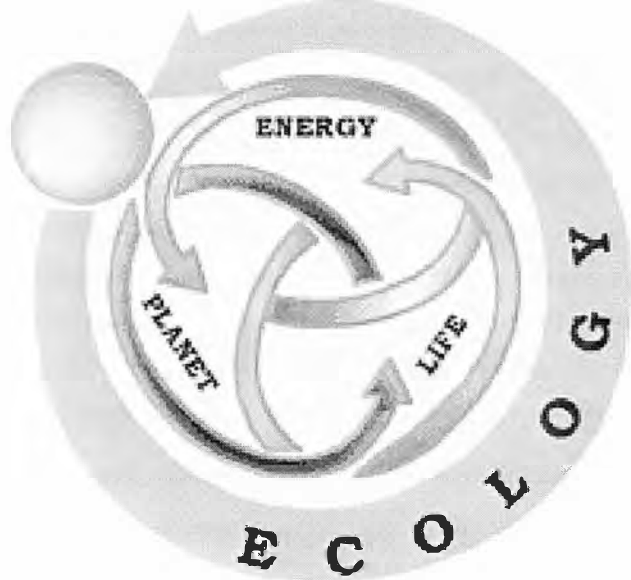
Coevolution of Life Systems and Earth



[M2U1]

Anaerobe Chamber Verification Experiment

Our experiment is supposed to show that life is possible under conditions where there is little or no oxygen. An experiment can be performed to confirm that the conditions in the anaerobe jar is one that is low in oxygen concentration.

Research Question: *How much oxygen is left in the jar when there is not enough oxygen for a candle to burn?*

Hypothesis: ______

Materials:
Anaerobe jar
Heavy duty aluminum foil
Tea Light Candles
Oxygen Probe with Airlink

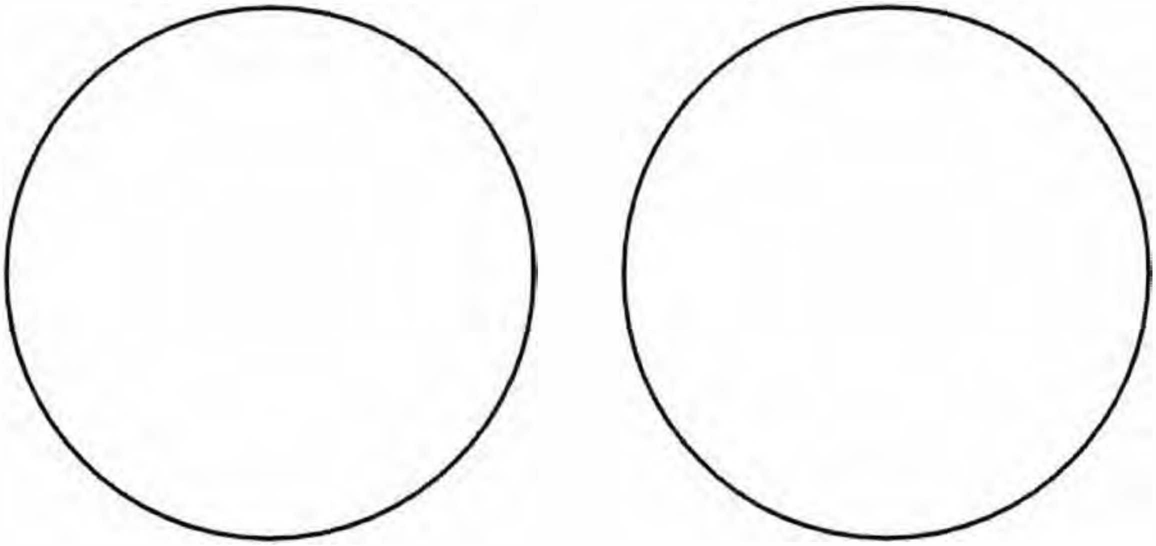
Procedure:
1. Set up a candle in an anaerobe jar.
2. Place the oxygen sensor and AirLink in the jar to measure the oxygen concentration. Use heavy duty aluminum foil to shield the Probe and lid of the jar from the heat of the candle.
3. Turn on the sensor and begin recording the oxygen level.
4. Light the candle and screw on the lid.
5. Continue recording until the candle has gone out and the jar has cooled.
6. Compare the oxygen concentration in normal air with the oxygen concentration in the anaerobe jar.

Data:

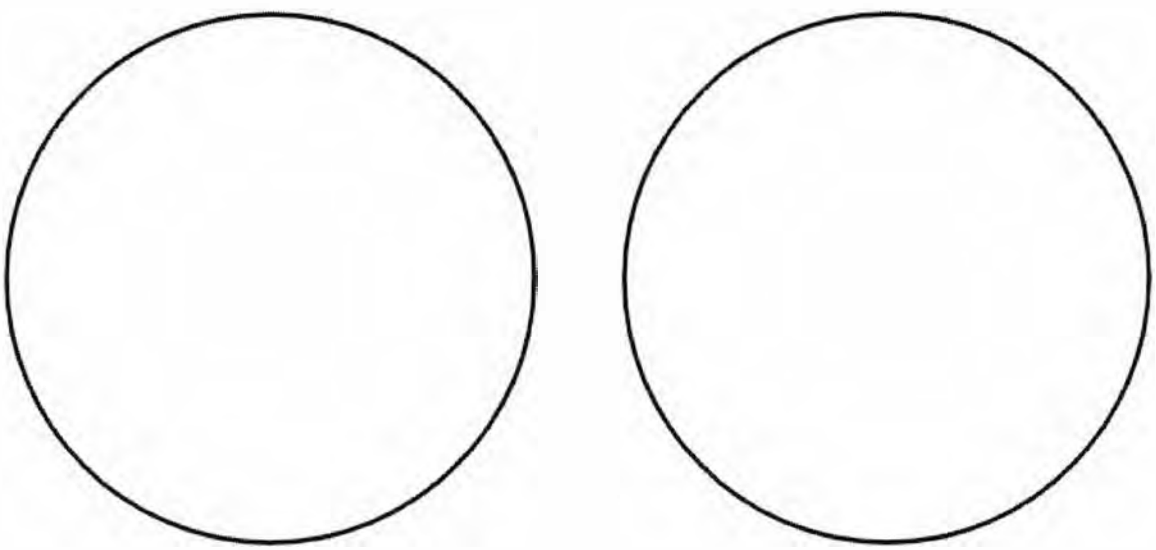
Concentration of oxygen in air - ________
Concentration of oxygen after candle burn - _______

Conclusion:
1. Was your hypothesis supported by the data?

2. What can you say regarding the oxygen concentration in the anaerobe jar?



Print these out and use them for practice in the development of good streak patterns



Investigating photosynthesis using algal balls

For these investigations students may need stop clocks and pens to label their bottles. They may also need sticky tape to fix paper/filters to the bottles.

The hydrogen carbonate indicator will need to be equilibrated to atmospheric CO_2 concentration by bubbling air through the solution until it is bright red (pH 8.4).

For investigation 1: Light and dark

- **Hydrogen carbonate indicator solution (enough for each student / group to fill 2 bijou bottles, plus spare)**
- **Bijou bottles and lids (2 per student / group)**
- **1 bright lamp (e.g. 42W portable CFL or 150W halogen floodlamp with heat sink) or several smaller desk lamps fitted with 100W filament or 100W equivalent energy saving (CFL) bulbs (see notes on lighting)**
- **Black sugar paper cut into strips to wrap around the bijou bottles**

For investigation 2a: Light intensity (distance from lamp)

- **Hydrogen carbonate indicator solution (enough for each student / group to fill 2 bijou bottles, plus spare)**
- **Bijou bottles and lids (2 per student / group)**
- **1 bright lamp (e.g. 42W portable CFL or 150W halogen floodlamp with heat sink) or several smaller desk lamps fitted with 100W filament or 100W equivalent energy saving (CFL) bulbs (see notes on lighting)**
- **Black sugar paper cut into strips to wrap around the bijou bottles**
- **50cm rulers**

For investigations 2b and 3: Light intensity / compensation point (neutral density filters)

- **Hydrogen carbonate indicator solution (enough for each student / group to fill 5 bijou bottles)**
- **Bijou bottles and lids (5 per student / group)**
- **0.15, 0.3 and 0.6 neutral density filters, cut to wrap around bijou bottles (1 of each per student / group)**
- **Colorimeter, cuvettes and pipettes if accurate compensation point investigations are required**

Neutral density (ND) filters block out light of all wavelengths and can be used as an alternative to moving the bottles further from the lamps. As the bottles can be placed at the same distance from the lamp, this removes the varying heat effect over distance when using halogen lamps. The ND filters suggested above have given good results (see supplier information for more details) and can be used to find the compensation point between photosynthesis and respiration.

M2U1L1

Materials:

- Beakers: 250-500 ml
- Test tubes
- Elodea - 4 10 cm sprigs per group
- Sodium Bicarbonate
- Light meter (or light meter ap on phone)
- Tap water
- Varying light source (different locations within the lab)
- Food coloring - Red, Blue, Green

Lab Report:

- Student teams will decide on what factor to test and design their experiment. The required elements are an **Introduction** to explain the factor that they are trying to test and the rationale behind their experimental design.
- The team members will compose a **Hypothesis** stating their expected outcome.
- They will include a comprehensive list of **Materials** they will need to conduct their experiment.
- The team will compose explicit, foolproof **Instructions** on how the experiment will be performed
- The team will state what **Data** they will collect and design a table for data entry
- A means of data **Analysis** will be proposed and an explanation of how the data will either support their hypothesis or prove it to be wrong.
- After the experiment the team will write a **Conclusion** as to whether or not their hypothesis was supported
- A **Discussion** will close the report telling about the difficulties encountered during the lab, explanations of how the data supported their ideas or not, suggested improvements to the lab, and speculation on the next question they want to find the answer to regarding photosynthesis.

v

Photosynthesis - The generation of Oxygen

Students can follow the procedure below or they can use the lab form. Please edit this to suit the conditions and equipment used in your classroom.

Phenomenon - Early Earth atmosphere had little oxygen. Evidence is shown in the types of minerals in rocks that are dated to times before photosynthesis.

Question - What conditions affect oxygen generation in photosynthetic organisms?

Experimental Design:
Students will design and test factors that might affect the rate of photosynthesis. This rate might be measured by the amount of oxygen generated or the rate of bubble formation (see video).

- ***Test the effect of light intensity on the rate of photosynthesis*** - Count the number of bubbles produced by the sprig of Elodea in a given amount of time (e.g. One minute)

Natural Light - Use a photometer or app. on your phone to choose three different locations in the room to represent areas of high light intensity, medium light intensity, and low light intensity. Record the light readings for these areas in the table below. Replace (units) with the units that are used in your light recording device (candela, lux, etc.).

Artificial Light - Set 3 different distances from a uniform light source and measure the light intensity for High Intensity (shortest distance from the light), Medium Intensity (medium distance from the light), and Low Intensity (longest distance from the light). Replace the (units) with the units of the light intensity meter.

Time = _____	Location or Distance from Light Source	Light Intensity (units)	Oxygen Production - Number of Bubbles
High Intensity			
Medium Intensity			
Low Intensity			

- Test the effect of the concentration of sodium bicarbonate on the rate of photosynthesis
- Test the effect of light color on the rate of photosynthesis

Student teams will submit their written proposal to the teacher for approval prior to performing their experiment. Included with their proposal will be their Lab Inquiry Form.

For investigation 4: Light colour/wavelength

- **Hydrogen carbonate indicator solution (enough for each student / group to fill 5 bijou bottles)**
- **Bijou bottles and lids (5 per student / group)**
- **1 bright lamp (e.g. 42W portable CFL or 150W halogen floodlamp with heat sink) between 2-6 students or several smaller desk lamps fitted with 100W filament or 100W equivalent energy saving (CFL) bulbs (see notes on lighting)**
- **green, red, blue and clear acetate films, cut to wrap around bijou bottles (one of each per student / group)**
- **Black sugar paper cut into strips to wrap around the bijou bottles (one per student / group)**

For accurate filters, we recommend Primary Red, Primary Green and Bray Blue. These can be obtained from Lee Filters (see suppliers section).

For investigation 5: Number of algal balls or concentration of algae in each ball

- **Hydrogen carbonate indicator solution (enough for students to fill 5 bijou bottles each)**
- **Bijou bottles and lids (5 per student)**
- **1 bright lamp (e.g. 42W portable CFL or 150W halogen floodlamp with heat sink) between 2-6 students or several smaller desk lamps fitted with 100W filament or 100W equivalent energy saving (CFL) bulbs (see notes on lighting)**

Lab Conclusion Format

1st paragraph- include Background information, purpose, and hypothesis

Example sentence frames:

-The purpose of this lab was to……

- Information from previous research shows……

- If…….., then……..(hypothesis)

2nd Paragraph- include procedures

- summarize the procedures in your own words. DO NOT COPY FROM LAB.

3rd paragraph - include data
observations made during labs
explanation of graphs or charts

Example sentence frames:

- The following chart, data, list, or graph shows…….

- Based on the data above…..

- This data shows that……

4th paragraph- analysis/conclusion

1st- conclusion: Restate the problem. Restate the hypothesis. Explain what steps you took to test your hypothesis (what was your procedure). Describe discrepancies. What did you find out? Explain your data? Why do you think you saw what you did?

Example sentence frames:

-The problem we investigated in this lab was ____________.

-The hypothesis I developed was ______________ .

-To test my hypothesis I ________________ .

-This observation supports/contradicts my hypothesis because _______________ .

2nd- Analysis: Was your hypothesis supported or does it need revision? If it needs revision what would you revise it to say? Are there any errors that you made during the lab that might account for this error in your hypothesis? Analysis questions may be answered in complete sentences in this section.

Example sentence frames:

-Errors in the process include ______________________ .

-An error was made when ____________ .

-Next time the error in this experiment could be eliminated by ______________ .

-Next time we could stop these errors from affecting our data by ________ .

-The results indicate(show) that ___________________ .

-It was apparent that ________ .

-The findings demonstrate/ confirm/ suggest ________________ .

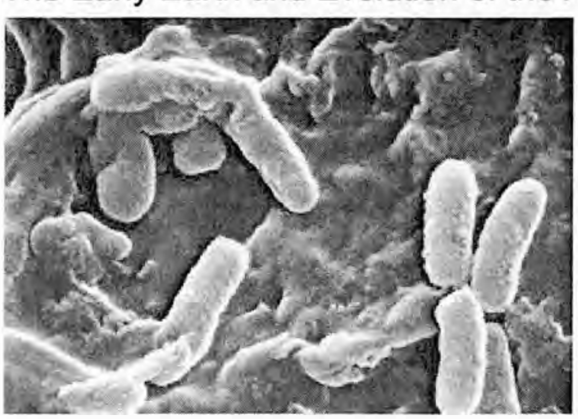
Development of an Oxygen Based Atmosphere

First of all, an Evolution Story….

Once upon a time, long long ago, the place we live in was not as it is now. For so very many years ago in our past, there was no oxygen in the air. There were no plants, no animals, in fact there was no life on our land. But in the waters of the Earth there lived Cyanobacteria. Cyanobacteria *was a very special type of simple life that could use the light of the sun and carbon dioxide to make sugar to feed itself. As it made the sugar, it also made oxygen. But* Cyanobacteria *didn't need or want the oxygen, so it threw the oxygen away. For many millions of years, the oxygen stayed in the water, where it oxidized the iron that was also in the water. As time passed there was more and more oxygen made by the tiny* Cyanobacteria, *until there was so much oxygen, the iron ions began to precipitate (come out in solid form) of the great Oceans and settled to the bottom of the ocean floor. As eons of time passed, rock was created from those iron ions and we can see today that iron in the great mountains of Minnesota. We also exist and can breathe oxygen, thanks to those tireless efforts of our friends the Cyanobacteria in our distant past!*

Now, the science information...

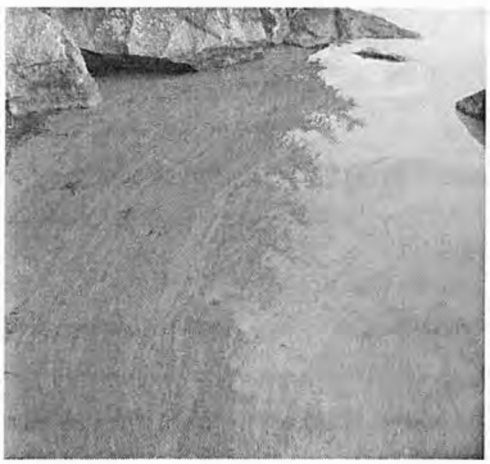
The Early Earth and Evolution of the Atmosphere.



The light color 'pill' shaped single cell organisms are anerobic *(without oxygen)* bacteria.

These bacteria are known as **prokaryotes**. Prokaryotes are unicellular (single celled) organisms that have no cell organelles--they are composed of a strand of genetic material enclosed in a cell membrane and they do not have a nucleus. These creatures are the earliest forms of life on earth. The first living organisms on Earth developed in oceans and much, ***much*** later life moved to land.They were the first organisms to develop **photosynthesis;** the process of using sunlight and carbon dioxide to create energy rich molecules and produce oxygen as a byproduct (left-over).

Oxygen was nearly absent in the atmosphere of early Earth. However as photosynthetic life evolved, it is possible that photosynthesis could have an increase of oxygen first in the ocean then later in the atmosphere.



Cyanobacteria
--bacteria which produce oxygen through photosynthesis - similar to those first forms of photosynthetic forms of life on Earth.

We can hypothesize that cyanobacteria may have contributed to the development of an oxygen rich atmosphere. However, before oxygen could build up in the atmosphere it must have oxidized (added oxygen atoms) ions in seawater.

Evidence that supports the above hypothesis includes the fact that Iron (Fe) is a very abundant element in the earth's crust. There is so much iron that it is released by the chemical disintegration (break down) of minerals contained in rocks. At first, the dissolved iron ions were found in seawater. However at some point the increasing oxygen build-up in the ocean from **prokaryote photosynthesis** resulted in the precipitation of insoluble iron compounds. We have evidence of this from rock formations which are reddish from rust (which is another way to describe oxidized iron) and have clearly visible bands, hence they are called Banded Iron Formations.

The Mesabi range of Minnesota is an example of such a deposit; it has clearly visible bands hence they are called Banded Iron Formations. These mountain ranges for much of US history were the primary source of iron ore for the steel mills/factories of Pittsburgh, Pennsylvania and Gary, Indiana.

Adapted from: http://eesc.columbia.edu/courses/ees/climate/lectures/earth.html

Cyanobacteria: Fossil Record

The cyanobacteria have an extensive fossil record. The oldest known fossils, in fact, are cyanobacteria from Archaean rocks of western Australia, dated 3.5 billion years old. This may be somewhat surprising, since the oldest *rocks* are only a little older: 3.8 billion years old! Cyanobacteria are among the easiest microfossils to recognize. Morphologies in the group have remained much the same for billions of years, and they may leave **chemical fossils** behind as well, in the form of breakdown products from pigments. Small fossilized cyanobacteria have been extracted from Precambrian rock, and studied through the use of SEM and TEM (scanning and transmission electron microscopy).

Ancient Fossil Bacteria : Pictured above are two kinds cyanobacteria from the Bitter Springs chert of central Australia, a site dating to the Late Proterozoic, about 850 million years old. On the left is a colonial chroococcalean form, and on the right is the filamentous *Palaeolyngbya*.

Many Proterozoic oil deposits are attributed to the activity of cyanobacteria, such as *Gloeocapsomorpha*. Small concentrically layered structures called **pisolites** are also the result of fossilized bacteria. Cyanobacteria are otherwise rarely preserved in rocks other than chert, though some possible blue-green bacteria have been recovered from shale.

At right is a layered **stromatolite**, produced by the activity of ancient cyanobacteria. The layers were produced as **calcium carbonate** precipitated over the growing mat of bacterial filaments; photosynthesis in the bacteria depleted carbon dioxide in the surrounding water, initiating the precipitation. The minerals, along with grains of sediment precipitating from the water, were then trapped within the sticky layer of mucilage that surrounds the bacterial colonies, which then continued to grow upwards through the sediment to form a new layer. As this process occured over and over again, the layers of sediment were created. This process still occurs today; Shark Bay in western Australia is well known for the stromatolite "turfs" rising along its beaches.

In some cases, the stromatolites were infiltrated with a mineral-rich solution which fossilized the bacteria along with the layers, but more often only the layers are preserved.

The oldest stromatolites date to the Early Archaean, and they became abundant by the end of the Archaean. In the Proterozoic, stromatolites were widespread on earth, and were ecologically important as the first reefs. By the close of the Proterozoic, the abundance of stromatolites decreased markedly, though cyanobacteria continued to leave a fossil record, such as *Langiella* and *Kidstoniella*known from the Lower Devonian Rhynie chert.
The cyanobacteria have also been tremendously important in shaping the course of evolution and ecological change throughout earth's history. The **oxygen** atmosphere that we depend on was generated by numerous cyanobacteria photosynthesizing during the Archaean and Proterozoic Era. Before that time, the atmosphere had a very different chemistry, unsuitable for life as we know it today.

Bitter Springs chert fossil image provided by J. William Schopf. Image of stromatolites provided by the University of Wisconsin Botanical Images Collection.

Source: T.N. & E.L. Taylor. 1993. The Biology and Evolution of Fossil Plants. Prentice Hall, New Jersey.

4) Vocabulary 1 Coevolution on Earth

Name ______________________________ Date _______ Period ___

term	*explanation/definition*	*Illustration of term*
coevolution		
cyanobacteria		
organic		
inorganic		
aerobic		

term	*explanation/definition*	*illustration*
anaerobic		
photosynthesis		
precipitate		
chemical element		
rock formation		

Geology and National Parks

Geology, Minerals, Energy and Geophysics Science Center home

The information found here reflects completed USGS work. The content of this page is static and has not been updated since the mid 2000's.

What is Geologic Time?

Concealed within the rocks that make up the Earth's crust lies evidence of over 4.5 billion years of time. The written record of human history, measured in decades and centuries, is but a blink of an eye when compared with this vast span of time. In fact, until the eighteenth century, it was commonly believed that the Earth was no older than a few thousand, or at most, million, years old. Scientific detective work and modern radiometric technology have only recently unlocked the clues that reveal the ancient age of our planet.

This image from Lake Mead NRA shows a sequence of sedimentary rock layers. The oldest layers, Cambrian (570-505 million years ago) are at the base, with younger layers piled on top. The older layers are lower 'relative' to the younger layers.

Evidence for an Ancient Earth

Long before scientists had developed the technology necessary to assign ages in terms of number of years before the present, they were able to develop a **'relative'** geologic time scale. They had no way of knowing the ages of individual rock layers in years (radiometric dates), but they could often tell the correct sequence of their formation by using relative dating principles and fossils. Geologists studied the rates of processes they could observe first hand, such as filling of lakes and ponds by sediment, to estimate the time it took to deposit sedimentary rock layers. They quickly realized that millions of years were necessary to accumulate the rock layers we see today. As the amount of evidence grew, scientists were able to push the age of the Earth farther and farther back in time. Piece by piece, geologists constructed a geologic time scale, using increasingly more sophisticated methods for dating rock formations.

Early geologists used the relative positions of rock layers as clues to begin to unravel the complex history of our planet. However, it was not until this century that nuclear age technology was developed that uses measurements of radioactivity in certain types of rocks to give us ages in numbers of years. These ages, usually called **radiometric ages,** are used in conjunction with relative dating principles to determine at least an approximate age for most of the world 's major rock formations.

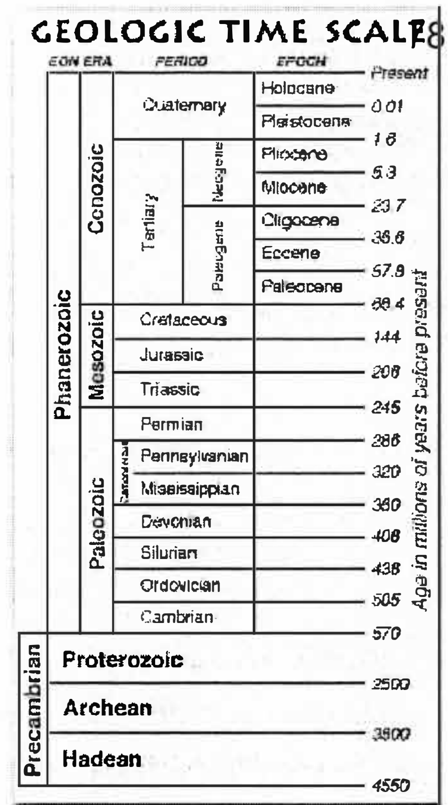
The Geologic Time Scale

The 4.55 billion-year geologic time scale is subdivided into different time periods of varying lengths. All of Earth history is divided into two great expanses of time. The **Precambrian** began when Earth first formed 4.55 billion years ago and ended about 570 million years ago. The **Phanerozoic Eon** began 570 million years ago and continues today.

This time scale, from the Decade of North American Geology, is widely used in North America. As we improve our ability to date rocks using radiometric dating methods, the time scale is amended. The time scale is constantly being refined, so don't be surprised to see continuing revisions as our technology and understanding of the Earth improves!

The time scale on the right shows the subdivisions of geologic time in a form that will fit on a single page. This format is useful, but it tends to conceal the immense span of time, over 85 percent of Earth's history, within the Precambrian.

To see the entire geologic time scale drawn to scale so you can see the divisions of time in their correct proportions, click here.



Next: Putting time into proportion

U.S. Department of the Interior | U.S. Geological Survey
URL: http://geomaps.wr.usgs.gov/parks/gtime/index.html
Page Contact Information: G & G Webmasters
Page Last Modified: 25-Apr-2017@09:48

Radioactive Decay Model - Radiometric Dating

HS-ESS1-6; PS1.C - Nuclear Processes

- Spontaneous radioactive decays follow a characteristic exponential decay law. Nuclear lifetimes allow radiometric dating to be used to determine the ages of rocks and other materials.

Abstract

What do rocks and clocks have in common? Both keep track of time. Yes, radioactive isotopes present in rocks and other ancient material decay atom by atom at a steady rate, much as clocks tick time away. Geologists use those radioactive isotopes to date volcanic ash or granite formations like the giant Half Dome in Yosemite National Park. Anthropologists, archeologists, and paleontologists also use radioactive isotopes to date mummies, pottery, and dinosaur fossils. Does this sound abstract and complicated? It is no more complicated than playing a dice game! In this science project you will see for yourself by modeling radioisotope dating with a few rolls of the dice.

Objective

Create a model of radioactive decay using dice and test its predictive power on dating the age of a hypothetical rock or artifact.

Credits

Sabine De Brabandere, Ph.D., Science Buddies

Introduction

As humans, it seems easy for us to keep track of time lapses, as long as they range from a couple of seconds to a number of years. That is what we encounter in our daily lives, right? The Earth orbits the Sun in about one year's time, the Earth rotates on its axis every 24 hours, 60 ticks of the second hand on a clock indicates 1 minute has passed. Geologists have a much harder job keeping track of time. Studying the Earth and its evolution, they work with time scales of thousands to billions of years. Where can they find a *clock* to measure these huge time periods? Or on a slightly smaller scale, where can paleontologists find a clock to tell the age of fossils, or how can archaeologists determine how old ancient pottery and buried artifacts are?

Geologists (along with paleontologists, archaeologists, and anthropologists) actually turn to the *elements* for answers to their geological time questions. We and everything around us are made of **atoms**. Atoms are tiny. They are mostly empty space with a denser tiny area called the *nucleus* and a cloud of *electrons surrounding* the nucleus.

The nucleus itself is made of *protons* and *neutrons*, collectively called **nucleons**. Figure 1 provides a visual representation of an atom.

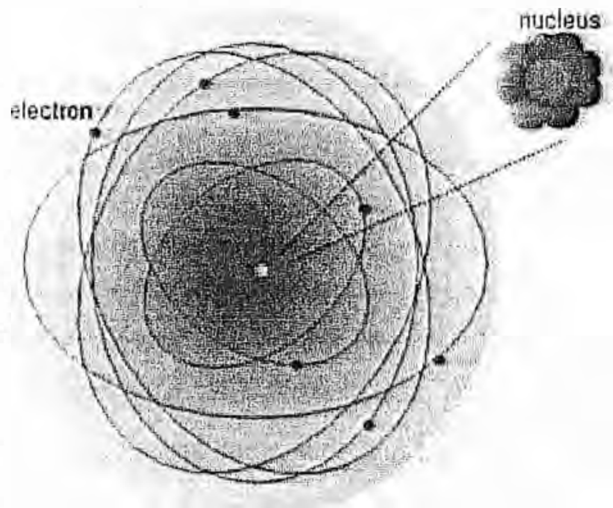


Figure 1. Representation of an atom with its nucleus and an electron cloud around it. Note that, in this drawing, the nucleus is shown disproportionately large.

The number of protons within an atom's nucleus is called the **atomic number**. It determines the identity of the atom. The atomic number is important for locating an element on the **periodic table**, shown in Figure 2. You might have seen the periodic table in your science textbook or displayed on a poster in the classroom. What do you know about it?

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Figure 2. Periodic table showing elements with their atomic symbol and atomic numbers.

In the periodic table, each entry represents an **element**. The element is listed by its *atomic symbol*, a one-, two- or three-letter long label. For example, gold's atomic symbol is Au. Above the atomic symbol, each entry lists the element's atomic number; e.g., the element gold (Au) has an atomic number of 79.

While an element always has the same atomic number, meaning it has the same number of protons in its nucleus, it can have a different number of total nucleons in its nucleus. Scientists call these different variations of the same element **isotopes** of each other. For example, the element potassium (which always has 19 protons in its nucleus) occurs in nature in three forms: an isotope with 39 nucleons (19 protons and 20 neutrons), one with 40 nucleons (19 protons and 21 neutrons), and one with 41 nucleons (19 protons and 22 neutrons) .

Some isotopes are radioactive. Any idea what the word *radioactive* means? **Radioactive** refers to the characteristic that these isotopes are **unstable** and tend to fall apart. They emit, or radiate, particles in their conversion to stability. We call this process **radioactive decay**. Isotopes exhibit a range of radioactive decay processes. Resources provided in the Bibliography enable you to research this topic in more detail. We will explore only the decay processes of interest to geologists.

Geologists who want to date objects are interested in the isotopes that change identity as they undergo radioactive decay. In other words, they change their number of protons during radioactive decay and turn into a different element. As an example, the potassium-40 isotope (which contains 19 protons, 40 nucleons, and is represented by the atomic symbol K) will change into the argon-40 isotope (which contains 18 protons, 40 nucleons, and is represented by the symbol Ar). When this happens, potassium-40, which is emitting particles in its conversion to a more stable form, is called the **parent isotope**. The isotope that is created during the process (here argon-40) is called the **daughter isotope**. The particles emitted in the process are what we call *radiation*.

