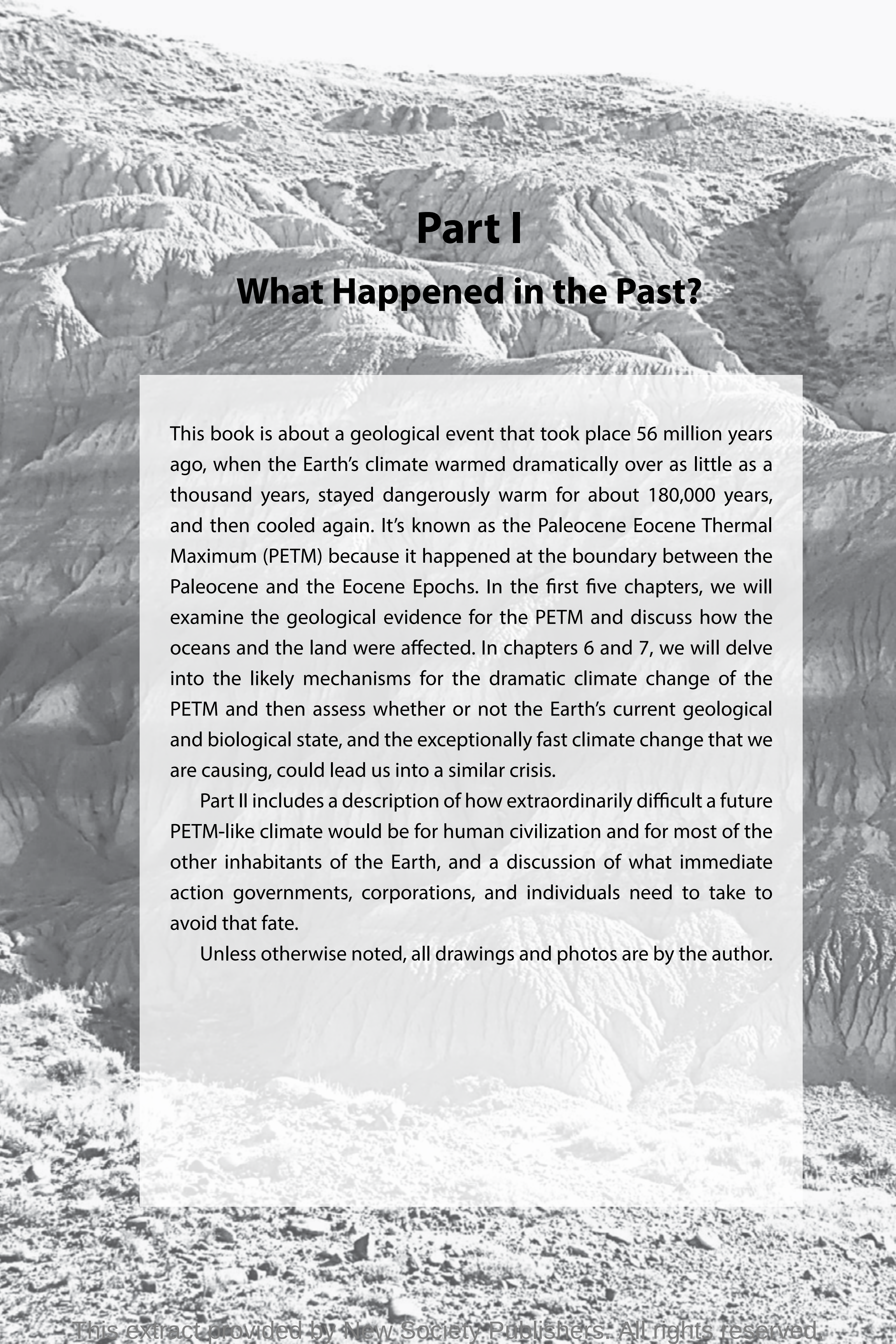

Part I

What Happened in the Past?

