

Hot Times in t



Glyptostrobus

Alnus (alder)

Coryphodon

Salvinia

Hom

Lygodium

Sabalites (palme)

in the Bighorn Basin

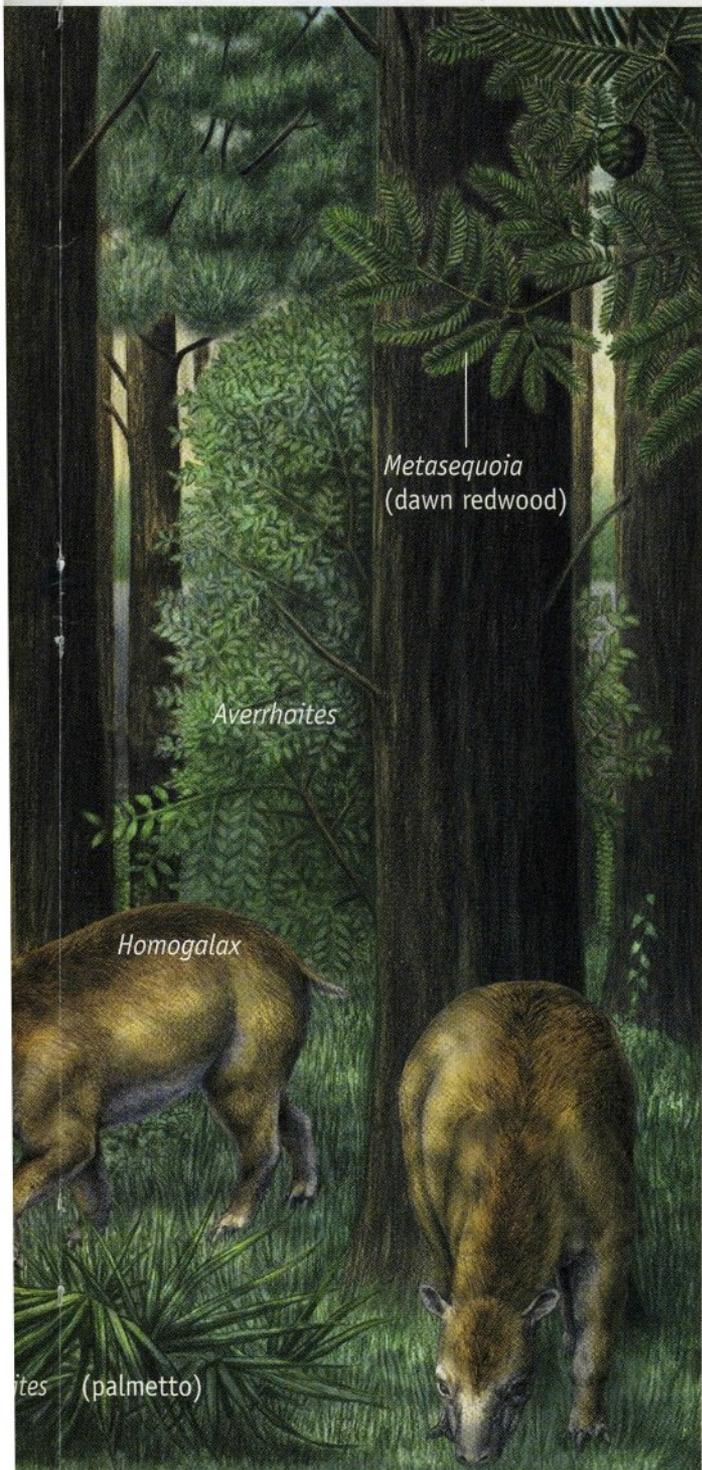
A modern desert provides clues to an ancient period of global warming.

Story by Scott L. Wing ~ Illustrations by Utako Kikutani

To most people who drive through, hurrying west to Yellowstone National Park, Wyoming's Bighorn Basin is nothing but a vast sagebrush plain crossed by two lanes of blacktop stretching away toward distant snowcapped peaks. Those with their eyes on the horizon may never notice badland hills striped with red and purple, and only those who leave the road will smell pungent, fresh-crushed sage, hear the total silence of the desert at midday, and feel dust as fine as powder between their fingers. Even those who experience the desert may not realize it is a country haunted by time travelers—paleontologists—who pull from the rocks not only fossils but an understanding of how the earth's climate has changed in the past and how plants and animals have responded to those changes. This part of Wyoming contains the world's best record of a period 55 million years ago, when the earth experienced an episode of global warming more rapid than any before, perhaps as rapid as the one we humans are about to cause and experience.