It is now time to explore why geologists are so interested in these radioactive decay processes as a means of dating objects. But before we do, can you list some characteristics a good clock should have? Predictable, reliable... but what do these words mean? Can you describe them in more detail? Now, try to link the clock characteristics you just listed to the characteristics of radioactive decay that appeal to geologists:

1. Radioactive decay processes happen at a stable measurable rate characterized by the **half-life time**. The half-life time is the time period after which the remainder of the parent isotopes is half of what you start out with. Do not worry if this sounds confusing; the following example will help clarify.
2. The steady, atom-by-atom transformation of one isotope to another is not affected by any influence of the environment outside the nucleus.
3. Nature offers a number of unstable isotopes with half-life times ranging from several billion years to only a ten-thousandth of a second, allowing for "clocks" that can tell wide ranges of time.

Could you link these to your list of characteristics of a good clock?

This example might help clarify the processes and terms just introduced: Looking at the parent isotope potassium-40 (abbreviated as K-40) that decays into the daughter isotope argon-40 (abbreviated as Ar-40), scientists measured the half-life time to be 1.25 billion years. This means that half of the K-40 atoms existing today will have made the transformation to Ar-40 at some point during the next 1.25 billion years, no matter what weather they experience, pressure they undergo, or any other outside circumstances. Science cannot predict which particular K-40 atom in this sample will decay and which will not during the next 1.25 billion years, but that is OK. It can predict what happens on average. It is like flipping a huge amount of coins: you know that the likelihood, or **probability**, is that you will end up with half of them heads up, but you have no idea which particular one will end up heads, or if even half of them will be heads for sure.

So, can radioactive isotopes be used as a clock? Can geologists say that once the amount of K-40 isotopes in the sample has reduced to half its original amount, 1.25 billion years will have gone by? Yes — as long as they use a big enough sample so **statistical fluctuations** average out. To take it a step further, once only 1/4 of the original amount of K-40 isotopes are left (half of the half left over after 1.25 billion years), geologists can say that 2.5 billion years (double the half-life time) have gone by. Now, can you predict how much time has gone by if only 1/8 is left? You can probably see now that as the sample ages, fewer and fewer parent isotopes will be present in the rock, so the rock will be less and less radioactive. Figure 3 shows a graphical representation of this example.

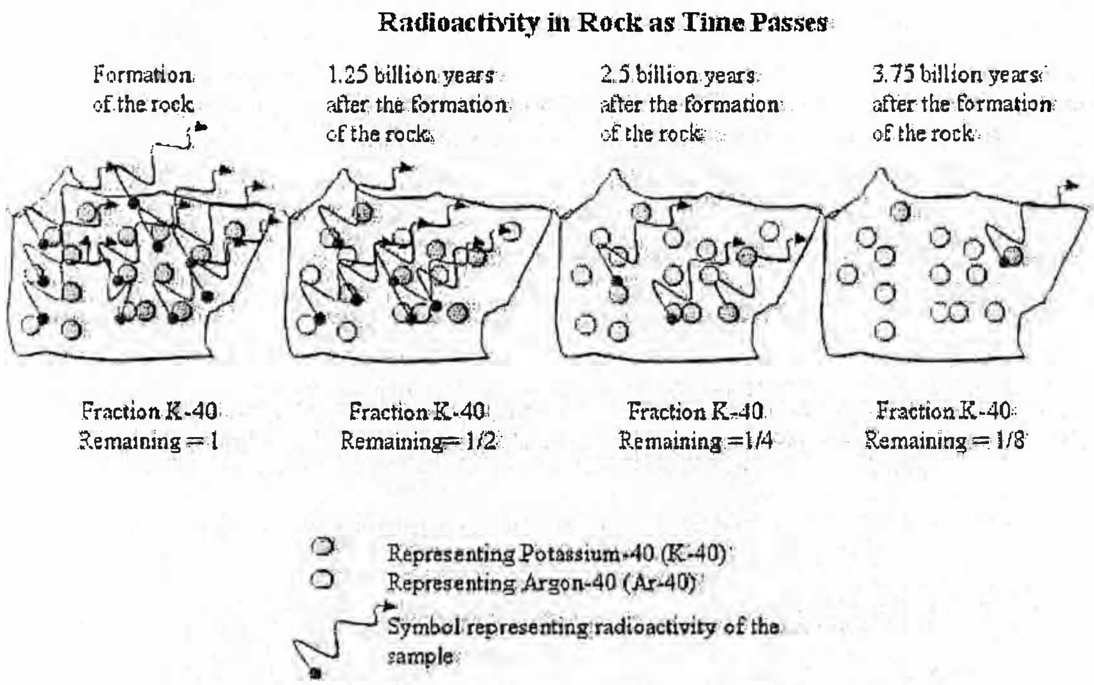


Figure 3. Representation of an aging rock. The radioactivity levels are indicated by wiggly arrows; green dots represent parent isotopes (here, K-40) and yellow dots represent daughter isotopes present in the rock at the indicated time after the formation of the rock. Snapshots of the rock are taken after multiples of 1.25 billion years (the half-life time of the parent isotope K-40).

So, how do geologists use radioactive decay as clocks to measure the age of a sample? Using a technique called **radiometric dating,** geologists take a sample of the material and measure the number of parent and daughter isotopes present in the sample. Adding these two values gives the original amount of parent isotopes in the sample. Geologists can then use Equation 1, referred to as the *radioactive decay formula*, to determine the age of a sample. Specifically, by dividing the number of parent isotopes currently left in the sample (N) by the original amount of parent isotopes in the sample (N_0), the geologists calculate a ratio termed N/N_0 . They can then use this ratio (N/N_0) in Equation 1 to calculate the time since formation of the sample (T) to determine the age of the sample.

Equation 1:

$$N/N_0=\left(\frac{1}{2}\right)^{T/T_{1/2}}$$

- N : number of parent isotope currently left in the sample
- N_0 : original number of parent isotope in the sample

- T : time since formation
- $T1/2$: half life time of the parent isotope

Is this radioactive decay formula intimidating? If so, try not to worry: This science project will only use its graphical representation, known as the **decay curve** . Coming back to our example, Figure 4 shows the decay curve for the potassium (K-40) isotope. Can you figure out that the half-life time of K-40 is 1.25 billion years from the graph? Can you also figure out that 1/4 of the K-40 parent isotopes in the sample are left after 2.5 billion years, and only 1/8 of the K-40 parent isotopes remain after 3.75 billion years? How long before all of the K-40 parent isotopes decay?

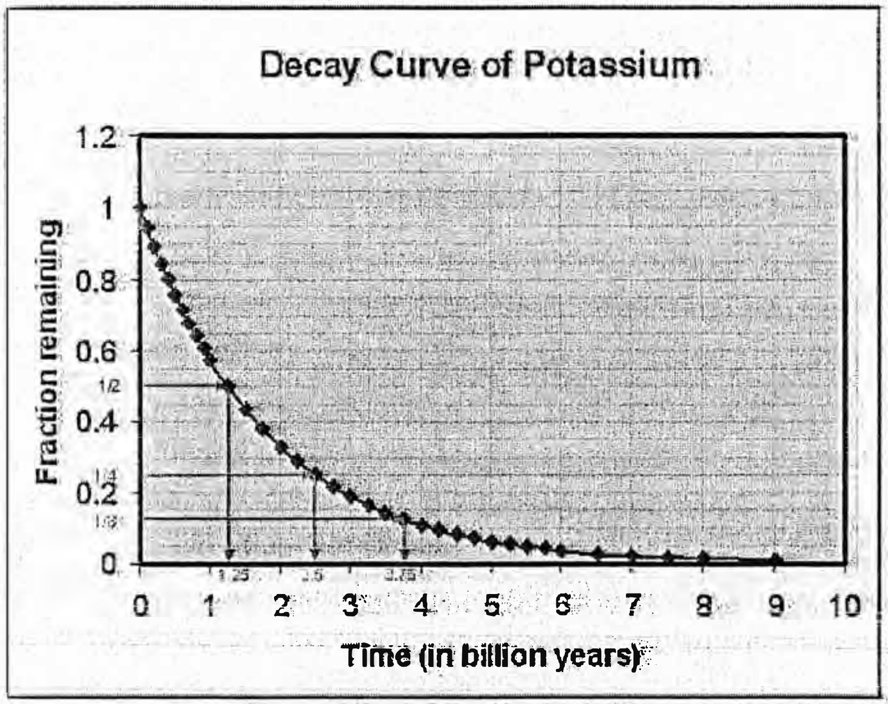


Figure 4. An example of the decay curve of potassium (K-40). This figure also illustrates how to use a decay curve to figure the time since formation, if the fraction of parent isotope remaining in the sample is known. The red lines show how to obtain the half-life time, or the time after which half of the parent isotopes have decayed. The green and pink lines guide you to the time after which only 1/4 and 1/8, respectively, of the parent isotopes remain. The arrows indicate how to read the graph, starting from a fraction of parent isotope remaining via a horizontal line to a point on the curve, and then vertically down to a time on the time axis.

Does this still seem a bit abstract? This geology science project will guide you through the process of radiometric dating, enabling you to explore and fill in the blanks. It explains how to create a model of radioactive decay using dice. The model will behave the same way as isotopes in nature in important ways. You will create a decay curve for your hypothetical rare isotope, and use it to estimate the time since formation of hypothetical samples created by a friend.

Terms and Concepts

- Atoms
- Nucleons
- Atomic number
- Periodic table
- Element
- Isotopes
- Radioactive
- Unstable
- Radioactive decay
- Parent isotope
- Daughter isotope
- Half-life time
- Probability
- Statistical fluctuations
- Radiometric dating
- Decay curve

Questions

- What are some important characteristics of isotope decay that make them interesting to geologists?
- How many isotopes (parent and daughter isotopes together) are present in a rock at any given time if, at formation, that rock had 1 trillion isotopes?
- Would you choose the same radioactive isotope to date material expected to be about 10,000 years old as material that is expected to be billions of years old?
- How do the decay curves of different isotopes with different half-life times compare? How are they similar and how are they different?

Bibliography

- Goldman, M. (n.d.). *Isotopes and radioactivity.* Physics 2000. Retrieved July 17, 2012, from http://www.colorado.edu/physics/2000/isotopes/index.html
- Nuclear Science Division - Lawrence Berkeley National Laboratory. (2007, March 30). *The ABC's of nuclear science.* Retrieved February 18, 2013, fromhttp://www.lbl.gov/abc/Basic.html#Nuclearstructure
- Kids.Net.Au. (2013). *Radiometric dating.* Retrieved February 18, 2013, from http://encyclopedia.kids.net.au/page/ra/Radiometric_dating

Examples of objects dated by radiometric dating can be found at the following site:

- U.S. Geological Survey. (2001, June 13). *Radiometric time scale* . USGS. Retrieved January 22, 2013, fromhttp://pubs.usgs.gov/gip/geotime/radiometric.html

The following article provides a real-world example of radiometric dating:

- Grens, K. (2013, March 1). *Coral clocks* . The Scientist. Retrieved March 8, 2013, from http://www.the-scientist.com/?articles.view/articleNo/34463/title/Coral-Clocks/

News Feed on This Topic

Radiometric Dating: Playing Half-life Odds, ***Science Buddies Blog***, April 30, 2013

Explore Radioactive Decay with Coins, ***Science Buddies Blog***, December 3, 2015

Our Solar System's 'shocking' origin story, ***EurekAlert!***, August 3, 2017

Materials and Equipment

- Six-sided dice (100), can be purchased online from Amazon.com or at a board-game shop or the toy section of a large department store.
- Stickers (100), small enough to fit on one side of a die
- Pot big enough to hold all 100 dice
- Sticky note
- Plastic bag to hold all the dice
- Permanent marker
- Lab notebook
- Graphing paper and pencil or pen or a graphing computer program
- Partner (volunteer)
- Colored (i.e., not black) pen or thin marker
- Paper and pen

Experimental Procedure

Creating a Radioactive Decay Model and Plotting the Decay Curve

In this part of the science project, you will make a model to explore radiometric dating. The model uses 100 six-sided dice, where each die represents one isotope in a radioactive sample used for dating. You will roll the dice to represent one unit of time passing, during which the parent isotopes have a chance to decay into the daughter isotopes. How much of a chance? Or, in other words, what is the probability of decay? One in six! Why? You will put a sticker on one side of the dice and if a die lands with the sticker facing up, this will represent that isotope decaying into the daughter isotope. If the sticker is not facing up, it means that the isotope has not decayed yet, so further rolls of the dice will decide when this parent isotope decays. You will collect the daughter isotopes in a separate bag so they can no longer decay and only use the remaining parent isotopes in the following roll. Table 1 lists the relation between model and real life.

Radioactive Isotope Decay Model	
Part of the Model	**What It Scientifically Represents**
Die	Isotope
Total number of dice	Total amount of isotopes (parent and daughter together) in the sample
Number of dice in pot	Number of parent isotopes in the sample
Number of dice in bag labeled "Daughter isotopes in sample"	Number of daughter isotopes in the sample

Die after roll - side facing up has no sticker	Isotope remaining a parent isotope
Die after roll - side facing up has a sticker	Isotope decaying into a daughter isotope
Chance of a die landing with the sticker facing up	Chance for a parent isotope to decay to the daughter isotope within the next time unit
Rolling the dice	One unit of time passing (in this case, the time in which 1/6 of the isotopes decay). At zero rolls, the material has just formed.

Table 1. Table showing how parts of the isotope decay model match up scientifically with the parts of radioactive isotope decay.

1. First you will prepare the model.
   a. Take each die, one at a time, and place a sticker on one side of each die.
   b. Place all 100 dice, with stickers on one side, in your pot.
   c. Write "Parent isotopes in sample" on a sticky note and affix it to the pot.
   d. Using the permanent marker, write "Daughter isotopes in sample" on the plastic bag.

2. Next, in your lab notebook, create a data table like Table 2. You will record your results in this data table.

[illegible]	Number of Parent Isotopes Left				Fraction of Parent Isotopes Remaining
	Trial 1	Trial 2	Trial 3	Average Value	
0	100	100	100	100	1
1					
2					
3					
...					

Table 2. In your lab notebook, create a data table like this one to record your results. You will record the number of parent isotopes left in your sample after each time unit passes (i.e., after each roll of dice) for three different trials and average the values over

the three trials. The data table also lists the fraction of parent isotopes remaining, which is the number of remaining isotopes (averaged over the three tests) divided by the original number of parent isotopes in the sample (100 in this case). The data collected will be used to graph the decay curve of this particular isotope.

3. Collect data for a decay of 100 isotopes over time and record your results in the data table. This table will be used later to graph its decay curve and determine its half-life time.
   a. Start by writing down "100" for the "Number of parent isotopes left" in your data table for Trial 1 (you will use 100 dice in your sample). For this first roll the time will be 1.
   b. Roll the dice out on the floor or table.
   c. Remove from the sample all the dice with the "daughter isotope" sticker facing up. These represent the isotopes that decayed during this given time unit. Collect them in the bag labeled "Daughter isotopes in the sample."
   d. Count the number of parent isotopes (dice) remaining on the floor.
   e. Note this number in your data table under "Number of parent isotopes left" for the following time slot.
   f. Place all the remaining dice (parent isotopes only) in your pot marked "Parent isotopes in sample" with the sticky note.
   g. Repeat steps 3.b.–3.f. until all parent isotopes have decayed (i.e., there are no dice remaining to be put in the pot).
   h. Note that, at any given time during the process, the number of parent isotopes (dice in your pot) plus the number of daughter isotopes (dice in your bag) adds up to 100, which is the initial number of parent isotopes in the sample. Atoms neither disappear nor are they created; they just change identity.

4. Repeat step 3 at least two more times for a total of at least three trials.
   a. Knowing that the decay of an isotope (a dice rolling and showing one particular side facing up) is a statistical process, do you expect variations between the values obtained in your different tests? Can you observe these variations?

5. Calculate the average of the number of parent isotopes left for each elapsed time and write it down in the "Average Value" column of your data table.

6. Calculate the fraction of parent isotopes remaining using the average numbers obtained in step 5 and write it down in the "Fraction of Parent Isotopes Remaining" column of your data table.
   a. For example, if your average value of parent isotopes left after one roll (time is 1) is 85, the fraction of parent isotopes left would be 85 divided by 100, or 0.85.

7. Your data table should now be completely filled in and ready to use in making a decay curve graph.

Graph the Decay Curve and Determine the Half-Life Time

In this part of the science project, you will create a graph of the decay curve of your isotope and use your curve to determine the half-life time of your isotope. Remember, the half-life time of an isotope is the time it takes for half of the initial amount of isotopes to decay. You will then compare the half-life time you obtained using your data to the predicted half-life time using probability. How close will your half-life time be to the calculated one?

1. Having the collected data for your isotope decay organized in your data table, it is time to graph the decay curve. Get a pen and graphing paper ready, or ready a particular graphing tool on your computer if you are familiar with one. (For an example of a decay curve, see Figure 4 in the Introduction in the Background tab.)
    a. The decay curve has the elapsed time (i.e., the number of times you rolled the dice) on the x-axis. Determine the range of your x-axis based on the data in your data table, divide your x-axis in appropriate equal-length units so all the values fit on your axis, and add reference numbers and labels.
    b. The decay curve has the fraction of parent isotopes remaining in your sample represented on the y-axis. Determine the range of your y-axis based on the data in your data table, divide your axis in appropriate equal length units, and add reference numbers and labels.
    c. Create the graph by plotting all the data points and connecting them by a continuous line, as shown in Figure 4. There you have it— the decay curve of your isotope.
    d. For any graph you make, always check if you have labeled your axes and added reference numbers.

2. Now determine the half-life time from your decay curve. Figure 4 in the introduction can provide clues on how to read the half-life time from the decay curve. Once you have found it, label the half-life time on your decay curve similarly to how it is labeled in Figure 4, using a different color pen.

3. Next you will calculate the half-life time of your particular isotope based on the probability that each isotope will decay within a unit of time passing. Table 3 is partly filled in to show you how to get started doing this. Make a data table like Table 3 in your lab notebook and completely fill it in.
    a. After each roll, based on probability, 1/6 of the parent isotopes will decay to daughter isotopes and 5/6 will remain parent isotopes. Look at how these calculations have been made in Table 3 for the first few rolls.

   i. For example, of the 100 parent isotopes you started out with, after the first roll 17 (1/6 of 100) are expected to decay into daughter isotopes and 83 (5/6 of 100) are expected to remain parent isotopes.
   ii. In the second roll, 1/6 of the 83 left after the first roll will decay, creating 14 daughter isotopes, and 5/6 of 83, or 69, will remain parent isotopes and be left to decay in future rolls of the dice.

b. Continue these calculations and fill out the data table in your lab notebook until no parent isotopes remain.
   i. Also be sure to fill out the "Fraction of Parent Isotopes Remaining" column.

c. After how many rolls are you likely to have approximately 50 parent isotopes remaining, or after how many rolls will the fraction of parent isotopes remaining be equal to 0.5? This is your calculated half-life time.

Time (number of rolls)	Number of Parent Isotopes before Roll	Number of Parent Isotopes Decayed into Daughter Isotopes This Roll	Number of Parent Isotopes Remaining	Fraction of Parent Isotopes Remaining
0	100	0	100	1
1	100	100 X 1/6 = 17	100 X 5/6 = 83	0.83
2	83	83 X 1/6 = 14	83 X 5/6 = 69	0.69
3	69	69 X 1/6 = ...	69 X 5/6 = ...	...
4	...	...	...	...
5	...	...	...	...

Table 3. In your lab notebook, make a data table like this one to calculate the number of parent isotopes remaining in a sample over time and determine the half-life time of your isotope based on probability.

4. How does your calculated half-life time compare with the half-life time read from the decay curve? If they are different, why do you think they are? How do you think you could make your collected data even closer to the calculated half-life time? *Hint:* Think about statistical fluctuations, which are discussed in the Introduction in the Background tab.

Do the Decay Test! Can You Amaze Your Partner?

It this section, you will ask a volunteer partner to roll the 100 six-sided dice, simulating the decay of isotopes in your sample just as you did to collect data for the decay curve. Your partner decides after how many rolls of the dice he or she would like to stop. Your partner will hand you over the bag of daughter isotopes and the pot of parent isotopes when they have finished. Your task is to use the sample (bag with the daughter isotopes and pot with the parent isotopes) and then estimate the number of times your partner rolled the dice (or the elapsed time of your sample).

1. Following are the things your partner should do:
    a. Have a paper and pen handy.
    b. Place all the dice in the pot.
    c. Roll the dice out on the floor or table.
    d. Remove all the dice with the "daughter isotope" sticker facing up from the sample and place them in the bag labeled "Daughter isotopes in the sample."
    e. Mark a tally on the paper indicating the number of times the dice have been rolled.
    f. Place all the remaining dice (parent isotopes) in the pot labeled "Parent isotopes in the sample."
    g. Repeat steps 1.c.–1.f. until your partner decides to stop.
    h. Once your partner stops, ask him or her to give the bag and pot back to you— but do NOT allow your partner to tell you how many times he or she rolled the dice at this point.

2. Following are the things you should do:
    a. In your lab notebook, make a data table like Table 4.
    b. Count the number of parent isotopes remaining in the sample (number of dice in the pot) and write it down in your data table.

Trial Number	Number of Parent Isotopes in Sample	Fraction of Parent Isotopes Remaining	Predicted Time Lapse Based on Decay Curve	Predicted Time Lapse Based on Probability	Actual Time Lapses (Number of Tallies on the Paper)
1					
2					
3					

c. **Table 4.** Create a data table in your lab notebook like this one to record your results.

d. Calculate the fraction of parent isotopes remaining and write it down in your data table.
e. Use your decay curve to estimate the number of times your partner rolled the dice (the elapsed time since formation of your sample) and write it down in your data table.
f. Repeat step 2.d. but this time use the data table you created based on probability, the one similar to Table 3.
g. Ask your partner to see his or her tallies, then count them and write them down in your data table.

3. Analyze your data:
   a. Compare the last three columns (predicted time lapse based on your decay curve, predicted time lapse based on probability, and actual time lapse) of your data table. How accurate are your predictions? Was one of your predicted time-lapse methods more accurate than the other? Why do you think this is so?
   b. See if you can observe trends in your accuracy: Are your estimations more accurate when the real time lapse is short, long, or somewhere in the middle?
   c. Can you find parameters that influence your accuracy? How do you think you could make your predictions more accurate?

4. After all this work, do you see how geologists used their creativity and ingenuity to find accurate "clocks" in their quest to date ancient material? Did it surprise you how a statistical process like radioactive decay—where you cannot predict what will happen with individual isotopes—still lets you deduce specific information?

Variations

- Use different dice (five-sided, eight-sided, ten-sided, etc.) or a coin to set up your model. Would you expect any differences in the decay probability, the decay curve, the half-life time, the accuracy of time estimations, etc.?
- Glue stickers on additional sides of your six-sided dice to set up your model, but be consistent with all of the dice (e.g., put stickers on three sides of all of your dice). Would you expect any differences in the decay probability, the decay curve, the half-life time, the accuracy of time estimations, etc.?
- This science project used a sample size of 100 dice. As a variation, do the experiment again with a different sample size (e.g., 200, 150, 50, or 25 dice total). How does the sample size affect the accuracy of the decay curve and time

readings? If you use more dice, is it more or less accurate at telling time than when you used 100 dice? What about when you use fewer dice?

- In this science project, you compare the half-life time read from the decay curve with the calculated half-life time. As a variation, do the comparison for different fractions of the initial amounts of parent isotopes remaining (e.g., 1/4, 3/4, 1/8, etc.) See if you can find and explain trends in accuracy (e.g., graph readings for smaller fractions remaining are more or less accurate).
- Study how sample size affects the accuracy of the estimations by allowing your partner to choose how many dice he or she likes to start out with (i.e., letting your partner choose the sample size). In this variation, you do not change the sample size to graph the decay curve or make your probability data table, only the test sample involving a partner changes. When trying to figure out how many rolls your partner has made, be sure to start with the number of parent isotopes that he or she decides to use in the sample size.

If radioactive decay processes intrigue you, the following two project ideas might grab your attention:

Half-Life of Pennyium: Radioactive Dating

Phenomenon: It has been observed that radioactive elements decay at steady, predictable rates. These rates do not change over time, nor are they affected by the natural concentration of the radioactive element. Because of this property, radioactive elements can be used to effectively determine the age of rocks. As radioactive atoms decay, they are changed into a degradation product (daughter atoms). By determining the proportions between the radioactive element and the daughter atoms, the age of rocks can be determined.

Discussion: Many people have heard the term "half-life" and know that it is related to radioactive elements. Half-life is defined as; "The time required for half of any given amount of a radioactive substance (Parent Atoms) to decay into another substance (Daughter Atoms)". Radioactive decay is a constant process where the unstable radioactive element breaks down to become a more stable element by releasing radioactive particles and radiation. In this lab you will use pennies to simulate how atoms radioactively decay and how rocks of different ages have different amounts of radioactive and decayed elements.

Background Information: Testing of radioactive minerals in rocks best determines the **absolute age of the rock**.

In radiometric dating, different isotopes of elements are used depending on the predicted age of the **igneous** rocks. Potassium/Argon dating is good for rocks 100,000 years old since Potassium 40 has a half-life of 1.3 billion years! Uranium/Lead dating is used for the most ancient rock, since U-238 has a half-life of 4.47 billion years.

By comparing the percentage of an original element (parent atom) to the percentage of the decay element (daughter atom), the age of a rock can be calculated. The ratio of the two atom types is a direct function of its age because when the rock was formed, it had all parent atoms and no daughter atoms.

Procedure: You will be given a sample of a radioactive element known as Pennyium, 50 pennies. Radioactive Pennyium is unstable when it is placed with the head side up and stabilizes into a more stable element when the tails side faces up. **Read the procedure before you start the lab**

1. Place the 50 pennies in the box heads side up. The Pennyium with the heads side up are the number of radioactive **unstable** "undecayed" Pennyium atoms (the parent atoms) in your igneous rock when it was formed
2. Shake the box - not too vigorously! Shake for about 7.13 seconds (this represents 713 million years passing).
3. Carefully open the lid and remove all the **stable** Pennyium atoms-those with the tails side up. Stable Pennyium atoms are really a new element.
4. Count and record the number of radioactive "undecayed" Pennyium atoms (heads side up) remaining. Record in the data table.
5. Repeat steps 2, 3 and 4 until all the pennies "decayed" (flipped tail side down) or 10 half lives or shakes of the box, which ever happens first.
6. Repeat this process for three trials.

Data Table

Half Lives Number of shakes	Number of Pennyium atoms undecayed (Heads side up)			
	Trial 1	Trial 2	Trial 3	Average
0	50	50	50	50
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Data Analysis

1. Make a graph using Google Sheets plotting the numbers of undecayed pennies on the y-axis and the number of shakes on the x-axis. Use the Insert - Chart command and select curved line chart.
2. The heads up pennies represent the ______________________.
3. The tails up pennies represent the ________________________.
4. How much of a radioactive element becomes stable in a half-life?
5. What is the half-life of Pennyium? (i.e., What is the amount of time necessary to reduce the radioactive isotopes by one-half?)
6. Suppose you had 20 radioactive pennies. Using your graph determine how many years had passed.
7. After 2,000 million years had passed how many radioactive pennies would be left? Number of decayed pennies?

Post-lab Questions

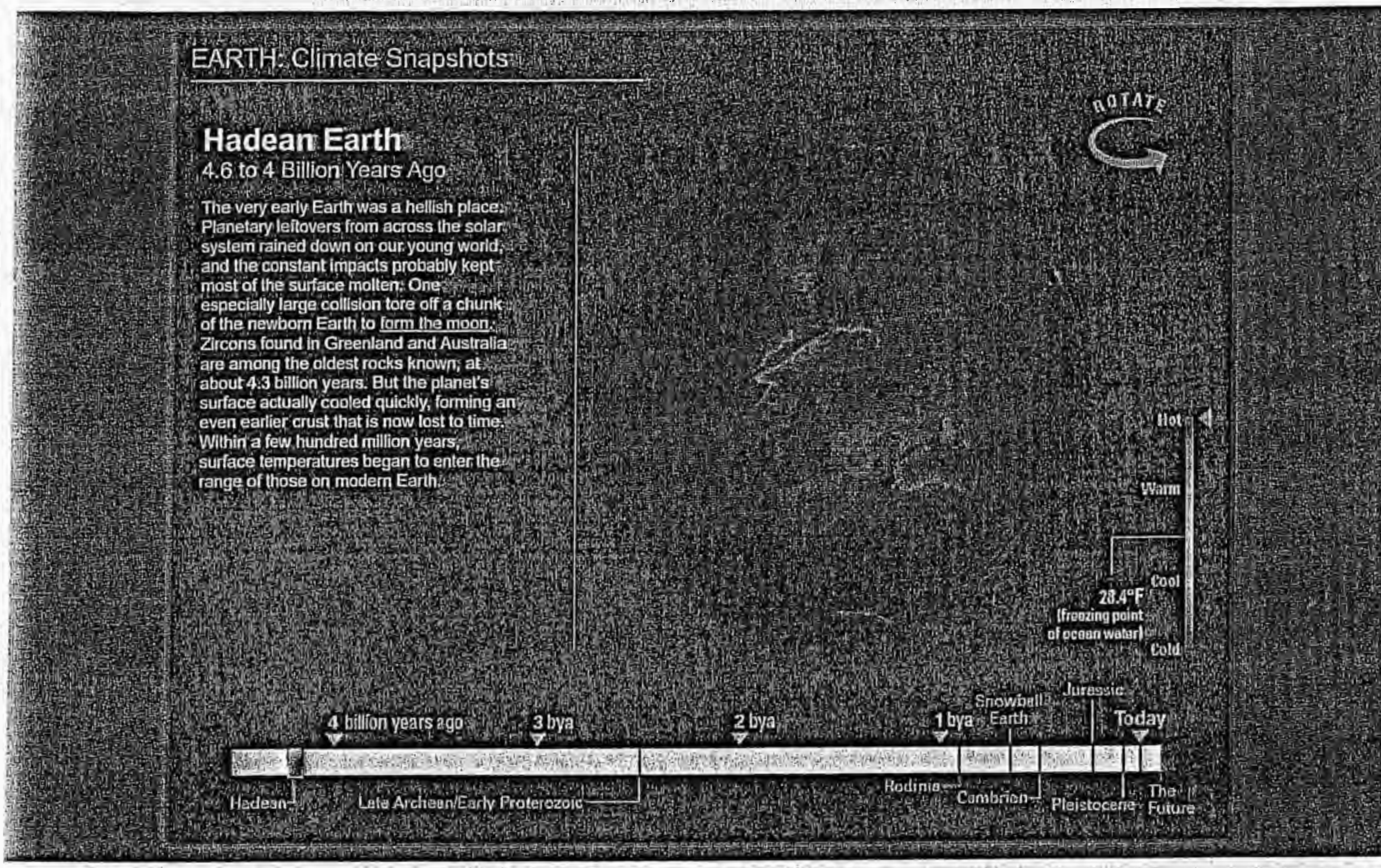
1. If you started with 100 pennies, would the half-life change? Please explain.
2. Looking at the table of elements used in radioactive dating, identify which element the radioactive pennies represent.