This book is about a geological event that took place 56 million years ago, when the Earth's climate warmed dramatically over as little as a thousand years, stayed dangerously warm for about 180,000 years, and then cooled again. It's known as the Paleocene Eocene Thermal Maximum (PETM) because it happened at the boundary between the Paleocene and the Eocene Epochs. In the first five chapters, we will examine the geological evidence for the PETM and discuss how the oceans and the land were affected. In chapters 6 and 7, we will delve into the likely mechanisms for the dramatic climate change of the PETM and then assess whether or not the Earth's current geological and biological state, and the exceptionally fast climate change that we are causing, could lead us into a similar crisis.

Part II includes a description of how extraordinarily difficult a future PETM-like climate would be for human civilization and for most of the other inhabitants of the Earth, and a discussion of what immediate action governments, corporations, and individuals need to take to avoid that fate.

Unless otherwise noted, all drawings and photos are by the author.

Chapter 1

The Bighorn Basin

> *It is certainly within the domain of science to determine when the earth was first fitted to receive life, and in what form the earliest life began. To trace that life in its manifold changes through past ages to the present is a more difficult task, but one from which modern science does not shrink.*
>
> —Othniel Marsh, 1877[1]

The Bighorn Basin is a thumbprint-shaped pocket of northwestern Wyoming about the size of Lake Ontario or Connecticut or Northern Ireland (figure 1.1). It consists of dry brown rolling hills and green flat river valleys and is surrounded by mountain ranges: the Bighorns to the east, the Absarokas (and Yellowstone National Park) to the west, and the Owl

Figure 1.1: *The location of the Bighorn Basin in northwestern Wyoming.*

Creek Range to the south. It can be uncomfortably hot in the summer, and cold and snowy in the winter. Although it is a semidesert and dominated by sagebrush and grasses, it is well watered by streams. The main one is the Bighorn River, which flows in from the south through a gap in the Owl Creek Range, and out to the north through a gap in the Bighorn Range and then on to join the Yellowstone River.

The basin was originally home to the Eastern Shoshone People. Chief Washakie ("Shoots the Buffalo Running"), a warrior and diplomat, was prominent among the Eastern Shoshone in the nineteenth century. Shoshone territory was colonized by ranchers and was made famous by colourful characters like Buffalo Bill Cody and Butch Cassidy, and by ambitious fossil hunters such as Edward Cope and Othniel Marsh. Today the basin is an important farming region—where irrigation water is available—and it is dotted with oil and gas wells. But it is still only sparsely populated, with no town exceeding 10,000.

So, what are we doing here in the Bighorn? As you might have guessed, it's not the sagebrush, the pronghorn antelope, or the wall-to-wall Republicans that we're here to observe, but what's underneath, and there is a fascinating geological history that extends over 500 million years. This history is written in the rocks shown in cross-section in figure 1.2. The oldest rocks of Wyoming are Precambrian in age (older than 539 million years), and they are a southern extension of the metamorphic and igneous rocks of the Canadian Shield. These are overlain by a series of sedimentary layers ranging in age from about 500 million (Cambrian) to around 50 million years (Eocene). Unlike the metamorphosed Precambrian rocks underneath, these ones have lots of great

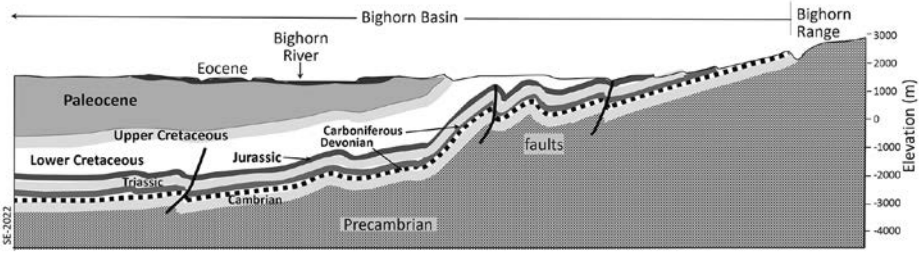

Figure 1.2: *Geological cross-section of the eastern part of the Bighorn Basin. (Based on Wyoming State Geological Survey, Geological Cross Sections, Bighorn Basin.)*

fossils, and they tell a wonderful story about the geological history of North America.