The Bighorn Basin is roughly 4,000 square miles (about 10,000 square kilometers) of badlands, sagebrush flats, and irrigated fields. Except for a narrow opening to the northwest, it is surrounded by mountains. Like other basins in the Rocky Mountains, the Bighorn Basin formed 60–50 million years ago, during the late Paleocene and early Eocene, as mountains were pushed up on all sides. Fast-moving streams eroded mud and sand from the rising mountains and, slowing as they reached flatter land, spread sediment across the bottom of the basin. Year after year, flood after flood, layers of sediment accumulated until in some areas the pile was more than six miles deep, burying—and preserving—the remains of countless organisms. In the past few million years, this part of the North American continent experienced renewed uplift, the climate became colder and drier, and the vast deposits began to erode rapidly, dissecting the soft rocks into strange and intricate shapes and littering the slopes

Fifty-five million years ago, parts of Wyoming's Bighorn Basin were lush and swampy. Here, a hippolike *Coryphodon* mother and her young feed on aquatic plants, while a pair of tapirlike *Homogalax* walk among the palmettos at the base of some dawn redwoods.



Metasequoia
(dawn redwood)

Averrhoites

Homogalax

(palmetto)

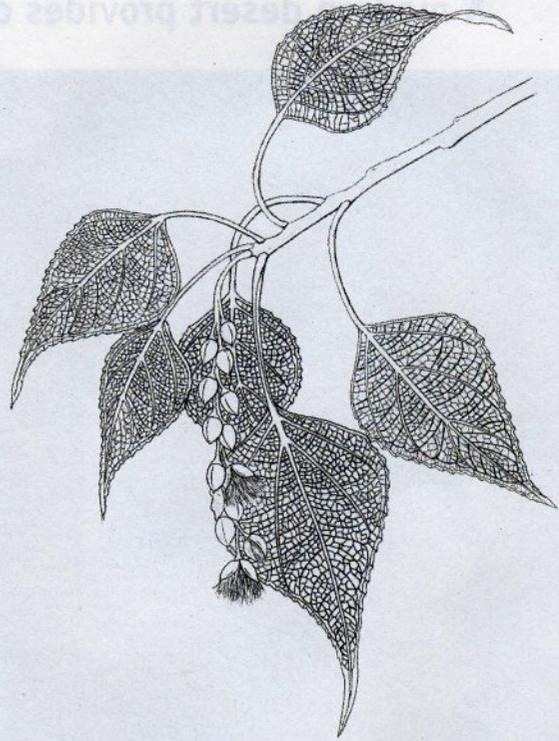
and flats with the fossils once contained inside.

Fossil riches first attracted paleontologists to the Bighorn Basin more than a century ago. Early scientists worked from horseback; photographs of their expeditions show U.S. Army cavalymen, brought along to ensure safety. In photographs from the early twentieth century, field crews cluster around buckboard wagons or Model T Fords, replaced in more recent photos by weathered pickups and four-wheel-drive vehicles. Traveling in the badlands is still difficult and sometimes dangerous—anyone who has worked long in the basin has spent time digging a stuck vehicle out of a dry creek bed or walked miles to the nearest road to seek help. Stories of such experiences, retold around campfires, remind us of some constants in fieldwork—even if we now locate fossil sites with global positioning systems rather than with cairns and enter data into computers at night as well as into notebooks during the day.

The generations of effort have paid off handsomely. Hundreds of thousands of fossils—mammal bones, leaves, shells—fill the cabinets of museums around the country and even the world. There are fossil pollen grains by the millions. Each fossil reveals something about a once-living organism: a leaf may contain the fossilized trail of an insect larva that tunneled within it for food; the cusps and crests of a mammal tooth bear evidence of the food it was suited to chew; the bones of large land tortoises, soft-shelled aquatic turtles, and alligators show that

work in the basin are familiar with the colors and shapes that indicate the likely presence of fossils. Bands of red, orange, purple, and light gray (evidence of well-drained soil) often contain fossil bones. Plant fossils occur in several types of rocks, including brown and dark gray layers—all that is left

Poplars growing in the basin's streamside forests had graceful pointed leaves and small hanging flowers, right, much like those of their living relatives.



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the ancient climate was warm and that the rivers teemed with life.

