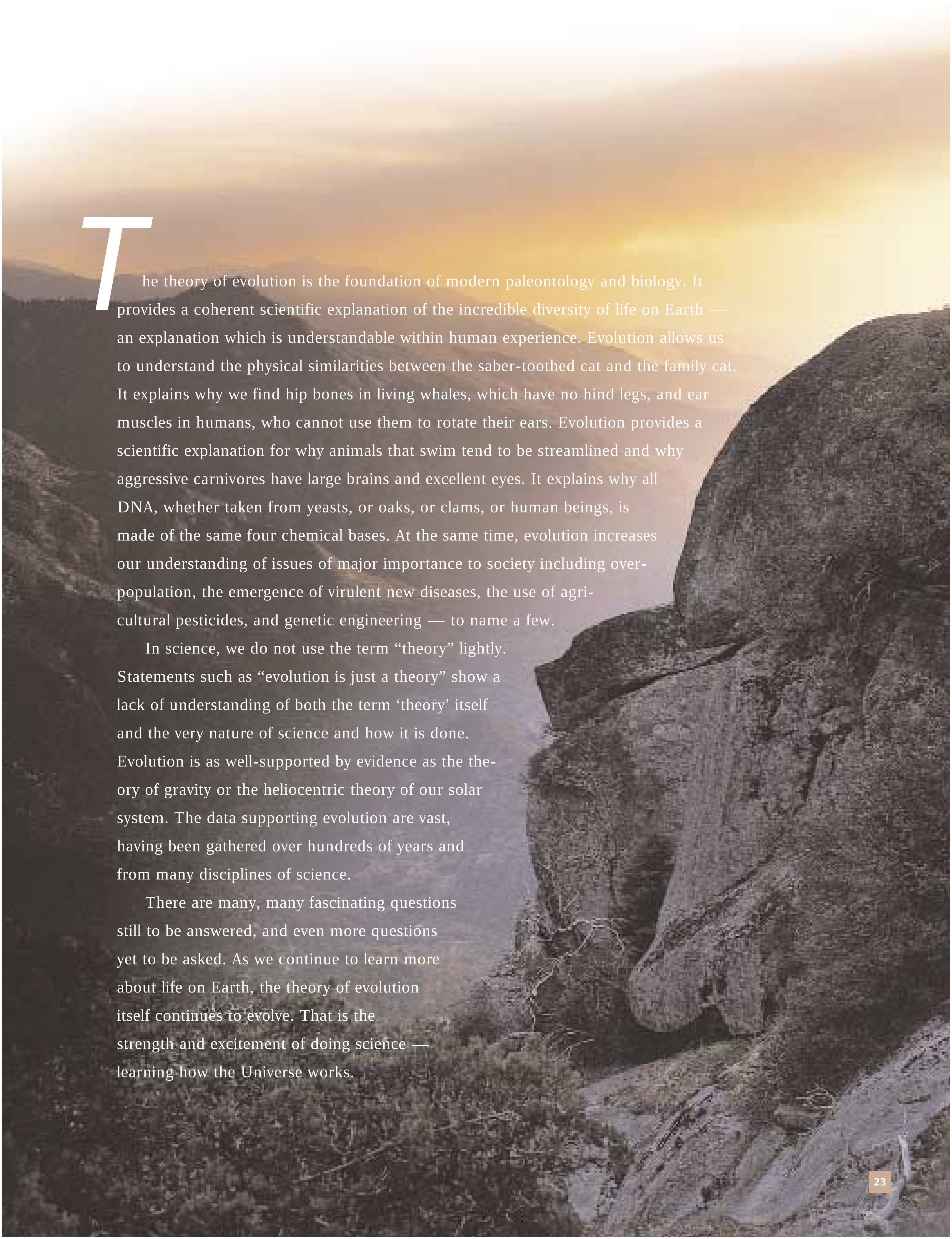
From late Eocene time onward, evolution in whales shows reduction of the hind-limbs, modification of the forelimbs and hands into flippers for steering, development of a massive tail, etc.; all of these changes are modifications for the powerful swimming of modern whales. The fossil *Rodhocetus* from the upper Eocene rocks, about 38 mya, of Pakistan already shows some of these modifications.