That's interesting, but in fact we're really here because this small part of North America has arguably the best rocks in the world for studying the short interval at the start of Eocene (56 million years ago) known as the Paleocene-Eocene Thermal Maximum (PETM), a short period of runaway climate change that we all might benefit from knowing more about.

Before we go back in time, it would be useful to quickly review the geological time scale. The last 600 million years are represented in figure 1.3 (although this is only about one-eighth of all of the Earth's history). The diagram is labelled with the approximate times of some of the important events in the history of life on Earth.

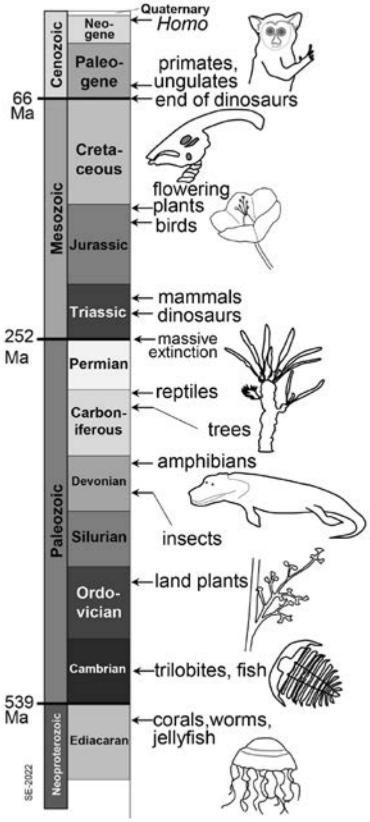

Figure 1.3: *The geological time scale for the past 600 million years. (Based on the International Commission on Stratigraphy, stratigraphy.org.)*

The oldest sedimentary rocks in the Bighorn region[2] are Cambrian in age—about 500 Ma (Ma = mega-annum, so that's 500 million years ago)—and they are dominated by limestone, formed in warm shallow water off the coast of the continent of Laurentia, which straddled the equator at that time (figure 1.4). Laurentia forms the core of what is now North America. There was no actual Bighorn Basin then. The Maurice Limestone, which has fossils of trilobites and brachiopods, is contemporaneous with and formed in a similar continent-margin setting to British Columbia's Burgess Shale, which has abundant evidence of what we call the Cambrian Explosion: the rapid evolution of the ancestors of many of Earth's modern life-forms.

About 100 million years later, in the early Devonian, Laurentia had moved farther south and the area that is now the Bighorn was right on the coast (figure 1.4). There were small primitive plants on land at this time (e.g., *Psilophyton*,[3] a plant without leaves or roots) and arthropods (e.g., scorpion-like creatures). A two-metre-long aquatic arthropod

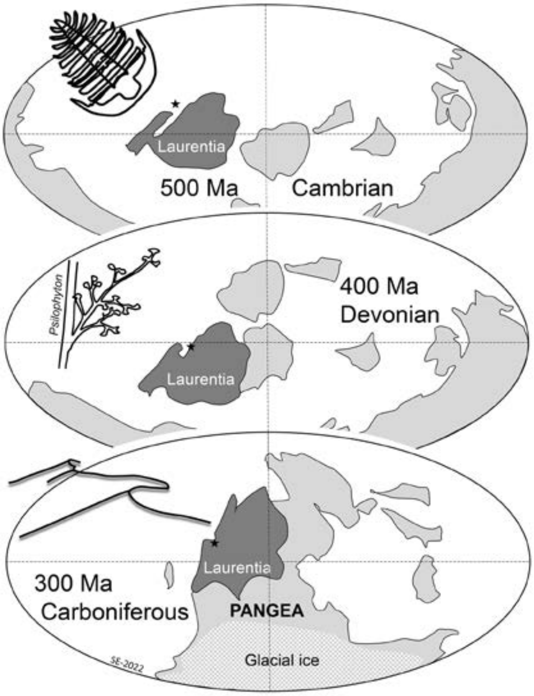

Figure 1.4: *Distribution of the continents in the Cambrian, Devonian, and Carboniferous. The star indicates the approximate location of the Bighorn Basin. (Based on maps by Christopher Scotese.[4])*

known as eurypterid patrolled the shallow water hunting for fish and other creatures.