Evidence of past conditions also comes from the Bighorn Basin rocks themselves. The varicolored bands running across the hills are fossilized soils. The bands' colors indicate such things as the wetness of the original soil, and their thickness provides evidence of the length of time over which they developed. The depth and sinuosity of sandstone deposits reveal the original dimensions and course of ancient river channels. Coal-dark deposits show where the floodplain was especially wet, inhibiting the decay of plant remains by the fungi, bacteria, and arthropods living in the soil. Veterans of field-

of ancient swamps—and also coarse silt and fine sand layers deposited millions of years ago by overflowing rivers. Sediments containing fossil plants also typically contain the mineral gypsum, which forms large crystals as it weathers out of the rocks. The flashing of gypsum crystals in the desert sunlight can beckon a fossil hunter from miles away.

Taken together, all the evidence yields a picture of the environment and life of the basin during the late Paleocene and early Eocene. The streams—mostly small, slow moving, and gently meandering—were lined with low, natural levees on which grew a variety of trees, including relatives of sycamore, poplar, walnut, and hazelnut. The most common streamside tree was a relative of the katsura tree (*Cercidiphyllum*), a genus restricted today to two species in eastern Asia but once common across the mid and high latitudes of the northern continents. In the understory of these streamside woodlands lived several types of ferns still found in temperate forests, but the areas of open grassland that are so common today were absent. (Grasses had evolved by this time but had not yet become im-

portant forms of vegetation.) A variety of turtles lived in the rivers, along with gar, freshwater clams and snails, crayfish, and alligators. More than a hundred species of mammals roamed the forested floodplains, including some of the earliest primates, dawn horses, the earliest even-toed ungulates (the group that includes deer, pigs, and antelope), early true carnivores, and other mammals that have no extant close relatives (see “Wyoming’s Garden of Eden,” page 55). Among the birds was *Diatryma*, a six-foot-tall relative of today’s cranes.

Plants of the lower, wetter floodplains included dawn redwood (*Metasequoia*), a Chinese relative of bald cypress (*Glyptostrobus*), alder, a relative of witch hazel, and more than a hundred less-common species. Also flourishing in these swamp forests were relatives of a number of living, mostly tropical or subtropical plant families, including palms, cycads, tree ferns, ginger, magnolias, laurels, and hibiscus.

My work in the Bighorn Basin has focused on the plant fossils and the story of climatic change that can be learned from them. Even after nearly thirty years of fieldwork in the area, I still find it exciting to collect fossils of subtropical plants in a high desert where winter temperatures sometimes drop to -40°F (-40°C). One indication that the global climate has cooled radically in the past 50 million years comes from the identification of fossil plants whose living descendants are restricted to relatively mild parts of the planet. But the shapes and sizes of leaves have their own story to tell. Today, for example, plants with smooth-margined leaves (such as magnolias) are more diverse in warmer climates; plants with toothed or jagged leaf margins (such as elms or birches) make up a larger proportion of the species in cooler areas. We don’t fully understand the reasons for this difference, although we do know that the tissue in a leaf’s marginal teeth matures more quickly and begins to photosynthesize earlier than its other parts—a developmental schedule that may be advantageous for plants in cool climates with short growing seasons. Water evaporates faster from the teeth, however, and in warmer, drier climates the cost of lost water may outweigh the benefit of a photosynthetic head start.

The size of a leaf, too, can inform us about past climatic conditions. The larger the leaf, the more quickly it heats up—and loses water. As a result, plants of drier climes tend to have smaller, more water-efficient leaves. Extrapolating from the relationships between leaf size and shape in living plants and contemporary levels of precipitation and tem-

perature, scientists can use the sizes and shapes of fossil leaves to infer past levels of precipitation and temperature. The estimated mean annual temperature in the Bighorn Basin during the Paleocene and early Eocene varied from about 50 to 68°F (10 – 20°C). Winter frosts, if they occurred at all, were short-lived and mild. The ground never froze.

Other clues to past temperatures exist in the ratio of two oxygen isotopes: ^{16}O and ^{18}O . These isotopes occur in rainwater and therefore also in the surface water that animals drink and that helps form soil minerals. The warmer the climate, the warmer the rain and the higher the ratio of ^{16}O to ^{18}O . Knowing this, scientists can estimate the temperature of ancient rain from the ratio of isotopes trapped in fossil mammal teeth and soil minerals.

A common tree in Wyoming’s ancient swamps was *Glyptostrobus*, in the bald cypress family. A fossil, below, shows a branch with scalelike leaves and a cone at the tip.



A view of the Bighorn Basin. When looking for fossils, paleontologists are guided by the shapes and colors of the basin's rocks. Red and orange bands are fossil soils that often contain mammal bones.