Reconstruction of *Ambulocetus natans*, the "walking whale that swims." *Modified from Thewissen and others (1996).*

Succession of Eocene Whale Fossils





The theory of evolution is the foundation of modern paleontology and biology. It provides a coherent scientific explanation of the incredible diversity of life on Earth — an explanation which is understandable within human experience. Evolution allows us to understand the physical similarities between the saber-toothed cat and the family cat. It explains why we find hip bones in living whales, which have no hind legs, and ear muscles in humans, who cannot use them to rotate their ears. Evolution provides a scientific explanation for why animals that swim tend to be streamlined and why aggressive carnivores have large brains and excellent eyes. It explains why all DNA, whether taken from yeasts, or oaks, or clams, or human beings, is made of the same four chemical bases. At the same time, evolution increases our understanding of issues of major importance to society including over-population, the emergence of virulent new diseases, the use of agri-cultural pesticides, and genetic engineering — to name a few.

In science, we do not use the term "theory" lightly. Statements such as "evolution is just a theory" show a lack of understanding of both the term 'theory' itself and the very nature of science and how it is done. Evolution is as well-supported by evidence as the the-ory of gravity or the heliocentric theory of our solar system. The data supporting evolution are vast, having been gathered over hundreds of years and from many disciplines of science.

There are many, many fascinating questions still to be answered, and even more questions yet to be asked. As we continue to learn more about life on Earth, the theory of evolution itself continues to evolve. That is the strength and excitement of doing science — learning how the Universe works.

Glossary

Fossil Dragonfly
(Jurassic)

appendage A body part that extends outward from the torso of an animal, such as arms, legs, wings, fins or the antennae of an insect.

articulated Body parts held together by a joint, which is often moveable.

artificial selection The process whereby humans choose animals or plants with desirable characteristics and breed them to continue or enhance the desirable features in succeeding generations. Compare with *natural selection*.

assemblage A group of organisms found together at the same place and/or time.

biogeography The study of the geographic distribution of organisms.

biostratigraphy The science that deals with the distribution of fossils in the rock record and organizes strata into units on the basis of their contained fossils.

biota All living organisms in an area under study; the flora, fauna, microbes, etc. considered as a whole.

Brachiopod
(Devonian)

bipedal Used to define animals that walk on two legs, such as birds.

brachiopods A group of marine animals that have a shell with two halves and superficially resemble clams. They are more common in Paleozoic rocks than in younger rocks.

contact metamorphism Reconstitution of rocks that takes place at or near their contact with a body of molten igneous rocks, such as a dike, and that is related to its intrusion.

dogma A doctrine that is laid down as true and beyond dispute.

fitness The quality of having characteristics and/or behaviors that make an organism well-suited to surviving in its environment; biological fitness means the production of viable offspring.

fact In science, an observation or explanation that has been repeatedly tested and is accepted as true.

gene pool The sum total of all genetic information in a specified group of organisms; usually applied to a population or a species.

genetic drift Gradual change over time in the genetic composition of a continuing population that seems to be unrelated to the environmental benefits or detriment of the genes involved.

geochronology The science of dating and determining the time sequence of events in the history of Earth.

half-life The time it takes for 50% of the original amount of a radioactive isotope (the parent) to break down (decay) to another element (the daughter element).

heliocentric theory The theory that holds that the sun is the center of our solar system.

hypothesis A tentative scientifically testable explanation provisionally adopted to explain some aspect or behavior of the natural world.

invertebrate Used to characterize animals without backbones.

isotope One or more varieties of an element having the same number of protons in the nucleus, but differing from one another in the number of neutrons in the nucleus.