Another 100 million years later, almost all the continental areas have been pushed together by plate tectonics, creating one super-continent known as Pangea. Land plants had become large and abundant by the early Carboniferous, and their vigorous growth consumed enough of the atmosphere's carbon dioxide to cool the climate. That allowed for accumulation of snow in the southern polar regions and then to the formation of glaciers, which eventually covered the whole of southern Pangea. There was no glacial ice in Laurentia, but the Bighorn area was a cold and windy desert with massive sand dunes. Bighorn Basin rocks from this time have few fossils, but plants were still abundant in other parts of the world and vertebrates (amphibians and reptiles) had started to colonize the land.

Pangea was still mostly in one piece at around 220 Ma, during the Triassic (figure 1.5), and was slowly moving north. Small continents

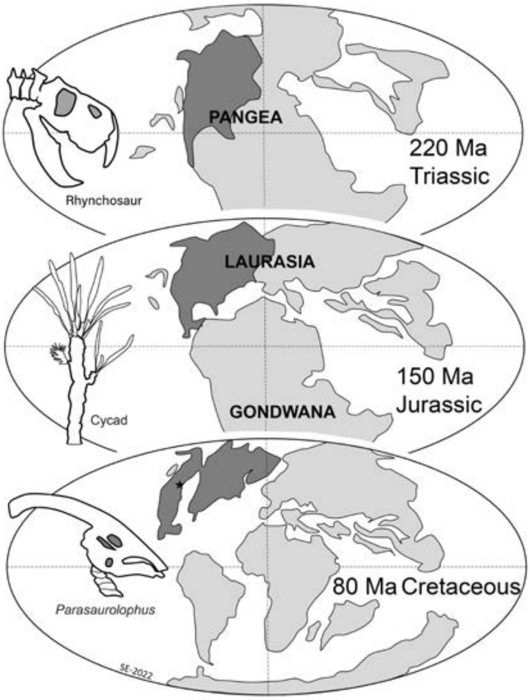

Figure 1.5: *Distribution of the continents during the Triassic, Jurassic, and Cretaceous.*

collided with and got stuck onto its western edge so that the Bighorn region was now much further inland. Sedimentary rocks from this time have a distinctive red colour because much of the area was a hot desert. The Bighorn Basin's Triassic Chugwater Formation has fossils of rhynchosaurs, an herbivorous reptile with a parrot-like "beak" and lots of teeth for grinding up vegetation. Dinosaurs did exist by this time (in what are now South America and Africa), but they are not known in the Triassic rocks of the Bighorn.

By the late Jurassic (150 Ma), Pangea had started to split apart along a line between Laurentia and the "Africa" part of Gondwana, forming the proto-Atlantic Ocean. The Jurassic rocks of the Bighorn Basin include the Morrison Formation, arguably the most prolific sequence of rocks for dinosaur fossils in the world, with skeletons of giant long-necked sauropods, bizarre ornithopods, spiky ankylosaurs, and fierce theropods both large and small, but no birds yet (at least not here). There are also fossils of various small mammals and reptiles. The region was richly forested with conifers, cycads, and ginkgoes, and with abundant ferns and horsetails in the understory, but no flowering plants yet.