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The results of calculations using the isotopic method are generally in agreement with those based on studying leaves. Both show a complex pattern. Temperatures warmed fairly quickly during the last million or so years of the Paleocene (from about 56 to 55 million years ago). Then, about 55 million years ago—near the boundary of the Paleocene and the Eocene—they warmed even more, and very rapidly. Detailed analyses of cores taken from the ocean bottom suggest that this warming took place over about 10,000 to 20,000 years—very fast for such a large change. Over the

The release of enormous amounts of methane gas from the seafloor may have contributed to a period of rapid global warming 55 million years ago.

course of the following 100,000 to 200,000 years, the moderate climate seen through much of the late Paleocene and early Eocene returned. Later in the early Eocene, temperatures cooled and then warmed once more (reaching the highest temperatures seen in the past 65 million years).

In the Bighorn Basin, evidence of the sharp warming near the time of the Paleocene-Eocene boundary can be found in several exceptionally

thick, greatly weathered fossil soils. It is in these layers that fossils of odd-toed ungulates, even-toed ungulates, and primates first appear. These new mammals arrived simultaneously in Europe, and at the same time a number of hard-to-explain global events occurred: Single-celled seafloor organisms went extinct in record numbers. Warmth-loving plankton appeared in middle- and high-latitude oceans, such as the North Atlantic and the oceans surrounding Antarctica. Ocean surface waters at high latitudes warmed by as much as 14°F (about 8°C). The ratio of light to heavy carbon isotopes increased dramatically in rocks and fossils. (Like oxygen, carbon has two common stable isotopes: light, or ¹²C, and heavy, or ¹³C. Many organisms use ¹²C preferentially in their metabolism, because it's more chemically reactive, so an increase in the amount of ¹²C in rocks and fossils could indicate that something had caused the release of large amounts of carbon previously used by living things.)

What was responsible for the rapid warming 55 million years ago, and did it perhaps have anything to do with these other events? We can pretty much rule out one known cause of rapid climate change—the melting and growth of ice sheets—because polar ice caps and continental ice sheets probably didn't exist during the Paleocene and Eocene. Recently, however, scientists proposed a new the-

ory to explain the Paleocene-Eocene climate change: the melting of methane ice on the seafloor.

Microbes that feed on organic material raining down to the ocean bottom produce methane gas as a by-product of their decay. When this gas combines with water under the high pressures and low temperatures found on the seafloor, it can form ice-like compounds called clathrates. According to the new theory, rising ocean temperatures, an earthquake beneath the seabed, or some as yet unknown mechanism triggered the release of enormous quantities of methane that had been locked up in clathrates. This would have led to further warming of the atmosphere and the ocean (methane is a powerful greenhouse gas), encouraging the additional release of seafloor methane in a potentially self-reinforcing process. The released methane would have reacted rapidly with oxygen, producing carbon dioxide and water vapor (both powerful greenhouse gases), and both of these would have made their own contributions to the warming.

Eventually, however, much of this carbon dioxide would have reacted with rocks during the process of chemical weathering or been used by plants in photosynthesis. Much of the water vapor produced by the methane-oxygen reaction would have rained out of the atmosphere. The result of these processes would have been a gradual return to the earlier atmosphere and climate.

The methane theory illuminates more than just the increase in temperature that occurred 55 mil-

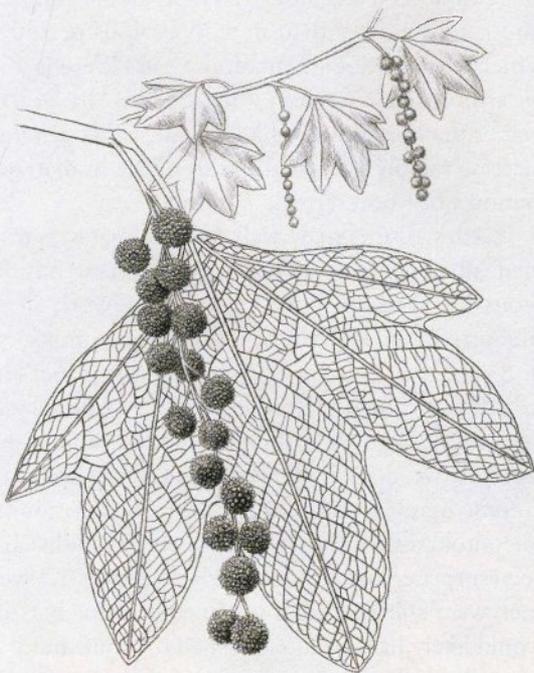


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lion years ago. A by-product of decaying organic matter, methane has a high ratio of light to heavy carbon, which could explain why geochemists have found more ^{12}C in rocks from that period. In addition, carbon dioxide that formed when methane reacted with oxygen that was dissolved in seawater or contained in the atmosphere could have changed the chemistry of the deep-sea environment, making it more corrosive. This, plus the reduced amount of oxygen in the water, would help account for the extinction of bottom-dwelling microorganisms. Moreover, the temporarily increased rainfall and higher temperatures explain the highly weathered soils seen in the Bighorn Basin rocks of this time.