Late When used with the name of a geological Period (or any named subdivision of a Period), 'Late' denotes time; specifically, the last (youngest) portion of the specified time unit. Compare with *Upper.*

law A repeatedly tested and reaffirmed general statement of how some aspect of the natural universe behaves under a given set of circumstances.

mutation A change in the sequence of genetic material in DNA.

mya Abbreviation for million years ago.

natural selection The process by which favorable variations are naturally passed from generation to generation; involves elimination by the environment of less-fit organisms before they reproduce. Compare with *artificial selection.*

radioactivity The emission of energetic particles and/or radiation from the nucleus of an atom during radioactive decay.

rudimentary In biology, features of an organism which do not develop to a useable stage in one species, but which closely related species may possess in fully functional form.

sedimentary rock Rock formed from particles of preexisting rocks (for example, sandstone and shale) through the life activities of organisms (for example, coal and many limestones, which are often composed of shells and shell fragments), or by direct precipitation from water (for example, table salt).

strata Layers, specifically, sedimentary rock layers. Singular: stratum.

stratigraphy Study of the relative ages of sedimentary (layered) rocks.

superposition The order in which sedimentary rocks are accumulated in beds one above another, the highest bed being the youngest.

taxonomy The science that deals with the identification, naming, and classification of organisms.

tetrapod A vertebrate animal with four jointed limbs; amphibians, reptiles, birds, and mammals are tetrapods.

theory A well-established testable explanation of some aspect of the natural world; the framework within which new hypotheses are formulated and against which new data are evaluated.

Upper When used with the name of a geological Period or any named subdivision of a Period, 'Upper' indicates the rocks that were formed in the last (youngest) portion of the time unit. Compare with *Late.*

vertebrate A term applied to animals that have a backbone.

Fossil Amphibian
(Permian)

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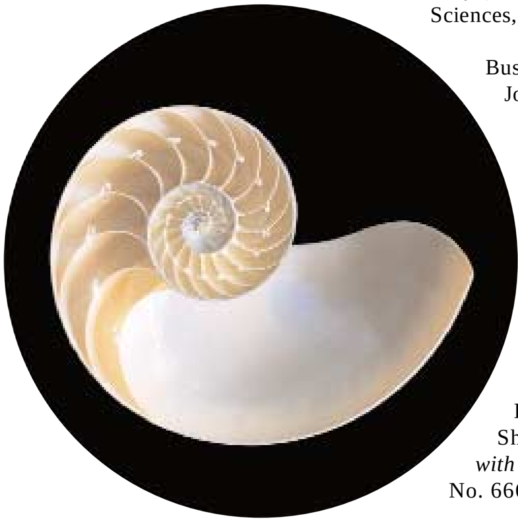

Suggested Readings

Edwards, L.E., and Pojeta, John, Jr. 1994. *Fossils, Rocks, and Time*. U.S. Government Printing Office 1998-675-105, 24p. An illustrated booklet that explains how fossils are used to tell time and that discusses relative and numeric time scales.

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National Academy of Sciences. 1999, 2nd ed. *Science and Creationism: A View from the National Academy of Sciences*. National Academy Press, 33p. Summarizes key aspects of several important lines of evidence supporting evolution and describes and analyzes some of the positions taken by advocates of creation science. The report lays out the case against presenting religious concepts in science classes.

Pojeta, John, Jr., and Edwards, L.E. 1994. *Fossils Through Time*. U.S. Geological Survey Poster, General Interest Publication. A photographic collage of life on the ‘Blue Planet’ over the past 600,000,000 years.

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Scotchmoor, Judy, and McKinney, F.K.,(editors). 1996. *Learning From the Fossil Record*. The Paleontological Society Papers, v. 2, 329p. Resource book developed to accompany a workshop intended to give K-12 teachers information on how scientists use evidence from fossils to reconstruct the past and to provide an intrinsically interesting entry into teaching science and scientific thinking to students.

Scotchmoor, Judy, and Springer, D.A.,(editors). 1999. *Evolution: Investigating the Evidence*. The Paleontological Society, Special Publications, v. 9, 406p. Resource book for K-16 teachers; a multifaceted book of ideas and examples.

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