The Cretaceous world of 80 Ma is starting to look more like the modern world. Pangea has split apart, and North and South America, Africa, and Eurasia have become separate continents. India is steaming north towards Asia, but Australia is still attached to Antarctica. It was warm almost everywhere, so sea level was high because there were no glaciers. Part of the interior of North America had been pulled downward by an underlying subducting oceanic plate, creating a wide inland sea. Giant ammonites lurked in the deeper water, along with large marine reptiles. Dinosaurs (such as *Parasaurolophus*) were still the dominant terrestrial animals. Pterosaurs—which are not dinosaurs—patrolled the skies. The forests were not very different from those of the Jurassic, except that angiosperms (flowering plants) were present, both as trees and shrubs, and there were birds.

Kapow!

Almost everything changed in an instant at 66 Ma, when a 12-kilometere diameter meteoroid slammed into Yucatan, Mexico, marking the end of the Cretaceous and the Mesozoic and the beginning of the

Paleogene and the Cenozoic. A massive volume of debris was blasted out of the crust, and as the fragments glowed white hot on re-entry, they generated flesh-burning heat over much of the Earth and sparked continent-scale wildfires. That was followed by months of near-complete darkness and bitter cold, and then by strong warming. Gone forever were terrestrial dinosaurs, pterosaurs, ammonites, and giant marine reptiles. Most bird and mammal groups survived, and once things settled down, most of the plants that had thrived in the late Cretaceous regenerated from seeds and roots.

Early in the Paleogene, the continents were close to their current locations (figure 1.6), but the northern part of the Atlantic may still have been closed between Greenland and Europe. India had not quite converged with Asia. It was very warm almost everywhere. The Fort Union Formation shale of the Bighorn Basin provides evidence that forested swampy conditions were common, and those swamps were home to small mammals, living in the trees (like *Plesiadapsis*), and to crocodiles and turtles.

The part of the geological time scale that is most relevant to this book is shown on figure 1.7. The Paleocene and Eocene are epochs within the Paleogene Period.[5] By the late Paleocene, the Earth's average temperature was a few degrees warmer than it was during the Cretaceous and about 10°C warmer than it is today. There were no glaciers anywhere,