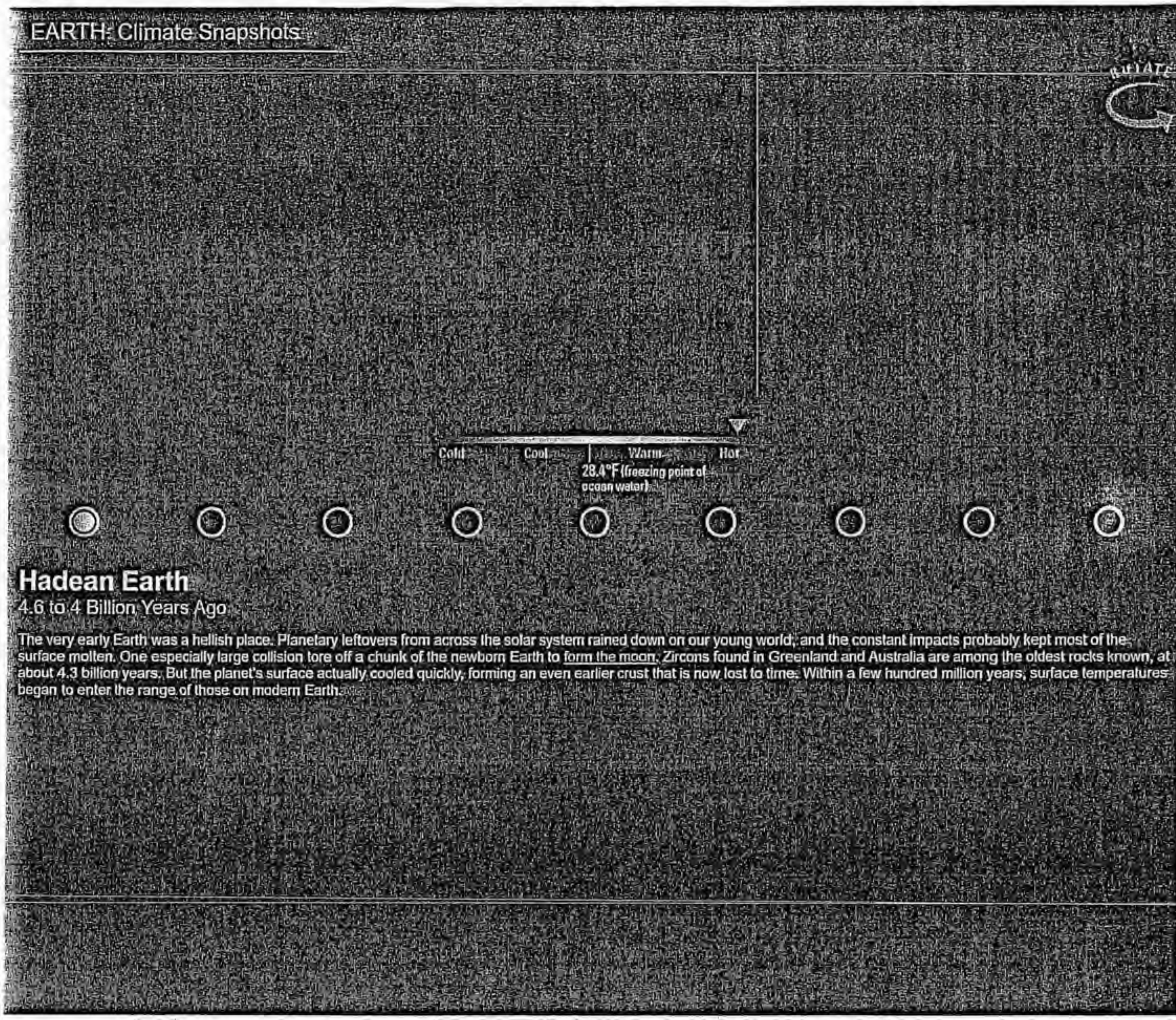
Elements used in radioactive dating		
Radioactive element	**Half-life (years)**	**Dating range (years)**
carbon-14	5,730	500-50,000
potassium-40	1.3 billion	50,000-4.6 billion
rubidium-87	47 billion	10 million-4.6 billion
thorium-232	14.1 billion	10 million-4.6 billion
uranium-235	713 million	10 million-4.6 billion
uranium-238	4.5 billion	10 million-4.6 billion

3. After 1 half-life what would be the proportions of parent atoms to daughter atoms?
4. After 2 half-lifes what would be the proportions of parent atoms to daughter atoms?
5. The half-life of U-238 is 4.5 billion years. If a rock was found to contain uranium and had not been disturbed since the formation of the Earth, what portion of U-238 would you expect to remain in the rock?

THE AGE OF HUMANS

LIVING IN THE ANTHROPOCENE





Travel Through Deep Time With This Interactive Earth

Explore key moments in Earth's transformative history as continents drift and climate fluctuates over 4.6 billion years

By Victoria Jaggard; Interactive by International Mapping; Paleogeographic maps by Ron Blakey
smithsonian.com
September 30, 2014

Earth is a planet defined by change, swinging through periods of intense heat and deep freeze even as oceans and continents are reshaped by the actions of plate tectonics. This constant reconfiguration has been a huge driver in the development of life on Earth. But scientists agree that human activity has now begun to influence the planet, changing the climate and drastically altering surface conditions.

Understanding how humans are affecting Earth's system requires a better grasp on the natural cycles and events that have shaped our planet through deep time. Slide through the timeline above to explore how the globe has changed over seven major "snapshots" in our climate history, and to see how it might look in the far future.

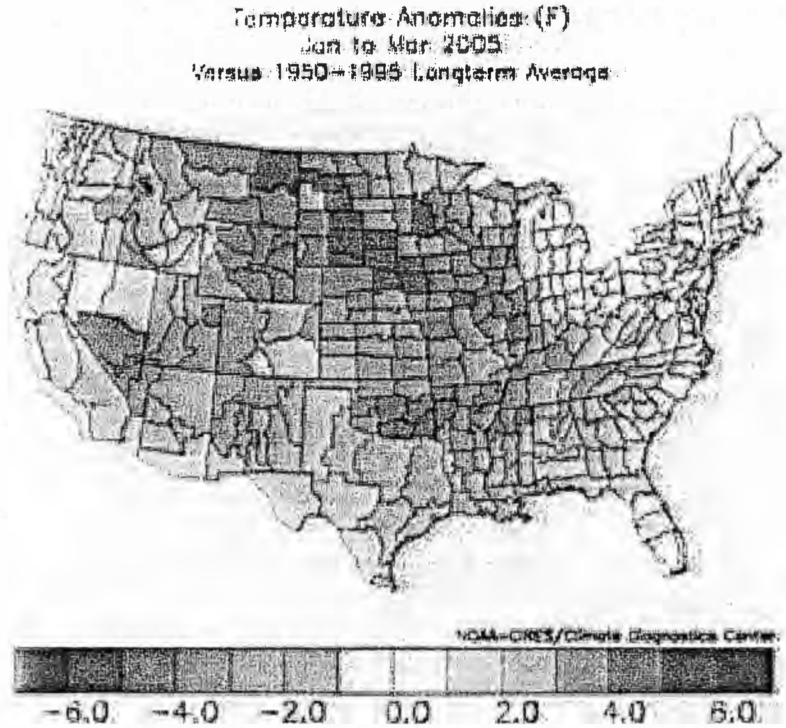
Alex Tait is Vice President of International Mapping in Ellicott City, Maryland.

Tim Montenyohl is a 3-D Artist and Animator at International Mapping.

Ron Blakey is professor emeritus of geology at Northern Arizona University and founder of Colorado Plateau Geosystems Inc.

Feb. 1, 2005

NASA - What's the Difference Between Weather and Climate?



Latest three month average temperature and precipitation anomalies for the United States. ***Credits: NOAA***

The difference between weather and climate is a measure of time. Weather is what conditions of the atmosphere are over a short period of time, and climate is how the atmosphere "behaves" over relatively long periods of time.

When we talk about climate change, we talk about changes in long-term averages of daily weather. Today, children always hear stories from their parents and grandparents about how snow was always piled up to their waists as they trudged off to school. Children today in most areas of the country haven't experienced those kinds of dreadful snow-packed winters, except for the Northeastern U.S. in January 2005. The change in recent winter snows indicate that the climate has changed since their parents were young.

If summers seem hotter lately, then the recent climate may have changed. In various parts of the world, some people have even noticed that springtime comes earlier now than it did 30 years ago. An earlier springtime is indicative of a possible change in the climate.

In addition to long-term climate change, there are shorter term climate variations. This so-called climate variability can be represented by periodic or intermittent changes related to El Niño, La Niña, volcanic eruptions, or other changes in the Earth system.

What Weather Means

Weather is basically the way the atmosphere is behaving, mainly with respect to its effects upon life and human activities. The difference between weather and climate is that weather consists of the short-term (minutes to months) changes in the atmosphere. Most people think of weather in terms of temperature, humidity, precipitation, cloudiness, brightness, visibility, wind, and atmospheric pressure, as in high and low pressure.

In most places, weather can change from minute-to-minute, hour-to-hour, day-to-day, and season-to-season. Climate, however, is the average of weather over time and space. An easy way to remember the difference is that climate is what you expect, like a very hot summer, and weather is what you get, like a hot day with pop-up thunderstorms.

Things That Make Up Our Weather

There are really a lot of components to weather. Weather includes sunshine, rain, cloud cover, winds, hail, snow, sleet, freezing rain, flooding, blizzards, ice storms, thunderstorms, steady rains from a cold front or warm front, excessive heat, heat waves and more.

In order to help people be prepared to face all of these, the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS), the lead forecasting outlet for the nation's weather, has over 25 different types of warnings, statements or watches that they issue. Some of the reports NWS issues are: Flash Flood Watches and Warnings, Severe Thunderstorm Watches and Warnings, Blizzard Warnings, Snow Advisories, Winter Storm Watches and Warnings, Dense Fog Advisory, Fire Weather Watch, Tornado Watches and Warnings, Hurricane Watches and Warnings. They also provide Special Weather Statements and Short and Long Term Forecasts.

NWS also issues a lot of notices concerning marine weather for boaters and others who dwell or are staying near shorelines. They include: Coastal Flood Watches and Warnings, Flood Watches and Warnings, High Wind Warnings, Wind Advisories, Gale Warnings, High Surf Advisories, Heavy

Freezing Spray Warnings, Small Craft Advisories, Marine Weather Statements, Freezing Fog Advisories, Coastal Flood Watches, Flood Statements, Coastal Flood Statement.

Who is the National Weather Service?

According to their mission statement, "The National Weather Service provides weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure which can be used by other governmental agencies, the private sector, the public, and the global community."

To do their job, the NWS uses radar on the ground and images from orbiting satellites with a continual eye on Earth. They use reports from a large national network of weather reporting stations, and they launch balloons in the air to measure air temperature, air pressure, wind, and humidity. They put all this data into various computer models to give them weather forecasts. NWS also broadcasts all of their weather reports on special NOAA weather radio, and posts them immediately on their Interactive Weather Information Network website at: http://iwin.nws.noaa.gov/iwin/graphicsversion/bigmain.html.

What Climate Means

In short, climate is the description of the long-term pattern of weather in a particular area.

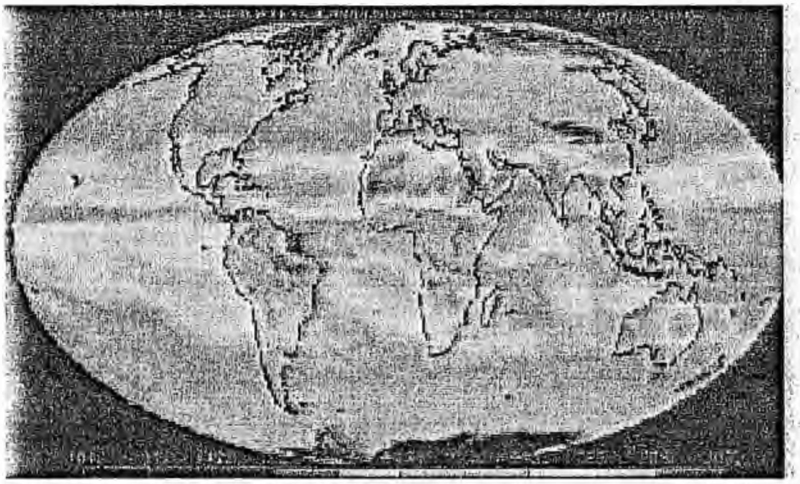
Some scientists define climate as the average weather for a particular region and time period, usually taken over 30-years. It's really an average pattern of weather for a particular region.

When scientists talk about climate, they're looking at averages of precipitation, temperature, humidity, sunshine, wind velocity, phenomena such as fog, frost, and hail storms, and other measures of the weather that occur over a long period in a particular place.

For example, after looking at rain gauge data, lake and reservoir levels, and satellite data, scientists can tell if during a summer, an area was drier than average. If it continues to be drier than normal over the course of many summers, than it would likely indicate a change in the climate.

Why Study Climate?

The reason studying climate and a changing climate is important, is that will affect people around the world. Rising global temperatures are expected to raise sea levels, and change precipitation and other local climate conditions. Changing regional climate could alter forests, crop yields, and water supplies. It could also affect human health, animals, and many types of ecosystems. Deserts may expand into existing rangelands, and features of some of our National Parks and National Forests may be permanently altered.



An example of a Monthly Mean Outgoing Longwave Radiation (OLR) product produced from NOAA polar-orbiter satellite data, which is frequently used to study global climate change. ***Credits: NOAA***

The National Academy of Sciences, a lead scientific body in the U.S., determined that the Earth's surface temperature has risen by about 1 degree Fahrenheit in the past century, with accelerated warming during the past two decades. There is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities. Yet, there is still some debate about the role of natural cycles and processes.

Human activities have altered the chemical composition of the atmosphere through the buildup of greenhouse gases – primarily carbon dioxide, methane, and nitrous oxide. The heat-trapping property of these gases is undisputed although uncertanties exist about exactly how Earth's climate responds to them. According to the U.S. Climate Change Science Program (http://www.climatescience.gov), factors such as aerosols, land use change and others may play important roles in climate change, but their influence is highly uncertain at the present time.

Who Studies Climate Change?

Modern climate prediction started back in the late 1700s with Thomas Jefferson and continues to be studied around the world today.

At the national level, the U.S. Global Change Research Program coordinates the world's most extensive research effort on climate change. In addition, NASA, NOAA, the U.S. Environmental Protection Agency (EPA) and other federal agencies are actively engaging the private sector, states, and localities in partnerships based on a win-win philosophy and aimed at addressing the challenge of global warming while, at the same time, strengthening the economy. Many university and private scientists also study climate change.

What is the U.S. Global Change Research Program?

The United States Global Change Research Program (USGCRP) was created in 1989 as a high-priority national research program to address key uncertainties about changes in the Earth's global environmental system, both natural and human-induced; to monitor, understand, and predict global change; and to provide a sound scientific basis for national and international decision-making.

Since its inception, the USGCRP has strengthened research on global environmental change and fostered insight into the processes and interactions of the Earth system, including the atmosphere, oceans, land, frozen regions, plants and animals, and human societies. The USGCRP was codified by Congress in the Global Change Research Act of 1990. The basic rationale for establishing the program was that the issues of global change are so complex and wide-ranging that they extend beyond the mission, resources, and expertise of any single agency, requiring instead the integrated efforts of several agencies.

Some Federal Agencies Studying Climate

In the 1980s the National Weather Service established the Climate Prediction Center (CPC), known at the time as the Climate Analysis Center (CAC). The CPC is best known for its United States climate forecasts based on El Niño and La Niña conditions in the tropical Pacific.

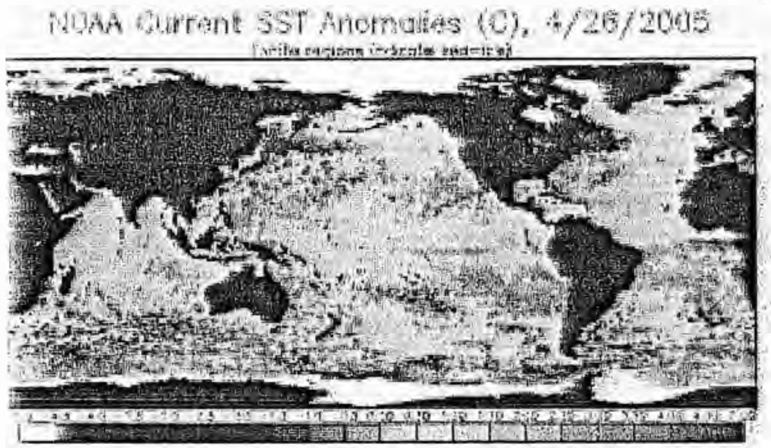


Image Above: The operational SST anomaly charts are useful in assessing ENSO (El Niño - Southern Oscillation) development, monitoring hurricane "wake" cooling, and even major shifts in coastal upwelling. ***Credits: NOAA***

CPC was established to give short-term climate prediction a home in NOAA. CPC's products are operational predictions or forecasts of how climate may change and includes real-time monitoring of climate. They cover the land, the ocean, and the atmosphere, extending into the upper atmosphere (stratosphere). Climate prediction is very useful in various industries, including agriculture, energy, transportation, water resources, and health.

NASA has been using satellites to study Earth's changing climate. Thanks to satellite and computer model technology, NASA has been able to calculate actual surface temperatures around the world and measure how they've been warming. To accomplish the calculations, the satellites actually measure the Sun's radiation reflected and absorbed by the land and oceans.NASA satellites keep eyes on the ozone hole, El Nino's warm waters in the eastern Pacific, volcanoes, melting ice sheets and glaciers, changes in global wind and pressure systems and much more.

At the global level, countries around the world have expressed a firm commitment to strengthening international responses to the risks of climate change. The U.S. is working to strengthen international action and broaden participation under the support of the United Nations Framework Convention on Climate Change..

Today, scientists around the world continue to try and solve the puzzle of climate change by working with satellites, other tools and computer models that simulate and predict the Earth's conditions.

For information about the U.S. Global Change Research Program, please visit:

http://www.usgcrp.gov/

For information about NASA's study of Earth's climate, please visit on the Internet:

http://www.nasa.gov/vision/earth/features/index.html

For a review of 2004's Global Temperature, please visit:

http://www.nasa.gov/vision/earth/lookingatearth/earth_warm.html

For information about NASA, please visit on the Internet:

http://www.nasa.gov

For information about the National Weather Service, please visit on the Internet:

http://www.nws.noaa.gov/

For immediate watches and warnings, visit the NWS Interactive Weather Information Network website at:

http://iwin.nws.noaa.gov/iwin/graphicsversion/bigmain.html

To find a NOAA weather radio station near you:

http://www.nws.noaa.gov/nwr/

For a glossary of weather terms, please visit the National Weather Service Weather Glossary on the Internet at:

http://www.nws.noaa.gov/glossary/

Rob Gutro
NASA's Earth-Sun Science News Team/SSAI
NASA Goddard Space Flight Center, Greenbelt, Md., and excerpts from NOAA's CPC web page, and the U.S. EPA web page. 2/2005
Edits: Dr. J. Marshall Shepherd, NASA/GSFC, Drew Shindell, NASA/GISS, Cynthia M. O'Carroll, NASA/GSFC
Last Updated: Aug. 7, 2017
Editor: NASA Content Administrator Tags: Climate

M2U1

University of California Museum of Paleontology

See the world (and its fossils) with UCMP's field notes.

Geologic time scale

Take a journey back through the history of the Earth — jump to a specific time period using the time scale below and examine ancient life, climates, and geography. You might wish to start in the Cenozoic Era (65.5 million years ago to the present) and work back through time, or start with Hadean time (4.6 to 4 billion years ago)* and journey forward to the present day — it's your choice. [Note: "mya" means "millions of years ago"]

Ways to begin your exploration:

- Use the links in the "time machine" below and explore a specific period that interests you.
- Read more about the geologic time scale, its origins and its time divisions.
- Find out more about plate tectonics, an important geological concept in any time period!

Phanerozoic (542.0 mya to present)	Cenozoic (65.5 mya to present)	Quaternary (2.588 mya to present) Holocene (11,700 yrs to present) Pleistocene (2.588 mya to 11,700 yrs)
		Neogene (23.03 to 2.588 mya) Pliocene (5.332 to 2.588 mya) Miocene (23.03 to 5.332 mya)
		Paleogene (65.5 to 23.03 mya) Oligocene (33.9 to 23.03 mya) Eocene (55.8 to 33.9 mya) Paleocene (65.5 to 55.8 mya)
	Mesozoic (251.0 to 65.5 mya)	Cretaceous (145.5 to 65.5 mya) Upper (99.6 to 65.5 mya) Lower (145.5 to 99.6 mya)
		Jurassic (199.6 to 145.5 mya) Upper (161.2 to 145.5 mya) Middle (175.6 to 161.2 mya) Lower (199.6 to 175.6 mya)
		Triassic (251.0 to 199.6 mya) Upper (228.7 to 199.6 mya) Middle (245.9 to 228.7 mya) Lower (251.0 to 245.9 mya)

	Paleozoic (542.0 to 251.0 mya)	Permian (299.0 to 251.0 mya) Lopingian (260.4 to 251.0 mya) Guadalupian (270.6 to 260.4 mya) Cisuralian (299.0 to 270.6 mya)
		Carboniferous (359.2 to 299.0 mya) Pennsylvanian (318.1 to 299.0 mya) Upper (307.2 to 299.0 mya) Middle (311.7 to 307.2 mya) Lower (318.1 to 311.7 mya) Mississippian (359.2 to 318.1 mya) Upper (328.3 to 318.1 mya) Middle (345.3 to 328.3 mya) Lower (359.2 to 345.3 mya)
		Devonian (416.0 to 359.2 mya) Upper (385.3 to 359.2 mya) Middle (397.5 to 385.3 mya) Lower (416.0 to 397.5 mya)
		Silurian (443.7 to 416.0 mya) Pridoli (418.7 to 416.0 mya) Ludlow (422.9 to 418.7 mya) Wenlock (428.2 to 422.9 mya) Llandovery (443.7 to 428.2 mya)
		Ordovician (488.3 to 443.7 mya) Upper (460.9 to 443.7 mya) Middle (471.8 to 460.9 mya) Lower (488.3 to 471.8 mya)
		Cambrian (542.0 to 488.3 mya) Furongian (499 to 488.3 mya) Series 3 (510 to 499 mya) Series 2 (521 to 510 mya) Terreneuvian (542.0 to 521 mya)
Precambrian (4600 to 542.0 mya)	Proterozoic (2500 to 542.0 mya)	Neoproterozoic (1000 to 542.0 mya)
		Mesoproterozoic (1600 to 1000 mya)
		Paleoproterozoic (2500 to 1600 mya)
	Archean (4000 to 2500 mya)	Neoarchean (2800 to 2500 mya)
		Mesoarchean (3200 to 2800 mya)
		Paleoarchean (3600 to 3200 mya)
		Eoarchean (4000 to 3600 mya)
	Hadean (4600 to 4000 mya)	

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009; colors adopted from the Commission for the Geological Map of the World, 5/26/2011.

Allen G. Collins created this page, 11/26/94; Robert Guralnick and Brian R. Speer made revisions, 9/15/95; Brian R. Speer made further modifications, 6/4/98; Allen G. Collins reordered the time units with younger times above older times, 12/14/98; Sarah Rieboldt updated the page using the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith created a new geologic time table using the ICS dates, adapted the page to the new site format, and made some content changes, 5/26/2011

The Pliocene Epoch

The picture below shows a modern herd of zebra grazing on an African savanna. Grazing mammals, such as the perissodactyls and artiodactyls diversified in the Miocene and Pliocene as grasslands and savanna spread across most continents.

The Pliocene, 5.3 to 2.6 million years ago,* was a time of global cooling after the warmer Miocene. The cooling and drying of the global environment may have contributed to the enormous spread of grasslands and savannas during this time. The change in vegetation undoubtedly was a major factor in the rise of long-legged grazers who came to live in these areas.

Additionally, the Panamanian land-bridge between North and South America appeared during the Pliocene, allowing migrations of plants and animals into new habitats. Of even greater impact was the accumulation of ice at the poles, which would lead to the extinction of most species living there, as well as the advance of glaciers and ice ages of the Late Pliocene and the following Pleistocene.

Tectonics and paleoclimate

The epoch was marked by a number of significant tectonic events that created the landscape we know today. One such event was the joining of the tectonic plates of North and South America. This joining was brought about by a shift of the Caribbean Plate, which moved slightly eastwards and formed a land bridge across the Isthmus of Panama. The connection between North and South America had a significant impact on flora and fauna in two respects: (1) On land, the creation of a land bridge enabled species to migrate between the two continents. This led to a migration of armadillo, ground sloth, opposum, and porcupines from South to North America and an invasion of dogs, cats, bears and horses in the opposite direction. (2) The joining of the two tectonic plates also led to changes in the marine environment. An environment with species that had been interacting for billions of years now became separated into the Atlantic and Pacific Oceans. This in turn had a significant impact on the evolution of the species which became isolated from each other.

During the Pliocene the tectonic plates of India and Asia also collided, which formed the Himalayas. In North America, the Cascades, Rockies, Appalachians, and the Colorado plateaus were uplifted, and there was activity in the mountains of Alaska and in the Great Basin ranges of Nevada and Utah. The end of the Pliocene was marked in North America by the Cascadian revolution, during which the Sierra Nevada was elevated and tilted to the west. In Europe, many mountain ranges built up, including the Alps, which were folded and thrusted.

Over the course of the Pliocene, the global climate became cooler and more arid. The beginning of the epoch saw numerous fluctuations in temperature, which gave way to the general cooling trend towards the end of the Pliocene. This long term cooling, actually started in the Eocene and continued up to the ice ages of the Pleistocene. During the Pliocene, large polar ice caps started to develop and Antarctica became the frozen continent that it is today.

It is uncertain what caused this climate cooling during the Pliocene. Changes in the amount of heat transported by oceans has been suggested as one possible explanation; higher concentrations of greenhouse gases in the atmosphere may also have contributed. It is also possible that the raising of the Himalayas, caused by plate collisions between India and Asia, accelerated the cooling process.

Generally though, the climate of the Pliocene is thought to have been much warmer than it is today. The warmest phase was in the middle of the epoch, the interval between three and four million years ago. The climate was especially mild at high latitudes and certain species of both plants and animals existed several hundred kilometers north of where their nearest relatives exist today. Less ice at the poles also resulted in a sea level that is thought to have been about 30 meters higher than today's.

Accompanying the general cooling trend of the Pliocene was, as already mentioned, an increased aridity. This led to a number of noteworthy changes in the environment. The Mediterranean Sea dried up completely and remained plains and grasslands for the next several million years. Another environmental change was the replacement of many forests by grasslands. This in turn favored grazing animals, at the expense of browsers. Generally, these grazers became larger and developed larger teeth suitable for a diet of grass. Also, the longer legs they developed enabled them to walk long distances to new feeding grounds and to detect and escape predators. It was also during this time that some apes came down from trees and started to exist on the plains in Africa. In fact, it is generally believed that *Australopithecus* evolved in the late Pliocene.

Localities

- **Bodjong Formation, Indonesia:** A rich plant community from this locality includes pine, fir, barberry, and a variety of other species all very well preserved.

Resources

- Find out more about the Tertiary paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Pliocene.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

David Polly created the original pages 4/30/1994; Brian Speer updated the format 10/4/1995; the material on tectonics and paleoclimate was added by Samir Patel, Richard Chang, Adia Jackson, Pia Sorenson, and Ying-Ying Wu as part of a Biology 1B project for Section 112 under Brian Speer 5/1/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/10/2011; zebras photo by Dr. Robert T. and Margaret Orr © 1999 California Academy of Sciences.

The Miocene Epoch

At right is pictured (in front), *Chalicotherium*, a Miocene mammal from Kazakhstan. *Chalicotherium* was an unusual "odd-toed" hoofed mammal, or perissodactyl. Both the perissodactyls and artiodactyls underwent a period of rapid evolution during the Miocene.

The Miocene Epoch, 23.03 to 5.3 million years ago,* was a time of warmer global climates than those in the preceeding Oligocene or the following Pliocene and it's notable in that two major ecosystems made their first appearances: kelp forests and grasslands. The expansion of grasslands is correlated to a drying of continental interiors as the global climate first warmed and then cooled.

Life

The overall pattern of biological change for the Miocene is one of expanding open vegetation systems (such as deserts, tundra, and grasslands) at the expense of diminishing closed vegetation (such as forests). This led to a rediversification of temperate ecosystems and many morphological changes in animals. Mammals and birds in particular developed new forms, whether as fast-running herbivores, large predatory mammals and birds, or small quick birds and rodents.

Plant studies of the Miocene have focused primarily on spores and pollen. Such studies show that by the end of the Miocene 95% of modern seed plant families existed, and that no such families have gone extinct since the middle of the Miocene. A mid-Miocene warming, followed by a cooling is considered responsible for the retreat of tropical ecosystems, the expansion of northern coniferous forests, and increased seasonality. With this change came the diversification of modern graminoids, especially grasses and sedges.

In addition to changes on land, important new ecosystems in the sea led to new forms there. Kelp forests appeared for the first time, as did sea otters and other critters unique to those environments. At the same time, such ocean-going mammals as the Desmostylia went extinct.

Tectonics and paleoclimate

The Miocene saw a change in global circulation patterns due to slight position changes of the continents and globally warmer climates. Conditions on each continent changed somewhat because of these positional changes, however it was an overall increase in aridity through mountain-building that favored the expansion of grasslands. Because the positions of continents in the Miocene world were similar to where they lie today, it is easiest to describe the plate movements and resulting changes in the paleoclimate by discussing individual continents.

In North America, the Sierra Nevada and Cascade Mountain ranges formed, causing a non-seasonal and drier mid-continent climate. The increasing occurrences of drought and an overall decrease in absolute rainfall promoted drier climates. Additionally, grasslands began to spread, and this led to an evolutionary radiation of open-habitat herbivores and carnivores. The first of the major periods of immigration via the Bering land connection between Siberia and Alaska occurred in the middle of the Miocene, and by the end of the Miocene the Panama isthmus had begun to form between Central and South America.

Plate tectonics also contributed to the rise of the Andes Mountains in South America, which led to the formation of a rain shadow effect in the southeastern part of the continent. The movement of the plates also facilitated trends favoring non-desert and highland environments. 11

In Australia, the climate saw an overall increase in aridity as the continent continued to drift northwards, though it went through many wet and dry periods. The number of rainforests began to decrease and were replaced by dry forests and woodlands. The vegetation began to shift from closed broad-leaved forests to more open, drier forests as well as grasslands and deserts.

Eurasia also experienced increasing aridification during the Miocene. Extensive steppe vegetation began to appear, and the grasses became abundant. In southern Asia, grasslands expanded, generating a greater diversity of habitats. However, southern Asia was not the only area to experience an increase in habitat variability. Southern Europe also saw an increase in grasslands, but maintained its moist forests. Although most of Eurasia experienced increasing aridity, some places did not. The climate in some Eurasian regions, such as Syria and Iran, remained wet and cool.