Warming probably also made high-latitude land bridges across what are now the Bering Strait and the North Atlantic Ocean more hospitable to mammals, enabling intercontinental migration and explaining the animals' sudden appearance in the basin. Unfortunately, we have found no fossil plants from the warmest period, but fossils from just after the Paleocene-Eocene boundary show that only a few new types of plants (including several ferns) appeared at this time. The modest change in vegeta-

The lobes and veins of a fossilized *Macginitiea* leaf, above, show that it belongs to the sycamore family. An Eocene insect chewed a semicircular cut in the leaf's central lobe. Left: An artist's rendering of an intact *Macginitiea* leaf shows male and female flowers as well.



tion is curious, because plants are famously sensitive to climate change. Perhaps warm-climate (probably evergreen) species found it difficult to adapt to the polar nights on the high-latitude land connections. Or perhaps plants were slow to disperse because their seeds did not germinate and grow well in the shade of preexisting dense vegetation.

The warming that took place around the transition from the Paleocene to the Eocene demonstrates that greenhouse climates can come and go in

mate change in the future, the message is not so simple. The difference between plant response to the Paleocene-Eocene warming and to the last deglaciation suggests that vegetation can't always respond quickly. (It may, for example, be easier for seeds to establish themselves on the new ground exposed by retreating glaciers.) Moreover, the past makes an imperfect predictor because of the complicated effects of human actions—including habitat fragmentation, introduction of nonnative species, and conservation efforts. These actions may skew the odds in favor of some plants and against others.

Much remains to be learned about climate change during the Paleocene and Eocene. Our current knowledge has come from the efforts of hundreds of scientists—paleontologists, geochemists, climate modelers, and oceanographers—working all over the globe. New methods of analyzing fossils and sediments allow us to ask new questions. For instance, we may soon have reliable estimates of the concentrations of carbon dioxide in the atmosphere during this time. As work continues in the Bighorn Basin and elsewhere, our static snapshots of individual reconstructed moments from the past are being transformed into a motion picture revealing the responses of ecosystems to long-term shifts in global climate and regional environments. In effect, scientists are discovering a movie about life during the last great warming.

This may be a movie worth watching. The past decade was by far the warmest since the beginning of good record keeping. Average global temperature is now higher than in any previous period for which written documentation exists. Present levels of atmospheric carbon dioxide are 30 percent higher than preindustrial levels and will continue to increase rapidly if current trends in the human generation of carbon dioxide continue.

Earth's future may well hold climates warmer than any experienced in the last several hundred thousand years. But we know from work in the Bighorn Basin and elsewhere that greenhouse climates are not without precedent in our planet's history. If our climatic future looks even a little like the greenhouse past, then the paleontological and geological work done in the Bighorn Basin is not just an exercise in intellectual curiosity. The horse-mounted paleontologists of the 1880s probably wouldn't have been surprised to learn that their successors 120 years later were still finding fossils in the basin, but they would likely have been astonished that our minds are as much on the future as on the past. □

Common in the Tropics today, *Salvinia* was also an abundant aquatic fern during the Eocene. Its small, hairy, oval leaves floated on the water's surface.



CHIP CLARK

a geological blink and that lasting rearrangements of animal life may accompany the changes. Although the temperature increase reversed within a geological moment, the effects on the mammalian community were permanent. The lineages that appeared during this period went on to dominate faunas for millions of years, largely replacing those that had been important on the northern conti-

The fossils from the Bighorn Basin tell a story about how plants, animals, and whole ecosystems respond to long-term shifts in global climate.

nents for the previous 10 million years. Descendants of some of these immigrants, such as deer and pronghorns, are still dominant in this area today.

The lack of dramatic change in vegetation raises questions about how successfully plants can respond to warming climates, especially if they disperse slowly. Most of our knowledge about the issue has come from studying the recent geological past (the past 20,000 years), during which glaciers retreated from the northern continents. Plant populations altered their distributions very rapidly during this period, sometimes averaging more than half a mile (about one kilometer) a year. For those who hope this means plants will be able to cope with rapid cli-