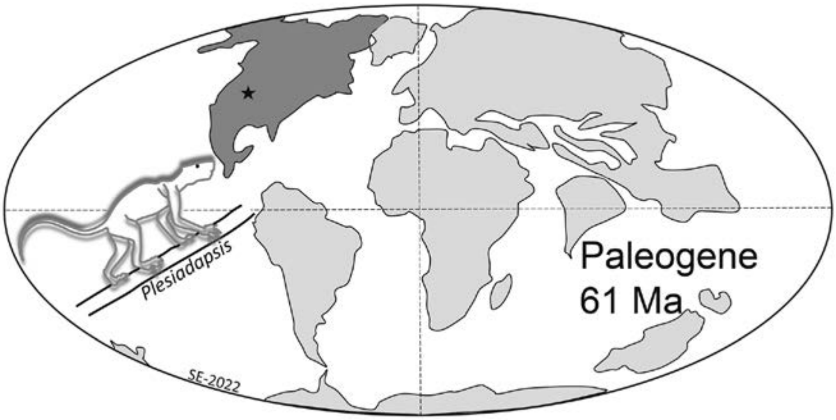

Figure 1.6: *Distribution of the continents during the Paleogene.*

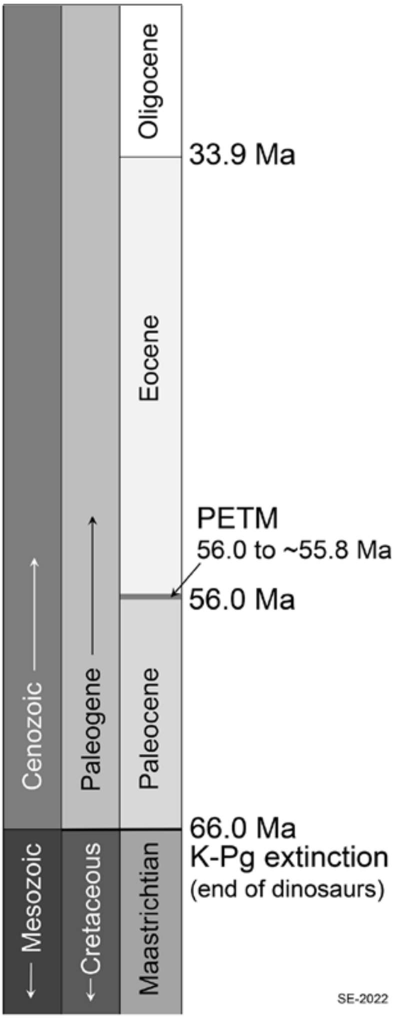

Figure 1.7: *The geological time scale for the early part of the Cenozoic. (Based on the International Commission on Stratigraphy, stratigraphy.org)*

although there was likely extensive permafrost and snow in Antarctica and some mountainous regions (but not the Himalayas, as they didn't exist yet). Because no water was tied up in glacial ice, sea level was at least 70 meters higher than it is today. Plants and animals of the time were able to cope with high temperatures because they had evolved in hot climates, and because natural climate change is typically very slow. Over the 10 million years of the Paleocene, the climate warmed by a total of about 3°C.[6] Late Paleocene plant communities were not very different from those of the Cretaceous, and also not that different from modern-day communities.

Late Paleocene in the Bighorn Basin

Let's pretend that we can time-travel to a Bighorn Basin forest at the very end of the Paleocene. Dial up "56.0 Ma" on your time machine, and you might find yourself in the welcome shade of some cypress conifers, with a few metasequoias in the mix. In wetter parts of the region, you will be able to wander through birch forests where you should also see walnut, laurel, magnolia, katsura, and dogwood. The understory will be populated with ferns and horsetails, along with ancestors of modern grapes and maybe even some grasses. In other words, many of the late Paleocene plants will be recognizable to most people. We all might feel at home in such a forest, if not for the stifling heat.

Be still now. Listen to the wind in the trees and the sounds of strange creatures. If you wait long enough, you might get lucky and see some bizarre mammals with unpronounceable names. The most common are the Eulipotyphla (means "truly fat and blind") insectivores, which are the ancestors of modern-day shrews, moles, and hedgehogs, but you'll have to look carefully, as these weigh in at just a few grams and they are good at hiding. Next most common are the Multituberculata, which are a little bigger, some up to nearly a kilogram. They are rodent-like (but not actual rodents) and have no living descendants, so will appear quite strange. Up in the trees, you might catch a glimpse of a Primatomorpha. They are mostly small, but some could be up to a few kilograms. The most common in this forest is *Plesiadapis,* which is about the size of a weasel. True primates were not present during the Paleocene. This one is *not* your distant ancestor, but it may be within a sister clade to the ancestors of the real primates that evolved early in the Eocene. If you hear something larger cracking a dry twig, it could be one of the condylarths. Again, there is a lack of consensus about this group, but they are considered to be the ancestors of hoofed animals (ungulates). The biggest ones around here are *Phenacodus*, at around 50 kilograms, and *Ectocion* at around 10 kilograms. Both are thought, by some, to be ancestors to the perissodactyls, ungulates with odd numbers of weight-bearing toes (1 or 3), like horses. If you hear something bigger still, off in the distance, that could be a Dinocerata. This is another hoofed mammal, not a dinosaur. Most were the size of pigs (around 50 kilograms), but they could reach rhino-size, so you might want to look for a tree to hide behind, or climb! If one of them comes into view, it will be like nothing you've ever seen (or hope to see!), with an array of tusk-like nobs protruding upward and outward from its skull and its snout and two sabre-like teeth extending down from the front of the upper jaw. Don't panic, it is an herbivore, and does not want to eat you! Dinoceratas disappeared in the Oligocene. And finally, while you're not likely to get this lucky, there should be some representatives of the order Carnivora in this forest, including *Didymictus*, which weighs in at around 5 kilograms (about the size of a small fox). *Didymictus* and its relations are more accurately carnivoramorphs, because while they have carnivore-like teeth, they lack other important carnivore features. They are not the ancestors of your cat or your dog.[7]