During the Miocene, Eurasia underwent some significant tectonic rearrangements. The Tethys Sea connection between the Mediterranean and Indian Ocean was severed in the mid-Miocene causing an increase in aridity in southern Europe (see next paragraph for more on this). The Paratethys barrier, which isolated western Europe from the exchange of flora and fauna, was periodically disrupted, allowing for the migration of animals. Additionally, faunal routes with Africa were well established and occasional land bridges were created.

Africa also encountered some tectonic movement, including rifting in East Africa and the union of the African-Arabian plate with Eurasia. Associated with this rifting, a major uplift in East Africa created a rain shadow effect between the wet Central-West Africa and dry East Africa. The union of the continents of Africa and Eurasia caused interruption and contraction of the Tethys Sea, thereby depleting the primary source of atmospheric moisture in that area. Thus rainfall was significantly reduced, as were the moderating effects of sea temperature on the neighboring land climates. However, this union enabled more vigorous exchanges of flora and fauna between Africa and Eurasia.

Antarctica became isolated from the other continents in the Miocene, leading to the formation of a circumpolar ocean circulation. Global ocean and atmospheric circulation were also affected by the formation of this circumpolar circulation pattern, as it restricted north-south circulation flows. This reduced the mixing of warm, tropical ocean water and cold, polar water causing the buildup of the Antarctic polar ice cap. This enhanced global cooling and accelerated the development of global seasonality and aridity.

Stratigraphy

The Miocene was first recognized and defined by Charles Lyell in the early nineteenth century. While examining rocks in the Paris Basin, he noted that different strata contained varying percentages of living mollusc species. The Miocene consisted of layers in which only 18% of the fossils were represented among living mollusc species.

Stratigraphy within the Miocene, as with much of the Cenozoic, is often defined on a highly regional basis. Terrestrial faunas are recognized in *ages* which vary from continent to continent, primarily because the animals themselves varied from place to place. These ages are usually defined on the basis of the land mammals, so that North America, Europe, Australia, etc., each have their own Land Mammal Ages. Read more about the North American Land Mammal Age (NALMA) on Wikipedia.

For marine stratigraphy, diatoms and foraminifera are the primary groups used to recognize ages. By this time, both groups were abundant and diversified globally, so much so that diatomite is a common marine sediment of the Miocene. Because the diatoms are abundant, and make up a large portion of many marine deposits, they are particularly useful for identifying the relative ages of fossil deposits.

Localities

- **Monterey Formation, California:** Vast area with exposed outcrops along the coastal ranges of California contains fossils of macroalgae, microfossils, shells, crabs, and porpoises.
- **Villavieja Formation, Colombia:** Our only good source of information about Tertiary animals in the South American tropics. Many of these groups have been found nowhere else outside of the continent.

Resources and references

- Behrensmeyer, A.K., et al. 1992. *Terrestrial Ecosystems Through Time: Evolutionary Paleoecology of Terrestrial Plants and Animals*. Chicago: University of Chicago Press.
- Find out more about the Tertiary paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Miocene.

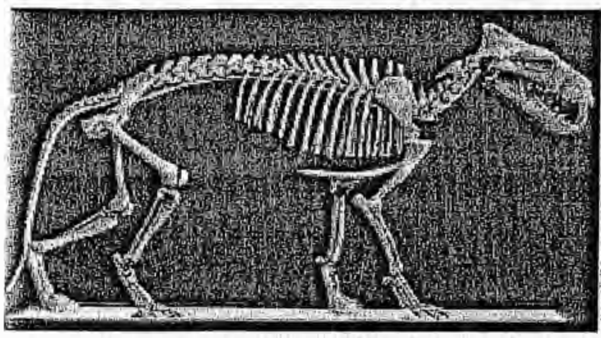
* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

David Polly created the original content 4/30/1994; Brian Speer updated and expanded the content 7/14/1997; the material on tectonics and paleoclimate was added by Lucy Brining, Valerie Chan, Ellen Choi, Michael De Sosa, and Christina Lee as part of a Biology 1B project for Section 112 under Brian Speer 5/1/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/10/2011; *Chalicotherium* photo assumed to be by Dr. Alexander Lavrov, Paleontological Institute, Russia

The Oligocene Epoch

The Oligocene Epoch, right smack in the middle of the Tertiary Period (and end of the Paleogene), lasted from about 33.9 to 23 million years ago.* Although it lasted a "short" 11 million years, a number of major changes occurred during this time. These changes include the appearance of the first elephants with trunks, early horses, and the appearance of many grasses — plants that would produce extensive grasslands in the following epoch, the Miocene.

Life



Hyaenodon horridus, a large carnivorous mammal from the White River Oligocene of South Dakota. Deposits containing *Hyaenodon* are found in Badlands National Park.

As a result of the cooling trend prevalent throughout the Oligocene Epoch, the lives and habitats of many organisms were directly affected. In the oceans, marine biotic provinces became more fragmented as sea dwellers capable of withstanding cooler temperatures congregated to places further from the warmer equator, where other species could better survive. The cooling trend was also responsible for the reduced diversity in marine plankton, the foundation of the food chain.

On land, mammals such as horses, deer, camel, elephants, cats, dogs, and primates began to dominate, except in Australia. The continuation of land mammal faunal migration between Asia and North America was responsible for the dispersion of several lineages to new continents. Early forms of amphicyonids, canids, camels, tayassuids, protoceratids, and anthracotheres appeared, as did caprimulgiformes, birds that possess gaping mouths for catching insects. Diurnal raptors, such as falcons, eagles, and hawks, along with seven to ten families of rodents also first appeared during the Oligocene. The "bulk feeding" in the open grasslands and savannas that occurred in this period resulted in the increase of general herbivore size. As an example, ungulates continued to get larger throughout the Oligocene.

The early Oligocene was marked by a multitude of different events ranging from the appearance of new groups such as elephants to the decline in taxonomic diversity in middle- and high-latitude forests. "Micro-mammals" experienced a period of diversification, as did the marsupials in Australia. This period was also marked by a relative free change of animals among northern continents, as evidenced by the similarity in vertebrate faunas.

In North America, the cricetids (voles and hamsters) first appeared while the mesothermal dicotyledons (a group of flowering plants) went extinct. South America became dominated by forests, and the first primates appeared in Africa. Primates found in Southeast Asia during this period represent primitive members of the New World and Old World higher primates.

In western Europe, an extraordinary, sudden change in the fauna, known as the Grand Coupure, occurred. This event involved the immigration of many new taxa, artiodactyls and perissodactyls in particular (e.g., rhinocerotoids, chalicotheriids, anthracotheres, and tayassuids), from areas to the east and the extinction of many Eocene genera and species. At least 17 generic extinctions, 20 first appearances, and 25 unaffected genera of mammals are represented across the Eocene-Oligocene boundary in western Europe.

On a global scale, broad-leaved evergreen vegetation became restricted to 35° latitude around the equator, and megathermal, multistratal vegetation was confined to 15° latitude around the equator. Broad-leaved evergreen plants became increasingly confined to lower latitudes in Eurasia, and microthermal, broad-leaved forest became common over large regions of the Northern Hemisphere.

The mid-Oligocene was marked by a worldwide marine regression; this included a decline in the total number of marine species. On land, the first of the open grassland faunas appeared in Mongolia while in North America, microthermal broad-leaved deciduous forests extended further into southern regions typified before by evergreen species and for the first time in history covered vast regions of the Northern Hemisphere.

The late Oligocene was marked by the expansion of grasslands and prairies that were intimately linked to the expansion of grazing animals. Grasses and composites increased in abundance on the global scale, and humid forests became increasingly common in the southern parts of South America. Horses experienced a period of diversification; anatomical modifications in horses indicate an increase in cursoriality compared to more primitive ancestors. Primitive beavers appeared and the earliest of the New World monkeys inhabited South America.

The late Oligocene Deseadan record includes two major groups that are thought to represent early waif dispersals from other continents. One of these, the caviomorph rodents (e.g., porcupines, capybaras, chinchillas, and a wide assortment of smaller forms), was the only group of rodents in South America until the Plio-Pleistocene. They diversified into 16 families, only two of which are now extinct. The second group of early immigrants was the primates.

Localities

- **Creede Formation, Colorado:** A rich plant community from this locality includes pine, fir, barberry, and a variety of other species all very well preserved.

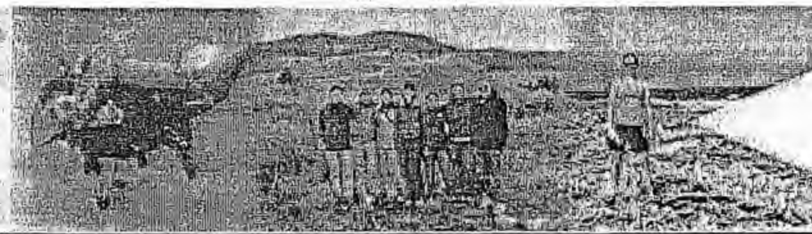
Resources

- Find out more about the Tertiary paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Oligocene.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

P. David Polly created the original content 4/30/1994; Brian R. Speer updated the format 10/4/1995 and split the content into five pages 7/7/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/10/2011; source of *Hyaenodon* photo is unknown.

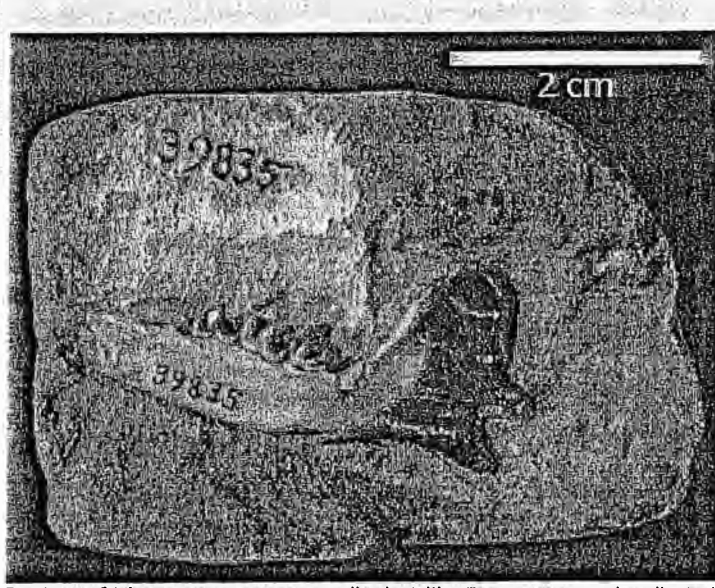
University of California Museum of Paleontology



See the world (and its fossils) with UCMP's field notes.

The Eocene Epoch

The Eocene is the second of five epochs in the Tertiary Period — the second of three epochs in the Paleogene — and lasted from about 55.8 to 33.9 million years ago.* The oldest known fossils of most of the modern orders of mammals appear in a brief period during the early Eocene and all were small, under 10 kg. Both groups of modern ungulates, Artiodactyla and Perissodactyla, became prevalent mammals at this time, due to a major radiation between Europe and North America.



Dentary of *Viverravus acutus*, a small, civet-like Eocene mammal, collected by Malcolm McKenna, Big Horn County, WY, 1950.

Tectonics and paleoclimate

The early Eocene (Ypresian) is thought to have had the highest mean annual temperatures of the entire Cenozoic Era, with temperatures about 30° C; relatively low temperature gradients from pole to pole; and high precipitation in a world that was essentially ice-free. Land connections existed between Antarctica and Australia, between North America and Europe through Greenland, and probably between North America and Asia through the Bering Strait. It was an important time of plate boundary rearrangement, in which the patterns of spreading centers and transform faults were changed, causing significant effects on oceanic and atmospheric circulation and temperature.

In the middle Eocene, the separation of Antarctica and Australia created a deep water passage between those two continents, creating the circum-Antarctic Current. This changed oceanic circulation patterns and global heat transport, resulting in a global cooling event observed at the end of the Eocene.

By the Late Eocene, the new ocean circulation resulted in a significantly lower mean annual temperature, with greater variability and seasonality worldwide. The lower temperatures and increased seasonality drove increased body size of mammals, and caused a shift towards increasingly open savanna-like vegetation, with a corresponding reduction in forests.

Localities

- **Florissant Formation, Colorado:** Few localities have such remarkably preserved fossil insects as this Rocky Mountain site.
- **Green River Formation:** Rich in fossils of plants, insects, and fish, this American locality extends across Utah, Colorado, and Wyoming.

Resources

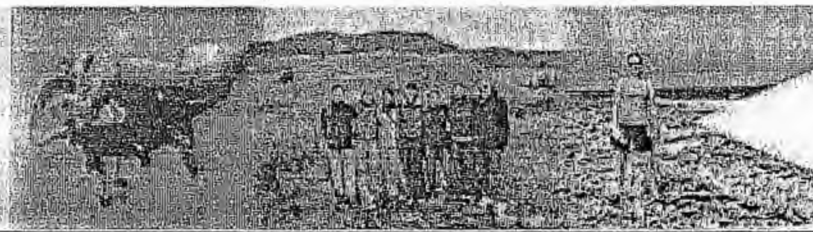
- Find out more about the Tertiary paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Eocene.

Note: For information on the Paleocene Epoch, 65.5 to 55.8 million years ago,* see the Wikipedia page.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

David Polly created the original pages 4/30/1994; Brian Speer updated the format 10/4/1995; Brian Speer added more pages 8/29/1999; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page and adapted it to the new site format, 6/15/2011; *Viverravus acutus* specimen from the UCMP vertebrate collections, photographer unknown

University of California Museum of Paleontology



See the world (and its fossils) with UCMP's field notes.

The Cenozoic Era

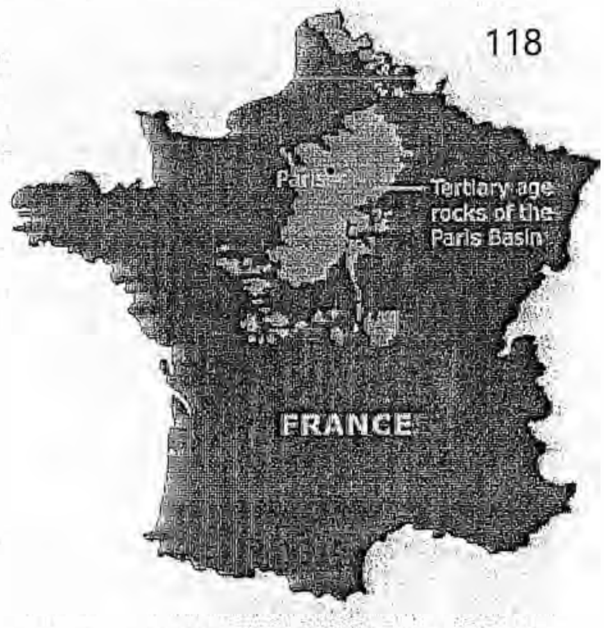
The Cenozoic Era is the most recent of the three major subdivisions of animal history. The other two are the Mesozoic and Paleozoic Eras. The Cenozoic spans only about 65 million years, from the end of the Cretaceous Period and the extinction of non-avian dinosaurs to the present. The Cenozoic is sometimes called the Age of Mammals, because the largest land animals have been mammals during that time. This is a misnomer for several reasons. First, the history of mammals began long before the Cenozoic began. Second, the diversity of life during the Cenozoic is far wider than mammals. The Cenozoic could have been called the "Age of Flowering Plants" or the "Age of Insects" or the "Age of Teleost Fish" or the "Age of Birds" just as accurately.

The Cenozoic (65.5 million years ago to present) is divided into three periods: the Paleogene (65.5 to 23.03 million years ago), Neogene (23.03 to 2.6 million years ago) and the Quaternary (2.6 million years ago to present). Paleogene and Neogene are relatively new terms that now replace the deprecated term, Tertiary. The Paleogene is subdivided into three epochs: the Paleocene (65.5 to 55.8 million years ago), the Eocene (55.8 to 33.9 million years ago), and the Oligocene (33.9 to 23.03 million years ago). The Neogene is subdivided into two epochs: the Miocene (23.03 to 5.332 million years ago) and Pliocene (5.332 to 2.588 million years ago).*

Stratigraphy

The concepts of Tertiary and Quaternary have an interesting history. In the 1760s and 1770s a geologist named Giovanni Arduino was studying the rocks and minerals in Tuscany. He classified mountains according to the type of rocks that he found in them. Unfossiliferous schists, granites, and basalts (all volcanic rocks) that formed the cores of large mountains he called Primitive. Fossil-rich rocks of limestone and clay that were found on the flanks of mountains over the Primitive rocks were called Secondary. Finally, there were another group of fossiliferous rocks of limestones and sandstones lying over the Secondary rocks and forming the foothills of the mountains that Anduino called Tertiary. So at first, Tertiary referred to a certain type of rock found in the area of Tuscany. But later, geologists used the fossils found in the Tertiary rocks there to recognize rocks of the same age elsewhere. Rocks with the same species of fossils were the same age.

Extensive Tertiary age rocks were recognized in the Paris Basin, which is the area around Paris, France. In the 1820s and 1830s Charles Lyell, a noted English geologist who had a great influence on Charles Darwin, subdivided the Tertiary rocks of the Paris Basin on their fossils. Lyell came up with an ingenious idea. He noticed that the rocks at the top of the section had a very high percentage of fossils of living mollusc species. Those at the bottom of the section had very few living forms. He deduced that this difference was because of the extinction of older forms and the evolution of living forms during the time that the rocks were being deposited. He divided the Tertiary rocks into three sub-ages: the Pliocene, the Miocene, and the Eocene. 90% of the fossil molluscs in Pliocene rocks were living today. In the Miocene rocks, only 18% of the molluscs were of living species, and in Eocene rocks, only 9.5%.



These subdivisions of the Tertiary have been correlated around the world using the fossil species in them. Rocks with the same species as Lyell's Eocene, are considered to be the same age as those in the Paris Basin. The same goes for the other subdivisions. Some time later it was noted that in areas other than the Paris Basin, there were rocks that seemed to be from time periods that were not represented in Lyell's sequence. This was because during those periods there had been no deposition in what would later be the Paris Basin. These two periods, later designated Oligocene and Paleocene, were inserted into the Tertiary in their proper places.

Cenozoic fossil localities

- **Bodjong Formation, Indonesia:** Numerous deep-water molluscs from this Pliocene locality have given us a picture of past tropical marine life in what is today a very species rich area.
- **Creede Formation:** A rich plant community from this Oligocene locality in southwestern Colorado includes pine, fir, barberry, and a variety of other species, all very well preserved.
- **Florissant Formation:** This Eocene locality lies in the Rocky Mountains of Colorado. Few U.S. localities have such remarkable preservation of fossil insects.
- **Green River Formation:** Rich in fossils of plants, insects, and fish, this Eocene locality extends across Utah, Colorado, and Wyoming in the western U.S.
- **Rancho La Brea Tar Pits:** One of the most famous fossil localities of all, La Brea is an asphalt seep containing Pleistocene fossils located in Los Angeles, California.
- **Monterey Formation:** Vast area of exposed Miocene outcrops along the coastal ranges of California. Fossils include macroalgae, microfossils, shells, crabs, and porpoises.
- **Villavieja Formation, Colombia:** Until recently, our only good source of information about Tertiary animals in the South American tropics was this site in Colombia. Many of the pre-Pliocene animal groups represented have been found nowhere else outside of the continent.

Resources

- For information about other Cenozoic localities, see our pages on the Eocene, Oligocene, and Miocene.
- Take a tour of the world's largest paleo institute, the Paleontological Institute of Russia, which includes many Cenozoic mammals from Russia.
- NEOMAP — The databases of MIOMAP and FAUNMAP are now linked, providing data for all published late Oligocene through Holocene mammals in the U.S.
- Find out more about the Cenozoic paleontology and geology of North America at the Paleontology Portal.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2008.

David Polly, Rob Guralnick, and Allen Collins all worked on the earliest versions of this page; Brian Speer made revisions and broke the single page into several pages, 3/6/1997; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format, corrected dates and made minor edits, 6/2011

University of California Museum of Paleontology

See the world (and its fossils) with UCMP's field notes.

The Cretaceous Period

The Cretaceous is usually noted for being the last portion of the "Age of Dinosaurs", but that does not mean that new kinds of dinosaurs did not appear then. It is during the Cretaceous that the first ceratopsian and pachycepalosaurid dinosaurs appeared. Also during this time, we find the first fossils of many insect groups, modern mammal and bird groups, and the first flowering plants.

The breakup of the world-continent Pangea, which began to disperse during the Jurassic, continued. This led to increased regional differences in floras and faunas between the northern and southern continents.

The end of the Cretaceous brought the end of many previously successful and diverse groups of organisms, such as non-avian dinosaurs and ammonites. This laid open the stage for those groups which had previously taken secondary roles to come to the forefront. The Cretaceous was thus the time in which life as it now exists on Earth came together.

Life

No great extinction or burst of diversity separated the Cretaceous from the Jurassic Period that had preceded it. In some ways, things went on as they had. Dinosaurs both great and small moved through forests of ferns, cycads, and conifers. Ammonites, belemnites, other molluscs, and fish were hunted by great "marine reptiles," and pterosaurs and birds flapped and soared in the air above. Yet the Cretaceous saw the first appearance of many lifeforms that would go on to play key roles in the coming Cenozoic world.

Perhaps the most important of these events, at least for terrestrial life, was the first appearance of the flowering plants, also called the angiosperms or Anthophyta. First appearing in the Lower Cretaceous around 125 million years ago, the flowering plants first radiated in the middle Cretaceous, about 100 million years ago. Early angiosperms did not develop shrub- or tree-like morphologies, but by the close of the Cretaceous, a number of forms had evolved that any modern botanist would recognize. The angiosperms thrived in a variety of environments such as areas with damper climates, habitats favored by cycads and cycadeoids, and riparian zones. High southern latitudes were not invaded by angiosperms until the end of the Cretaceous. Ferns dominated open, dry and/or low-nutrient lands. Typical Jurassic vegetation, including conifers, cycads, and other gymnosperms, continued on into the Lower Cretaceous without significant changes. At the beginning of this period, conifer diversity was fairly low in the higher latitudes of the Northern Hemisphere, but by the middle of the period, species diversification was increasing exponentially. Swamps were dominated by conifers and angiosperm dicots.

At about the same time, many modern groups of insects were beginning to diversify, and we find the oldest known ants and butterflies. Aphids, grasshoppers, and gall wasps appear in the Cretaceous, as well as termites and ants in the later part of this period. Another important insect to evolve was the eusocial bee, which was integral to the ecology and evolution of flowering plants.

The Cretaceous also saw the first radiation of the diatoms in the oceans (freshwater diatoms did not appear until the Miocene).

The Cretaceous-Tertiary extinction

The most famous of all mass extinctions marks the end of the Cretaceous Period, about 65 million years ago. As everyone knows, this was the great extinction in which the dinosaurs died out, except for the birds, of course. The other lineages of "marine reptiles" — the ichthyosaurs, plesiosaurs, and mosasaurs — also were extinct by the end of the Cretaceous, as were the flying pterosaurs, but some, like the ichthyosaurs, were probably extinct a little *before* the end of the Cretaceous. Many species of foraminiferans went extinct at the end of the Cretaceous, as did the ammonites. But many groups of organisms, such as flowering plants, gastropods and pelecypods (snails and clams), amphibians, lizards and snakes, crocodilians, and mammals "sailed through" the Cretaceous-Tertiary boundary, with few or no apparent extinctions at all.

What on Earth — or not — caused this extinction and how can we know? What killed the dinosaurs?

Tectonics and paleoclimate

The Cretaceous is defined as the period between 145.5 and 65.5 million years ago,* the last period of the Mesozoic Era, following the Jurassic and ending with the extinction of the dinosaurs (except birds). By the beginning of the Cretaceous, the supercontinent Pangea was already rifting apart, and by the mid-Cretaceous, it had split into several smaller continents. This created large-scale geographic isolation, causing a divergence in evolution of all land-based life for the two new land masses. The rifting apart also generated extensive new coastlines, and a corresponding increase in the available near-shore habitat. Additionally, seasons began to grow more pronounced as the global climate became cooler. Forests evolved to look similar to present day forests, with oaks, hickories, and magnolias becoming common in North America by the end of the Cretaceous.

At the end of the Cretaceous Period, 65 million years ago, an asteroid hit Earth in the Yucatan Peninsula, Mexico, forming what is today called the Chicxulub impact crater. It has been estimated that half of the world's species went extinct at about this time, but no accurate species count exists for all groups of organisms. Some have argued that many of the species to go extinct did so before the impact, perhaps because of environmental changes occuring at this time. Whatever its cause, this extinction event marks the end of the Cretaceous Period and of the Mesozoic Era.

Localities

- **Clayton Lake, New Mexico:** This Cretaceous site has some of the most extensive and best preserved dinosaur trackways in the United States.
- **Pt. Loma Formation, California:** This Cretaceous locality has yielded important fossils for understanding western North American dinosaurs.

Resources

- Find out more about the Cretaceous paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Cretaceous.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Ben Waggoner created the original content, 11/26/1995; Brian Speer added graphics, 3/11/1997, and additional text, 2/1/1998; the material on tectonics and paleoclimate was added by Quynh-Huong Bui, Julia Davis, Ariane Helou, Saro Manoukian, and Musetta So as part of a Biology 1B project for Section 112 under Brian Speer, 5/1/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/15/2011

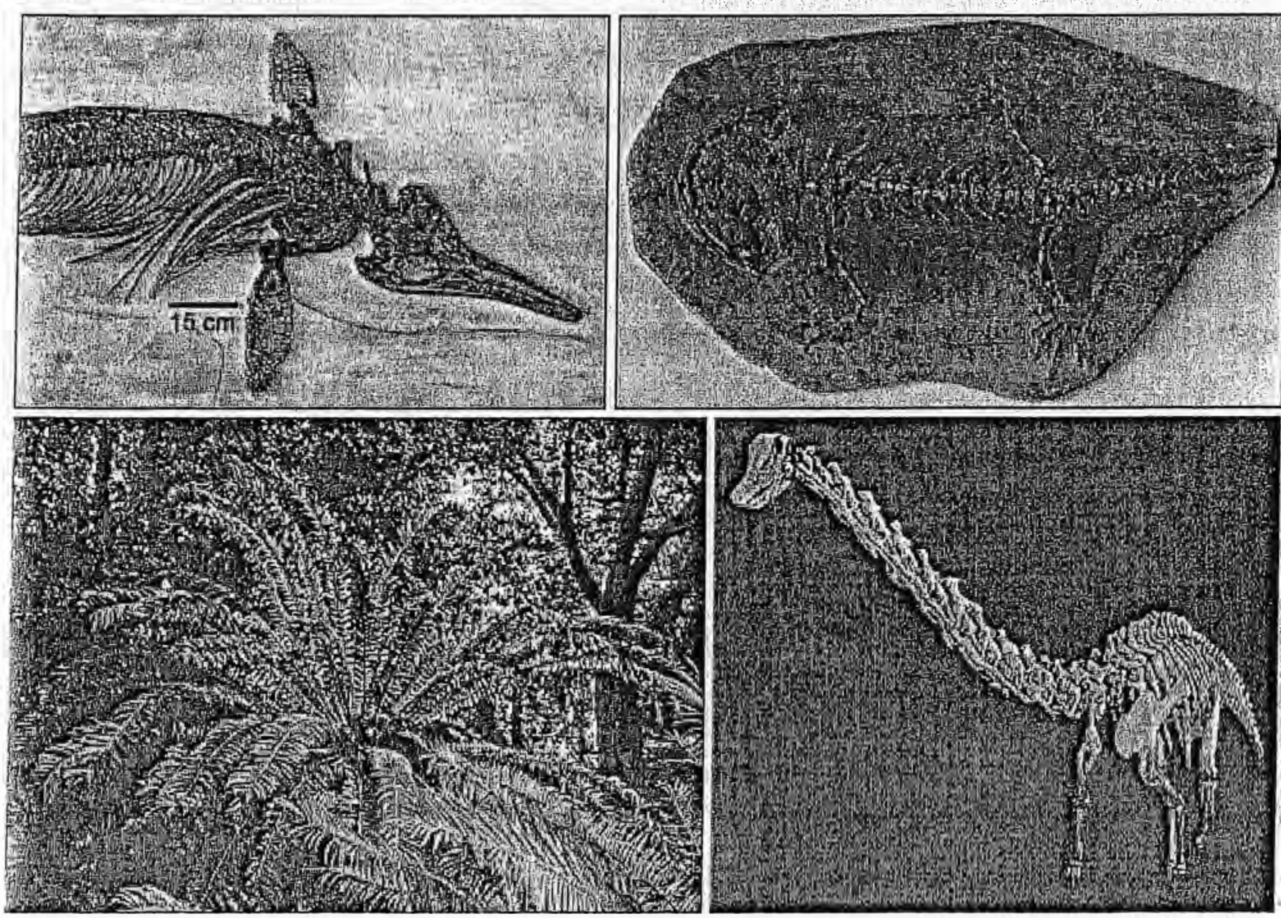
University of California Museum of Paleontology

See the world (and its fossils) with UCMP's field notes.

The Jurassic Period

Great plant-eating dinosaurs roaming the earth, feeding on lush ferns and palm-like cycads and bennettitaleans ... smaller but vicious carnivores stalking the great herbivores ... oceans full of fish, squid, and coiled ammonites, plus great ichthyosaurs and long-necked plesiosaurs ... vertebrates taking to the air, like the pterosaurs and the first birds. This was the Jurassic Period, 199.6 to 145.5 million years ago* — a 54-million-year chunk of the Mesozoic Era.

Named for the Jura Mountains on the border between France and Switzerland, where rocks of this age were first studied, the Jurassic has become a household word with the success of the movie *Jurassic Park.* Outside of Hollywood, the Jurassic is still important to us today, both because of its wealth of fossils and because of its economic importance — the oilfields of the North Sea, for instance, are Jurassic in age.



Clockwise from top left, *Ichthyosaurus intermedius*, a Lower Jurassic ichthyosaur from Glastonbury, England. *Karaurus sharovi*, one of the earliest known salamanders, from Kazakhstan. *Diplodocus*, a large, long-necked sauropod. Modern cycads.

Life

Today, the name "Jurassic" conjures up images of the phenomenally successful book and movie, *Jurassic Park*. It is quite true that the dinosaurs dominated the land fauna — although many of the dinosaurs featured in *Jurassic Park*, such as Triceratops and Tyrannosaurus rex, did not evolve until after the Jurassic was over. The largest dinosaurs of the time — in fact, the largest land animals of all time — were the gigantic sauropods, such as the famous *Diplodocus* (top right, above), *Brachiosaurus* and *Apatosaurus*. Other herbivorous dinosaurs of the Jurassic included the plated stegosaurs. Predatory dinosaurs of the Jurassic included fearsome carnosaurs such as *Allosaurus*, small, fast coelurosaurs, and ceratosaurs such as *Dilophosaurus*. The Jurassic also saw the origination of the first birds, including the well-known *Archaeopteryx*, probably from coelurosaurian ancestors.

But there was more to life than dinosaurs! In the seas, the fishlike ichthyosaurs (top left, above) were at their height, sharing the oceans with the plesiosaurs, giant marine crocodiles, and modern-looking sharks and rays. Also prominent in the seas were cephalopods — relatives of the squids, nautilus, and octopi of today. Jurassic cephalopods included the ammonites, with their coiled external shells (upper left), and the belemnites, close relatives of modern squid but with heavy, calcified, bullet-shaped, partially internal shells. Among the plankton in the oceans, the dinoflagellates became numerous and diverse, as did the coccolithophorids (microscopic single-celled algae with an outer covering of calcareous plates).

Land plants abounded in the Jurassic, but floras were different from what we see today. Although Jurassic dinosaurs are sometimes drawn with palm trees, there were no palms or any other flowering plants — at least as we know them today — in the Jurassic. Instead, ferns, ginkgoes, bennettitaleans or "cycadeoids," and true cycads — like the living cycad pictured above, lower left — flourished in the Jurassic. Conifers were also present, including close relatives of living redwoods, cypresses, pines, and yews. Creeping about in this foliage, no bigger than rats, were a number of early mammals.

Localities

- **Blue Nile Gorge, Ethiopia:** Come along on a fossil-hunting trip to Ethiopia with UCMP researchers and see the first dinosaur fossils found there.
- **Solnhofen Limestone, Germany:** Exquisitely detailed fossils have come from these Jurassic deposits in southern Germany.

Resources

- Find out more about the Jurassic paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Jurassic.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Ben Waggoner created the original content, 9/10/1995 and 11/25-28/1995; Brian Speer made modifications, 11/27/1995; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/16/2011; *Ichthyosaurus* photo by Sarah Rieboldt, UCMP; *Karaurus* photo by Pat Holroyd, UCMP; source of *Diplodocus* photo is unknown; cycads photo by Dr. Robert T. and Margaret Orr © 2004 California Academy of Sciences.

University of California Museum of Paleontology

123

The Triassic Period

In many ways, the Triassic, lasting from 251.0 mya to 199.6 mya,* was a time of transition. It was at this time that the world-continent of Pangea existed, altering global climate and ocean circulation. The Triassic also follows the largest extinction event in the history of life, and so is a time when the survivors of that event spread and recolonized.

The organisms of the Triassic can be considered to belong to one of three groups: holdovers from the Permo-Triassic extinction, new groups which flourished briefly, and new groups which went on to dominate the Mesozoic world. The holdovers included the lycophytes, glossopterids, and dicynodonts. While those that went on to dominate the Mesozoic world include modern conifers, cycadeoids, and the dinosaurs.

Tectonics and paleoclimate

As with almost any other period of the Earth's history, the Triassic had a unique climate and biota indigenous to that time. The paleoclimate was influenced largely by tectonic events that never existed before or since.

At the beginning of the Triassic Period, the land masses of the world were still bound together into the vast supercontinent known as Pangea. Pangea began to break apart in the Middle Triassic, forming Gondwana (South America, Africa, India, Antarctica, and Australia) in the south and Laurasia (North America and Eurasia) in the north. The movement of the two resulting supercontinents was caused by sea floor spreading at the midocean ridge lying at the bottom of the Tethys Sea, the body of water between Gondwana and Laurasia. While Pangea was breaking apart, mountains were forming on the west coast of North America by subduction of the ocean plates beneath the continental plates. Throughout the Middle to Upper Triassic, mountain-forming continued along the coast extending from Alaska to Chile. As mountains were forming in the Americas, North Africa was being split from Europe by the spreading rift. This division of the continents advanced further westward, eventually splitting eastern North America from North Africa.

The climate of the Triassic Period was influenced by Pangea, its centralized position straddling the equator, and the geologic activity associated with its breakup. Generally speaking, the continents were of high elevation compared to sea level, and the sea level did not change drastically during the period. Due to the low sea level, flooding of the continents to form shallow seas did not occur. Much of the inland area was isolated from the cooling and moist effects of the ocean. The result was a globally arid and dry climate, though regions near the coast most likely experienced seasonal monsoons. There were no polar ice caps, and the temperature gradient in the north-south direction is assumed to have been more gradual than present day. The sea level rose as the rift grew between North Africa and southern Europe, resulting in the flooding of Central and South Europe; the climates of terrestrial Europe were hot and dry, as in the Permian. Overall, it appears that the climate included both arid dune environments and moist river and lake habitats with gymnosperm forests.

Some conclusions can be drawn about more specific regional climates and species based on experimental research. The presence of coal-rich sequences in the high northern and southern latitudes, as well as the presence of large amphibians there, indicates that the paleoclimate was wetter in those areas. Living species of some Mesozoic ferns (including the families Osmundacae and Dipteridacae) now live in wet, shady areas under forest canopies, so it is likely that the paleoclimate their Triassic ancestors inhabited were also damp and shaded. The Mesozoic era might also have had large, open areas with low-growing vegetation, including savannas or fern prairie with dry, nutrient poor soil populated by herbaceous plants, such as ferns of the families Matoniaceae and Gleicheniaceae. Thus, despite the union of the continental landmasses, the Triassic vegetation was quite provincial, though this decreased as the Triassic wore on. The northern forests at the beginning of the Triassic were dominated by conifers, ginkgos, cycads, and bennettitaleans, while the forests of Gondwana were dominated by *Dicroidium* and *Thinnfeldia*. By the end of the Triassic, both hemispheres gave way to conifer and cycad vegetation. 124

The Triassic-Jurassic boundary is similar to the Permo-Triassic boundary in that the global climate was not radically altered, though a major extinction of terrestrial vertebrates occurred. With the end of the Triassic and the beginning of the Jurassic, Pangea continued to break apart, inevitably affecting the climate, though not as radically as it had during the Triassic.

Localities

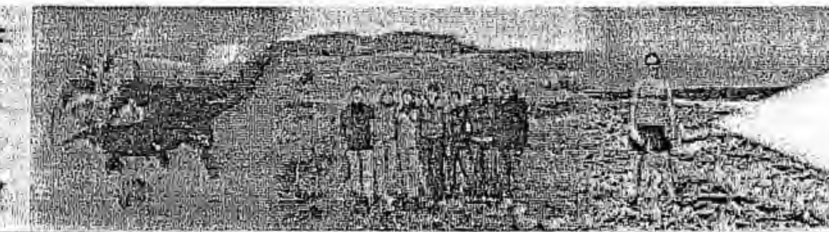
- **Ischigualasto Formation, Argentina:** The best-known and best-preserved early dinosaurs come from this Triassic locality in South America.

Resources and references

- Behrensmeyer, A.K., J.D. Damuth, W.A. Dimichelle, R. Potts, H.-D. Sues, and S. Wing 1992. Terrestrial ecosystems through time: Evolutionary paleoecology of terrestrial plants and animals. Chicago: University of Chicago Press. 588 pp.
- Long, R.A., and R. Houk. 1988. Dawn of the dinosaurs: The Triassic in Petrified Forest. Petrified Forest, AZ: Petrified Forest Museum Association. 96 pp.
- Read about the field work of UCMP alums Randy Irmis and Sterling Nesbitt as they search for information about dinosaur precursors in the Triassic Chinle Formation of New Mexico.
- See this National Park Service pdf on the Triassic dinosaurs and other animals of Petrified Forest National Park in Arizona.
- Find out more about the Triassic paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Triassic.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Brian R. Speer wrote the original text and posted this page, 3/9/1997; the material on tectonics and paleoclimate was added by Manish Asaravala, Hayley Lam, Stephanie Litty, Jason Phillips, and Ting-Ting Wu as part of a Biology 1B project for Section 112 under Brian Speer, 5/1/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/29/2011



Online exhibits : Geologic time scale : Paleozoic Era

The Permian Period

The Permian period lasted from 299 to 251 million years ago* and was the last period of the Paleozoic Era. The distinction between the Paleozoic and the Mesozoic is made at the end of the Permian in recognition of the largest mass extinction recorded in the history of life on Earth. It affected many groups of organisms in many different environments, but it affected marine communities the most by far, causing the extinction of most of the marine invertebrates of the time. Some groups survived the Permian mass extinction in greatly diminished numbers, but they never again reached the ecological dominance they once had, clearing the way for another group of sea life. On land, a relatively smaller extinction of diapsids and synapsids cleared the way for other forms to dominate, and led to what has been called the "Age of Dinosaurs." Also, the great forests of fern-like plants shifted to gymnosperms, plants with their offspring enclosed within seeds. Modern conifers, the most familiar gymnosperms of today, first appear in the fossil record of the Permian. The Permian was a time of great changes and life on Earth was never the same again.

The global geography of the Permian included massive areas of land and water. By the beginning of the Permian, the motion of the Earth's crustal plates had brought much of the total land together, fused in a supercontinent known as Pangea. Many of the continents of today in somewhat intact form met in Pangea (only Asia was broken up at the time), which stretched from the northern to the southern pole. Most of the rest of the surface area of the Earth was occupied by a corresponding single ocean, known as Panthalassa, with a smaller sea to the east of Pangea known as Tethys.

Models indicate that the interior regions of this vast continent were probably dry, with great seasonal fluctuations due to the lack of a moderating effect provided by nearby bodies of water. Only portions of this interior region received rainfall throughout the year. There is little known about the Panthalassic Ocean itself. There are indications that the climate of the Earth shifted during the Permian, with decreasing glaciation as the interiors of continents became drier.

Stratigraphy

Until the later 1990s, there was little consensus on the order of strata in the late Permian. Since the upper strata of various Permian locations tend to be relatively fossil deficient, correlation using index fossils has been difficult. Correlation was attempted using fossils that were in some cases native only to the local regions where they were found and older work was based on assumptions that have changed in more recent years.

Older classifications relied on the Ural Mountains stratigraphy. In 1994, Jin et al. proposed a worldwide stratigraphy of the Permian Period made up of four series/epochs: the Uralian, the Chihsian, the Guadalupian, and the Lopingian. In the early 2000s, work by Jin and others resulted in the stratigraphy currently accepted by the International Commission on Stratigraphy.

The current stratigraphy divides the Permian into three series or epochs: the Cisuralian (299 to 270.6 mya), Guadalupian (270.6 to 260.4 mya), and Lopingian (260.4 to 251 mya).* Find out more about how these periods of time are defined.

Permian shales, sandstones, siltstones, limestones, sands, marls, and dolostones were deposited as a result of sea-level fluctuations. These fluctuation cycles can be seen in the rock layers. Relatively few sites lend themselves to direct radioactive dating, so the age of intermediate strata is often estimated.

Permian fossils that have been used as index fossils include brachiopods, ammonoids, fusilinids, conodonts, and other marine invertebrates, and some genera occur within such specific time frames that strata are named for them and permit stratigraphic identification through the presence or absence of specified fossils. 126

Localities

- **Glass Mountains, Texas:** Permian fossils from the Glass Mountains are of shallow, warm-water marine life.

Resources and references

- Jin, Y.-G., B.R. Glenister, C.K. Kotlyar, and J.-Z. Sheng. 1994. An operational scheme of Permian chronostratigraphy. *Palaeoworld* 4:1-14.
- Jin, Y.-G., S. Shen, C.M. Henderson, X. Wang, W. Wang, Y. Wang, C. Cao, and Q. Shang. 2006. The global stratotype section and point (GSSP) for the boundary between the Capitanian and Wuchiapingian Stage (Permian). *Episodes* 29(4):253-262.
- Jin, Y.-G., Y. Wang, C. Henderson, B.R. Wardlaw, S. Shen, and C. Cao. 2006. The global boundary stratotype section and point (GSSP) for the base of Changhsingian Stage (Upper Permian). *Episodes* 29(3):175-182.
- Jones, T.S. 1953. Stratigraphy of the Permian Basin of West Texas. West Texas Geological Society Publication 53-29. 63 pp.
- Menning, M. 1995. A numerical time scale for the Permian and Triassic periods: An integrative time analysis. Pp. 77-97 *in* P.A. Scholle, T.M. Peryt, and D.S. Ulmer-Scholle (eds.), The Permian of Northern Pangea, Vol. 1. Springer-Verlag, Berlin.
- Ross, C.A., and J.R.P Ross 1995. Permian sequence stratigraphy. Pp. 98-123 *in* P.A. Scholle, T.M. Peryt, and D.S. Ulmer-Scholle (eds.), The Permian of Northern Pangea, Vol. 1. Springer-Verlag, Berlin.

- Find out more about the Brule Trackways, Nova Scotia, where hundreds of Permian age trackways have been found.
- Find out more about the Permian paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Permian.

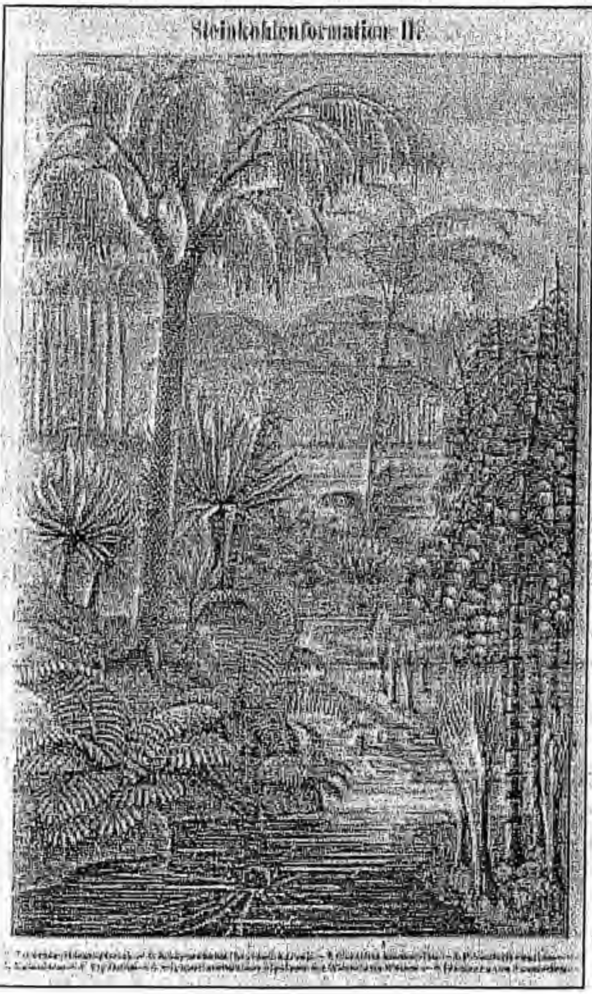
* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Page content written and completed by Chavé Alexander, Henry Chang, Carl Tsai, and Peggy Wu as part of a Biology 1B project for Section 115 under Brian R. Speer, 5/11/1998; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made some content updates, 6/30/2011

University of California Museum of Paleontology

See the world (and its fossils) with UCMP's field notes.

The Carboniferous Period

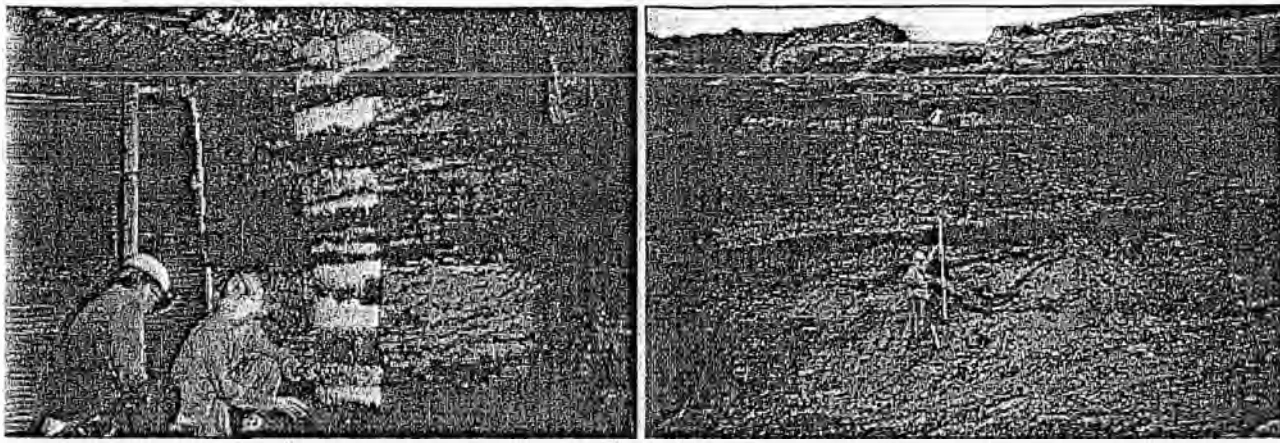


The Carboniferous Period is famous for its vast swamp forests, such as the one depicted here. Such swamps produced the coal from which the term Carboniferous, or "carbon-bearing," is derived.

The Carboniferous Period lasted from about 359.2 to 299 million years ago* during the late Paleozoic Era. The term "Carboniferous" comes from England, in reference to the rich deposits of coal that occur there. These deposits of coal occur throughout northern Europe, Asia, and midwestern and eastern North America. The term "Carboniferous" is used throughout the world to describe this period, although in the United States it has been separated into the Mississippian (early Carboniferous) and the Pennsylvanian (late Carboniferous) Subsystems. This division was established to distinguish the coal-bearing layers of the Pennsylvanian from the mostly limestone Mississippian, and is a result of differing stratigraphy on the different continents. The Mississippian and Pennsylvanian, in turn, are subdivided into a number of internationally recognized stages based on evolutionary successions of fossil groups . These stages are (from early to late) Tournaisian, Visean, and Serpukhovian for the Mississippian — and Bashkirian, Moscovian, Kasimovian, and Gzhelian for the Pennsylvanian.

In addition to having the ideal conditions for the formation of coal, several major biological, geological, and climatic events occurred during this time. Biologically, we see one of the greatest evolutionary innovations of the Carboniferous: the amniote egg, which allowed for the further exploitation of the land by certain tetrapods. It gave the ancestors of birds, mammals, and reptiles the ability to lay their eggs on land without fear of desiccation. Geologically, the Late Carboniferous collision of Laurasia (present-day Europe, Asia, and North America) into Gondwana (present-day Africa, South America, Antarctica, Australia, and India) produced the Appalachian Mountain belt of eastern North America and the Hercynian Mountains in the United Kingdom. A further collision of Siberia and eastern Europe created the Ural Mountains of Russia. And climatically, there was a trend towards mild temperatures during the Carboniferous, as evidenced by the decrease in lycopods and large insects, and an increase in the number of tree ferns.

The stratigraphy of the Mississippian can be easily distinguished from that of the Pennsylvanian. The Mississippian environment of North America was heavily marine, with seas covering parts of the continent. As a result, most Mississippian rocks are limestone, which are composed of the remains of crinoids, lime-encrusted green algae, or calcium carbonate shaped by waves. The North American Pennsylvanian



At left, scientists in a coal mine have color coded the successive layers of coal ball formation. Each layer represents an individual flood event in the coal swamp. On the right, a scientist observes the evidence of glacial and interglacial strata in Kansas. Glacial periods result in lowered ocean levels, while interglacial periods result in a rise in ocean levels, covering the continental shelf with shallow seas.

Coal beds, which can be up to 11 to 12 meters thick, characterize the late Carboniferous. The forests of seedless vascular plants that existed in the tropical swamp forests of Europe and North America provided the organic material that became coal. Dead plants did not completely decay and were turned to peat in these swamp forests. When the sea covered the swamps, marine sediments covered the peat. Eventually, heat and pressure transformed these organic remains into coal. Coal balls, pockets of plant debris that were preserved as fossils and not converted to coal, are sometimes found within the coal layers.

Multiple transgressions and regressions of the Pennsylvanian seas across the continent can be seen in the rocks, and even counted, because they leave a telltale sequence of layers. As sea levels rise, the layers may go from sandstone (beach), to silty shale or siltstone (tidal), to freshwater limestone (lagoon), to underclay (terrestrial), to coal (terrestrial swampy forest). Then as sea levels fall, one may see a shale (nearshore tidal) grade to limestone (shallow marine) and finally to black shale (deep marine).

Index fossils are the remains of plants and animals that characterize a well-defined time span and occur over a wide range of geography. Fossils of marine life characterize the Mississippian, as shallow epicontinental seas covered the United States at that time. These fossils include solitary corals and *Syringopora*, tubular colonial corals. Other fossil colonial corals include *Stelechophyllum* and *Siphonodendron*. Because conodont fossils are distributed all over the world, they are utilized internationally to date Mississippian rocks.

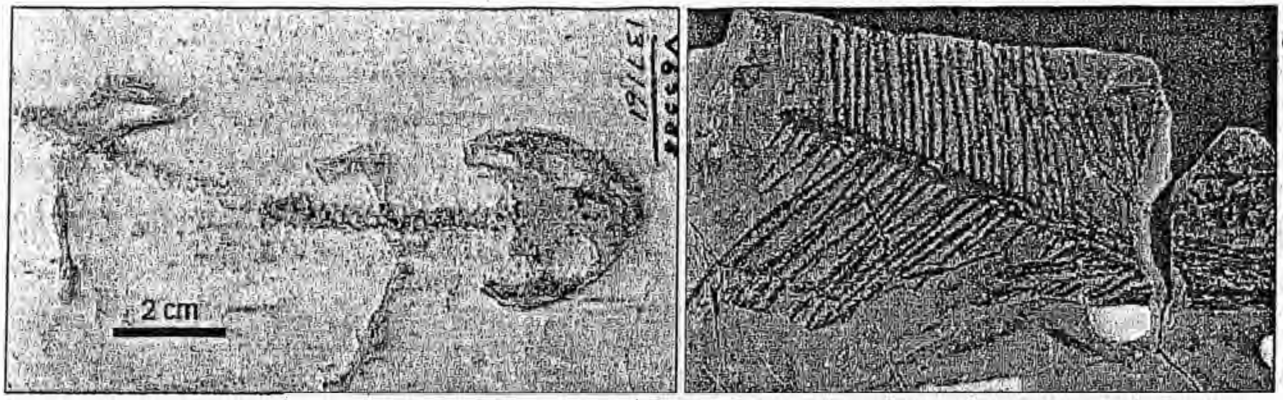
Index fossils used for the Pennsylvanian Subsystem are fusulinid foraminifers and the pollen and spores from the coal forests prevalent during that time. The Mississippian-Pennsylvanian boundary is marked by the appearance of the fusulinid *Pseudostaffella antiqua*. Other fossils used to identify the early Pennsylvanian are the three ammonoid cephalopod genera *Gastrioceras*, *Daiboloceras*, and *Paralegoceras*, all found in marine deposits.

Localities

- **Joggins, Nova Scotia:** This Pennsylvanian UNESCO World Heritage Site was home to early tetrapods such as *Dendrerpeton*.
- **Mazon Creek, Illinois:** This site has become famous for its iron concretions preserving both plants and marine invertebrates.

Resources and references

- Case, E.C. 1919. The environment of vertebrate life in the late Paleozoic in North America: A paleogeographic study. The Carnegie Institution of Washington, Washington, D.C.
- Case, E.C. 1926. Environment of tetrapod in the late Paleozoic of regions other than North America. The Carnegie Institution of Washington, Washington, D.C.
- Dickins, J.M. et al (eds.). 1997. Late Paleozoic and early Mesozoic circum-Pacific events and their global correlation. Cambridge University Press, Cambridge.
- Dott, R.H., Jr., and D.R. Prothero. 1994. Evolution of the Earth, 5th ed. McGraw-Hill, Inc., New York.
- Lemon, R.R. 1993. Vanished Worlds: An Introduction to Historical Geology. Wm. C. Brown Publishers, Dubuque, IA.



9

Many groups that appeared in the Carboniferous would give rise to groups that dominated the Permian and Mesozoic. On the left is *Amphiblamus lyelli*, an early temnospondyl. These amphibian-like early tetrapods grew to the size of crocodiles in the Permian and Triassic. On the right, *Lebachia*, an early relative of the conifers.

The uplift of the continents caused a transition to a more terrestrial environment during the Pennsylvanian Subsystem, although swamp forests were widespread. In the swamp forests, seedless plants such as lycopsids flourished and were the primary source of carbon for the coal that is characteristic of the period. The lycopods underwent a major extinction event after a drying trend, most likely caused by increased glaciation, during the Pennsylvanian. Ferns and sphenopsids became more important later during the Carboniferous, and the earliest relatives of the conifers appeared. The first land snails appeared and insects with wings that can't fold back, such as dragonflies and mayflies, flourished and radiated. These insects, as well as millipedes, scorpions, and spiders became important in the ecosystem.

A trend towards aridity and an increase in terrestrial habitat led to the increasing importance of the amniotic egg for reproduction. The earliest amniote fossil was the lizard-like *Hylonomus*, which was lightly built with deep, strong jaws and slender limbs. The basal tetrapods became more diverse during the Carboniferous. Predators with long snouts, short sprawling limbs and flattened heads such as temnospondyls, like *Amphibiamus* (above) appeared. Anthracosaurs — basal tetrapods and amniotes with deep skulls and a less sprawling body plan that afforded greater agility — appeared during the Carboniferous and were quickly followed by diapsids which divided into two groups: (1) the marine reptiles, lizards, and snakes, and (2) the archosaurs — crocodiles, dinosaurs, and birds. The synapsids also made their first appearance, and presumably the anapsids did as well, although the oldest fossils for that group are from the Lower Permian.

Stratigraphy

The appearance or disappearance of fauna usually marks the boundaries between time periods. The Carboniferous is separated from the earlier Devonian by the appearance of the conodont *Siphonodella sulcata* or *Siphondella duplicata*. Conodonts are fossils that resemble the teeth or jaws of primitive eel- or hagfish-like fish. The Carboniferous-Permian boundary is distinguished by the appearance of the fusulinid foram *Sphaeroschwagerina fusiformis* in Europe and *Pseudoschwagerina beedei* in North America. Fusulinids are giants among protists and could reach a centimeter in length. They were abundant enough to form sizable deposits known as "rice rock" because of the resemblance between fusulinids and rice grains.

The Mississippian Subsystem is differentiated from the Pennsylvanian by the appearance of the conodont *Declinognathodus noduliferus*, the ammonoid genus *Homoceras*, and the foraminifers *Millerella pressa* and *Millerella marblensis*, though these markers apply only to marine deposits. The distinction between the Mississippian and Pennsylvanian subsystems may also be illustrated by a break in the flora due to transitional changes from a marine to a more terrestrial environment.

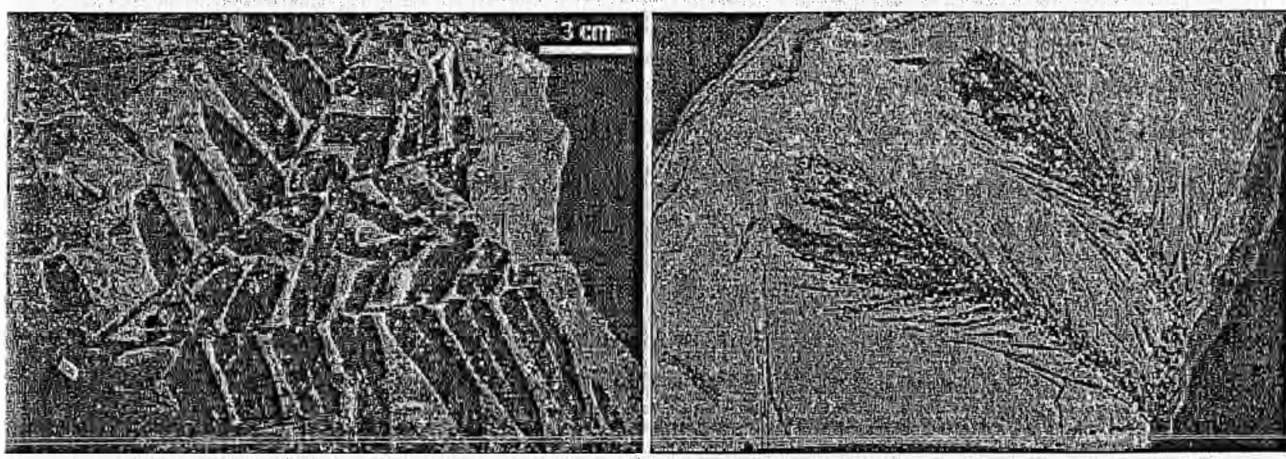
The stratigraphy of the Mississippian is distinguished by shallow-water limestones. Some of these limestones are composed of parts of organisms, primarily the remains of crinoids that thrived in the shallow seas. Other limestones include lime mudstones, composed of the carbonate mud produced by green algae, and oolithic limestones, composed of calcium carbonate in concentric spheres produced by high wave energy. Also found in Mississippian strata, though not as common, are sandstones (sedimentary rock composed of quartz sand and cemented by silica or calcium carbonate) and siltstones (rock composed of hardened silt).

environment was alternately terrestrial and marine, with the transgression and regression of the seas caused by glaciation. These environmental conditions, with the vast amount of plant material provided by the extensive coal forests, allowed for the formation of coal. Plant material did not decay when the seas covered them, and pressure and heat eventually built up over millions of years to transform the plant material to coal.

Life

The beginning of the Carboniferous generally had a more uniform, tropical, and humid climate than exists today. Seasons if any were indistinct. These observations are based on comparisons between fossil and modern-day plant morphology. The Carboniferous plants resemble those that live in tropical and mildly temperate areas today. Many of them lack growth rings, which suggests a uniform climate. This uniformity in climate may have been the result of the large expanse of ocean that covered the entire surface of the globe, except for a localized section where Pangea, the massive supercontinent that existed during the late Paleozoic and early Triassic, was coming together.

Shallow, warm, marine waters often flooded the continents. Attached filter feeders such as bryozoans, particularly fenestellids, were abundant in this environment, and the sea floor was dominated by brachiopods. Trilobites were increasingly scarce while foraminifers were abundant. The heavily armored fish from the Devonian became extinct, being replaced with more modern-looking fish fauna.



Though many spectacular plant forms dominated the Carboniferous, most of them disappeared before the end of the Paleozoic. On the left, *Neuropteris*, a leaf form associated with the cycad-like seed-ferns. On the right, terminal branches from *Lepidodendron sternbergii*, one of the great scale trees, most of which went extinct in the late Middle Pennsylvanian.

Uplifting near the end of the Mississippian resulted in increased erosion, with an increase in the number of floodplains and deltas. The deltaic environment supported fewer corals, crinoids, blastoids, cryozoans, and bryzoans, which were abundant earlier in the Carboniferous. Freshwater clams made their first appearance, and there was an increase in gastropod, bony fish, and shark diversity. As the continents moved closer to forming Pangea, there was a net decrease in coastline, which in turn affected the diversity of marine life in those shallow continental waters.

Two large ice sheets at the southern pole locked up large amounts of water as ice. With so much water taken out of the water cycle, sea levels dropped, leading to an increase in terrestrial habitat. Increases and decreases in glaciation during the Pennsylvanian resulted in sea level fluctuations that can be seen in the rocks as striped patterns of alternating shale and coal layers.