Most of the modern orders of birds (excluding the Passeriformes, or perching birds) had evolved by this time,[8] but bird fossils are rare in the Paleocene rocks of Wyoming, probably because the delicate bones of birds don't fossilize well. Nevertheless, it is likely that some of the calls that you hear in this forest are from birds, and those would probably be ancestors of the raptors, woodpeckers, or maybe even ducks or geese. You won't hear any bird calls that are "musical," at least not to your ears.

Earliest Eocene

Now, let's tick forward in time by just 10,000 years, into the early Eocene. Turn the dial to 55.99 Ma. The floodplain shale beds of the Eocene Willwood Formation are of primary importance to us here. They are mostly drab grays and browns, but the lowest 60 meters of the formation (representing the earliest Eocene) has distinctive fiery red and dull purple layers. These are from a critical interval in Earth history known as the Paleocene-Eocene Thermal Maximum (PETM), and our goal (mine, and yours I hope) in this book is to try to understand what happened, how and why it happened, whether it could happen again, and finally, what we can do to prevent that.

Evidence from many locations around the world (presented in later chapters) shows that the Earth's average temperature—which, as you know, was already hot by today's standards—soared by another 6° to 8°C over a period of a few thousand years (or less) at the start of the Eocene, and that there were other dramatic changes, both on land and in the ocean. While that rate of change was still much slower (about 10 times slower) than what humans have caused over the past century, it was fast enough to result in significant changes to the plant and animal communities of the Bighorn Basin. Some of those changes had implications for us humans and for the animal communities that we coexist with now.

At 55.99 Ma in the PETM, the early Eocene forest is completely different from the one you wandered through at the end of the Paleocene. The conifers are gone, as are most of the other plants that might have looked familiar earlier; in fact, over 90% of the plant species that were here just 10,000 years ago are gone. The predominant tree species now is a legume that is related to the modern-day mimosa (sorry, the tree, not the drink, aka, silk tree or *Albizia*). These types of plants were not present in this region prior to the PETM but had been growing over 1,000 kilometers further south. This forest is also much brighter than the one that was here before, and where there were swamps and rivers before, now there are just ephemeral streams.

Let's be quiet now and see what shows up. There's a chance that we'll get a fleeting view of a tiny *Diacodexis*, which could be the very earliest of the artiodactyls (hoofed animals with an even number of weight-bearing toes). It's under 3 kilograms and only about 50 centimeters long, with a tail almost as long. *Diacodexis's* relations are the ancestors of deer, antelope, goats, sheep, moose, giraffes, and whales. Yes, whales! This *Diacodexis* may have been in a hurry to avoid meeting up with something known as *Arfia*, which is a type of carnivore, but not like any modern ones. *Arfia* is in the Hyeanadontidae family. That just means that they have "hyena-like teeth"; they are not related to the hyenas that you're thinking of. Listen, something small is moving around in the tree above you. If you're lucky, you might catch a glimpse of a *Teilhardina*. It will look like a marmoset or a tarsier but is no bigger than a mouse

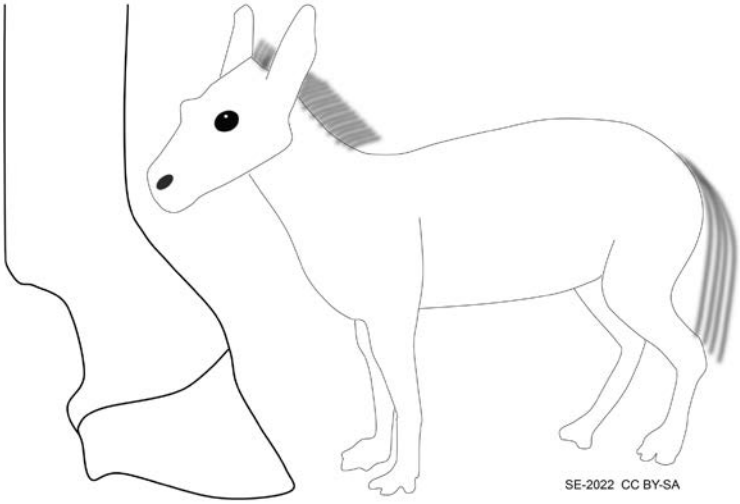

Figure 1.8: Sifrhippus, *the earliest known horse, with the lower leg of a modern-day horse for scale. (Based on an Eduard Solà photograph of a specimen in the Swedish Museum of Natural History.*[9]*)*

and is indeed the earliest known primate. Yes, this one actually could be your distant ancestor. They might have originated in southern Asia, and if so, it likely took many hundreds of generations for them to reach the Bighorn Basin. *Teilhardina* leaps to another branch, and another, and then it disappears behind the leaves.

All is quiet for a time, but then something else catches your eye within a dry stream channel. No? Nothing there? Wait, yes, there is something there, but it must be small. Oh, it's our lucky day! That tiny thing is a *Sifrhippus*, which means "Zero horse," because, as far as we know, this is the first ever horse (figure 1.8). It's no bigger than a fox! It nibbles on some leaves and some blades of grass. It flicks its tail to ward off a fly, and then twitches one of its ears. It's looking nervous, which isn't surprising for a horse, especially one this size. It's probably not alone, but its companions are not in sight.

It's very likely that *Sifrhippus* evolved here in North America,[10] in the earliest Eocene. There are early Eocene equids in western Europe, but they are in rocks that are just a little bit younger than those of the

Bighorn. Note that it has three toes, making it a perissodactyl (odd number of weight-bearing toes). Over the next several million years, two of those toes will get shorter as horses evolve to have only one weight-bearing toe, like the modern horse foot beside it.

Where did it go? It must have heard, or smelt, or felt something that we didn't. Oh shit! What was that awful shriek? There's only one thing in this forest that could make a noise like that, *Gastornis*! It's a giant flightless bird, about two meters tall, with an oversized head and massive beak. Although there is some debate about what *Gastornis* ate, the recent evidence points to a vegetarian diet, so we and *Sifrhippus* can relax a little. What a day! A ridiculously small horse and a ridiculously large bird, all in a matter of minutes. But wait, if *Gastornis* isn't a predator, it must be something's prey, and so why did it make such a fearful noise?

Yikes! Enough time travel for me! Back to the "safety" of the Anthropocene.

Summary

What have we discovered? There are a lot of amazing fossiliferous rocks in the Bighorn Basin of Wyoming, and an especially important interval within those rocks represents the latter part of the Paleocene and the beginning of the Eocene, right around 56 Ma. In the late Paleocene, Earth was hot, and the Bighorn Basin area was quite humid. It was forested with plants that would have looked familiar to us, and with animals that likely wouldn't. Just a few thousands of years later—a geological instant, really—conditions were very different. It had become hotter still, much hotter, and quite dry. Over 90% of the plant species that had been there were gone, and the new forest, made up of plants that had earlier only grown much farther south, was likely quite sparse. The animals were also quite different, and some of the ones that were new here represent the very beginnings of some important modern groups: the artiodactyls (like deer), the perissodactyls (like horses), and the primates (like us).

In the next several chapters, we will review the conditions at the end of the Paleocene, the geological evidence for a rapid temperature spike and atmospheric change at the start of the Eocene (PETM), and how that affected the oceans and ocean life. We'll go further into how it affected the land and life on land, how long it lasted, and what finally brought it to an end.

In part 2, we will investigate the likelihood that something similar could happen in the near future as a result of anthropogenic climate change, and what that might look like for us and for the rest of life on Earth. Finally, we will explore some of the things that we can do to reduce the possibility that there will be a PETM-like runaway climate event in our future.