- Chengyuan, W. 1987. Carboniferous boundaries in China: Contribution to the 11th International Congress of Carboniferous Stratigraphy and Geology, 1987, Beijing, China. Science Press, Beijing, China.
- Linxin, Z. 1987. Carboniferous Stratigraphy in China. Science Press, Beijing, China.
- Find out about fossil fish of the Mississippian from the Bear Gulch Limestone of Montana.
- Find out more about the Carboniferous paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Carboniferous.

*Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Original concept for this page by Ben M. Waggoner, 7/2/1996; page content rewritten and completed by Angela Hoe, Azalea Jusay, Ray Mayberry, and Connie Yu as part of a Biology 1B project for Section 115 under Brian R. Speer, 5/11/1998; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made some content updates, 6/30/2011; Carboniferous forest etching is in the public domain; photographer of *Neuropteris*, *Lepidodendron* branch, *Amphibiamus*, and *Lebachia* unknown; photos of scientists in a coal mine and scientist measuring glacial and interglacial strata by Nan Crystal Arens

The Devonian Period

The Rhynie Chert in Scotland is a Devonian age deposit containing fossils of both zosterophylls and trimerophytes, some of the earliest vascular plants. This indicates that prior to the start of the Devonian, the first major radiations of plants had already happened. The oldest known vascular plants in the Northern Hemisphere are from the Devonian Period.

The vegetation of the early Devonian consisted primarily of small plants, the tallest being only a meter tall. By the end of the Devonian, ferns, horsetails and seed plants had also appeared, producing the first trees and the first forests.

At left, the fern-like leaves of *Archaeopteris*, one of the first tree-like plants. It grew to an average height of about 10 meters, produced spores, and had a global distribution. At right, a beautifully pyritized Devonian brachiopod, *Paraspirifer bownockeri*, from Ohio.

During the Devonian, two major animal groups colonized the land. The first tetrapods — land-living vertebrates — appeared during the Devonian, as did the first terrestrial arthropods, including wingless insects and the earliest arachnids. In the oceans, brachiopods flourished. Crinoids and other echinoderms, tabulate and rugose corals, and ammonites were also common. Many new kinds of fish appeared.

During the Devonian, there were three major continental masses: North America and Europe sat together near the equator, with much of their current area covered by shallow seas. To the north lay a portion of modern Siberia. A composite continent of South America, Africa, Antarctica, India, and Australia dominated the southern hemisphere.

Life

The Devonian seas

The Devonian seas were dominated by brachiopods, such as the spiriferids, and by tabulate and rugose corals, which built large reefs in shallow waters. Encrusting red algae also contributed to reef building. In the Lower Devonian, ammonoids appeared, leaving us large limestone deposits from their shells. Bivalves, crinoid and blastoid echinoderms, graptolites, and trilobites were all present, though most groups of trilobites disappeared by the close of the Devonian.

The Devonian is also notable for the rapid diversification in fish. Benthic, jawless, armored fish are common by the Lower Devonian. These early fish include a number of different groups. By the the Middle Devonian, placoderms, the first jawed fish, appear. Many of these grew to large sizes and were fearsome predators. Of the greatest interest to us is the rise of the first sarcopterygians, the lobe-finned fish, which eventually produced the first tetrapods just before the end of the Devonian.

133

The Devonian landscape

By the Devonian Period, colonization of the land was well underway. Before this time, there was no organic accumulation in the soils, resulting in soils with a reddish color. This is indicative of the underdeveloped landscape, probably colonized only by bacterial and algal mats.

By the start of the Devonian, early terrestrial vegetation had begun to spread. These plants did not have roots or leaves like most plants today, and many had no vascular tissue at all. They probably spread vegetatively, rather than by spores or seeds, and did not grow much more than a few centimeters tall. These plants included the now extinct zosterophylls and trimerophytes. The early fauna living among these plants were primarily arthropods: mites, trigonotarbids, wingless insects, and myriapods, though these early faunas are not well known.

By the Late Devonian, lycophytes, sphenophytes, ferns, and progymnosperms had evolved. Most of these plants have true roots and leaves, and many grew quite tall. The progymnosperm *Archaeopteris* (see photo above) was a large tree with true wood. It was the oldest known tree until the 2007 identification of *Wattieza* in 2007. By the end of the Devonian, the first seed plants had appeared. This rapid appearance of so many plant groups and growth forms has been called the "Devonian Explosion." Along with this diversification in terrestrial vegetation structure, came a diversification of the arthropods.

Tectonics and paleoclimate

Significant changes in the world's geography took place during the Devonian. During this period, the world's land was collected into two supercontinents, Gondwana and Euramerica. These vast landmasses lay relatively near each other in a single hemisphere, while a vast ocean covered the rest of the globe. These supercontinents were surrounded on all sides by subduction zones. With the development of the subduction zone between Gondwana and Euramerica, a major collision was set in motion that would bring the two together to form the single world-continent Pangea in the Permian.

In addition to global patterns of change, many important regional activities also occurred. The continents of North America and Europe collided, resulting in massive granite intrusions and the raising of the Appalachian Mountains of eastern North America. Vigorous erosion of these newly uplifted mountains yielded great volumes of sediment, which were deposited in vast lowlands and shallow seas nearby.

Extensive reef building, producing some of the world's largest reef complexes, proceeded as stromatoporoids and corals appeared in increasing numbers. These were built in the equatorial seas between the continents. Large shallow seas in North America, central Asia, and Australia became basins in which great quantities of rock salt, gypsum, and other minerals precipitated.

Near the end of the Devonian, a mass extinction event occurred. Glaciation and the lowering of the global sea level may have triggered this crisis, since the evidence suggests warm water marine species were most affected. Meteorite impacts have also been blamed for the mass extinction, or changes in atmospheric carbon dioxide. It is even conceivable that it was the evolution and spread of forests and the first plants with complex root systems that may have altered the global climate. Whatever the cause, it was about this time that the first vertebrates moved onto the land.

Localities

Rhynie Chert, Scotland: This has been one of the most important sources of fossils of early land plants and terrestrial arthropods. The anatomy of specimens is preserved in three-dimensional detail.

Resources

- See this excellent University Münster website on The Rhynie Chert and its Flora.
- Visit Falls of the Ohio State Park, the largest exposed Devonian fossil bed in the world.
- Find out more about the Devonian paleontology and geology of North America at the Paleontology Portal.

- See the Wikipedia page on the Devonian.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Page content written and completed by Brian R. Speer, 10/6/1995; revised by Brian R. Speer, 2/1/1998; tectonics and paleoclimate material by Rachel Grande, Larry Jean, Aariel Rowan, Angela Sumner, and Amy Tan as part of a Biology 1B project for Section 112 under Brian R. Speer, 5/1/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made some content updates, 7/1/2011; Carboniferous forest graphic origins unknown; photographer of *Archaeopteris* and *Paraspirifer* unknown

University of California Museum of Paleontology

135

See the world (and its fossils) with UCMP's field notes.

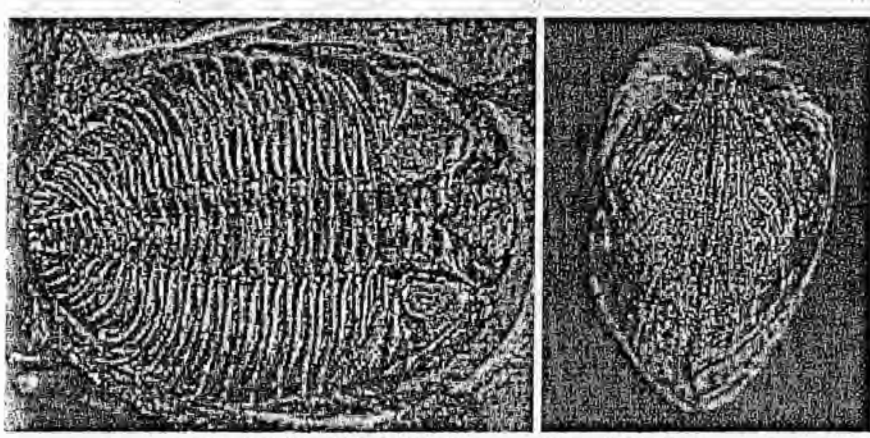
The Silurian Period

The Silurian (443.7 to 416.0 million years ago)* was a time when the Earth underwent considerable changes that had important repercussions for the environment and life within it. One result of these changes was the melting of large glacial formations. This contributed to a substantial rise in the levels of the major seas. The Silurian witnessed a relative stabilization of the Earth's general climate, ending the previous pattern of erratic climatic fluctuations.

Coral reefs made their first appearance during this time, and the Silurian was also a remarkable time in the evolution of fishes. Not only does this time period mark the wide and rapid spread of jawless fish, but also the highly significant appearances of both the first known freshwater fish as well as the first fish with jaws. It is also at this time that our first good evidence of life on land is preserved, such as relatives of spiders and centipedes, and also the earliest fossils of vascular plants.

Life

The Silurian is a time when many biologically significant events occurred. In the oceans, there was a widespread radiation of crinoids, a continued proliferation and expansion of the brachiopods, and the oldest known fossils of coral reefs. As mentioned earlier, this time period also marks the wide and rapid spread of jawless fish, along with the important appearances of both the first known freshwater fish and the appearance of jawed fish. Other marine fossils commonly found throughout the Silurian record include trilobites, graptolites, conodonts, corals, stromatoporoids, and mollusks.

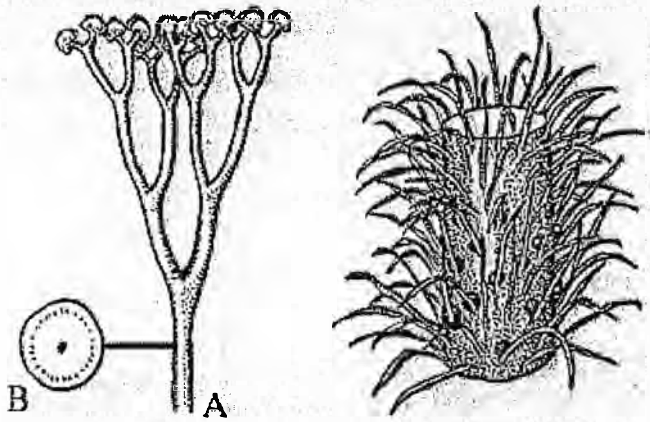


On the left, *Dalmanites limuluris*, a trilobite from the Silurian of New York. To the right, *Grammysia cingulata*, a bivalve from the Upper Ludlow of England.

It is also in the Silurian that we find the first clear evidence of life on land. While it is possible that plants and animals first moved onto the land in the Ordovician, fossils of terrestrial life from that period are fragmentary and difficult to interpret. Silurian strata have provided likely ascomycete fossils (a group of fungi), as well as remains of the first arachnids and centipedes.

Perhaps most striking of all biological events in the Silurian was the evolution of vascular plants, which have been the basis of terrestrial ecology since their appearance. Most Silurian plant fossils have been assigned to the genus *Cooksonia*, a collection of branching-stemmed plants which produced sporangia at their tips. None of these plants had leaves, and some appear to have lacked vascular tissue. Also from the Silurian of

Australia comes a controversial fossil of *Baragwanathia*, a lycophyte. If such a complex plant with leaves and a fully-developed vascular system was present by this time, then surely plants must have been around already by the Ordovician. In any event, the Silurian was a time for important events in the history of evolution, including many "firsts," that would prove highly consequential for the future of life on Earth.



Cooksonia, on the left, has usually been considered the oldest known land plant. Fossils assigned to several species are known from North America, Europe, Asia, and Africa, and from both the Late Silurian and Early Devonian. The lycophyte *Baragwanathia*, on the right, is structurally more complex than *Cooksonia*, but Silurian fossils of this plant have been found in Australia, significantly earlier than in the Northern Hemisphere.

Stratigraphy

The Silurian's stratigraphy is subdivided into four epochs (from oldest to youngest): the Llandovery, Wenlock, Ludlow, and Pridoli. Each epoch is distinguished from the others by the appearance of new species of graptolites. Graptolites are a group of extinct colonial, aquatic animals that put in their first appearance in the Cambrian Period and persisted into the early Carboniferous. The beginning of the Silurian (and the Llandovery) is marked by the appearance of *Parakidograptus acuminatus*, a species of graptolite.

The Llandovery (443.7-428.2 million years ago*) preserves its fossils in shale, sandstone, and gray mudstone sediment. Its base (beginning) is marked by the appearance of the graptolites *Parakidograptus acuminatus* and *Akidograptus ascensus*. The Llandoverian epoch is subdivided into the Rhuddanian, Aeronian, and Telychian stages.

At the close of the Telychian stage, the appearance of *Cyrtograptus centrifugus* marks the start of the Wenlockian epoch (428.2 to 422.9 million years ago).* The fossils are found in siltstone and mudstone under limestone. Missing from the fossil record of the Wenlock was the conodont *Pterospathodus amorphognathoides*, present in earlier strata. This is an epoch with excellent preservations of brachiopod, coral, trilobite, clam, bryozoan, and crinoid fossils. The Wenlock is subdivided into the Sheinwoodian and Homerian stages.

The Ludlow (422.9 to 418.7 million years ago)* consists of siltstone and limestone strata, marked by the appearance of *Neodiversograptus nilssoni*. There is an abundance of shelly animal fossils. The Gorstian and Ludfordian stages make up the Ludlow epoch.

Platy limestone strata rich in cephalopods and bivalves characterize the Pridolian (418.7 to 416.0 million years ago),* the final epoch of the Silurian. It is marked by the appearance of the index fossil *Monograptus parultimus*, and also by two new species of chitinozoans (marine plankton), *Urnochitina urna* and *Fungochitina kosovensis*, which appear at the base or just above the base of the Pridoli.

Tectonics and paleoclimate

Although there were no major periods of volcanism during the Silurian, the period is marked by major orogenic events in eastern North America and in northwestern Europe (the Caledonian Orogeny), resulting in the formation of the mountain chains there. The ocean basins between the regions known as Laurentia (North America and Greenland), Baltica (central and northern Europe and Scandinavia) and Avalonia (western Europe) closed substantially, continuing a geologic trend that had begun much earlier. The modern Philippine Islands were near the Arctic Circle, while Australia and Scandinavia resided in the tropics; South

America and Africa were over the South Pole. While not characterized by dramatic tectonic activity, the Silurian world experienced gradual continental changes that would be the basis for greater global consequences in the future, such as those that created terrestrial ecosystems. A deglaciation and rise in sea levels created many new marine habitats, providing the framework for significant biological events in the evolution of life. Coral reefs, for example, made their first appearance in the fossil record during this time.

The Silurian Period's condition of low continental elevations with a high global stand in sea level can be strongly distinguished from the present-day environment. This is a result of the flood of 65% of the shallow seas in North America during the Llandovery and Wenlock times. The shallow seas ranged from tropical to subtropical in climate. Coral mound reefs with associated carbonate sediments were common in the shallow seas. Due to reduced circulation during the Ludlow and Pridoli times, the process of deposition of evaporites (salts) was set in motion. Some of these deposits are found in northern Europe, Siberia, South China and Australia.

Resources and references

- Behrensmeyer, A.K., J.D. Damuth, W.A. DiMichele, R. Potts, H.-D. Sues, and S.L. Wing. 1992. Terrestrial Ecosystems Through Time: Evolutionary Paleoecology of Terrestrial Plants and Animals. University of Chicago Press, Chicago.
- Taylor, T.N., and E.L. Taylor. 1993. The Biology and Evolution of Fossil Plants. Prentice Hall, Inc., Englewood Cliffs, NJ. 982 pp. [There is now a 2008 second edition]
- Find out more about the Silurian paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Silurian.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Page content written and completed by Dan Fischer, Tammy (Yue) Liu, Emily Yip, and Korsen Yu as part of a Biology 1B project for Section 115 under Brian R. Speer, 5/11/1998; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made some content updates, 7/5/2011; *Dalmanites* and *Grammysia* photos by Brian Speer; *Cooksonia* and *Baragwanathia* drawings by Caroline Strömberg

University of California Museum of Paleontology

138

See the world (and its fossils) with UCMP's field notes.

The Ordovician Period

The Ordovician Period lasted almost 45 million years, beginning 488.3 million years ago and ending 443.7 million years ago.* During this period, the area north of the tropics was almost entirely ocean, and most of the world's land was collected into the southern supercontinent Gondwana. Throughout the Ordovician, Gondwana shifted towards the South Pole and much of it was submerged underwater.

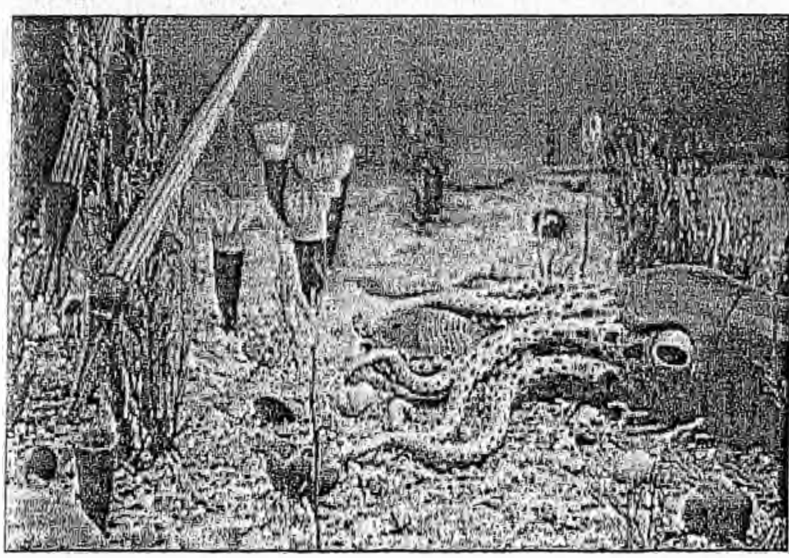
The Ordovician is best known for its diverse marine invertebrates, including graptolites, trilobites, brachiopods, and the conodonts (early vertebrates). A typical marine community consisted of these animals, plus red and green algae, primitive fish, cephalopods, corals, crinoids, and gastropods. More recently, tetrahedral spores that are similar to those of primitive land plants have been found, suggesting that plants invaded the land at this time.

From the Lower to Middle Ordovician, the Earth experienced a milder climate — the weather was warm and the atmosphere contained a lot of moisture. However, when Gondwana finally settled on the South Pole during the Upper Ordovician, massive glaciers formed, causing shallow seas to drain and sea levels to drop. This likely caused the mass extinctions that characterize the end of the Ordovician in which 60% of all marine invertebrate genera and 25% of all families went extinct.

Life

Ordovician strata are characterized by numerous and diverse trilobites and conodonts (phosphatic fossils with a tooth-like appearance) found in sequences of shale, limestone, dolostone, and sandstone. In addition, blastoids, bryozoans, corals, crinoids, as well as many kinds of brachiopods, snails, clams, and cephalopods appeared for the first time in the geologic record in tropical Ordovician environments. Remains of ostracoderms (jawless, armored fish) from Ordovician rocks comprise some of the oldest vertebrate fossils.

Despite the appearance of coral fossils during this time, reef ecosystems continued to be dominated by algae and sponges, and in some cases by bryozoans. However, there apparently were also periods of complete reef collapse due to global disturbances.



The major global patterns of life underwent tremendous change during the Ordovician. Shallow seas covering much of Gondwana became breeding grounds for new forms of trilobites. Many species of graptolites went extinct by the close of the period, but the first planktonic graptolites appeared.

In the late Lower Ordovician, the diversity of conodonts decreased in the North Atlantic Realm, but new lineages appeared in other regions. Seven major conodont lineages went extinct, but were replaced by nine new lineages that resulted from a major evolutionary radiation. These lineages included many new and morphologically different taxa. Sea level transgression persisted causing the drowning of almost the entire Gondwana craton. By this time, conodonts had reached their peak development.

Although fragments of vertebrate bone and even some soft-bodied vertebrate relatives are now known from the Cambrian, the Ordovician is marked by the appearance of the oldest complete vertebrate fossils. These were jawless, armored fish informally called ostracoderms, but more correctly placed in the taxon Pteraspidomorphi. Typical Ordovician fish had large bony shields on the head, small, rod-shaped or platelike scales covering the tail, and a slitlike mouth at the anterior end of the animal. Such fossils come from nearshore marine strata of Ordovician age in Australia, South America, and western North America.

Perhaps the most "groundbreaking" occurrence of the Ordovician was the colonization of the land. Remains of early terrestrial arthropods are known from this time, as are microfossils of the cells, cuticle, and spores of early land plants.

Stratigraphy

The Ordovician was named by the British geologist Charles Lapworth in 1879. He took the name from an ancient Celtic tribe, the Ordovices, renowned for its resistance to Roman domination. For decades, the epochs and series of the Ordovician each had a type location in Britain, where their characteristic faunas could be found, but in recent years, the stratigraphy of the Ordovician has been completely reworked. Graptolites, extinct planktonic organisms, have been and still are used to correlate Ordovician strata.

Particularly good examples of Ordovician sequences are found in China (Yangtze Gorge area, Hubei Province), Western Australia (Emanuel Formation, Canning Basin), Argentina (La Chilca Formation, San Juan Province), the United States (Bear River Range, Utah), and Canada (Survey Peak Formation, Alberta). Ordovician rocks over much of these areas are typified by a considerable thickness of lime and other carbonate rocks that accumulated in shallow subtidal and intertidal environments. Quartzites are also present. Rocks formed from sediments deposited on the margins of Ordovician shelves are commonly dark, organic-rich mudstones which bear the remains of graptolites and may have thin seams of iron sulfide.

Tectonics and paleoclimate

During the Ordovician, most of the world's land — southern Europe, Africa, South America, Antarctica, and Australia — was collected together in the super-continent Gondwana. Throughout the Ordovician, Gondwana moved towards the South Pole where it finally came to rest by the end of the period. In the Lower Ordovician, North America roughly straddled the equator and almost all of that continent lay underwater. By the Middle Ordovician North America had shed its seas and a tectonic highland, roughly corresponding to the later Appalachian Mountains, formed along the eastern margin of the continent. Also at this time, western and central Europe were separated and located in the southern tropics; Europe shifted towards North America from higher to lower latitudes.

During the Middle Ordovician, uplifts took place in most of the areas that had been under shallow shelf seas. These uplifts are seen as the precursor to glaciation. Also during the Middle Ordovician, latitudinal plate motions appear to have taken place, including the northward drift of the Baltoscandian Plate (northern Europe). Increased sea floor spreading accompanied by volcanic activity occurred in the early Middle Ordovician. Ocean currents changed as a result of lateral continental plate motions causing the opening of the Atlantic Ocean. Sea levels underwent regression and transgression globally. Because of sea level transgression, flooding of the Gondwana craton occurred as well as regional drowning which caused carbonate sedimentation to stop.

During the Upper Ordovician, a major glaciation centered in Africa occurred resulting in a severe drop in sea level which drained nearly all craton platforms. This glaciation contributed to ecological disruption and mass extinctions. Nearly all conodonts disappeared in the North Atlantic Realm while only certain lineages became extinct in the Midcontinental Realm. Some trilobites, echinoderms, brachiopods, bryozoans, graptolites, and chitinozoans also became extinct. The Atlantic Ocean closed as Europe moved towards

North America. Climatic fluctuations were extreme as glaciation continued and became more extensive. Cold climates with floating marine ice developed as the maximum glaciation was reached. 140

Localities

- **Canning Basin, Australia:** A great diversity of fossil gastropods has been uncovered in the Canning Basin.
- **Lake Winnipeg, Manitoba, Canada:** The limestones of this region have preserved many spectactular fossils of Ordovician macroalgae.

Resources

- Find out more about the Ordovician paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Ordovician.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Page content written and completed by Christina Avildsen, Jennifer Bie, Chirag Patel, and Brie Sarvis as part of a Biology 1B project for Section 115 under Brian R. Speer, 5/11/1998; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made some content updates, 7/6/2011; Image of Ordovician sea life courtesy of William B.N. Berry

University of California Museum of Paleontology

See the world (and its fossils) with UCMP's field notes.

The Cambrian Period

The Cambrian Period marks an important point in the history of life on Earth; it is the time when most of the major groups of animals first appear in the fossil record. This event is sometimes called the "Cambrian Explosion," because of the relatively short time over which this diversity of forms appears. It was once thought that Cambrian rocks contained the first and oldest fossil animals, but these are now found in the earlier Ediacaran (Vendian) strata.

Life

Almost every metazoan phylum with hard parts, and many that lack hard parts, made its first appearance in the Cambrian. The only modern phylum with an adequate fossil record to appear after the Cambrian was the phylum Bryozoa, which is not known before the early Ordovician. A few mineralized animal fossils, including sponge spicules and probable worm tubes, are known from the Ediacaran Period immediately preceding the Cambrian. Some of the odd fossils of the biota from the Ediacaran may also have been animals representative of living phyla, although this remains a somewhat controversial topic. However, the Cambrian was nonetheless a time of great evolutionary innovation, with many major groups of organisms appearing within a span of only forty million years. Trace fossils made by animals also show increased diversity in Cambrian rocks, showing that the animals of the Cambrian were developing new ecological niches and strategies — such as active hunting, burrowing deeply into sediment, and making complex branching burrows. Finally, the Cambrian saw the appearance and/or diversification of mineralized algae of various types, such as the coralline red algae and the dasyclad green algae.

This does not mean that life in the Cambrian seas would have been perfectly familiar to a modern-day SCUBA diver! Although almost all of the living marine phyla were present, most were represented by classes that have since gone extinct or faded in importance. For example, the Brachiopoda was present, but greatest diversity was shown by inarticulate brachiopods (like the one pictured below, left). The articulate brachiopods, which would dominate the marine environment in the later Paleozoic, were still relatively rare and not especially diverse. Cambrian echinoderms were predominantly unfamiliar and strange-looking types such as early edrioasteroids, eocrinoids, and helicoplacoids. The more familiar starfish, brittle stars, and sea urchins had not yet evolved, and there is some controversy over whether crinoids (sea lilies) were present or not. Even if present, crinoids were rare in the Cambrian, although they became numerous and diverse through the later Paleozoic. And while jawless vertebrates were present in the Cambrian, it was not until the Ordovician that armored fish became common enough to leave a rich fossil record.

Left: *Acrothele*, a fairly common inarticulate brachiopod from the the Wheeler Shale of western Utah. **Middle:** *Olenellus fremontii* from the Latham Shale of southern California. **Right:** A hyolith, also from the Latham Shale.

Other dominant Cambrian invertebrates with hard parts were trilobites (like the one pictured above), archaeocyathids (relatives of sponges that were restricted to the Lower Cambrian), and problematic conical fossils known as hyolithids (like the one pictured above, right). Many Early Cambrian invertebrates are known only from "small shelly fossils" — tiny plates, scales, spines, tubes, and so on. Many of these were probably pieces of the skeletons of larger animals.

A few localities around the world that preserve soft-bodied fossils of the Cambrian show that the "Cambrian radiation" generated many unusual forms not easily comparable with anything today. The best-known of these sites is the legendary Burgess Shale (middle Cambrian) in the British Columbian Rocky Mountains. Sites in Utah, southern China, Siberia, and north Greenland are also noted for their unusually good preservation of non-mineralized fossils from the Cambrian. One of these "weird wonders", first documented from the Burgess Shale, is *Wiwaxia*, depicted at lower left. *Wiwaxia* was an inch-long, creeping, scaly and spiny bottom dweller that may have been a relative of the molluscs, the annelids, or possibly an extinct animal group that combined features of both phyla.

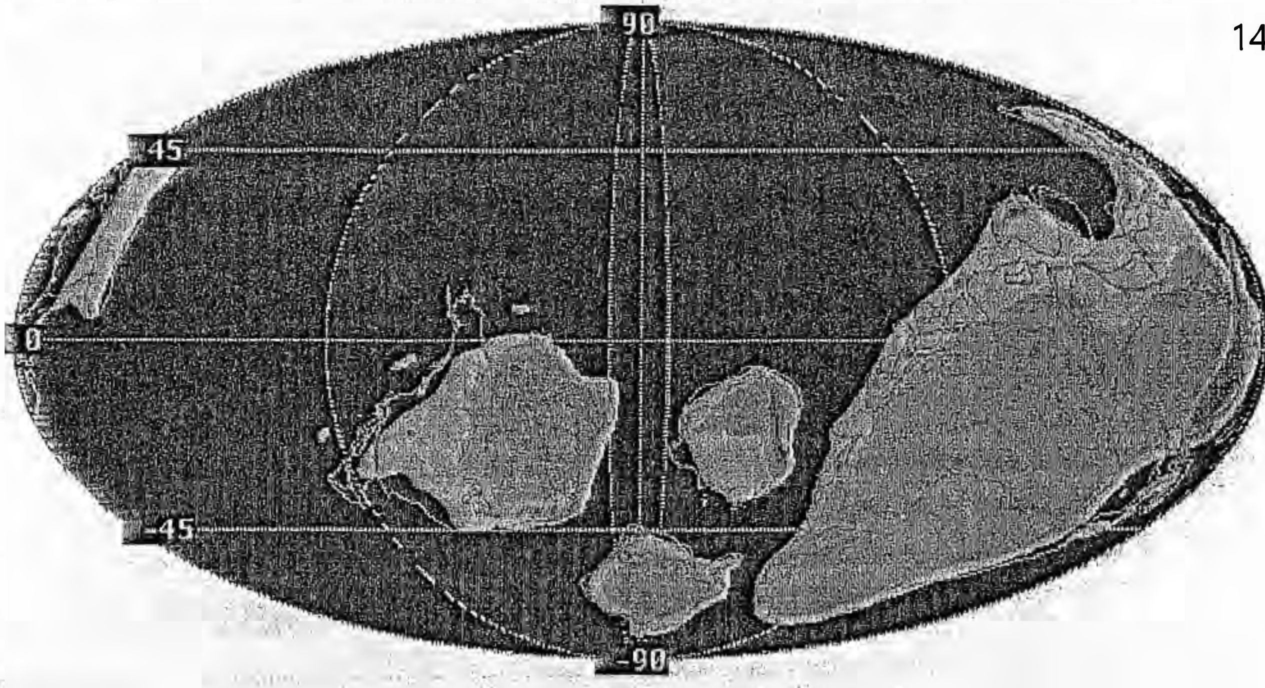
Stratigraphy

A lot can happen in 40 million years, the approximate length of the Cambrian Period. Animals showed dramatic diversification during this period of Earth's history. This has been called the "Cambrian Explosion". When the fossil record is scrutinized closely, it turns out that the fastest growth in the number of major new animal groups took place during the as-yet-unnamed second and third stages (generally known as the Tommotian and Atdabanian stages) of the early Cambrian, a period of about 13 million years. In that time, the first undoubted fossil annelids, arthropods, brachiopods, echinoderms, molluscs, onychophorans, poriferans, and priapulids show up in rocks all over the world.

Stratigraphic boundaries are generally determined by the occurences of fossils. For instance, the trace fossil *Treptichnus pedum* marks the base of the Cambrian. This boundary is an unusual case, since stratigraphic boundaries are normally defined by the presence or absence of groups of fossils, called assemblages. In fact, much paleontological work is concerned with questions surrounding when and where stratigraphic boundaries should be defined. At first glance, this may not seem like important work, but consider this: if you wanted to know about the evolution of life on Earth, you would need a fairly accurate timeline. Questions such as: "how long did something stay the same?" or,"how fast did it change?" can only be assessed in the context of time.

Tectonics and paleoclimate

The Cambrian follows the Ediacaran Period, during which time the continents had been joined in a single supercontinent called Rodinia (from the Russian word for "homeland", *rodina*). As the Cambrian began, Rodinia began to fragment into smaller continents, which did not always correspond to the ones we see today. The reconstruction below shows the rifting of Rodinia during the second stage (Tommotian) of the Cambrian . Green represents land above water at this time, red indicates mountains, light blue indicates shallow seas of the continental shelves, and dark blue denotes the deep ocean basins. (For clarity, the outlines of present-day continents have been superimposed on the map.)



World climates were mild; there was no glaciation. Landmasses were scattered as a result of the fragmentation of the supercontinent Rodinia that had existed in the late Proterozoic. Most of North America lay in warm southern tropical and temperate latitudes, which supported the growth of extensive shallow-water archaeocyathid reefs all through the early Cambrian. Siberia, which also supported abundant reefs, was a separate continent due east of North America. Baltica — what is now Scandinavia, eastern Europe, and European Russia — lay to the south. Most of the rest of the continents were joined together in the supercontinent Gondwana, depicted on the right side of the map; South America, Africa, Antarctica, India, and Australia are all visible. What is now China and east Asia was fragmented at the time, with the fragments visible north and west of Australia. Western Europe was also in pieces, with most of them lying northwest of what is now the north African coastline. The present-day southeastern United States are visible wedged between South America and Africa; they did not become part of North America for another 300 million years. Tectonism affected regions of Gondwana, primarily in what are now Australia, Antarctica, and Argentina. The continental plate movement and collisions during this period generated pressure and heat, resulting in the folding, faulting, and crumpling of rock and the formation of large mountain ranges.

The Cambrian world was bracketed between two ice ages, one during the late Proterozoic and the other during the Ordovician. During these ice ages, the decrease in global temperature led to mass extinctions. Cooler conditions eliminated many warm water species, and glaciation lowered global sea level. However, during the Cambrian there was no significant ice formation. None of the continents were located at the poles so land temperatures remained mild. In fact, global climate was probably warmer and more uniform than it is today. With the retreat of Proterozoic ice, the sea level rose significantly. Lowland areas such as Baltica were flooded and much of the world was covered by epeiric seas. This event opened up new habitats where marine invertebrates, such as trilobites, radiated and flourished.

Plants had not yet evolved, and the terrestrial world was devoid of vegetation and inhospitable to life as we know it. Photosynthesis and primary production were the monopoly of bacteria and algal protists that populated the world's shallow seas.

Also during the Cambrian, the oceans became oxygenated. Although there was plentiful atmospheric oxygen by the beginning of the period, it wasn't until the Cambrian that there was a sufficient reduction in the number of oxygen-depleting bacteria to permit higher oxygen levels in the waters. This dissolved oxygen may have triggered the "Cambrian Explosion" — when most of the major groups of animals, especially those with hard shells, first appeared in the fossil record.

Localities

- **Aldan River, Siberia,:** This early Cambrian fauna tells us about the early evolution of animals with skeletons.

- **Burgess Shale, British Columbia:** Thousands of soft-bodied animal fossils paint us a picture of early marine life.
- **House Range, Utah:** An array of Cambrian critters has been found in the Wheeler Shale and the Marjum Formation.
- **Marble Mountains, California:** Olenellid trilobites and more are found in this Mojave Desert locality.
- **White-Inyo Mountains, California:** Visit ancient Cambrian reefs in these mountains of eastern California.

Resources

- Find out more about the Cambrian paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Cambrian.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Page content written and completed by Ben M. Waggoner and Allen G. Collins, 11/22/1994; tectonics and paleoclimate material added by Karen Hsu, Myun Kang, Amy Lavarias, Kavitha Prabaker, and Cody Skaggs as part of a Biology 1B project for Section 112 under Brian R. Speer, 5/1/2000; Ben M. Waggoner revised the Life content, 9/2001; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made some content updates, 7/6/2011; *Acrothele* and hyolith photos by Ben M. Waggoner; *Olenellus* photo by Dave Smith; source of Tommotian map unknown

First, a few words about the Precambrian, an informal name for the vast expanse of time prior to the Phanerozoic Eon (which includes the Paleozoic, Mesozoic, and Cenozoic Eras). The Earth formed. It then took nearly *four thousand million* years before the first animals would leave their traces on the planet. This span of time makes up roughly seven-eighths of the Earth's history. During the Precambrian, the most important events in biological history took place. Consider that the Earth formed, life arose, the first tectonic plates arose and began to move, eukaryotic cells evolved, the atmosphere became enriched in oxygen — and just before the end of the Precambrian, complex multicellular organisms, including the first animals, evolved.

The Precambrian is divided into three eons. From youngest to oldest, they are: the Proterozoic, the Archean, and the Hadean (this latter being an informal name).

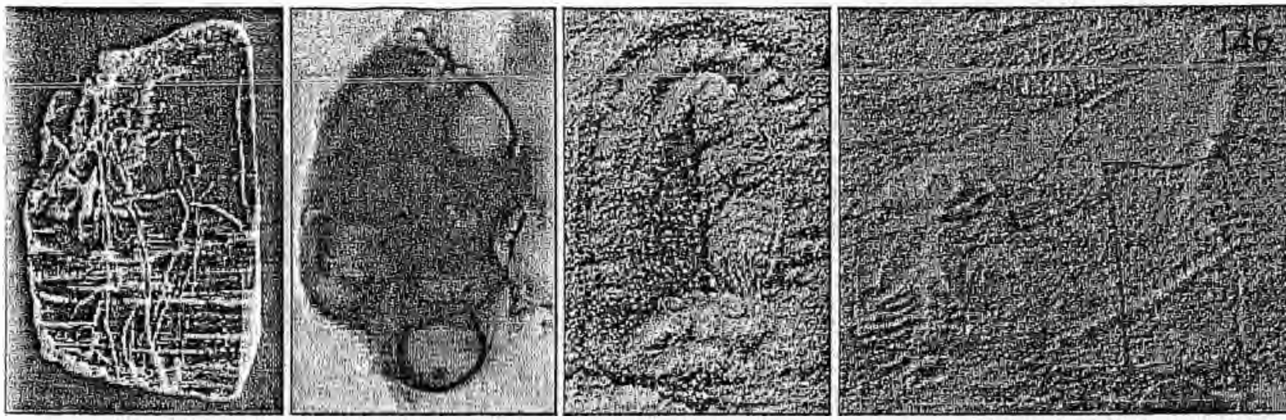
The Proterozoic Eon

The period of Earth's history that began 2.5 billion years ago and ended 542.0 million years ago is known as the Proterozoic, which is subdivided into three eras: the Paleoproterozoic (2.5 to 1.6 billion years ago), Mesoproterozoic (1.6 to 1 billion years ago), and Neoproterozoic (1 billion to 542.0 million years ago).* Many of the most exciting events in the history of the Earth and of life occurred during the Proterozoic — stable continents first appeared and began to accrete, a long process taking about a billion years. Also coming from this time are the first abundant fossils of living organisms, mostly bacteria and archaeans, but by about 1.8 billion years ago eukaryotic cells appear as fossils too.

With the beginning of the Mesoproterozoic comes the first evidence of oxygen build-up in the atmosphere. This global catastrophe spelled doom for many bacterial groups, but made possible the explosion of eukaryotic forms. These included multicellular algae, and toward the end of the Proterozoic, the first animals.

Life

The first traces of life appear nearly 3.5 billion years ago, in the early Archean. However, clearly identifiable fossils remain rare until the late Archean, when stromatolites, layered mounds produced by the growth of microbial mats, become common in the rock record. Stromatolite diversity increased through most of the Proterozoic. Until about one billion years ago, they flourished in shallow waters throughout the world. Their importance for understanding Proterozoic life is tremendous; stromatolites that have been silicified (forming a type of rock known as stromatolitic chert) often preserve exquisite microfossils of the microbes that made them (see two photos, below left).



From left, (1) A sample of stromatolitic chert from the Bitter Springs Formation of central Australia, about 850 million years old. Note the typical fine banding patterns. (2) Cyanobacteria, probably *Myxococcoides minor*, a colonial chroococcalean form from the Bitter Springs chert. (3) *Kimberella* was a bilaterally symmetric Ediacaran animal that had rigid parts — note the deep depression that a rigid shell-like covering made in the silt upon burial. This specimen, from the White Sea region of Russia, is about 1.5 cm across and 2.5-3 cm long. (4) Two specimens of *Charniodiscus* from Mistaken Point, Newfoundland. These Ediacaran organisms have a bulb-shaped or disc-shaped "holdfast" which was attached to the sea floor, and a leaf-shaped main body that probably was held up in the water column.

Stromatolites began to decline in abundance and diversity about 700 million years ago. A popular theory for their decline (though certainly not the only possible explanation) is that herbivorous eukaryotes, perhaps including the first animals, evolved at about this time and began feeding extensively on growing stromatolites. Stromatolites are rare fossils after about 450 million years ago. Today, they are found only in restricted habitats with low levels of grazing, such as the shallow, saline waters of Shark Bay, Australia.

The oldest fossil that may represent a macroscopic organism is about 2.1 billion years old. Several types of fossil that appear to represent simple multicellular forms of life are found by the end of the Paleoproterozoic. These fossils, known as carbon films, are just that: small, dark compressions, mostly resembling circles, ribbons, or leaves; they are most common and widespread in the Neoproterozoic. Some resemble seaweeds and may represent eukaryotic algae; we know from independent evidence that red algae and green algae appeared in the Proterozoic, probably over one billion years ago.

There are tantalizing hints from trace fossils and molecular biology that animals may have appeared as much as one billion years ago. However, the oldest relatively non-controversial, well-studied animal fossils appear in the last hundred million years of the Proterozoic, just before the Cambrian radiation of taxa. The time from 635 million years ago to 542 million years ago, known as the Ediacaran Period (sometimes called the Vendian), saw the origin and first diversification of soft-bodied organisms (see two photos, above right). The period and the fauna are named after the Ediacara Hills of southern Australia, where the first abundant and diverse fossils of this kind were found.

Ancient global pollution

The first "pollution crisis" hit the Earth about 2.2 billion years ago. Several pieces of evidence — the presence of iron oxides in paleosols (fossil soils), the appearance of "red beds" containing metal oxides, and others — point to a fairly rapid increase in levels of oxygen in the atmosphere at about this time. Atmospheric oxygen levels in the Archean had been less than 1% of present levels, but by about 1.8 billion years ago, oxygen levels were greater than 15% of present levels and rising. It may seem strange to call this a "pollution crisis," since most of the organisms that we are familiar with not only tolerate but require oxygen to live. However, oxygen is a powerful degrader of organic compounds. Even today, many bacteria and protists are killed by oxygen. Organisms had to evolve biochemical methods for rendering oxygen harmless; one of these methods, oxidative respiration, had the advantage of producing large amounts of energy for the cell, and is now found in most eukaryotes.

Where was the oxygen coming from? Cyanobacteria, photosynthetic organisms that produce oxygen as a byproduct, had first appeared 3.5 billion years ago, but became common and widespread in the Proterozoic. Their photosynthetic activity was primarily responsible for the rise in atmospheric oxygen.

Proterozoic fossil localities

- **Bitter Springs Formation:** The oldest known eukaryotic fossils come from this Late Proterozoic dolomite in central Australia.

- **Ediacara Hills:** Fossils of some of the oldest known animals were discovered at this Australian locality in 1946.
- **Mistaken Point, Newfoundland:** Mysterious fossils from the coast of Newfoundland.
- **Nopah Range:** The oldest sedimentary rocks in this Southern California region are 1.5 billion years old; younger deposits are rich in stromatolites.
- **White Sea:** Located on the northern coast of Russia, this has been a site of active research by UCMP into the Vendian fauna.

Resources and references

- Hofmann, H.J. 1994. Proterozoic carbonaceous compressions ("metaphytes" and "worms"). Pp. 342-357 *in* S. Bengtson (ed.), Early Life on Earth. Columbia University Press, New York.
- Holland, H.D. 1994. Early Proterozoic atmospheric change. Pp. 237-244 *in* S. Bengtson (ed.), Early Life on Earth. Columbia University Press, New York.
- Learn more about the Ediacaran Period and Ediacaran biota on Wikipedia.
- Find out more about the Precambrian paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Proterozoic.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Ben M. Waggoner created the original page, 2/20/1996, and began expansions and revisions 2/28/1997; Brian R. Speer provided a new introduction and graphics, 3/8/1997; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format, and made some content changes, 7/7/2011; Bitter Springs chert, *Kimberella*, and *Charniodiscus* photos by Ben M. Waggoner; *Myxococcoides* photo by J. William Schopf.

The Archean Eon and the Hadean

The Archean eon, which preceded the Proterozoic eon, spanned about 1.5 billion years and is subdivided into four eras: the Neoarchean (2.8 to 2.5 billion years ago), Mesoarchean (3.2 to 2.8 billion years ago), Paleoarchean (3.6 to 3.2 billion years ago), and Eoarchean (4 to 3.6 billion years ago).*

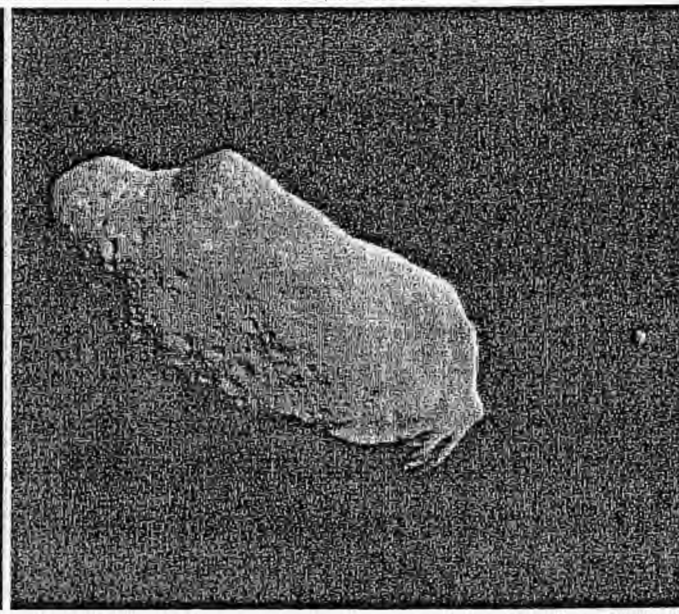
If you were able to travel back to visit the Earth during the Archean, you would likely not recognize it as the same planet we inhabit today. The atmosphere was very different from what we breathe today; at that time, it was likely a reducing atmosphere of methane, ammonia, and other gases which would be toxic to most life on our planet today. Also during this time, the Earth's crust cooled enough that rocks and continental plates began to form.

It was early in the Archean that life first appeared on Earth. Our oldest fossils date to roughly 3.5 billion years ago, and consist of bacteria microfossils. In fact, all life during the more than one billion years of the Archean was bacterial. The Archean coast was home to mounded colonies of photosynthetic bacteria called stromatolites. Stromatolites have been found as fossils in early Archean rocks of South Africa and western Australia. Stromatolites increased in abundance throughout the Archean, but began to decline during the Proterozoic. They are not common today, but they are doing well in Shark Bay, Australia (see photo below).

Former UCMP grad students Allen Collins (left) and Chris Meyer stand among living stromatolites in Shark Bay, at the westernmost point of Australia.

The Hadean

Hadean time (4.6 to 4 billion years ago)* is not a geological period as such. No rocks on the Earth are this old, except for meteorites. During Hadean time, the Solar System was forming, probably within a large cloud of gas and dust around the sun, called an accretion disc. The relative abundance of heavier elements in the Solar System suggests that this gas and dust was derived from a supernova, or supernovas — the explosion of an old, massive star. Heavier elements are generated within stars by nuclear fusion of hydrogen, and are otherwise uncommon. We can see similar processes taking place today in so-called diffuse nebulae in this and other galaxies, such as the Nebula M16, below left. 149



Left: A Hubble Space Telescope image of a star-forming region of Nebula M16 (Eagle Nebula). **Right:** Asteroid Ida and its moon as imaged by the Galileo spacecraft in 1993. The spacecraft was about 10,500 kilometers (6,500 miles) from the asteroid.

The sun formed within such a cloud of gas and dust, shrinking in on itself by gravitational compaction until it began to undergo nuclear fusion and give offlight and heat. Surrounding particles began to coalesce by gravity into larger lumps, or planetesimals, which continued to aggregate into planets. "Left-over" material formed asteroids and comets, like asteroid Ida, above right.

Because collisions between large planetesimals release a lot of heat, the Earth and other planets would have been molten at the beginning of their histories. Solidification of the molten material into rock happened as the Earth cooled. The oldest meteorites and lunar rocks are about 4.5 billion years old, but the oldest Earth rocks currently known are 3.8 billion years. Sometime during the first 800 million or so years of its history, the surface of the Earth changed from liquid to solid. Once solid rock formed on the Earth, its geological history began. This most likely happened prior to 3.8 billion years, but hard evidence for this is lacking. Erosion and plate tectonics has probably destroyed all of the solid rocks that were older than 3.8 billion years. The advent of a rock record roughly marks the beginning of the Archean eon.

Resources and references

- Bengtson, S. (ed.) 1994. Early Life on Earth: Nobel Symposium 84. Columbia University Press, New York.
- Schopf, J.W. (ed.) 1983. Earth's Earliest Biosphere: Its Origin and Evolution. Princeton University Press, Princeton. 543 pp.

- Read more about Shark Bay and its stromatolites or stromatolites in general on Wikipedia.
- Learn more about the Archean and Hadean on Wikipedia.
- Find out more about the Precambrian paleontology and geology of North America at the Paleontology Portal.

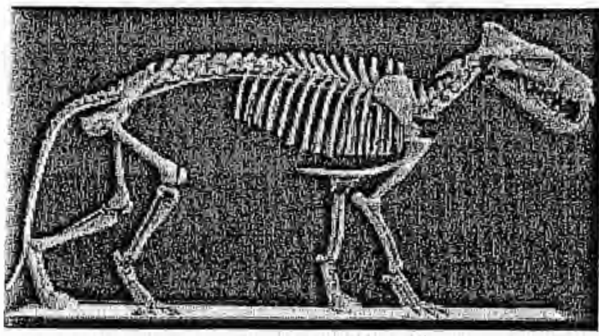
* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Brian R. Speer created the original Archean page, 3/9/1997; Ben M. Waggoner created the original Hadean page, 2/20/1996; Dave Smith combined the content into a single page, adapted it to the new site format, and made some content changes, 7/7/2011; Shark Bay photo courtesy of Allen Collins (?); Nebula M16 photo courtesy of NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University); asteroid Ida photo courtesy of NASA and the JPL

The Oligocene Epoch

The Oligocene Epoch, right smack in the middle of the Tertiary Period (and end of the Paleogene), lasted from about 33.9 to 23 million years ago.* Although it lasted a "short" 11 million years, a number of major changes occurred during this time. These changes include the appearance of the first elephants with trunks, early horses, and the appearance of many grasses — plants that would produce extensive grasslands in the following epoch, the Miocene.

Life



Hyaenodon horridus, a large carnivorous mammal from the White River Oligocene of South Dakota. Deposits containing *Hyaenodon* are found in Badlands National Park.

As a result of the cooling trend prevalent throughout the Oligocene Epoch, the lives and habitats of many organisms were directly affected. In the oceans, marine biotic provinces became more fragmented as sea dwellers capable of withstanding cooler temperatures congregated to places further from the warmer equator, where other species could better survive. The cooling trend was also responsible for the reduced diversity in marine plankton, the foundation of the food chain.

On land, mammals such as horses, deer, camel, elephants, cats, dogs, and primates began to dominate, except in Australia. The continuation of land mammal faunal migration between Asia and North America was responsible for the dispersion of several lineages to new continents. Early forms of amphicyonids, canids, camels, tayassuids, protoceratids, and anthracotheres appeared, as did caprimulgiformes, birds that possess gaping mouths for catching insects. Diurnal raptors, such as falcons, eagles, and hawks, along with seven to ten families of rodents also first appeared during the Oligocene. The "bulk feeding" in the open grasslands and savannas that occurred in this period resulted in the increase of general herbivore size. As an example, ungulates continued to get larger throughout the Oligocene.

The early Oligocene was marked by a multitude of different events ranging from the appearance of new groups such as elephants to the decline in taxonomic diversity in middle- and high-latitude forests. "Micro-mammals" experienced a period of diversification, as did the marsupials in Australia. This period was also marked by a relative free change of animals among northern continents, as evidenced by the similarity in vertebrate faunas.

In North America, the cricetids (voles and hamsters) first appeared while the mesothermal dicotyledons (a group of flowering plants) went extinct. South America became dominated by forests, and the first primates appeared in Africa. Primates found in Southeast Asia during this period represent primitive members of the New World and Old World higher primates.

In western Europe, an extraordinary, sudden change in the fauna, known as the Grand Coupure, occurred. This event involved the immigration of many new taxa, artiodactyls and perissodactyls in particular (e.g., rhinocerotoids, chalicotheriids, anthracotheres, and tayassuids), from areas to the east and the extinction of many Eocene genera and species. At least 17 generic extinctions, 20 first appearances, and 25 unaffected genera of mammals are represented across the Eocene-Oligocene boundary in western Europe.

On a global scale, broad-leaved evergreen vegetation became restricted to 35° latitude around the equator, and megathermal, multistratal vegetation was confined to 15° latitude around the equator. Broad-leaved evergreen plants became increasingly confined to lower latitudes in Eurasia, and microthermal, broad-leaved forest became common over large regions of the Northern Hemisphere.

The mid-Oligocene was marked by a worldwide marine regression; this included a decline in the total number of marine species. On land, the first of the open grassland faunas appeared in Mongolia while in North America, microthermal broad-leaved deciduous forests extended further into southern regions typified before by evergreen species and for the first time in history covered vast regions of the Northern Hemisphere.

The late Oligocene was marked by the expansion of grasslands and prairies that were intimately linked to the expansion of grazing animals. Grasses and composites increased in abundance on the global scale, and humid forests became increasingly common in the southern parts of South America. Horses experienced a period of diversification; anatomical modifications in horses indicate an increase in cursoriality compared to more primitive ancestors. Primitive beavers appeared and the earliest of the New World monkeys inhabited South America.

The late Oligocene Deseadan record includes two major groups that are thought to represent early waif dispersals from other continents. One of these, the caviomorph rodents (e.g., porcupines, capybaras, chinchillas, and a wide assortment of smaller forms), was the only group of rodents in South America until the Plio-Pleistocene. They diversified into 16 families, only two of which are now extinct. The second group of early immigrants was the primates.

Localities

- **Creede Formation, Colorado:** A rich plant community from this locality includes pine, fir, barberry, and a variety of other species all very well preserved.

Resources

- Find out more about the Tertiary paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Oligocene.

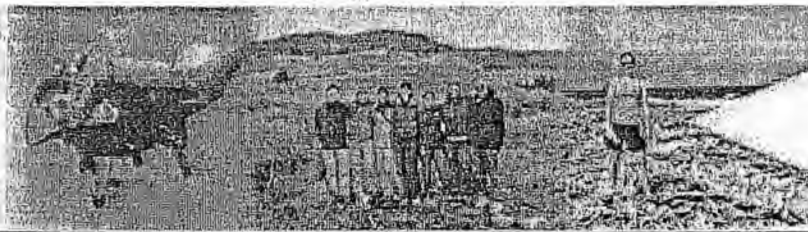
* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

P. David Polly created the original content 4/30/1994; Brian R. Speer updated the format 10/4/1995 and split the content into five pages 7/7/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/10/2011; source of *Hyaenodon* photo is unknown

HOME | SEARCH | GLOSSARY | SITE MAP | FREQUENTLY-ASKED QUESTIONS

ABOUT | CONTACT | COPYRIGHT | CREDITS | SUBSCRIBE/RSS

Other UCMP websites:
THE PALEONTOLOGY PORTAL | UNDERSTANDING EVOLUTION | UNDERSTANDING SCIENCE

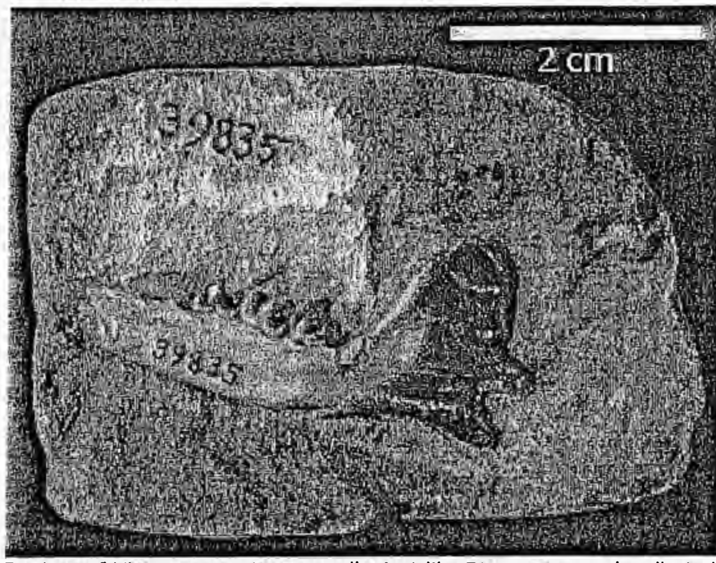


152

See the world (and its fossils) with UCMP's field notes.

The Eocene Epoch

The Eocene is the second of five epochs in the Tertiary Period — the second of three epochs in the Paleogene — and lasted from about 55.8 to 33.9 million years ago.* The oldest known fossils of most of the modern orders of mammals appear in a brief period during the early Eocene and all were small, under 10 kg. Both groups of modern ungulates, Artiodactyla and Perissodactyla, became prevalent mammals at this time, due to a major radiation between Europe and North America.



Dentary of *Viverravus acutus*, a small, civet-like Eocene mammal, collected by Malcolm McKenna, Big Horn County, WY, 1950.

Tectonics and paleoclimate

The early Eocene (Ypresian) is thought to have had the highest mean annual temperatures of the entire Cenozoic Era, with temperatures about 30° C; relatively low temperature gradients from pole to pole; and high precipitation in a world that was essentially ice-free. Land connections existed between Antarctica and Australia, between North America and Europe through Greenland, and probably between North America and Asia through the Bering Strait. It was an important time of plate boundary rearrangement, in which the patterns of spreading centers and transform faults were changed, causing significant effects on oceanic and atmospheric circulation and temperature.

In the middle Eocene, the separation of Antarctica and Australia created a deep water passage between those two continents, creating the circum-Antarctic Current. This changed oceanic circulation patterns and global heat transport, resulting in a global cooling event observed at the end of the Eocene.

By the Late Eocene, the new ocean circulation resulted in a significantly lower mean annual temperature, with greater variability and seasonality worldwide. The lower temperatures and increased seasonality drove increased body size of mammals, and caused a shift towards increasingly open savanna-like vegetation, with a corresponding reduction in forests.

Localities

- **Florissant Formation, Colorado:** Few localities have such remarkably preserved fossil insects as this Rocky Mountain site.
- **Green River Formation:** Rich in fossils of plants, insects, and fish, this American locality extends across Utah, Colorado, and Wyoming.

Resources

- Find out more about the Tertiary paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Eocene.

Note: For information on the Paleocene Epoch, 65.5 to 55.8 million years ago,* see the Wikipedia page.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

David Polly created the original pages 4/30/1994; Brian Speer updated the format 10/4/1995; Brian Speer added more pages 8/29/1999; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page and adapted it to the new site format, 6/15/2011; *Viverravus acutus* specimen from the UCMP vertebrate collections, photographer unknown

The Cenozoic Era

The Cenozoic Era is the most recent of the three major subdivisions of animal history. The other two are the Mesozoic and Paleozoic Eras. The Cenozoic spans only about 65 million years, from the end of the Cretaceous Period and the extinction of non-avian dinosaurs to the present. The Cenozoic is sometimes called the Age of Mammals, because the largest land animals have been mammals during that time. This is a misnomer for several reasons. First, the history of mammals began long before the Cenozoic began. Second, the diversity of life during the Cenozoic is far wider than mammals. The Cenozoic could have been called the "Age of Flowering Plants" or the "Age of Insects" or the "Age of Teleost Fish" or the "Age of Birds" just as accurately.

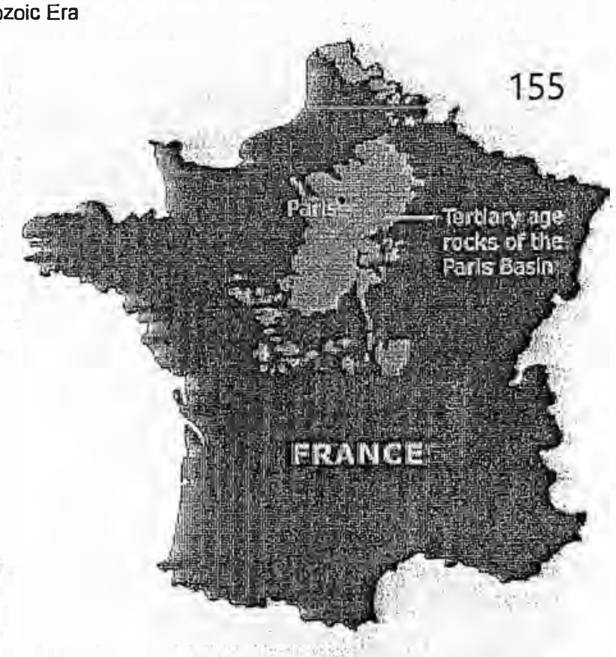
The Cenozoic (65.5 million years ago to present) is divided into three periods: the Paleogene (65.5 to 23.03 million years ago), Neogene (23.03 to 2.6 million years ago) and the Quaternary (2.6 million years ago to present). Paleogene and Neogene are relatively new terms that now replace the deprecated term, Tertiary. The Paleogene is subdivided into three epochs: the Paleocene (65.5 to 55.8 million years ago), the Eocene (55.8 to 33.9 million years ago), and the Oligocene (33.9 to 23.03 million years ago). The Neogene is subdivided into two epochs: the Miocene (23.03 to 5.332 million years ago) and Pliocene (5.332 to 2.588 million years ago).*

Stratigraphy

The concepts of Tertiary and Quaternary have an interesting history. In the 1760s and 1770s a geologist named Giovanni Arduino was studying the rocks and minerals in Tuscany. He classified mountains according to the type of rocks that he found in them. Unfossiliferous schists, granites, and basalts (all volcanic rocks) that formed the cores of large mountains he called Primitive. Fossil-rich rocks of limestone and clay that were found on the flanks of mountains over the Primitive rocks were called Secondary. Finally, there were another group of fossiliferous rocks of limestones and sandstones lying over the Secondary rocks and forming the foothills of the mountains that Anduino called Tertiary. So at first, Tertiary referred to a certain type of rock found in the area of Tuscany. But later, geologists used the fossils found in the Tertiary rocks there to recognize rocks of the same age elsewhere. Rocks with the same species of fossils were the same age.

Extensive Tertiary age rocks were recognized in the Paris Basin, which is the area around Paris, France. In the 1820s and 1830s Charles Lyell, a noted English geologist who had a great influence on Charles Darwin, subdivided the Tertiary rocks of the Paris Basin on their fossils. Lyell came up with an ingenious idea. He noticed that the rocks at the top of the section had a very high percentage of fossils of living mollusc species. Those at the bottom of the section had very few living forms. He deduced that this difference was because of the extinction of older forms and the evolution of living forms during the time that the rocks were being deposited. He divided the Tertiary rocks into three sub-ages: the Pliocene, the Miocene, and the Eocene. 90% of the fossil molluscs in Pliocene rocks were living today. In the Miocene rocks, only 18% of the molluscs were of living species, and in Eocene rocks, only 9.5%.

These subdivisions of the Tertiary have been correlated around the world using the fossil species in them. Rocks with the same species as Lyell's Eocene, are considered to be the same age as those in the Paris Basin. The same goes for the other subdivisions. Some time later it was noted that in areas other than the Paris Basin, there were rocks that seemed to be from time periods that were not represented in Lyell's sequence. This was because during those periods there had been no deposition in what would later be the Paris Basin. These two periods, later designated Oligocene and Paleocene, were inserted into the Tertiary in their proper places.



Cenozoic fossil localities

- **Bodjong Formation, Indonesia:** Numerous deep-water molluscs from this Pliocene locality have given us a picture of past tropical marine life in what is today a very species rich area.
- **Creede Formation:** A rich plant community from this Oligocene locality in southwestern Colorado includes pine, fir, barberry, and a variety of other species, all very well preserved.
- **Florissant Formation:** This Eocene locality lies in the Rocky Mountains of Colorado. Few U.S. localities have such remarkable preservation of fossil insects.
- **Green River Formation:** Rich in fossils of plants, insects, and fish, this Eocene locality extends across Utah, Colorado, and Wyoming in the western U.S.
- **Rancho La Brea Tar Pits:** One of the most famous fossil localities of all, La Brea is an asphalt seep containing Pleistocene fossils located in Los Angeles, California.
- **Monterey Formation:** Vast area of exposed Miocene outcrops along the coastal ranges of California. Fossils include macroalgae, microfossils, shells, crabs, and porpoises.
- **Villavieja Formation, Colombia:** Until recently, our only good source of information about Tertiary animals in the South American tropics was this site in Colombia. Many of the pre-Pliocene animal groups represented have been found nowhere else outside of the continent.

Resources

- For information about other Cenozoic localities, see our pages on the Eocene, Oligocene, and Miocene.
- Take a tour of the world's largest paleo institute, the Paleontological Institute of Russia, which includes many Cenozoic mammals from Russia.
- NEOMAP — The databases of MIOMAP and FAUNMAP are now linked, providing data for all published late Oligocene through Holocene mammals in the U.S.
- Find out more about the Cenozoic paleontology and geology of North America at the Paleontology Portal.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2008.

David Polly, Rob Guralnick, and Allen Collins all worked on the earliest versions of this page; Brian Speer made revisions and broke the single page into several pages, 3/6/1997; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format, corrected dates and made minor edits, 6/2011

University of California Museum of Paleontology

156

See the world (and its fossils) with UCMP's field notes.

The Cretaceous Period

The Cretaceous is usually noted for being the last portion of the "Age of Dinosaurs", but that does not mean that new kinds of dinosaurs did not appear then. It is during the Cretaceous that the first ceratopsian and pachycepalosaurid dinosaurs appeared. Also during this time, we find the first fossils of many insect groups, modern mammal and bird groups, and the first flowering plants.

The breakup of the world-continent Pangea, which began to disperse during the Jurassic, continued. This led to increased regional differences in floras and faunas between the northern and southern continents.

The end of the Cretaceous brought the end of many previously successful and diverse groups of organisms, such as non-avian dinosaurs and ammonites. This laid open the stage for those groups which had previously taken secondary roles to come to the forefront. The Cretaceous was thus the time in which life as it now exists on Earth came together.

Life

No great extinction or burst of diversity separated the Cretaceous from the Jurassic Period that had preceded it. In some ways, things went on as they had. Dinosaurs both great and small moved through forests of ferns, cycads, and conifers. Ammonites, belemnites, other molluscs, and fish were hunted by great "marine reptiles," and pterosaurs and birds flapped and soared in the air above. Yet the Cretaceous saw the first appearance of many lifeforms that would go on to play key roles in the coming Cenozoic world.

Perhaps the most important of these events, at least for terrestrial life, was the first appearance of the flowering plants, also called the angiosperms or Anthophyta. First appearing in the Lower Cretaceous around 125 million years ago, the flowering plants first radiated in the middle Cretaceous, about 100 million years ago. Early angiosperms did not develop shrub- or tree-like morphologies, but by the close of the Cretaceous, a number of forms had evolved that any modern botanist would recognize. The angiosperms thrived in a variety of environments such as areas with damper climates, habitats favored by cycads and cycadeoids, and riparian zones. High southern latitudes were not invaded by angiosperms until the end of the Cretaceous. Ferns dominated open, dry and/or low-nutrient lands. Typical Jurassic vegetation, including conifers, cycads, and other gymnosperms, continued on into the Lower Cretaceous without significant changes. At the beginning of this period, conifer diversity was fairly low in the higher latitudes of the Northern Hemisphere, but by the middle of the period, species diversification was increasing exponentially. Swamps were dominated by conifers and angiosperm dicots.

At about the same time, many modern groups of insects were beginning to diversify, and we find the oldest known ants and butterflies. Aphids, grasshoppers, and gall wasps appear in the Cretaceous, as well as termites and ants in the later part of this period. Another important insect to evolve was the eusocial bee, which was integral to the ecology and evolution of flowering plants.

The Cretaceous also saw the first radiation of the diatoms in the oceans (freshwater diatoms did not appear until the Miocene).

The Cretaceous-Tertiary extinction

The most famous of all mass extinctions marks the end of the Cretaceous Period, about 65 million years ago. As everyone knows, this was the great extinction in which the dinosaurs died out, except for the birds, of course. The other lineages of "marine reptiles" — the ichthyosaurs, plesiosaurs, and mosasaurs — also were extinct by the end of the Cretaceous, as were the flying pterosaurs, but some, like the ichthyosaurs, were probably extinct a little *before* the end of the Cretaceous. Many species of foraminiferans went extinct at the end of the Cretaceous, as did the ammonites. But many groups of organisms, such as flowering plants, gastropods and pelecypods (snails and clams), amphibians, lizards and snakes, crocodilians, and mammals "sailed through" the Cretaceous-Tertiary boundary, with few or no apparent extinctions at all.

What on Earth — or not — caused this extinction and how can we know? What killed the dinosaurs?

Tectonics and paleoclimate

The Cretaceous is defined as the period between 145.5 and 65.5 million years ago,* the last period of the Mesozoic Era, following the Jurassic and ending with the extinction of the dinosaurs (except birds). By the beginning of the Cretaceous, the supercontinent Pangea was already rifting apart, and by the mid-Cretaceous, it had split into several smaller continents. This created large-scale geographic isolation, causing a divergence in evolution of all land-based life for the two new land masses. The rifting apart also generated extensive new coastlines, and a corresponding increase in the available near-shore habitat. Additionally, seasons began to grow more pronounced as the global climate became cooler. Forests evolved to look similar to present day forests, with oaks, hickories, and magnolias becoming common in North America by the end of the Cretaceous.

At the end of the Cretaceous Period, 65 million years ago, an asteroid hit Earth in the Yucatan Peninsula, Mexico, forming what is today called the Chicxulub impact crater. It has been estimated that half of the world's species went extinct at about this time, but no accurate species count exists for all groups of organisms. Some have argued that many of the species to go extinct did so before the impact, perhaps because of environmental changes occuring at this time. Whatever its cause, this extinction event marks the end of the Cretaceous Period and of the Mesozoic Era.

Localities

- **Clayton Lake, New Mexico:** This Cretaceous site has some of the most extensive and best preserved dinosaur trackways in the United States.
- **Pt. Loma Formation, California:** This Cretaceous locality has yielded important fossils for understanding western North American dinosaurs.

Resources

- Find out more about the Cretaceous paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Cretaceous.

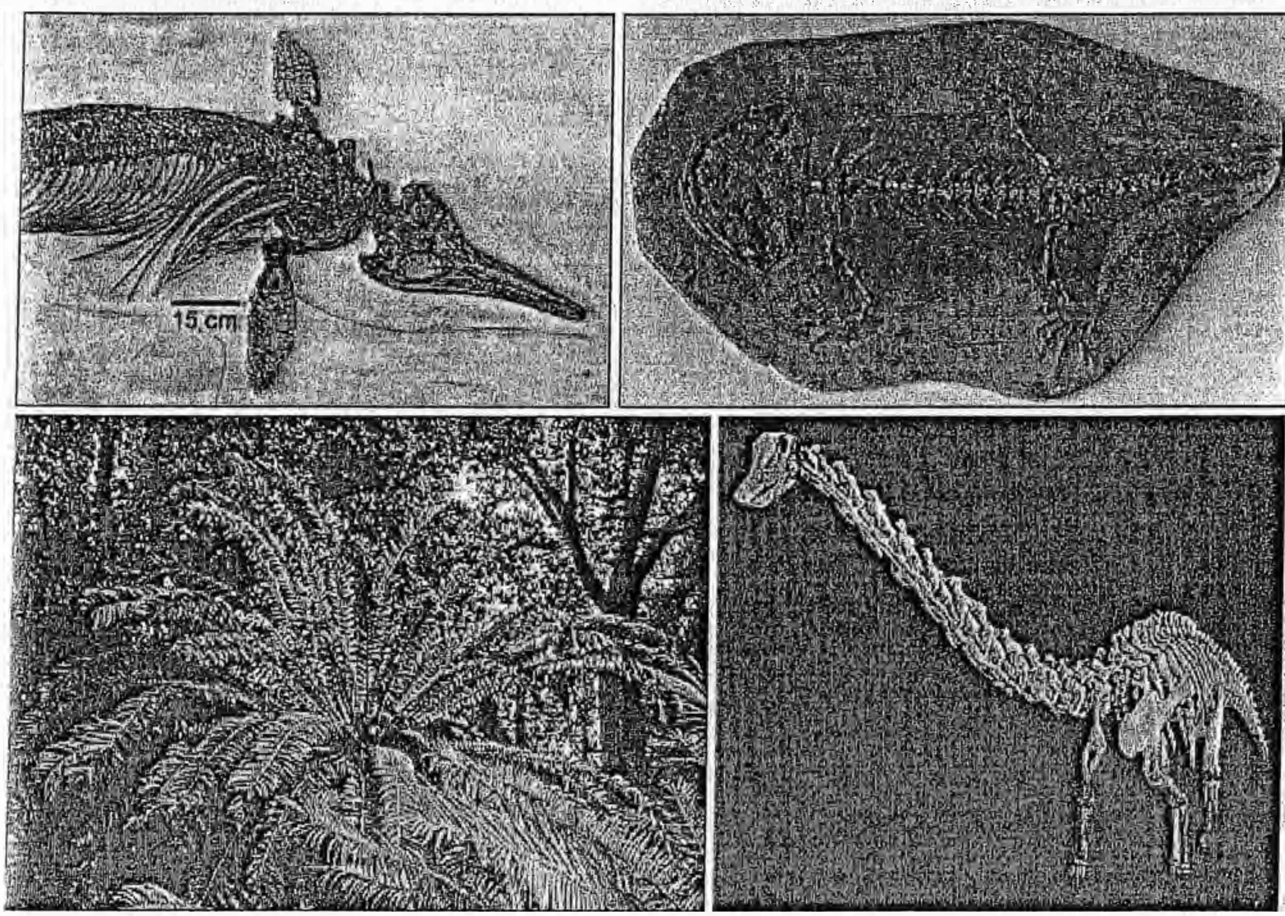
* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Ben Waggoner created the original content, 11/26/1995; Brian Speer added graphics, 3/11/1997, and additional text, 2/1/1998; the material on tectonics and paleoclimate was added by Quynh-Huong Bui, Julia Davis, Ariane Helou, Saro Manoukian, and Musetta So as part of a Biology 1B project for Section 112 under Brian Speer, 5/1/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/15/2011

The Jurassic Period

Great plant-eating dinosaurs roaming the earth, feeding on lush ferns and palm-like cycads and bennettitaleans ... smaller but vicious carnivores stalking the great herbivores ... oceans full of fish, squid, and coiled ammonites, plus great ichthyosaurs and long-necked plesiosaurs ... vertebrates taking to the air, like the pterosaurs and the first birds. This was the Jurassic Period, 199.6 to 145.5 million years ago* — a 54-million-year chunk of the Mesozoic Era.

Named for the Jura Mountains on the border between France and Switzerland, where rocks of this age were first studied, the Jurassic has become a household word with the success of the movie *Jurassic Park*. Outside of Hollywood, the Jurassic is still important to us today, both because of its wealth of fossils and because of its economic importance — the oilfields of the North Sea, for instance, are Jurassic in age.



Clockwise from top left, *Ichthyosaurus intermedius*, a Lower Jurassic ichthyosaur from Glastonbury, England. *Karaurus sharovi*, one of the earliest known salamanders, from Kazakhstan. *Diplodocus*, a large, long-necked sauropod. Modern cycads.

Life

Today, the name "Jurassic" conjures up images of the phenomenally successful book and movie, *Jurassic Park*. It is quite true that the dinosaurs dominated the land fauna — although many of the dinosaurs featured in *Jurassic Park*, such as Triceratops and Tyrannosaurus rex, did not evolve until after the Jurassic was over. The largest dinosaurs of the time — in fact, the largest land animals of all time — were the gigantic sauropods, such as the famous *Diplodocus* (top right, above), *Brachiosaurus* and *Apatosaurus*. Other herbivorous dinosaurs of the Jurassic included the plated stegosaurs. Predatory dinosaurs of the Jurassic included fearsome carnosaurs such as *Allosaurus*, small, fast coelurosaurs, and ceratosaurs such as *Dilophosaurus*. The Jurassic also saw the origination of the first birds, including the well-known *Archaeopteryx*, probably from coelurosaurian ancestors.

But there was more to life than dinosaurs! In the seas, the fishlike ichthyosaurs (top left, above) were at their height, sharing the oceans with the plesiosaurs, giant marine crocodiles, and modern-looking sharks and rays. Also prominent in the seas were cephalopods — relatives of the squids, nautilus, and octopi of today. Jurassic cephalopods included the ammonites, with their coiled external shells (upper left), and the belemnites, close relatives of modern squid but with heavy, calcified, bullet-shaped, partially internal shells. Among the plankton in the oceans, the dinoflagellates became numerous and diverse, as did the coccolithophorids (microscopic single-celled algae with an outer covering of calcareous plates).

Land plants abounded in the Jurassic, but floras were different from what we see today. Although Jurassic dinosaurs are sometimes drawn with palm trees, there were no palms or any other flowering plants — at least as we know them today — in the Jurassic. Instead, ferns, ginkgoes, bennettitaleans or "cycadeoids," and true cycads — like the living cycad pictured above, lower left — flourished in the Jurassic. Conifers were also present, including close relatives of living redwoods, cypresses, pines, and yews. Creeping about in this foliage, no bigger than rats, were a number of early mammals.

Localities

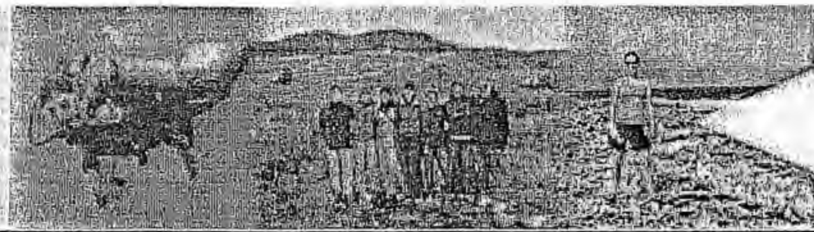
- **Blue Nile Gorge, Ethiopia:** Come along on a fossil-hunting trip to Ethiopia with UCMP researchers and see the first dinosaur fossils found there.
- **Solnhofen Limestone, Germany:** Exquisitely detailed fossils have come from these Jurassic deposits in southern Germany.

Resources

- Find out more about the Jurassic paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Jurassic.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Ben Waggoner created the original content, 9/10/1995 and 11/25-28/1995; Brian Speer made modifications, 11/27/1995; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/16/2011; *Ichthyosaurus* photo by Sarah Rieboldt, UCMP; *Karaurus* photo by Pat Holroyd, UCMP; source of *Diplodocus* photo is unknown; cycads photo by Dr. Robert T. and Margaret Orr © 2004 California Academy of Sciences



See the world (and its fossils) with UCMP's field notes.

160

The Triassic Period

In many ways, the Triassic, lasting from 251.0 mya to 199.6 mya,* was a time of transition. It was at this time that the world-continent of Pangea existed, altering global climate and ocean circulation. The Triassic also follows the largest extinction event in the history of life, and so is a time when the survivors of that event spread and recolonized.

The organisms of the Triassic can be considered to belong to one of three groups: holdovers from the Permo-Triassic extinction, new groups which flourished briefly, and new groups which went on to dominate the Mesozoic world. The holdovers included the lycophytes, glossopterids, and dicynodonts. While those that went on to dominate the Mesozoic world include modern conifers, cycadeoids, and the dinosaurs.

Tectonics and paleoclimate

As with almost any other period of the Earth's history, the Triassic had a unique climate and biota indigenous to that time. The paleoclimate was influenced largely by tectonic events that never existed before or since.

At the beginning of the Triassic Period, the land masses of the world were still bound together into the vast supercontinent known as Pangea. Pangea began to break apart in the Middle Triassic, forming Gondwana (South America, Africa, India, Antarctica, and Australia) in the south and Laurasia (North America and Eurasia) in the north. The movement of the two resulting supercontinents was caused by sea floor spreading at the midocean ridge lying at the bottom of the Tethys Sea, the body of water between Gondwana and Laurasia. While Pangea was breaking apart, mountains were forming on the west coast of North America by subduction of the ocean plates beneath the continental plates. Throughout the Middle to Upper Triassic, mountain-forming continued along the coast extending from Alaska to Chile. As mountains were forming in the Americas, North Africa was being split from Europe by the spreading rift. This division of the continents advanced further westward, eventually splitting eastern North America from North Africa.

The climate of the Triassic Period was influenced by Pangea, its centralized position straddling the equator, and the geologic activity associated with its breakup. Generally speaking, the continents were of high elevation compared to sea level, and the sea level did not change drastically during the period. Due to the low sea level, flooding of the continents to form shallow seas did not occur. Much of the inland area was isolated from the cooling and moist effects of the ocean. The result was a globally arid and dry climate, though regions near the coast most likely experienced seasonal monsoons. There were no polar ice caps, and the temperature gradient in the north-south direction is assumed to have been more gradual than present day. The sea level rose as the rift grew between North Africa and southern Europe, resulting in the flooding of Central and South Europe; the climates of terrestrial Europe were hot and dry, as in the Permian. Overall, it appears that the climate included both arid dune environments and moist river and lake habitats with gymnosperm forests.

Some conclusions can be drawn about more specific regional climates and species based on experimental research. The presence of coal-rich sequences in the high northern and southern latitudes, as well as the presence of large amphibians there, indicates that the paleoclimate was wetter in those areas. Living species of some Mesozoic ferns (including the families Osmundacae and Dipteridacae) now live in wet, shady areas under forest canopies, so it is likely that the paleoclimate their Triassic ancestors inhabited were also damp and shaded. The Mesozoic era might also have had large, open areas with low-growing vegetation, including savannas or fern prairie with dry, nutrient poor soil populated by herbaceous plants, such as ferns of the families Matoniaceae and Gleicheniaceae. Thus, despite the union of the continental landmasses, the Triassic vegetation was quite provincial, though this decreased as the Triassic wore on. The northern forests at the beginning of the Triassic were dominated by conifers, ginkgos, cycads, and bennettitaleans, while the forests of Gondwana were dominated by *Dicroidium* and *Thinnfeldia*. By the end of the Triassic, both hemispheres gave way to conifer and cycad vegetation.

161

The Triassic-Jurassic boundary is similar to the Permo-Triassic boundary in that the global climate was not radically altered, though a major extinction of terrestrial vertebrates occurred. With the end of the Triassic and the beginning of the Jurassic, Pangea continued to break apart, inevitably affecting the climate, though not as radically as it had during the Triassic.

Localities

- **Ischigualasto Formation, Argentina:** The best-known and best-preserved early dinosaurs come from this Triassic locality in South America.

Resources and references

- Behrensmeyer, A.K., J.D. Damuth, W.A. Dimichelle, R. Potts, H.-D. Sues, and S. Wing 1992. Terrestrial ecosystems through time: Evolutionary paleoecology of terrestrial plants and animals. Chicago: University of Chicago Press. 588 pp.
- Long, R.A., and R. Houk. 1988. Dawn of the dinosaurs: The Triassic in Petrified Forest. Petrified Forest, AZ: Petrified Forest Museum Association. 96 pp.
- Read about the field work of UCMP alums Randy Irmis and Sterling Nesbitt as they search for information about dinosaur precursors in the Triassic Chinle Formation of New Mexico.
- See this National Park Service pdf on the Triassic dinosaurs and other animals of Petrified Forest National Park in Arizona.
- Find out more about the Triassic paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Triassic.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Brian R. Speer wrote the original text and posted this page, 3/9/1997; the material on tectonics and paleoclimate was added by Manish Asaravala, Hayley Lam, Stephanie Litty, Jason Phillips, and Ting-Ting Wu as part of a Biology 1B project for Section 112 under Brian Speer, 5/1/2000; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made minor edits, 6/29/2011

162

See the world (and its fossils) with UCMP's field notes.

The Permian Period

The Permian period lasted from 299 to 251 million years ago* and was the last period of the Paleozoic Era. The distinction between the Paleozoic and the Mesozoic is made at the end of the Permian in recognition of the largest mass extinction recorded in the history of life on Earth. It affected many groups of organisms in many different environments, but it affected marine communities the most by far, causing the extinction of most of the marine invertebrates of the time. Some groups survived the Permian mass extinction in greatly diminished numbers, but they never again reached the ecological dominance they once had, clearing the way for another group of sea life. On land, a relatively smaller extinction of diapsids and synapsids cleared the way for other forms to dominate, and led to what has been called the "Age of Dinosaurs." Also, the great forests of fern-like plants shifted to gymnosperms, plants with their offspring enclosed within seeds. Modern conifers, the most familiar gymnosperms of today, first appear in the fossil record of the Permian. The Permian was a time of great changes and life on Earth was never the same again.

The global geography of the Permian included massive areas of land and water. By the beginning of the Permian, the motion of the Earth's crustal plates had brought much of the total land together, fused in a supercontinent known as Pangea. Many of the continents of today in somewhat intact form met in Pangea (only Asia was broken up at the time), which stretched from the northern to the southern pole. Most of the rest of the surface area of the Earth was occupied by a corresponding single ocean, known as Panthalassa, with a smaller sea to the east of Pangea known as Tethys.

Models indicate that the interior regions of this vast continent were probably dry, with great seasonal fluctuations due to the lack of a moderating effect provided by nearby bodies of water. Only portions of this interior region received rainfall throughout the year. There is little known about the Panthalassic Ocean itself. There are indications thatt he climate of the Earth shifted during the Permian, with decreasing glaciation as the interiors of continents became drier.

Stratigraphy

Until the later 1990s, there was little consensus on the order of strata in the late Permian. Since the upper strata of various Permian locations tend to be relatively fossil deficient, correlation using index fossils has been difficult. Correlation was attempted using fossils that were in some cases native only to the local regions where they were found and older work was based on assumptions that have changed in more recent years.

Older classifications relied on the Ural Mountains stratigraphy. In 1994, Jin et al. proposed a worldwide stratigraphy of the Permian Period made up of four series/epochs: the Uralian, the Chihsian, the Guadalupian, and the Lopingian. In the early 2000s, work by Jin and others resulted in the stratigraphy currently accepted by the International Commission on Stratigraphy.

The current stratigraphy divides the Permian into three series or epochs: the Cisuralian (299 to 270.6 mya), Guadalupian (270.6 to 260.4 mya), and Lopingian (260.4 to 251 mya).* Find out more about how these periods of time are defined.

Permian shales, sandstones, siltstones, limestones, sands, marls, and dolostones were deposited as a result of sea-level fluctuations. These fluctuation cycles can be seen in the rock layers. Relatively few sites lend themselves to direct radioactive dating, so the age of intermediate strata is often estimated.

Permian fossils that have been used as index fossils include brachiopods, ammonoids, fusilinids, conodonts, and other marine invertebrates, and some genera occur within such specific time frames that strata are named for them and permit stratigraphic identification through the presence or absence of specified fossils.

163

Localities

- **Glass Mountains, Texas:** Permian fossils from the Glass Mountains are of shallow, warm-water marine life.

Resources and references

- Jin, Y.-G., B.R. Glenister, C.K. Kotlyar, and J.-Z. Sheng. 1994. An operational scheme of Permian chronostratigraphy. *Palaeoworld* 4:1-14.
- Jin, Y.-G., S. Shen, C.M. Henderson, X. Wang, W. Wang, Y. Wang, C. Cao, and Q. Shang. 2006. The global stratotype section and point (GSSP) for the boundary between the Capitanian and Wuchiapingian Stage (Permian). *Episodes* 29(4):253-262.
- Jin, Y.-G., Y. Wang, C. Henderson, B.R. Wardlaw, S. Shen, and C. Cao. 2006. The global boundary stratotype section and point (GSSP) for the base of Changhsingian Stage (Upper Permian). *Episodes* 29(3):175-182.
- Jones, T.S. 1953. Stratigraphy of the Permian Basin of West Texas. West Texas Geological Society Publication 53-29. 63 pp.
- Menning, M. 1995. A numerical time scale for the Permian and Triassic periods: An integrative time analysis. Pp. 77-97 *in* P.A. Scholle, T.M. Peryt, and D.S. Ulmer-Scholle (eds.), The Permian of Northern Pangea, Vol. 1. Springer-Verlag, Berlin.
- Ross, C.A., and J.R.P Ross 1995. Permian sequence stratigraphy. Pp. 98-123 *in* P.A. Scholle, T.M. Peryt, and D.S. Ulmer-Scholle (eds.), The Permian of Northern Pangea, Vol. 1. Springer-Verlag, Berlin.

- Find out more about the Brule Trackways, Nova Scotia, where hundreds of Permian age trackways have been found.
- Find out more about the Permian paleontology and geology of North America at the Paleontology Portal.
- See the Wikipedia page on the Permian.

* Dates from the International Commission on Stratigraphy's International Stratigraphic Chart, 2009.

Page content written and completed by Chavé Alexander, Henry Chang, Carl Tsai, and Peggy Wu as part of a Biology 1B project for Section 115 under Brian R. Speer, 5/11/1998; Sarah Rieboldt updated the pages to reflect the Geological Society of America (GSA) 1999 Geologic Timescale, 11/2002; Dave Smith recombined the content into a single page, adapted it to the new site format and made some content updates, 6/30/2011.

Co-Evolution Presentation Rubric

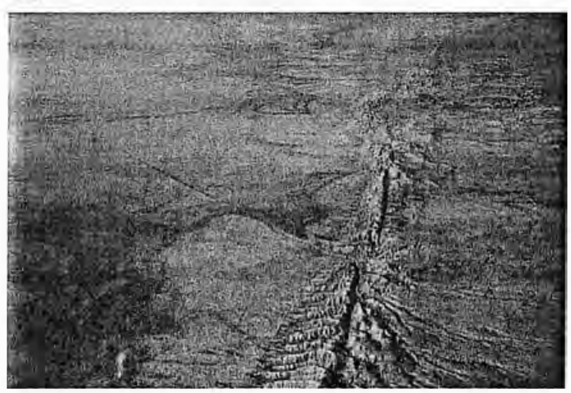
Category	4	3	2	1
Introduction	Includes a compelling argument for why this topic is important. Description of the topic is concise and important information about the topic given.	Includes an adequate argument for why the topic is important. A lot of information given but some that is not important	Includes a superficial argument for why the topic is important. Information given may not be important to the topic, some important instances missing.	Missing, incomplete, or inaccurate
Illustrating the history of co-evolution	Several examples of co-evolution are presented and explained	Co-evolution is explained but only one example of environment changing organism and organism changing environment given	The idea of Co-evolution unclear or only examples or environment affecting organisms (or vice-versa) given.	Missing, incomplete, or inaccurate
Effects of globally Catastrophic Events	Two or more catastrophic events are described. Their causes and effects discussed and the likelihood of reoccurrence discussed.	There are at least 2 diagrams used in the presentation. The diagrams were created by the group using drawing software and support the explanation of inheritance and the example.	The diagrams were found, not made	Missing, incomplete, or inaccurate
Prediction into the Future	The writer demonstrates a deep understanding of the interaction between life on Earth and how life can change the planet and how the planet can change life. Additionally, understanding of developments that are catastrophic to life in its form at that time and the progression of organisms from that point forward that leads to recolonization of new habitats.	The writer demonstrates a basic understanding of the interaction between life and Earth and how they affect one another. Examples are basically correct but are lacking in details. Predictions into the future may not be grounded in the principles presented in this unit.	The writer may have some serious misconceptions about the interplay between Earth and its inhabitants. They may not be able to make any logical predictions into the future due to a lack of understanding the past. Might conclude that life on Earth will end.	The writer may not understand the principles that explain how organisms changed the planet or how the planet changes life. The writer has no idea of what might happen in the near future nor predict what might happen in the event of another catastrophic event.
Citations	All information is cited in all cases	Most of the sources are cited	Some of the sources are cited	Missing, incomplete, or inaccurate

21B) Assessment Dynamic Earth

Devils Postpile, California

Shasta Mountain, California

Red Rock Canyon, California



San Andreas Fault, Carrizo Plains, California

Bumpass Hell, Lassen Volcanic Park, California

How mountains are formed; 3 minute video
http://www.bbc.co.uk/science/earth/surface_and_interior/mountain_formation#p00fzsnd

Observe the gallery of images which show the various way in which physical features change our planet Earth. Choose two of the images and describe the processes of physical evolution that are shown in the images and explain how these processes are evidence for evolution.

	Rubric 4- student uses 2 examples to describe **and** explain how the process of evolution occurs 3-- student uses 2 examples to describe **or** explain how the process of evolution occurs 2- student uses 1 examples to describe **or** explain how the process of evolution occurs **or** explains some processes but missing some.

	1- student uses 1 examples to describe **or** explains in part how the process of evolution occurs **or** writes of evolution but does not explain.